Tests on London Clay from Deep Borings at Paddington, Victoria and the South Bank

Essais sur l'Argile Londonienne Provenant de Forages Profonds à Paddington, Victoria et la Rive Sud de la Tamise

by A. W. SKEMPTON, D.Sc., A.M.I.C.E., Professor, and D. J. HENKEL, B.Sc., A.M.I.C.E., Imperial College of Science and Technology, University of London, England

Summary

Tests have been made on samples taken from deep borings at three sites in the London clay. The properties measured include shear strength, Young's modulus, compressibility and coefficient of consolidation. The variations of these properties with depth are studied. Both Young's modulus and compressibility are correlated with shear strength.

Sommaire

On a fait des essais sur certains échantillons provenant de sondages profonds dans l'argile de Londres. Les propriétés mesurées comprennent la résistance au cisaillement, le module d'élasticité, la compresisbilité et le coefficient de consolidation. On a étudié la variation de ces propriétés par rapport à la profondeur. Le module d'élasticité et la compressibilité sont tous les deux en corrélation avec la résistance au cisaillement.

Introduction

There can be few clays so widespread and, at the same time, bearing such a density of buildings as the London clay. Yet in the past, apart from a few exceptional structures such as Victoria Tower (Houses of Parliament) and the tower of Senate House (London University), the vast majority of buildings in the London area have not exceeded 10 storeys in height. Thus, until recently, no deep borings have been made for geotechnical purposes. During the last 4 or 5 years, however, a notable change in outlook has taken place in London and schemes have been considered for the erection of several buildings of 25 storeys or more.

The authors have been fortunate in being associated with three of these proposals for high buildings in London, and the results of the tests made on samples taken from depths to 140 ft. in borings at the various sites are recorded in the present paper. It is hoped that the results will be of general interest, as providing data on a deep bed of over-consolidated clay exceptionally uniform in its mineralogy, and of more particular interest to engineers who will, in the future, be faced with foundation problems associated with tall or exceptionally heavy structures built on the London clay.

The Sites

The first site is located quite close to Paddington Station (see Fig. 1). A boring 140 ft. deep was made in February 1954 at the request of the Committee for the Investigation of High Buildings in the U.K. to whom Mr S. Kadleigh and Mr P. Horsbrugh were architects and Mr R. Freeman and Mr R. T. James were consulting engineers; the senior author acting as the advisory consultant. The High Paddington project envisaged buildings 38 storeys high. At Paddington the London clay extends right up to the surface, and has a total thickness of about 200 ft. (Fig. 2).

The second site is near Victoria Station, and the investigations here were carried out at the request of Messrs Holland, Hannen & Cubitt in relation to a proposed 25 storey office building. Three borings were made in October 1954, the deepest being 110 ft., and in this paper the test results of all three borings are grouped together. At Victoria the London clay is covered by about 35 ft. of sandy gravel and alluvium (see Figs. 2 and 4).

The third site is on the South Bank, near the Royal Festival Hall and Waterloo Station. Several borings have been made, in connection with the Shell buildings which are to be erected at this location, and in this paper we give the combined results of two borings, both about 150 ft. deep, carried out in August 1955 for the 27 storey office block. Sir Howard Robertson (of Easton & Robertson) is the architect and Messrs Scott & Wilson, Kirkpatrick & Partners are the engineers, to whom the authors are advisers. As at Victoria, the London clay at the South Bank is found about 35 ft. below ground level and at both sites the thickness of the clay is roughly 120 ft.

The borings at Victoria and the South Bank were carried out by Messrs Le Grand, Sutcliffe & Gell, who also made the tests on the Victoria samples. The South Bank samples were tested partly at the Imperial College of Science and Technology and partly by Messrs Scott & Wilson. The Paddington tests were made at Imperial College and in the laboratory of Messrs George Wimpey, who carried out the sampling operations at this site.

Geology

The London clay (so named by William Smith in 1812) was deposited under marine conditions in the Eocene period, roughly 30 million years ago*. The lowest part is sandy, known as the Basement Bed, and is seen in the South Bank borings (Fig. 4). Above this the clay is remarkably uniform, and was originally about 400 ft. thick. On the London clay were deposited the Claygate Beds, followed by the Bagshot, Bracklesham and Barton Beds, all predominantly sandy with occasional clay layers. Over a typical point in the London clay, say 100 ft. above its base, the total thickness of sediment must have been at least 500 ft. and more probably 700 ft.; corresponding therefore to a pre-consolidation load of about 20 ton/sq. ft.† Uplift and erosion have removed, in the

* For brief accounts of the geology of the London area, see SHERLOCK (1935). For the dating of the deposits and for details of the Pleistocene gravels, see ZEUNER (1945, 1946).

† This estimate is confirmed approximately by laboratory tests (COOLING and SKEMPTON, 1942).

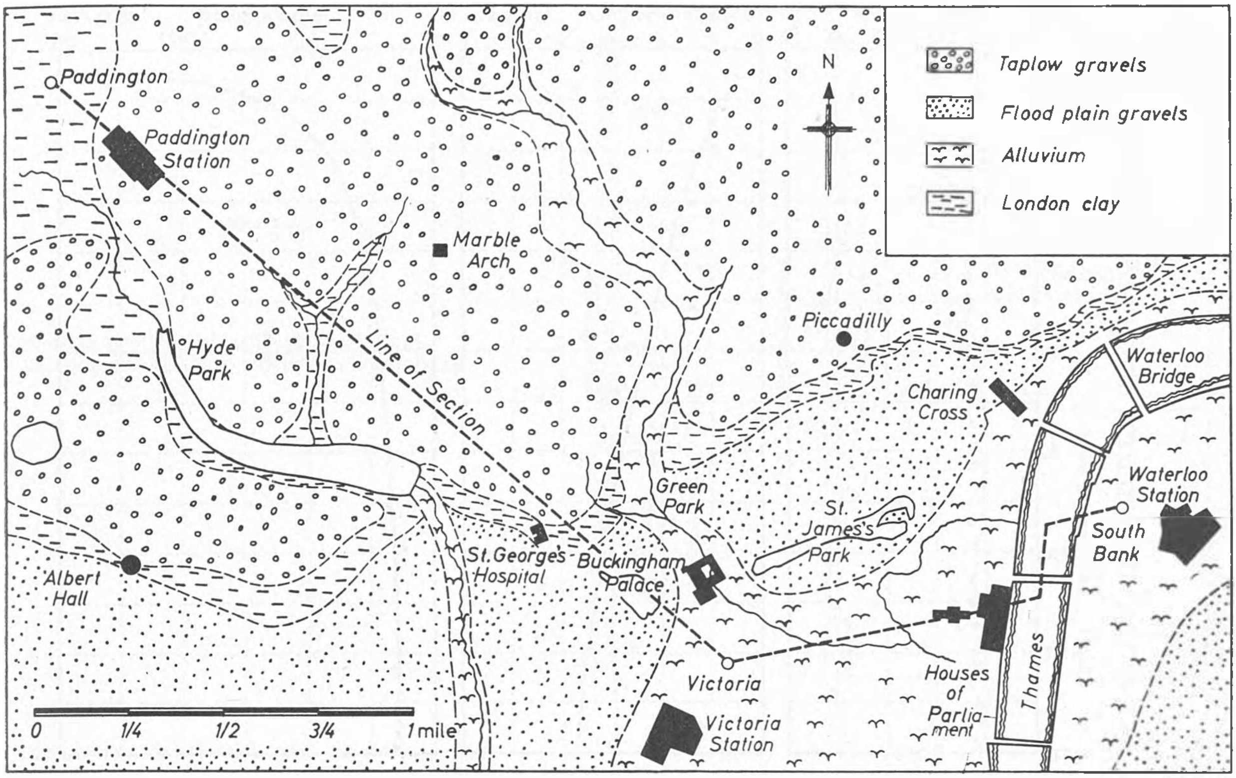

Fig. 1 Geological map, showing position of the three sites
Carte géologique, montrant les emplacements des trois investigations

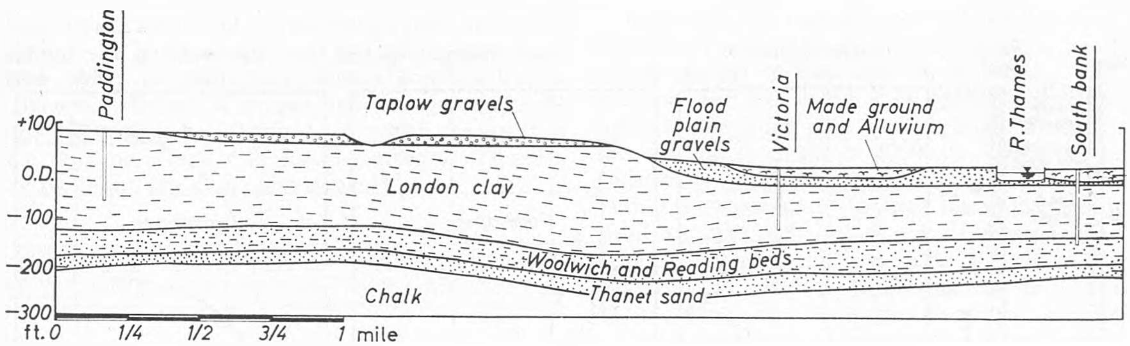

Fig. 2 Geological section
Profile géologique

central London area, the overlying deposits and one-half to two-thirds of the London clay. Much of the erosion was accomplished by the Thames at intervals during the Pleistocene glaciations and, following each period of down-cutting, terrace gravels were deposited. The Taplow gravels (Fig. 2), with their surface at about 70 ft. O.D., are thought to have been formed some 150,000 years ago; and the Flood Plain gravels, with a surface level of about 25 ft. O.D. perhaps 50,000 years later. The alluvium overlying the Flood Plain gravels is post-glacial and contains Neolithic as well as Roman remains.

Where the London clay is exposed at ground level, as at Paddington, the top 20 ft. (or thereabouts) is brown; actually varying from yellow brown near the surface to grey brown at depth. There is then a fairly sudden transition to the grey clay, known traditionally as the 'blue' London clay. Under the Taplow and Flood Plain gravels, however, the brown clay is rarely more than a few feet thick, and sometimes entirely absent*. This seems to indicate that where the gravels now exist the brown clay, which had been formed by oxidation of the blue clay, when the ground water was low, was eroded away and that little oxidation of the newly exposed surface could occur before the gravels were deposited.

Under the London clay are the hard mottled red and brown clays, and the sands, of the Woolwich and Reading Beds, which were deposited in estuarine conditions. Then come the sands of the Thanet Beds which rest unconformably on the Chalk. Comparatively little geotechnical data exist on the Reading clay as it is not often encountered in foundation work. But it is a stronger and less compressible material than the London clay.

* The difference between the thickness of brown clay under the gravels and where the clay extends to the surface can be seen from numerous records of bore holes made for water supply (BUCHAN, 1938). It is from these well borings that the geological section in Fig. 2 has been prepared.

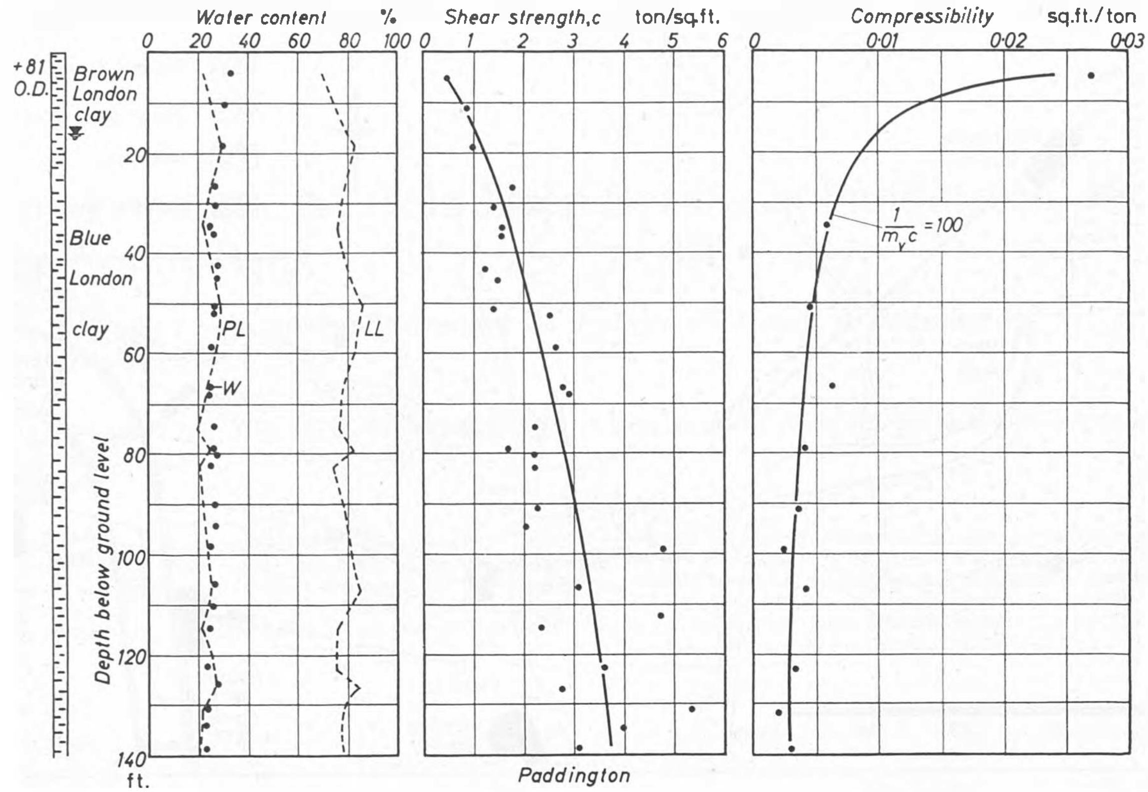

Fig. 3 Test results at Paddington
Observations à Paddington

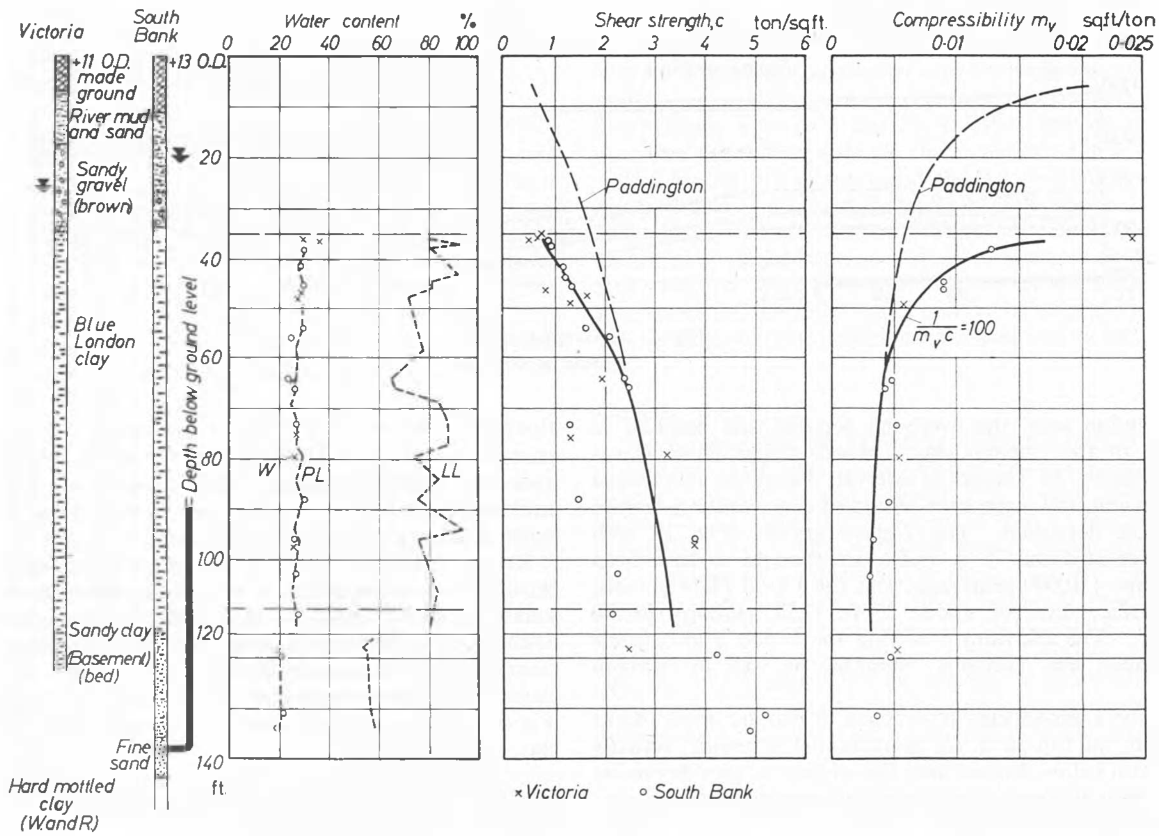

Fig. 4 Test results at Victoria and South Bank
Observations à Victoria et à la South Bank

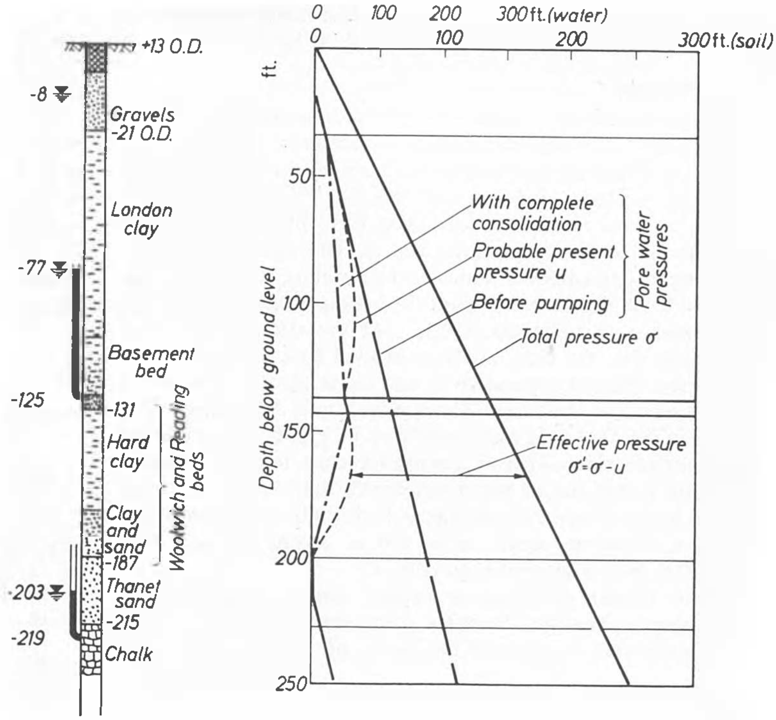

Fig. 5 Pressure/depth relationship at South Bank
Relation pression/profondeur à la South Bank

Water Content and Atterberg Limits

From Figs. 3 and 4 it is seen that the liquid limit of the London clay lies in the range 70 to 90 at all depths in all three sites, and the plastic limit is approximately 26 throughout. In the Basement Bed the limits are about 55 and 20 respectively. The relatively small variations in Atterberg Limits are quite characteristic of the London clay, and the values from these three sites are closely similar to those obtained from an investigation at Waterloo Bridge (COOLING and SKEMPTON, 1942). These values are included in Table 1, in which the average results for a deep boring near St Paul's Cathedral (1¼ miles northeast of the South Bank) are also quoted*.

Table 1
Average values of water content and Atterberg limits
Valeure moyennes de teneur en eau et limites d'Atterberg

Site	*w*	*LL*	*PL*	*PI*
Paddington	26	79	24	55
Victoria	27	73	29	44
South Bank	27	78	28	50
Waterloo Bridge	27	77	27	50
St Paul's	24	73	24	49
Average	26	76	26	50

Except near the surface of the clay, the water contents are closely equal to the plastic limit. This fact, apart from other considerations, indicates that the clay is heavily over-consolidated (TERZAGHI, 1936).

From previous work (SKEMPTON, 1953) it is known that the clay fraction (finer than 2 microns) of the London clay lies between 40 and 70 per cent, varying in a systematic manner with the plasticity index; the relationship being expressed as follows:

$$\text{plasticity index} = 0{\cdot}95 \times \text{clay fraction}$$

Thus, corresponding to the average value of $PI = 50$, the clay fraction is 47 per cent.

* Personal communication from Mr S. Serota, of Richard Costain Ltd.

The clay is fully saturated, and the specific gravity of the particles is 2·74. Hence the density corresponding to the average water content of 26 is 125 lb./cu. ft. (2·0 g/c.c.).

Piezometric Levels

Before the 19th century most of London's water supply came from the Thames and its tributaries, and a small amount was obtained from shallow wells in the gravels. But in the 1790s the first deep wells were sunk to the Thanet Sand, and their number thereafter increased rapidly. Their depth also increased and from about 1850 all further wells and borings penetrated the Chalk (BUCHAN, 1938). Pumping from these wells has progressively lowered the water level in the Thanet Sand and the Chalk, and at present, at the South Bank site for example, the water in these strata is standing at about − 200 O.D. (Fig. 5). Before pumping started the piezometric surface of the water in the Chalk must have been at about 0·0 O.D.

The water level in the sand layer at the base of the London clay, however, has not been lowered by more than roughly one-third of the drop in level of the water in the Thanet and Chalk beds; no pumping seems to have been carried out in this sand and the lowering of water level is probably the result of leakage into the deep wells. The piezometric level in the sand is about − 80 O.D. (Fig. 5) as measured in two borings at the South Bank.

The decrease in water levels during the past 150 years has caused consolidation of the clays, and a consequent regional settlement (WILSON and GRACE, 1942). If this process had been completed the pore pressure in the clay would be as shown by the chain-dotted line in Fig. 5. Actually consolidation is not complete and an estimate of the present pore pressures is shown by the dotted line. It may be noted that a typical point in the Reading clay may be twice as deep as a point in the London clay, but the effective pressure at the former is 2½ times as great as at the latter.

Where the London clay extends to ground surface, as at Paddington, the piezometric pattern is nevertheless similar to that shown in Fig. 5; the upper layer of brown clay being more permeable than the unweathered blue clay, and therefore acting in a manner hydraulically comparable to that of the gravels.

That is to say, a perfectly definite perched water table can be observed in shallow bore holes in the clay (Fig. 3).

Shear Strength

The undrained shear strength (c) is plotted against depth in Figs. 3 and 4, and against effective overburden pressure (p) in Fig. 6. At Paddington the clay has been subjected to a simple unloading process, due to the removal of overburden by erosion, and the results are seen (Fig. 6) to fit in well with the probable pre-consolidation load and the strength of the clay in its normally consolidated state, corresponding to the relationship $c = 0{\cdot}30\,p$ as deduced from the average plasticity index of 50 (Skempton and Henkel, 1953). At Victoria and the South Bank, however, the clay has been eroded to a depth of about 35 ft. below present ground level, and subsequently reloaded by the deposition of the Flood Plain gravels and Alluvium. This process is revealed as a hysteresis loop in Fig. 6, and it has the important practical effect of leaving the clay, under the gravel, in a softer condition, at any given depth, than is the case when the clay has not been exposed (as at Paddington). This softening effect, however, ceases to be felt at depths of more than about 70 ft. below ground level (Fig. 4).

Bishop (1948) describes a rather similar strength/depth relationship at Walton, 15 miles southwest of London, where the London clay is covered by 20 ft. of gravel. The shear

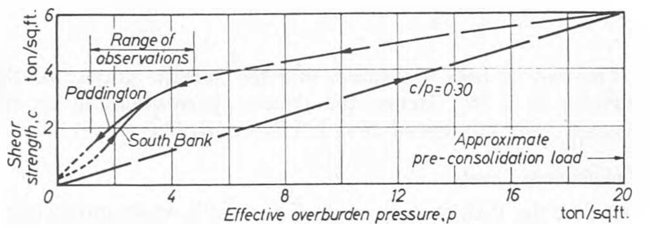

Fig. 6 Relation between strength and effective pressure for London clay

Relation entre la résistance au cisaillement et la pression intergranulaire du London clay

strength immediately under the gravel is about 0·6 ton/sq. ft. (cf. Fig. 4) but the gain in strength with depth is more rapid than at Victoria and the South Bank; the softening effect apparently ceasing about 15 ft. below the gravel. At depths of more than 60 ft. below the surface, however, the strengths are almost identical with those found at the three sites described in this paper. In borings made near St Paul's Cathedral, with about 30 ft. of gravel, etc., over the clay, the strengths below a depth of 55 ft. are also identical with those in Figs. 3 and 4, but from the base of the gravel to this depth of 55 ft. the strengths lie about midway between the Victoria and South Bank results, in Fig. 3, and the Paddington results*.

It seems, therefore, that the softening effect under the gravels at Victoria and the South Bank is rather more marked than at some other sites. Hence it is important to pay particular attention to the clay in the zone under the gravel.

The tests were carried out in the triaxial apparatus on 1½-in. diameter specimens, cut from undisturbed samples 4-in. diameter. The strength is independent of the cell pressure, so long as this exceeds the overburden pressure on the sample in the ground. Typical results, being the average of tests on 6 samples of clay from Paddington, are as follows:

Cell pressure (lb./sq. in.)	20	40	60
Shear strength (lb./sq. in.)	27·3	26·7	27·8

Unconfined compression tests, however, tend to give values of measured strength about 20 per cent too low, and are not reliable (Glossop, 1948).

* The authors are indebted to Mr S. Serota for permission to study the St Paul's tests and summarize them in the present paper.

A few tests were made in which the whole 4-in. diameter sample was used, but the measured strength was always lower than that obtained from the 1½-in. specimens*; probably owing to the fissures, which could come into effect in the larger specimens but which only occasionally influence the smaller specimens. In certain cases this influence was very apparent, and such tests were rejected. In general, however, each strength value quoted in Tables 2 to 4 is the average of three tests. Some of the results are seen from Figs. 3 and 4 to be distinctly low, but there is at present no certain basis for deciding whether this is a purely random variation or whether we should have rejected these tests.

Table 2

Paddington tests results

Résultats des essais à Paddington

Depth	*Consistency*			γ lb./cu. ft.	c ton/sq. ft.	E ton/sq. ft.	m_v sq. ft./ton	c_v sq. ft./yr
	w	*LL*	*PL*					
ft. in.								
4 6	33	70	22	119	0·45		0·0270	4·4
10 6	30			122	0·85			
18 6	30	82	29	121	0·98			
26 6	27			119	1·78			
30 6	27			116	1·38			
34 6	25	75	22	124	1·56		0·0058	5·4
36 0	27			116	1·56			
42 6	28			124	1·21			
45 0	27			121	1·47			
50 6	27	85	28	124	1·38		0·0045	2·7
52 0	27			122	2·50			
58 6	26	82	27	124	2·63	350		
66 6	25	77	23	128	2·77		0·0062	4·4
68 0	24			121	2·86			
74 6	26	76	20	125	2·18	340		
78 6	27	82	25	124	1·65		0·0040	5·8
80 0	28			123	2·18			
82 6	25	74	20	127	2·18	330		
90 6	27	78	21	124	2·23		0·0034	5·8
94 6	27			124	2·00			
98 6	25			127	4·74		0·0024	3·4
106 6	26	85	25	126	3·04		0·0040	5·1
110 6	26			123	4·70			
114 6	25	76	21	127	2·28	410		
122 6	24	75	27	127	3·53		0·0031	3·4
126 6	28	84	27	123	2·73			
130 6	24	78	21	128	5·35	500	0·0018	3·4
134 6	23			125	3·92			
138 6	23	77	20	128	3·04		0·0028	5·4

Table 3

Victoria test results

Résultats des essais à Victoria

Depth below gravel	*Depth below ground*	*Consistency*			γ lb/cu. ft.	c ton/sq. ft.	E ton/sq. ft.	m_v sq. ft./ton	c_v sq. ft./yr
		w	*LL*	*PL*					
ft. in.	ft. in.								
6	33 6	30			123	0·71			
1 0	35 0	30			121	0·65			
1 6	37 6	36	79	29	119	0·45		0·0240	4·0
12 0	46 0	29	76	28	127	0·78			
13 0	45 0	27	70	30	128	1·63	230		
13 0	49 0	25	72	29	126	1·27	180	0·0059	2·6
29 0	65 0	26			129	1·96	200		
41 0	75 0	27			127	1·34			
44 0	80 0	26	74	30	131	3·24	250	0·0054	6·7
61 0	97 0	26			131	3·80			
82 0	118 0	20	54	23	131	2·48		0·0053	16·0

* No difference was found between 1½ in. specimens cut from 4 in. samples and 1½ in. specimens prepared from 1½ in. cores.

Table 4
South Bank test results
Résultats des essais au South Bank

Depth below gravel ft.	*Depth below ground* ft.	*Consistency*			γ lb./cu. ft.	c ton/sq. ft.	E ton/sq. ft.	m_v sq. ft./ton	c_v sq. ft./yr
		w	*LL*	*PL*					
3	35	29	91	30		0·90			
3	38	29	80	31	123	0·93	85	0·0128	2·9
7	42	28				1·16			
11	43	29	81	28	124	1·16	205	0·0090	3·1
11	46	29	81	31	124	1·33	240	0·0090	2·8
21	53	29				1·61			
21	56	23				2·06			
31	63	23	63	26	128	2·36	195	0·0049	8·3
31	66	26	66	26	128	2·47	250	0·0043	
41	73	26	88	27	126	1·28		0·0054	2·8
56	88	30	75	29	121	1·45	—	0·0048	2·6
61	96	26	75	27	127	3·80		0·0035	2·5
71	103	26				2·25		0·0030	3·0
76	111	28				2·18			
87	119	20	55	20	130	4·25	360	0·0048	17·8
96	131	21	72	25	129	5·20	450	0·0037	2·5
102	134	19	58	20		4·81			

MEYERHOF and MURDOCK (1953) reported that the strength of specimens of London clay tested a week or more after sampling was substantially less than the strength measured immediately after sampling. To investigate this point, tests were made, on specimens cut from 16 samples from the Paddington site, 1 day and 1 month after sampling*, but no significant difference could be found and it is concluded that the earlier result was fortuitous†.

Sensitivity

Tests were made on 12 samples from the Paddington site, on the clay both in its undisturbed state and when completely remoulded. The average undisturbed and remoulded strengths were 2·90 and 2·93 ton/sq. ft. respectively. The sensitivity of the clay is therefore almost exactly equal to 1·0.

Young's Modulus

The stress/strain curve in compression tests on London clay often shows an upward concavity in the early stages of the test, probably due largely to bedding errors. In such cases it is impossible to determine Young's modulus (E) with any accuracy. But where the stress/strain relationship is essentially linear under low stresses this modulus has been calculated. The values of E are found to increase with increasing strength (see Fig. 7), approximately in accordance with the equation

$$E = 140c$$

as previously found from the tests on the Waterloo Bridge samples (COOLING and SKEMPTON, 1942) and from tests on samples from relatively shallow bore holes at Sydenham, in South London‡. The value of E is required for the calculation of immediate settlement of foundations, but where deep excavations are made there will be an appreciable upward heave of the clay and to estimate the magnitude of this movement the modulus is required under conditions of decreasing stress. For this purpose specimens of the clay were subjected to an all-round pressure and the axial load was then reduced until failure occurred. The strength was found to be practically the same as in the usual mode of test, where the axial load is increased, but the modulus was between two and four times greater. The results are given in Table 5.

Table 5
Young's modulus in unloading tests, South Bank samples
Module d'elasticité pour des essais de décharge avec des echantillons du South Bank

Depth ft.	c ton/sq. ft.	*E (unloading)* ton/sq. ft.
43	1·15	450
63	1·97	990
88	1·45	1120

It is considered that the tests from depths of 63 and 88 ft. were very satisfactory. The other test may have given a result which is rather too low.

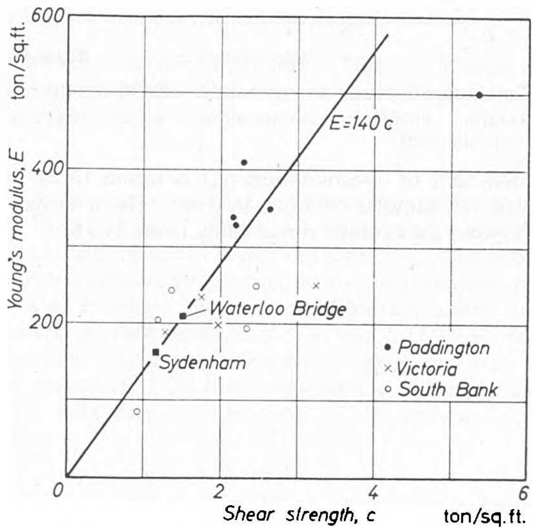

Fig. 7 Correlation between Young's modulus and shear strength
Relation entre le module d'élasticité et la résistance au cisaillement

Compressibility

Consolidation tests were carried out in the oedometer, care being taken to adjust the first pressure to a value just sufficient to prevent any swelling of the clay. Since the London clay is heavily over-consolidated the compressibility is derived directly from the p/e curve, without correction; and since the curvature is slight within the range of pressure increment usually imposed on the clay by foundations, the compressibility (m_v) may be expressed by a single constant for each test. Thus

$$m_v = \frac{e_0 - e}{\sigma(1 + e_0)}$$

where e_0 is the void ratio corresponding to the effective overburden pressure p in the ground, and e is the void ratio corresponding to a pressure $p + \sigma$, where σ is a typical increment of, say, 1 ton/sq. ft.

It has previously been pointed out (SKEMPTON, 1951) that the compressibility of a particular clay stratum varies inversely with the strength, and for London clay the relationship (Fig. 8) may be expressed by the equation

$$1/m_v = 100c$$

The new data, presented here, enable an earlier value of $m_v.c = 1/75$, as derived from the Waterloo Bridge tests, to be corrected.

* The authors are grateful to Dr L. J. Murdock, of George Wimpey & Co., for arranging that these special tests should be made, and for allowing the results to be mentioned in this paper.

† Average results, 1 day: 2·45 ton/sq. ft., 1 month: 2·69 ton/sq. ft. Thus, in fact, the month tests gave slightly *higher* values than the day tests, but there is no statistical significance in this result.

‡ Unpublished report by the authors to Ove Arup & Partners dated January 1955.

This relationship is helpful in assessing the reliability of test results, and in plotting the variations of compressibility with depth (see Figs. 3 and 4).

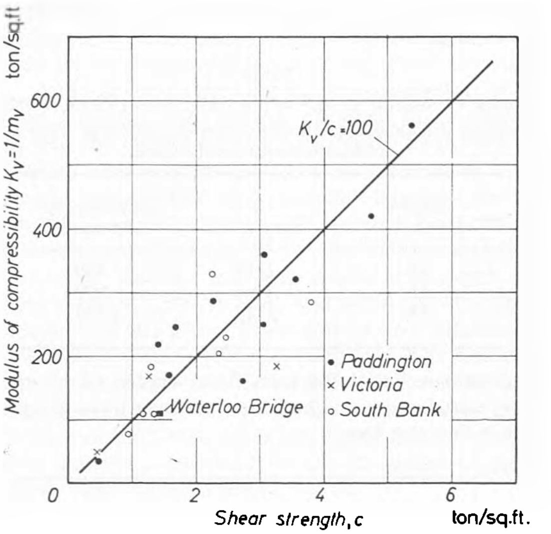

Fig. 8 Correlation between compressibility and shear strength
Relation entre la compressibilité et la résistance au cisaillement

The coefficient of consolidation (c_v) is found to be almost constant for all samples of London clay. The average value is 4 sq. ft./year, the extreme range being from 2 to 8.

References

BISHOP, A. W. (1948). Some factors involved in the design of a large earth dam in the Thames valley. *Proc. 2nd International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2, pp. 13–18

BUCHAN, S. (1938). *The Water Supply of the County of London from Underground Sources.* London; H.M.S.O.

COOLING, L. F. and SKEMPTON, A. W. (1942). A laboratory study of London Clay. *J. Instn. Civ. Eng.*, **17**, 251

GLOSSOP, R. (1948). The London Clay. *Verres et Silicates Industriel*, **13**, 93

MEYERHOF, G. G. and MURDOCK, L. J. (1953). An investigation of the bearing capacity of some bored and driven piles in London Clay. *Géotechnique, Lond.*, **3**, 267

SHERLOCK, R. L. (1935). *British Regional Geology: London and Thames Valley.* London

SKEMPTON, A. W. (1951). The bearing capacity of clays. *Bldg. Res. Congress Papers*, Div. 1, pp. 180–89

— (1953). The colloidal activity of clays. *Proc. 3rd International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, pp. 57–61

— and HENKEL, D. J. (1953). The post-glacial clays of the Thames Estuary at Tilbury and Shellhaven. *Proc. 3rd International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, pp. 302–08

TERZAGHI, K. (1936). Stability of slopes of natural clay. *Proc. 1st International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, pp. 161–65

WILSON, G. and GRACE, H. (1942). The settlement of London due to underdrainage of the London Clay. *J. Instn. Civ. Eng.*, **19**, 100–27

ZEUNER, F. E. (1945). *The Pleistocene Period.* London

— (1946). *Dating the Past.* London