SOIL SUCTION IN FOUNDATION DESIGN

LA SUCCION DANS LES SOLS ET LE CALCUL DES FONDATIONS

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SYNOPSIS Recent attempts to include the suction term in a general statement of effective stress in desiccated clays have proved to be abortive, but a corollary of these generalised effective stress studies has been the emergence of a systematic approach to foundation design on such clays with separate consideration of each component of effective stress at all stages of measurement and computation.

Procedures for the prediction of the effective stress component are discussed and a modified oedometer is described in which each component of effective stress may be controlled separately. Typical test data are given.

INTRODUCTION

Approximately one half of the land surface of the earth is subjected to desiccating influences which may be highly significant in determing the foundation characteristics of soils. The desiccation may be either continuous or periodic in response to current environmental factors, or it may be a fossil effect of a prior environment.

It is not the purpose of this paper to discuss soil desiccation per se (see Aitchison ed 1965), but it is important to emphasise the frequently ignored point that soil desiccation is a dominating factor in foundation design at appreciable depths (often more than 15 metres) in climatic environments which are by no means extremely arid. Figure 1 illustrates the degree of desiccation (expressed in terms of a suction profile) beneath long established major buildings in the central city area of Adelaide, South Australia (which has a Mediterranean type of climate with a mean annual temperature of 63°F (17.3°C), an average annual rainfall of 24 inches (0.64m), and a Thornthwaite index I=-18). Figure 2 indicates the condition of the soil exposed beneath the floor of a building in this area which might be regarded as typical of a median environment within the desiccated areas of the earth.

Obviously the potential desiccation of an area is not always reflected in desiccation of the soils, since poorly drained areas or those with a shallow ground water table will approach the conditions of saturation which are traditionally studied in soil mechanics. Nevertheless the remaining area of desiccated soils is formidable - perhaps 30 per cent of the total land surface - and the task of rational comprehension of soil behaviour in these areas is equally formidable - and is the subject of this paper.

In this shadow zone of soil mechanics - rarely considered, but of widespread importance to those who must regard deformation as a prime variable - there are two factors of outstanding significance. The first is that the magnitude of the negative pore pressure variable is large in relation to the customary values of foundation pressures: while the second determining factor is that the soil mechanics concepts of a unique effective stress and of specific effective stress parameters are no longer valid.

The generalised effective stress equation

$$\sigma' = \sigma + \chi (u_a - u_w) - u_a \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

was introduced (Aitchison and Bishop 1960) in an attempt to give quantitative description to the influence of negative pore pressures on the physical behaviour of soils (principally unsaturated clays). Although Equation (1) has been shown to be useful in limited circumstances (e.g. in which the suction term is not large in comparison with the applied stress term - as in major earth dams) it is not unusual, and not unreasonable (Aitchison, 1965, Blight, 1967) to find that the apparent value of χ in Equation (1) does not fall on a smooth, extendable, curve. The discontinuities in the $\chi/(u_a-u_w)$ relationship are of significant magnitude; thereby rendering Equation (1) unworkable for unsaturated soils in the same way that Terzaghi's simple effective stress equation is occasionally unworkable in saturated sensitive or collapsing soils.

A further, but rarely stated, difficulty in the way of application of Equation (1) arises from the relevant physical states of soils following changes of effective stress arising firstly from change of applied stress, and secondly from a change of suction. Whereas an increase of effective stress due to applied stress leads to an increase in the effective continuity of the soil, a similar increase of effective stress due to an increase of suction leads to a decrease in the effective continuity of the sample - or to the establishment of discontinuities in the sample.

The crack pattern following suction increases in soils is widely observed in the field and is equally apparent in the laboratory sample which has followed an equivalent stress history (see Figures 2 and 3).

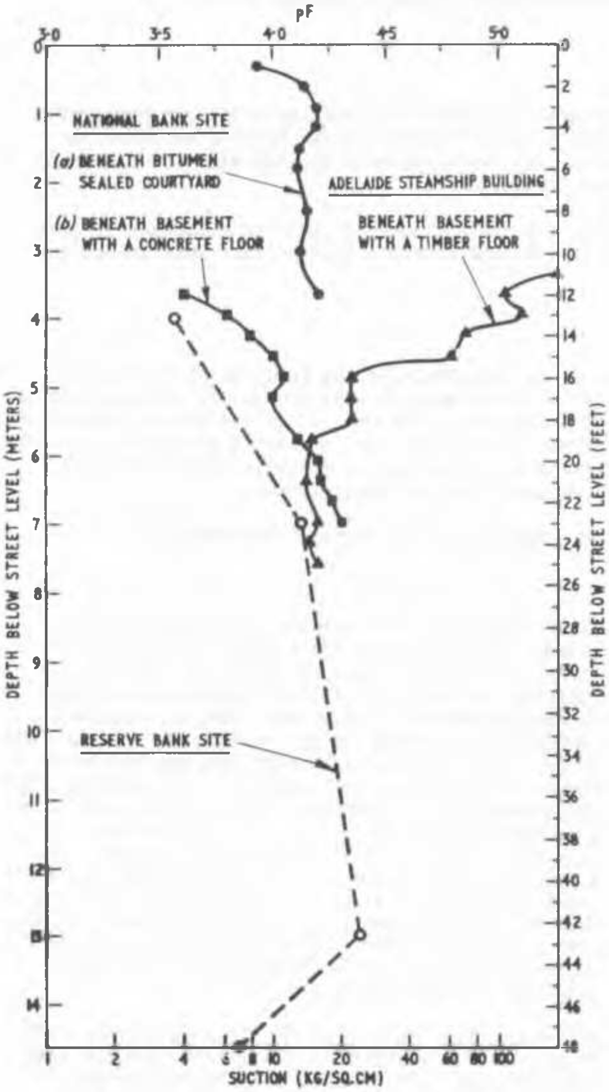

Figure 1. Suction profiles in clay beneath major buildings in Adelaide, South Australia.

Figure 2. Crack pattern at surface beneath timber floor in Adelaide Steamship Building, Adelaide, South Australia (see suction profile in Figure 1).

Figure 3. Crack pattern in 'modified oedometer' sample (of black earth) following stress cycle in Figure 10.

Following the creation of discontinuities in the soil, any further strains due to the σ_1 term must take place under zero or very low values of K_o. Thus the stress-strain relationship of normal importance in foundation engineering

i.e. the $\frac{\Delta H}{H_o}$: $\Delta\sigma_1$ relationship

becomes complex due to the highly variable (and discontinuous) values of K_o which are largely dependent upon the ambient and prior values of (u_a-u_w).

By contrast, the effective stress components due to suction will only depart from the isotropic state if the material possesses inherent anisotropy. Nevertheless, the effective stress-suction relationship may be complex and even discontinuous for reasons outlined elsewhere (Aitchison, loc. sit.) and consequently the prediction of the important foundation relationship

$$\frac{\Delta H}{H_o} : \Delta(u_a-u_w)$$

may be complicated.

Thus the two components of vertical strain are both irregular functions of both components (applied stress and suction) of effective stress. It is not irrational therefore to conclude that little progress can be made in the direction of using Equation (1) in an attempt to predict foundation behaviour.

II. THE DESIGN DILEMMA

It is an inescapable fact that very large values of the suction parameter (u_a-u_w) can, and do exist - in appropriate circumstances for considerable depths in clay soils (see Figure 1). It is an equally inescapable fact that some of these dry (high suction) soils must become wetted on some occasions, due to natural or man-made influences. In these circumstances of large changes of suction, the consequent foundation heaves can be very large - and have been so recorded.

Similarly, soils may exist in the fully wetted state and may be subjected to desiccation (towards the suction values of Figure 1 or greater in more arid environments) leading to shrinkages of large magnitude.

The foundation designer must therefore face the fact that, at any given applied load, there may be a large heave due to suction decrease, or a large settlement due to suction increase.It is essential that any such heave or settlement should be predictable and calculable in terms of rational soil mechanics, despite the general inapplicability of the effective stress equation (Equation 1.).

The simple solution to this dilemma lies in the separate consideration of each component (suction and applied load) of effective stress, always in relation to the appropriate physical state of the soil; with the behaviour pattern expressed in terms of a specific, relevant quantity. Two corollaries arise from the introduction of this procedural concept: the first is that, since measurable consequences of each measurable component of effective stress can be demonstrated, there is no need for any attempted quantification or explanation of any χ term in any version of Equation (1): while the second corollary is that any such method requires that data be obtained for each combination of change of each component of effective stress (thus requiring the specification of a particular cycle of applied stress and of suction prior to laboratory testing).

The purpose of this paper is to present an account of the principles and methods of measurement developed and used by the authors in the prediction of foundation performance on clays in the complex, unsaturated, range.

III. QUANTIFICATION OF THE SUCTION VARIABLE

$\Delta(u_a-u_w)$

The specific values of suction that occur in any soil are not haphazard. A suction profile represents a state of physical balance between various processes operating to add or to subtract water at any part of the profile. Each of these processes is identifiable and the physical laws governing each process are, in the main, well established. Thus the engineer, utilising the basic principles of soil physics, can always be aware both of the nature and magnitude of the environmental control determing any suction profile (see Table 1), and of the consequence, in terms of the new equilibrium suction profile which will follow the establishment of a new process of control or of modification of the environment.

The measurement of the initial values of suction through the profile can now follow well established procedures (Richards, 1968), using psychrometric techniques. Measurements can be made on samples taken from the profile, or *in situ*. The accuracy of measurement with either technique is of the order of ± 5 per cent.

With measured values of initial suction and with predicted values of suction under operational conditions, the range of values of (u_a-u_w) through which predictions of deformation are required, can be determined.

Table 1. Parameters of suction profile in typical environments (The suction profile - in many circumstances - can be approximated by a straight line within a zone of depth z_{max}. See Aitchison 1967).

Environmental Control	Pressure Deficiency in Pore Water at Soil Surface $-u_w$ kg/sq.cm.	$\frac{\Delta u_w}{\Delta z}$	Depth Limit (metres) z_{max}
1. Equilibrium with ground water table	$0.10\ z_w$	0.10	-
2. Continuous wetting (maximum)	0.1	0	-
3. Continuous drying (R.H. = 80%)	250	negligible	-
4. Well drained clay soil, Adelaide (I=-18) South Australia	8	0	10 +
5. Seasonal influences, Adelaide: Winter South Australia Summer (vegetated) do (non-vegetated)	0.1 20 20	0 0.1 0.1	2.0 2.0 0.5
6. Well drained clay soil, Alice Springs, Central Australia (I=-50)	300	negligible	10 +
7. Well drained clay soil, Cloncurry, Queensland, Australia (I=-44)	100	negligible	10 +
8. Well drained clay soil, Gordon, Victoria, Australia (I=+10)	1.2	0.1	3

I = Thornthwaite Moisture Index z in metres z_w = Depth to Watertable

IV. QUANTIFICATION OF THE RELATIONSHIPS

$$\frac{\Delta H}{H_0} : \Delta\sigma_1 \quad \text{and} \quad \frac{\Delta H}{H_0} : \Delta(u_a - u_w)$$

It is a comparatively simple matter, in principle, to determine dimension changes in a sample, due to changes in σ_1 and in suction, or due to a change in one component of effective stress at any ambient value of the second component. Figure 4 demonstrates a typical family of consolidation curves representing a range of ambient suctions. The normal oedometer test with an ambient zero pore pressure provides a limiting case for this set of curves. The remaining curves may all be produced in a modified oedometer as in Figure 5.

It is important to note however that the normal e-log p plot cannot be applied throughout the range of these modified oedometer tests. Due to the development of a crack pattern in the sample (see Figure 3), the volume change (observed in terms of ΔH is partly unidimensional and partly three dimensional. Consequently all dimension change data are expressed in terms of the $\frac{\Delta H}{H_0}$ ratio.

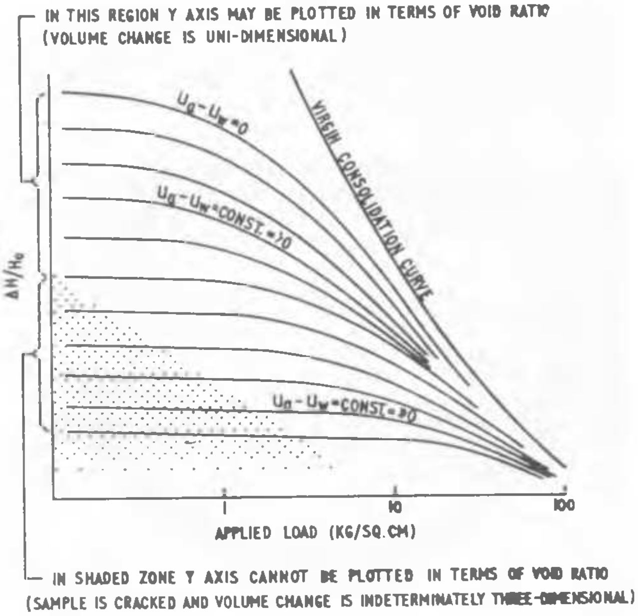

Figure 4. Typical consolidation curves throughout the suction range.

In apparatus of the type shown in Figure 5, any cycle of change of either or both of the components of effective stress can be followed. Figure 6 represents the characteristic form of stress-deformation curve (OAB) obtained when a sample - initially at a high suction - is wetted to zero pore pressure and subsequently loaded. It is important to note that the random occurrence of macro voids within the test sample must lead to differences (e.g.OA_1 or OA_2 in the measured swell. A further difficulty is often encountered due to deflocculation in the saturated macro voids leading to the inhibition of complete wetting (thus OA'). This latter difficulty is diminished when wetting occurs at higher loads (O'C) or at higher suctions.

The same apparatus can provide the normal swell pressure - free swell data as in O E F in Figure 7 (values of E_1 to E_4 being dependent again on the initial macro porosity of the test specimen).

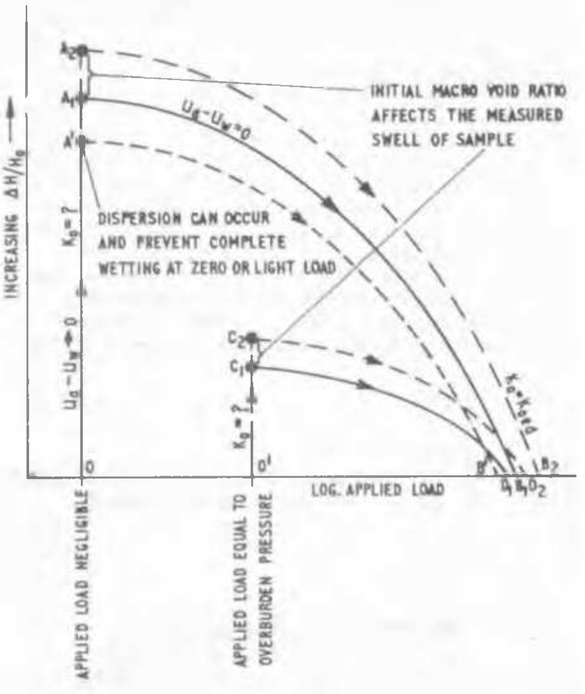

Figure 6. Consolidation after saturation

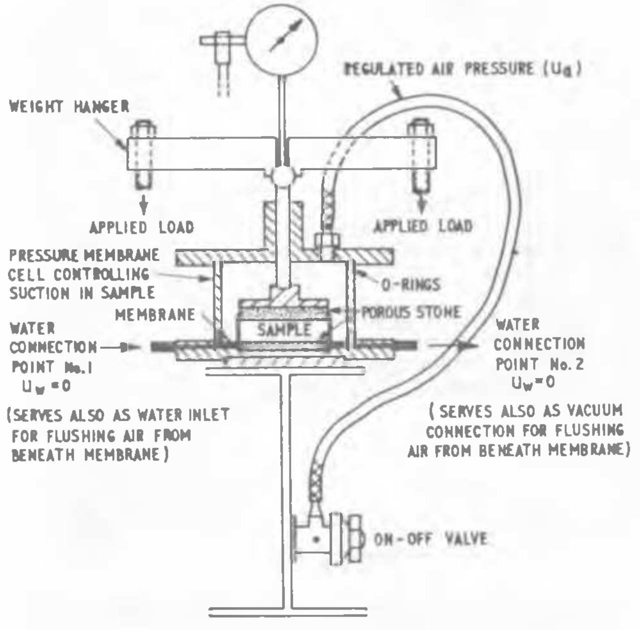

Figure 5. A modified oedometer to permit independent control of suction and of applied load

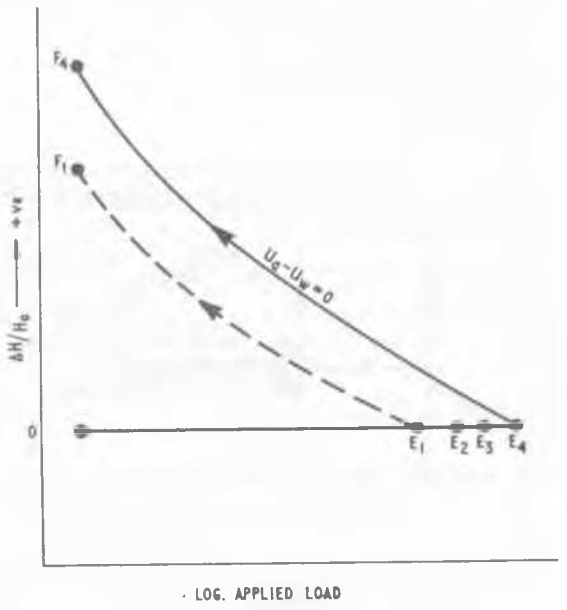

Figure 7. The Swell pressure - free swell cycle

In realistic terms a sample will rarely be found (within the above specified environments) to be at zero pore pressure or suction at any stage of the cycle of wetting or desiccation. Thus Figure 8 represents two of the typical stress cycles which must be considered in foundation design. Figure 8(a) depicts the case of a sample with a low initial suction subjected to loading and to an increase of suction. Stress path JKM represents the condition of foundation loading at a constant ambient suction (i.e. a 'drained' condition controlled by initial environment) followed by a suction increase to the selected design value - while stress path JLM represents the case of prior suction increase from the initial suction to the ambient design value followed by the application of load. A range of values for M can be expected arising both from the different stress paths and the initial random macro porosity. Figure 8(b) represents a sample which is initially at a high suction and which is to be subjected to an increase of load and a decrease of suction. Alternate stress paths JLM or JKM must be considered, together with the possibility of traversing an extended stress path JNPM due to increased wetting (possibly as a consequence of exposure during construction) in an intermediate stage between the initial and final conditions.

Any specified cycle as in Figure 8 may be followed by apparatus as in Figure 5 merely by the relevant control of suction (through u_a) and of applied load. At all times each component of effective stress is measurable, although of course the total effective stress is indeterminate.

By contrast, mention can be made of the 'double oedometer' test (Jennings 1957) in which two separate samples are subjected to loading as in Figure 9. Stress path STU (similar to OAB in Figure 6) is followed in one sample i.e. saturation at zero pore pressure followed by loading; while stress path SV is followed in a sealed sample in which the pore pressures are not known. Computation of potential deformation is made from the two curves with due allowance for sample differences. This procedure appears to couple the experimental difficulties of Figure 6 with an uncertainty of pore pressure evaluation. A further problem with Jenning's method appears to lie in the difficulty of extrapolation from the measured values of deformation at zero and at unknown initial suction to another (design) suction. It was largely as a result of the potential inaccuracies of such a generalised approach that the authors chose to follow specific stress paths in each measurement.

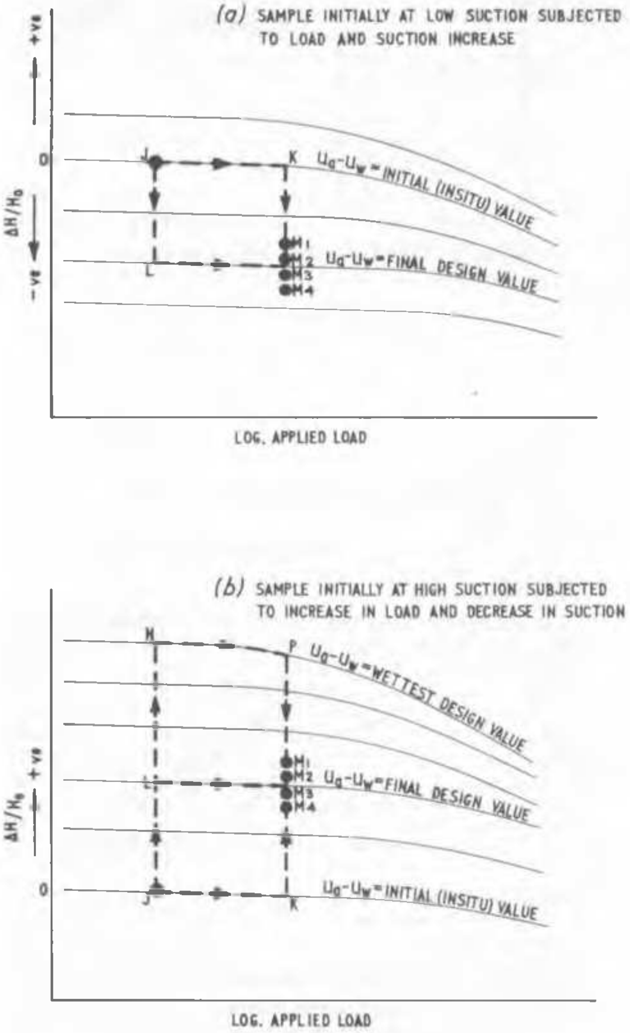

Figure 8. Typical stress paths for combinations of applied load and suction

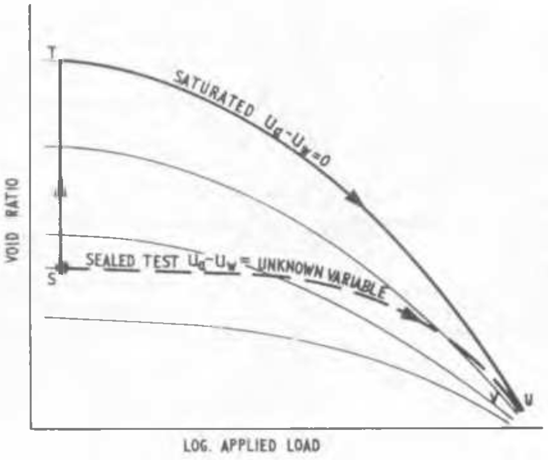

Figure 9. Stress paths in the double oedometer test

Figures 10 and 11 present typical experimental data on an expansive soil (a black earth) from the vicinity of Adelaide, South Australia. In one case (Figure 10) the soil was consolidated at a load of 0.28 kg/sq.cm., while the suction was maintained at an ambient value of 1.3 kg/sq.cm. corresponding to the initial *in situ* value. Following this consolidation the sample was subjected to increments of suction up to a maximum value of 10 kg/sq.cm. In the second example (Figure 11) the sample was subjected to decreasing suctions at a constant applied load of 0.28 kg/sq.cm. Figure 10 represents a potential design condition for a lightly loaded soil subjected to a characteristic drying cycle in the Adelaide area. Figure 11 also represents a potential design condition for the Adelaide area - in this case a lightly loaded, normally desiccated soil exposed to wetting due to artificial means. Thus it can be seen that a foundation design in this area may be involved in either a heave of the order of 2 per cent, or a settlement (due to suction change) of similar order.

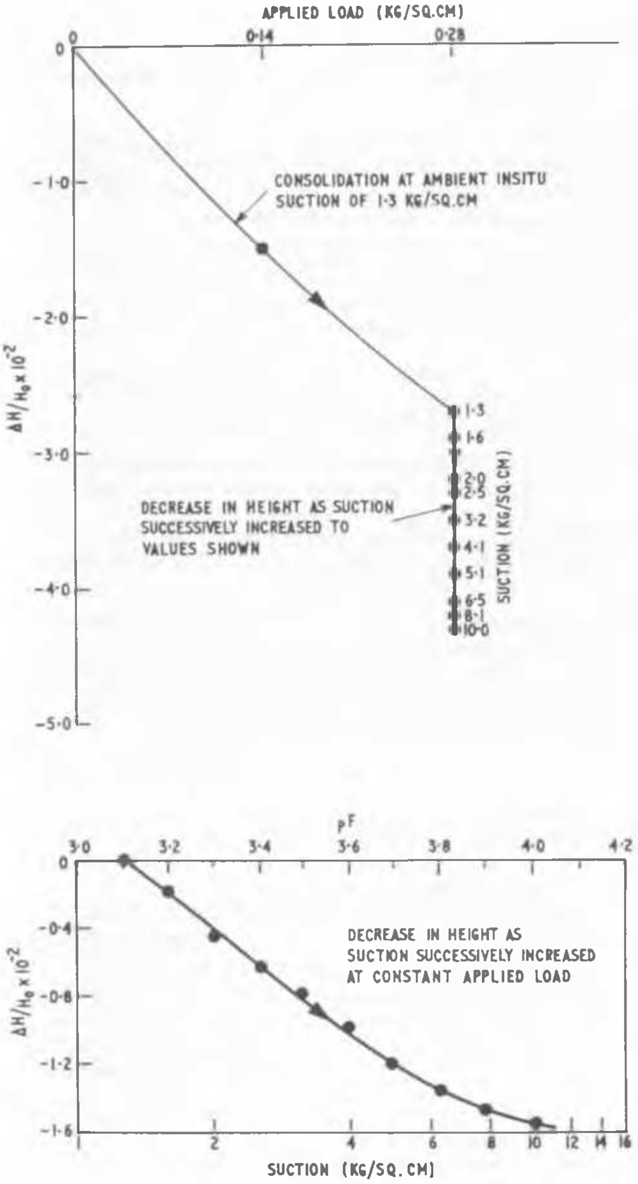

Figure 10. Consolidation at constant-suction followed by suction increase in loaded black earth

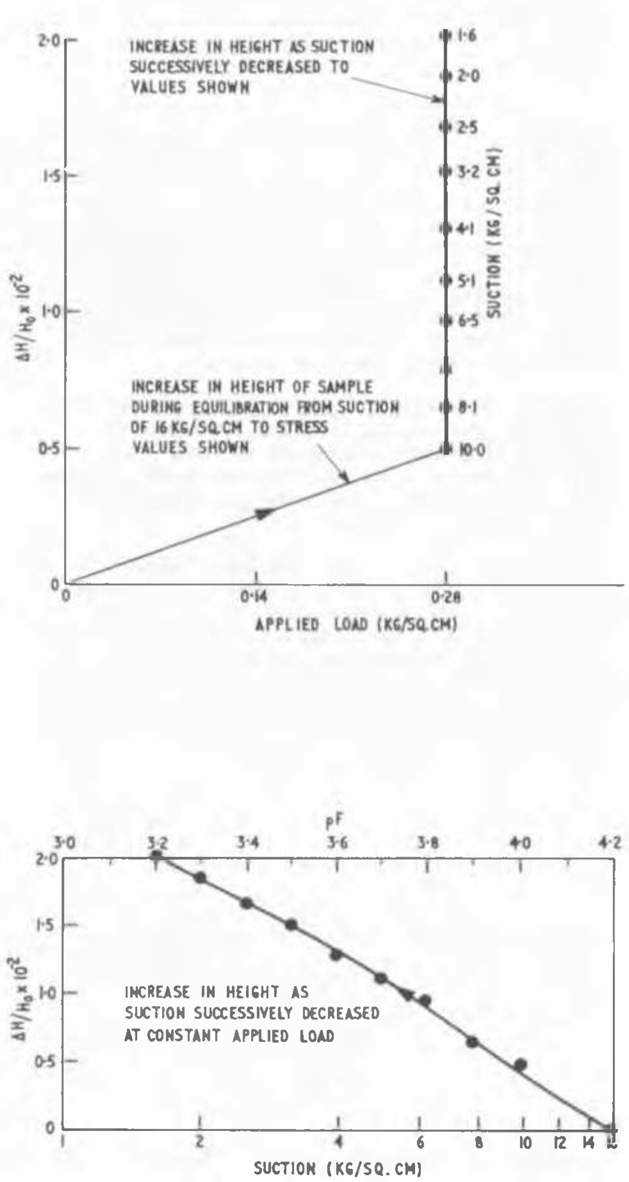

Figure 11. Swell/suction decrease relationship in loaded black earth

V. DISCUSSION

The difference of sign between the values of $\frac{\Delta H}{H_o}$ in Figures 10 and 11 highlights the essential problem of design of foundations on expansive soils, for it is patently impossible for the engineer to design for the worst condition which may exist on any site. In many circumstances there may be a more or less equal possibility of volume increase due to suction decrease or of volume decrease due to suction increase. Thus there is no singular 'worst' design situation to which any rational 'factor of safety' can be applied.

This conflict of possibilities does not reflect any lack of precision in the experimental approach, but rather reflects the fact that the management of the site may follow any one of a number of procedures. It is important therefore that any computation of foundation deformation should carry a clear statement of the environmental circumstances (and of the associated initial and design suction profiles) to which it applies. Within any such precisely defined terms of reference a deformation computation based upon the procedures suggested in this paper should be within the normal bounds of accuracy.

It may well be a further responsibility of the soil engineer to provide advice on the techniques of establishment and maintenance of the specified design environment - and possibly to provide further advice on the potential consequences of departures from the design environment.

At this point of time it has not been possible to obtain adequate field checks of predicted movements based upon data as in Figures 10 and 11. Difficulties associated with very long term field observations of *in situ* suction profiles, as well as of the usual structural loads and settlements, have not been fully resolved, nor has a satisfactory method of computation been evolved for the consolidation process in the discontinuous, high-suction state in heavy clays. For the present the authors have attempted merely to provide a logical procedure to define the direction and approximate magnitude of any deformation arising from a specified combination of applied load and of suction.

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