Soil Morphology and Foundation Engineering

Morphologie du sol et construction de fondations

by G. D. AITCHISON, M.E., A.M.I.E. Aust., University of Melbourne, Victoria, Australia

Summary

In the study of the foundation characteristics of the principal populated centres of Australia it has been found that the pedological system of soil classification is readily adaptable to engineering requirements.

Since each soil type (represented by a particular soil profile) reoccurs on a very large number of building sites, there is a wide potential application for all information relevant to the foundation behaviour of each soil. Every soil, once identified and described, may be recognised in the field solely on the basis of its characteristic morphology. Against each soil type can be recorded past experience of foundation performance as well as measured data defining the physical properties and seasonal characteristics of the soil. Foundation design—quantitative or qualitative—can follow from such records.

This approach to foundation engineering, based on soil morphology, has been developed specifically to be applicable to small domestic-type buildings within the Australian environment. Thus it relates to shallow foundations, and to soils which are subject to the influences of a pronounced seasonal cycle in a warm to temperate climate.

Sommaire

En étudiant les caractéristiques des sols du point de vue des fondations dans les principales agglomérations urbaines de l'Australie on trouve que le système pédologique de classification des sols s'adapte facilement aux besoins du génie civil.

Vu que chaque coupe de sol (représentée par une coupe caractéristique) reparaît dans grand nombre d'emplacements de bâtiments, il est possible d'appliquer sur une large échelle les renseignements recueillis sur l'action des fondations dans un sol. Chaque sol, une fois qu'il a été identifié et décrit, est facilement reconnu en place par sa seule morphologie. Pour chaque type de sol on enregistre les expériences préalablement faites sur l'action des fondations et les résultats de mesures donnant les propriétés physiques et les variations caractéristiques résultant du cycle des saisons. Les observations enregistrées peuvent servir de base à l'établissement du projet de fondation tant au point de vue volume que type.

Cette méthode basée sur la morphologie du sol a été particulièrement développée pour la construction de maisons d'habitation à un étage, dans les conditions régnant en Australie, c'est-à-dire des fondations peu profondes et des sols soumis aux influences du cycle bien marqué des saisons dans un climat chaud ou tempéré.

Introduction

Among the most complex foundation problems with which the engineer must contend are those in which he must design, not only for applied structural loadings, but also for certain variable forces of nature. Such problems are encountered in connection with quite a large proportion of those engineering structures which must be built on the surface of the soil: structures such as road pavements and domestic buildings are particularly susceptible to the effects of nature since in such cases the area of soil covered by the structure is comparatively small in relation to the perimeter or exposed edge.

The impact of natural forces is normally seen as a cyclic effect with repetition either annually (seasonally) or over a longer period (as an oscillation of climate). The influences of nature which affect the engineering behaviour of soils are broadly those of a penetration of a temperature wave and a cyclic variation of soil moisture; these may often be interdependent. Physical changes in soil properties which accompany these phenomena may be manifested in terms of a cycle of freezing and thawing, or wetting and drying. Within Australia, the average climate is such that a pronounced cycle of wetting and drying is the dominant seasonal effect in soils. In this paper therefore, consideration is given to the foundation behaviour of those soils in which there is normally an annual repetition of a more or less severe wetting and drying cycle.

Soil Classification

An essential pre-requisite to the proper study of the engineering behaviour of soils in nature, is the acceptance of a satisfactory system of soil classification. In any large scale study of soils and foundation performance, correlations may be found between any chosen category of any recognised engineering soil classification, and the corresponding foundation characteristics of the soil. However, there are serious limitations to the use of such classifications, due to necessity of assessing each soil layer by layer (i.e. horizon by horizon) and for introducing an additional factor to allow for climatic influences.

As an alternative to the engineering soil classifications, there is considerable merit in the system developed by pedologists, originally for agricultural purposes (*Stephens*, 1952). In such a system, the soil profile as a whole becomes the unit of the classification, thus eliminating the need for separate assessment of each soil horizon. Since the weathering processes in the soil profile are normally in equilibrium with the existing climatic conditions, the classification based on such a unit automatically embodies some expression of the seasonal factor.

Considerable engineering use has already been made of such pedological soil classifications—almost entirely in relation to problems of pavement construction (*Highway Research Board*, 1949, 1950, 1951). Consequently, in this paper, stress is laid on the alternative application—in shallow foundations for small buildings.

A useful characteristic of the pedological classification of soils is that it depends largely for its application upon the direct recognition in the field of features of the soil profile, i.e. it is based upon the observable aspects of soil morphology, principally depth, colour, texture and structure.

Since each individual problem in shallow foundation engineering is usually too small to warrant laboratory examination of the soil from each site, the field identification aspect of the pedological classification permits a new approach to an otherwise uneconomical problem. In any big city or town, the number of sites on which buildings may be erected is quite large, whereas the number of different soil types which may occur is usually quite limited. The estimated figures for two of Australia's capital cities—Melbourne and Adelaide—show a total of only 40 major soils for more than 800,000 actual or potential building sites.

Table 1 Soil Distribution in Populated Centres
Distribution des sols dans les agglomérations urbaines

	Locality	
	Melbourne (Victoria)	*Adelaide (S. Australia)*
Population	1,400,000	400,000
Area, square miles	270	100
Number of sites for buildings (existing and potential)[1])	600,000	200,000
Number of basic soil types[2])	15	25
Average number of building sites on each basic soil type	40,000	8,000

[1]) The majority of buildings are small, single-storied, domestic type
[2]) Transitional soil types and minor sub-types have been excluded

Table 2 Elements of the Soil Classification System—The Pedological Approach Adapted for the Purposes of Shallow Foundation Engineering
Eléments du système de classification des sols – La méthode pédologique est adaptée aux exigences des constructions à fondations peu profondes

Category	*I Orders*	*II Sub-Orders*	*III Great Soil Groups*	*IV Families*	*V Types*	*VI Sub-Types*
Number of Classes in Category	*2*	*7*	*40–50*	*Any Number*	*Large Number*	*Small Number (per Type)*
Determinant morphological attributes of category	Presence of lime or gypsum in A or B horizons. Position of horizons of organic matter, clay, sesquioxides, lime and gypsum		Profile color and presence of halomorphic calcimorphic or hydromorphic features	Parent material and depth of solum. (Category used only where such features dominate)	Texture, depth and structure of A and B horizon. Emphasis on B horizon	Texture, depth and drainage status of A horizon
Significance of category	Of fundamental importance in systematic classification. Not significant in determining land use		Most important category in classification but rarely interpretable for land use except on broad scale. The basis of regional soil maps	Useful grouping of soil types with similar physical properties	The basis of soil maps for land use. Each type is morphologically distinct and possesses definite engineering properties	The most detailed category. Rarely mappable. Related to specific engineering land use
Influence of land use in establishment of category	I, II and III are systematic, objective categories and are not determined by land use. No bias should be evident whether soil classified by engineer, agriculturalist, or pedologist			Each successive category is increasingly dependent on land use. An engineering bias in defining the determinant features of a soil type is entirely compatible with parallel practice in agricultural soil surveys		
Examples from Australian capital cities			Yellow Podsolic Soils Red Brown Earths	MS soils MT soils	MS 1[1]) MS 2 MT 1 MT 2 RB 3 RB 6 etc.	 RB 3*a*[1]) RB 3*b*

[1]) Each soil type (and sub-type) has been observed to show characteristic engineering behaviour and to possess characteristic physical or engineering properties (vide Tables 3 and 4)

Table 3 Soil Type and Foundation Experience
Types de sols et expériences recueillies

Great Soil Group	*Soil Type*	*Soil Morphology: Principal Features of the Soil Profile*	*Foundation Experience on the Soil*[1]		
			Incidence of Foundation Failure on the Soil	*Soil Property Responsible for Failure of Foundation*	*Observed Satisfactory Foundation Practice*
Red Brown Earths	RB 3	0–12″ *A* horizon: Brown silt loam. 12–33″ *B* horizon: Red brown clay with marked development of coarse prismatic structure. 33–120″ *B-C* horizon: Brown clay with lime. Concentration of lime diminishes with depth. Underlying soil is stiff fissured clay.	Failures are common. Cracks show in about 50% of houses on this soil. Serious disfiguration occurs in less than 5% of normal dwellings.	Differential movements of the soil (as the result of seasonal shrinking and swelling of the clay horizons).	Pier-and-beam Piers must be effectively supported at considerable depth below soil surface. (Approx. 9–12 ft. is recent practice for bored piles.)
	RB 6	0–11″ *A* horizon: Brown loamy sand. 11–18″ *B* horizon: Reddish brown sandy clay with poorly developed coarse prismatic structure. 18–22″ *B–C* horizon: Light brown sandy clay with lime. 22–60″ Reddish brown sandy clay.	Failures are rare. Some minor cracks occur in about 5% of houses on this soil.	Differential settlement may occur if foundation loading is uneven. Water-table is shallow causing soft, saturated subsoils.	Continuous strip footing on the soil surface.
	RB 9	0–6″ Grey brown clay loam. 6-12″ Light grey mottled clay. 12–21″ Reddish brown clay of prismatic to columnar structure 21–24″ Light brown friable clay with moderate lime. 24–60″ Reddish brown friable clay.	Few failures have been observed since most houses on this soil are newly constructed. About 10% of older houses show minor to moderate cracking.	Some swelling and shrinking movements of small magnitude occur seasonally or as a result of changes of level of the watertable after underground drainage.	Pier-and-beam or rigid type of continuous strip footing on the soil surface. Short bored piles (up to 6 ft. long) have been used as piers.
Black Earths	BE 1	0–20″ Dark grey to black granular clay. 20–40″ Dark grey or brown or redbrown coarsely structured clay. 40–120″ Light brown clay with varying amounts of lime. Underlying soil is stiff fissured clay.	Failures are commonplace. Almost every house on this soil is cracked to some extent. About 10% of houses are noticeably disfigured.	The seasonal shrinking and swelling movements are large throughout the whole profile. In addition the soil exhibits wide lateral variation and differential movements are consequently accentuated.	Pier-and-beam. Short bored piles (4–8 ft.) commonly used but show some instability. Extended bored piles (10–15 ft.) or under-reamed piers are suggested as superior alternatives.

[1]) Foundation experience recorded in Table 3 relates to domestic type brick or masonry buildings with normal foundations—i.e. footings placed upon the soil surface or supported at shallow depth.

Thus the problem of studying all of the soils, and of determining their properties, is quite small, whereas the application of such information can be quite extensive.

In all studies of the foundation behaviour of the soils of Australia, the pedological classification has been adopted. Since in the areas of greatest foundation interest—the capital cities—there were no prior soil surveys, the opportunity existed for the mapping and classification of soils with a view to direct engineering land use. This approach was found to be not incompatible with practices adopted elsewhere in Australia for agricultural purposes since both systems were based upon a common appreciation of the pedological background. An outline of the classification used is given in Table 2. The principles of soil survey and field classification adopted were those described by *Stephens* (1952). The symbolic notation used at present is quite arbitrary [at a later stage it may be desirable to introduce a more objective system of designation c.f. *Lueder* (*Highway Research Board*, 1950)].

Foundation Behaviour of the Soils

With the acceptance of an appropriate soil classification system, and the identification of the major soils of certain zones, it was found that each and every soil type exhibited characteristic foundation behaviour. For each soil type, experience was recorded to emphasise not only the incidence of foundation difficulties, but also the contributing property of the soil. Satisfactory foundation practices, which may have been developed for many soils by trial and error over the years, were also recorded.

Thus the stage was reached, almost solely on the basis of field examination of the soils and the structures supported thereon, at which a qualitative account could be rendered of the process of selection of foundations appropriate to each particular soil type. Table 3 lists some examples of such records of foundation behaviour in the suburban areas of Adelaide, South Australia.

The compilation of a complete account (for any area) of soil types and foundation behaviour, after the pattern of Table 3, permits the introduction of a wholly sound, though empirical form of foundation engineering. Such a stage has been reached in the metropolitan area of Adelaide (*G. D. Aitchison, R. C. Sprigg, G. W. Cochrane*, 1952). The determination of the proper foundation practice for any standard form of building requires only an awareness of soil morphology sufficient to permit the recognition of any one of a small number of previously described soil types.

Such an approach to foundation "design", though lacking exactitude in the sense of soil mechanics, is nevertheless frequently adequate to cope with the requirements of traditional building. On the other hand, for non-traditional building on soil types for which no satisfactory foundation practice is known from accumulated experience, the approach to foundation design must include an appropriate soil mechanics treatment. This, however, is not necessarily incompatible with the use of the pedological soil classification.

Soil Type and Foundation Design

The design of a footing, supported upon or within the soil profile requires the evaluation of the standard engineering soil properties, with due allowance for the effect of seasonal changes. In sandy soils the problem is normally one of bearing capacity, complicated slightly by the multi-layered character of the soil profile and the influence of varying soil moisture upon shear strengths. Apart from a knowledge of the critical soil moisture conditions in the profile (which information can only be obtained from long term field experimentation) such a problem is amenable to the standard treatments of soil mechanics—and hence does not require further discussion.

On clay soils however, an additional complication is introduced as a result of the reactive nature of the clay fraction. Each seasonal change of soil moisture is accompanied not only by a change of soil strength but also by a system of forces and displacements within the soil arising from the phenomenon of soil shrinking and swelling. Each such force and each such displacement is in fact a measurable quantity (although not all have been measured).

There is considerable weight of field evidence to suggest (on outward manifestations only) that the swelling and shrinking behaviour of any soil type is an essential characteristic of the soil. Hence it is postulated that each soil type is unique not only in its morphology and its normal engineering properties, but also in regard to the active aspect of soil behaviour resulting from the seasonal cycle.

The simplest measurement of soil swelling is in terms of the vertical displacements within the profile. Such measurements have been made on selected typical soils (*G. D. Aitchison* and *J. W. Holmes*, 1952), and some results are listed in Table 4. Swelling pressures throughout the whole profile are also of importance but have not been fully investigated.

The radical design of a stable foundation on a soil exhibiting shrinking and swelling movements is possible in the light of such measurements. To each soil type can be ascribed values of:—

(1) The depth (Z_m) of the zone of seasonal soil movement.

(2) The average shear strength (C_D) of the soil at and below foundation depth (D). (D is not less than Z_m.)

(3) The total frictional force (K) which may be exerted (as a result of swelling pressures and vertical soil displacement) against unit width of a fixed vertical surface (as of a pier) embedded in the soil.

The force K is a cyclic variable with a maximum value upwards (K_e) during the swelling of the soil profile and possibly a small value downwards (K_s) during the shrinking process (c.f. "negative" friction).

The design of any type of foundation can proceed on the basis of these soil "constants". A bored pile on a clay soil can be chosen as an example.

Since the pile must penetrate the zone of shrinkage and swelling, provision must be made for stability against such forces of nature. This requires a minimum pile lenght to provide anchorage.

This minimum pile length can be written as:—

D (min) = function (Z_m, C_D, K_e).

The allowable pile loading (P) for a bored pile of radius (r) can be written as:—

P = function (D, Z_m, C_D, K, r).

Details of the design approach are not given since the treatment, though straightforward, is not rigorous as assumptions must be introduced, relating to frictional support of the sides of the pile within the stable moisture zone.

Some typical pier sizes, for three troublesome clay soils of Adelaide, are given in Table 4.

Table 4 Soil Characteristics and Foundation Design on Typical Clay Soils Showing Seasonal Shrinkage and Swelling Movements

Caractéristiques des sols et constructions de fondations sur des sols argileux typiques montrant la contraction et le gonflement causés par le cycle des saisons

		Soil Type		
		RB_3	*RB_9*	*BEI*
Physical Properties of the Soil Profile:				
Depth of seasonal moisture change	feet	8–10	3–4	7–9
Vertical movement of soil surface	inches	1.4	0.6	3.2
Depth of zone of seasonal soil movement[1])	Z_m feet	7	2	7
Shear strength of soil at depths below zone of soil movement	C_D lbs./sq.inches	42	14	20
Foundation Details (12" dia. bored pile)[2])				
Minimum length	feet	8	2	9
Allowable load, length	D feet	8 10	4 6 8	10 12 15
load	P tons	4.5 7.5	3.0 4.5 6.0	3.0 5.0 7.5

[1]) Taken as depth below which vertical shrinking and swelling movement of the soil does not exceed 0.1 inch

[2]) Calculated values

Conclusion

It has been suggested throughout this paper that the soil type (representing a unique soil profile) provides the key to all recorded data on the soil: from knowledge of the incidence of foundation difficulties and the factors contributing thereto, to the selection of proper foundation techniques either on an empirical basis or quantitatively as the result of knowledge of the engineering properties of the soil profile. It is further suggested that only the simplest approach to soil identification is required—that of recognition of the evident physical features of the soil profile.

The task of the engineer in this approach to shallow foundation engineering is two-fold. Firstly, the soils of any area of major importance must be identified, described and studied to permit complete characterisation. This work must, of necessity, be carried out by a central authority, governmental or otherwise, since it is a long term project of some magnitude. With the completion of this first phase of the work, the remainder of the task—which may affect the individual practising engineer—is reduced to reasonable proportions, and consists mainly of the recognition of the previously defined soil type, followed by a straightforward foundation design.

The one fact which is outstanding is this—that there must be a common denominator in all phases of the work from soil classification to engineering land use. It appears to be logical that in this form of engineering land use—shallow foundation engineering—the common link from research to practice is that of a more or less detailed appreciation of soil morphology.

Acknowledgment

The subject matter of this paper is the outcome of part of the field program of the Division of Soils, of the Commonwealth Scientific and Industrial Research Organisation. This paper is presented by permission of the Chief, Division of Soils.

References

Aitchison, G. D., Sprigg, R. C. and *Cochrane, G. W.* (1952): The Soils and Geology of Adelaide and Suburbs. Bulletin Dept. Mines, South Australia (in press).

Aitchison, G. D. and *Holmes, J. W.* (1952): Aspects of Swelling in the Soil Profile. Unpublished paper. Division of Soils, C.S.I.R.O., Aust.

Highway Research Board (1949): Bulletin No. 22.

Highway Research Board (1950): Bulletin No. 28.

Highway Research Board (1951): Bulletin No. 46.

Stephens, C. G. (1952): A manual of Australian soils. Bulletin C.S.I.R.O. Australia (in press).