Comparison of in Situ Tests for Granular Soils

Comparaison des essais in situ pour les sables et les graviers

by A. C. Meigh, M.Sc., A.M.I.C.E.
and
I. K. Nixon, B.Sc., A.C.G.I., A.M.I.C.E. (Soil Mechanics Limited, London, England)

Summary

Elaborate methods are necessary for obtaining undisturbed samples of sands below the water table, and it is virtually impossible to obtain an undisturbed sample of gravel at depth. In situ tests are therefore of importance in determining those properties of granular soils relevant to bearing capacity and settlement calculations.

Three types of in situ tests are considered : plate loading tests, Standard penetration tests and Dutch deep sounding. Density measurement using radio isotopes is also mentioned.

Results are compared for a number of sites where granular soils occur, and where two or more of these techniques have been employed. In one case the results are correlated with settlement observations on footings.

It is concluded that the Standard penetration test gives a reasonable, if somewhat conservative, estimate of allowable bearing capacity in fine sands. In sandy gravels, however, it seriously under-estimates allowable bearing capacity of footings and there is some indication that in well graded sands and gravelly sands it also under-estimates allowable bearing capacity to some extent. Dutch deep sounding gives a reasonably good estimate of allowable bearing capacity both for fine sands and also sandy gravels, and the evidence suggests that it may also give reliable estimates of allowable bearing capacity for intermediate materials.

Sommaire

Pour obtenir des échantillons intacts de sables qui se trouvent sous une nappe d'eau, il faut adopter des procédés délicats et il est pratiquement impossible d'obtenir des échantillons intacts de graviers en profondeur. Des essais in situ sont, par conséquent, de première importance pour déterminer les propriétés des sables et des graviers relatives à la capacité portante et aux calculs de tassement.

Trois sortes d'essais in situ sont ici envisagés :

Essais de charge sur plaque.

Essais standards de pénétration.

Pénétration en profondeur suivant la méthode hollandaise.

La mesure de la densité par l'emploi des radio-isotopes est également décrite.

Une comparaison est faite entre plusieurs chantiers où l'on rencontre des sols graveleux et dans lesquels deux ou plusieurs de ces procédés ont été adoptés. Dans un des cas les résultats obtenus sont comparés aux observations faites sur le tassement des semelles.

En conclusion, on constate que l'essai de pénétration standard fournit une évaluation raisonnable, quoiqu'un peu prudente, de la capacité portante admissible des sables fins. En ce qui concerne les sables et graviers cette méthode sous-estime sérieusement la capacité portante admissible des semelles, et il semble que dans le cas des sables de granulométrie très variée, ou de sables pierreux, elle sous-estime dans une certaine mesure la capacité portante. L'essai de pénétration en profondeur suivant la méthode hollandaise donne une évaluation assez exacte de la capacité portante admissible pour les sables fins et aussi pour les sables et graviers et les résultats obtenus font penser que ce système pourra également fournir des évaluations sûres de capacité portante admissible pour des matériaux de granulométrie intermédiaire.

Introduction

Allowable bearing pressure for foundations on granular soils is usually limited by settlement considerations rather than by ultimate bearing capacity. In order to determine the settlement it is necessary to know something about the stress/strain characteristics of the granular soil concerned. To obtain undisturbed samples of sand at depth is often a difficult and expensive process, especially where the water table is high. With gravels it becomes virtually impossible. Furthermore, having obtained a relatively undisturbed sample it is difficult to set it up for a laboratory test without causing further disturbance, and to avoid bedding errors during stress/strain measurements.

Methods of testing the soil in situ are therefore of considerable importance, and a number of such methods has been developed. The principal methods in use are as follows:

1. Plate loading tests (*PLT*).
2. Standard penetration tests (Dynamic penetration tests) (*SPT*).
3. Dutch deep sounding (Static penetration tests) (*DS*).

The Standard penetration test (Raymond penetrometer) was developed originally for use in sands (Terzaghi & Peck, 1948) but its use has been extended to (sandy) gravels by fitting a solid cone to the end of the sampler (Palmer & Stuart, 1957). Dutch deep sounding was also developed for use in sands (Vermeiden, 1948), but it has since been used in gravels.

A more recent development is the radio-isotope probe for measurement of density in situ (Meigh & Skipp, 1960). With this instrument it is necessary to carry out maximum and minimum density determinations in the laboratory (disturbed samples can be used) in order to convert to relative density.

There are a number of sites where the authors' company have carried out more than one of these types of tests, and in the present paper an attempt has been made to draw comparisons between the results of such tests. This has been done by

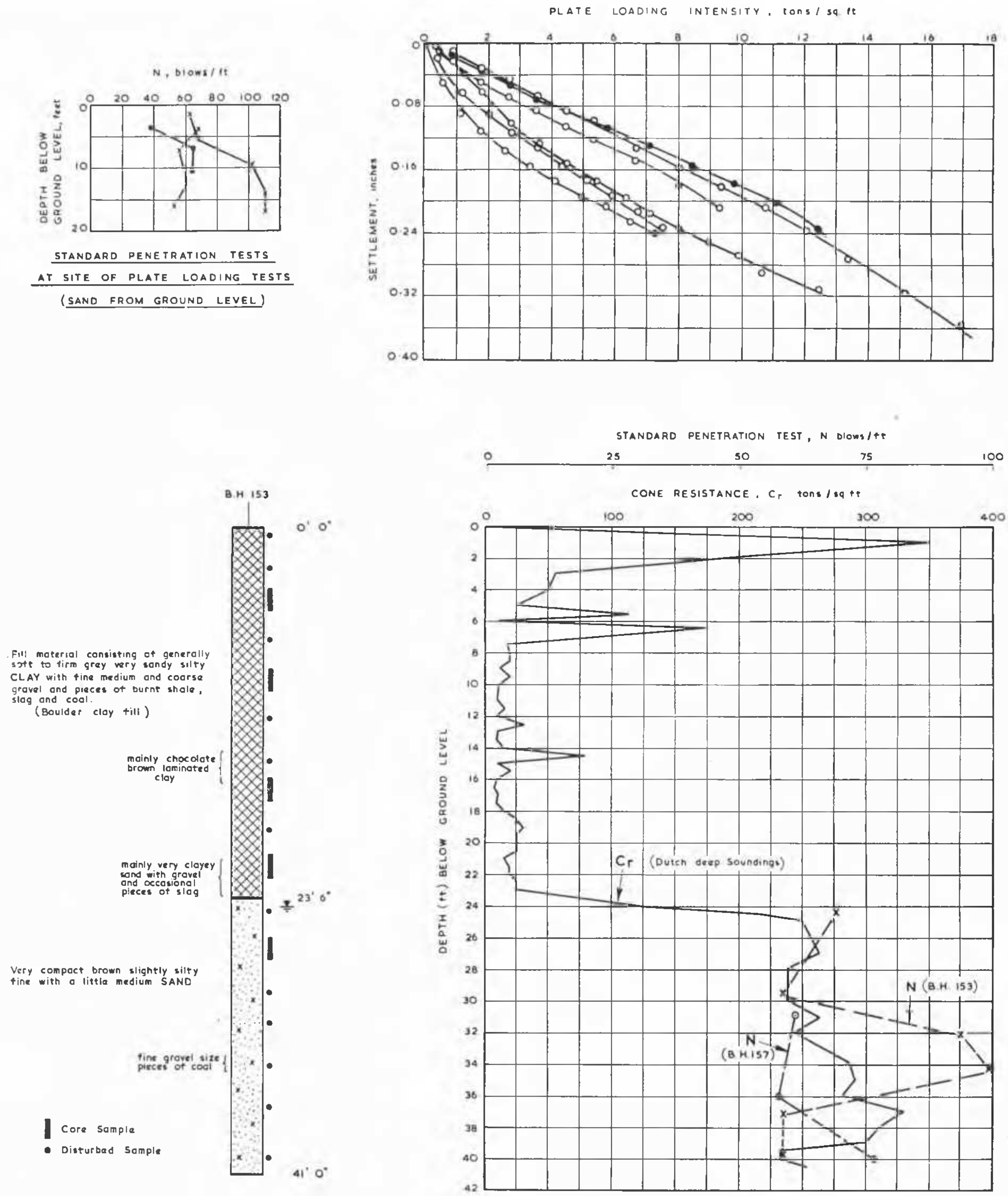

Fig. 1 Field test data, Motherwell, Lanarkshire.
Données des essais de chantier à Motherwell, Lanarkshire.

calculating for each set of test data the allowable pressure (q) which would cause 1 in. settlement of a 10 ft. square footing.

For the plate loading tests this has been based on the formula given by Terzaghi & Peck (1948)

$$S = S_1 \left(\frac{2B}{B+1} \right)^2$$

where S_1 is the settlement of a 1 ft. square plate and S is the settlement of a footing of width B subjected to the same loading intensity.

For the Standard penetration tests the empirical curves of Terzaghi and Peck (Peck, Hanson & Thornburn, 1953) have been used. These give the allowable bearing pressure corresponding to 1 in. total settlement. For the Dutch deep sounding test results the method described by De Beer and Martens (1957) has been used. In this method the cone resistance C_r is used to evaluate a dimensionless factor C related to the compressibility as follows :

$$C = \frac{3}{2} \cdot \frac{C_r}{p_o}$$

where p_o is the effective overburden pressure at the depth considered. The settlement per unit thickness is given as

$$S = \frac{1}{C} \log_e \frac{p_o + \Delta p}{p_o}$$

where Δp = pressure increment at the depth considered due to the applied load.

For sites where Deep soundings and Standard penetration tests have both been made, the results have been used to examine the validity of the relation between cone resistance, in tons/sq.ft., (C_r) and number of blows per foot, N. (MEYERHOF, 1956) $C_r = 4N$.

Field data

Motherwell, Lanarkshire—The glacial sands at this site are mainly fine, sometimes slightly silty, and sometimes containing a certain amount of medium sand and gravel. Ground water level is about 20 ft. below ground level. Six plate loading tests were carried out in excavations approximately 4 ft. deep, four with 12 in. square plates and the other two with 18 in. square plates. The results are plotted as load/settlement curves in Fig. 1 together with a plot of Standard penetration test results from 3 adjacent boreholes. In many cases, in spite of high loading intensities, the plate loading tests did not reach settlements corresponding to 1 in. settlement of a 10 ft. square footing, i.e. 0·3 in. for a 12 in. square plate and 0·43 in. for an 18 in. square plate. However, taking the results as a whole it is probable that the allowable bearing pressure calculated from these plate loading tests (q_{PLT}) is in excess of 10 tons/sq.ft. From the Standard penetration test results, taking an average value of $N = 65$, the allowable bearing pressure (q_{SPT}) is 6·6 tons/sq.ft.

At another part of the site, overlain by Boulder Clay fill, Dutch deep soundings were made and the results of a typical sounding are shown in Fig. 1, together with the log of an adjacent borehole and a plot of Standard penetration test results from that borehole and another nearby. Taking an average cone resistance of 260 tons/sq.ft. the allowable bearing pressure (10 ft. square footing, 1 in. settlement) is 6.5 tons/sq.ft. which is almost exactly the same as that calculated from the Standard penetration test results. It is of interest to note that a comparison of the Standard penetration test results and the cone resistance readings confirms the Meyerhof relationship $C_r = 4N$.

The various values of allowable bearing pressure, and certain ratios of these values, are summarised in Table 2.

Argyll Street, Glasgow—At this site two boreholes revealed more than 50 ft. of silty fine sand (glacial sand) and Standard penetration tests in the boreholes showed that this was medium dense becoming dense with depth. Ground water level was at 14′-6″ below ground level. In addition to the boreholes five Dutch deep soundings were carried out. The results in terms of Standard penetration test results and Dutch deep souding results are plotted in Fig. 2. The Standard penetration test values below water table have been replaced by equivalent values, using the Terzaghi and Peck expression

$$N_{eq} = 15 + \frac{1}{2}(N - 15)$$

Considering a 10 ft. square footing founded 4 ft. below ground level and taking the average Standard penetration test results from the borehole giving the lower values, i.e. $N = 16$, the allowable bearing pressyre is 1·4 tons/sq.ft. Taking the results of sounding No. 3 which gave the lowest values, the allowable bearing pressure based on the Dutch deep soundings is also 1·4 tons/sq.ft. There is a similar correspondence taking average values for the site with an allowable bearing pressure of about 1·6 tons/sq.ft.

The plot of test results also confirms the Meyerhof relationship $C_r = 4N$.

Sizewell, Suffolk—A site investigation was carried out recently at Sizewell on the east coast of Suffolk, where it is proposed to construct a nuclear power station. Sands of the Norwich Crag overlie London Clay, the upper surface of which is some 200 ft. below ground level. For the present purpose only the upper part of the Norwich Crag is considered and this consists of a medium dense light and dark brown fine and medium sand, with occasional very thin impersistent lenses of firm brown clayey silt and silty clay, and with some very thin iron-cemented bands.

Plate loading tests using 12 in. square plates and 2 ft. 6 in. square plates were carried out at four levels in a trial pit some 34 ft. deep. Fig. 3 shows Standard penetration test results against depth from the two adjacent boreholes, and separately Standard penetration test results for the whole site. It also shows particle size distribution curves for the sand and the load settlement curves for the plate loading tests. Fig. 4 shows a photograph of part of the exposed side of the trial pit, and in Table 1 is some information concerning dry densities and porosities of the sands which shows that the sand had an average relative density of approximately 50 per cent.

Table 1

Sizewell-Density & Porosity

B.H. or T.P.	*Sample No.*	*Depth*	*Nat : m/c %*	*Nat : Dry density lb./cu.ft.*	*Nat : Porosity*	*Max : Porosity*	*Min : Porosity*	*Relative density*	
104	3	5′-6″	6·6	108·2	0·35	0·50	0·29	0·79	
1	—	10′-0″	12·9	92·0					
1	—	10′-0″	7·3	96·1					
104	5	10′-6″	5·9	97·3	0·42	0·50	0·33	0·52	
1	—	15′-0″	9·1	97·1					
104	7	15′-6″	6·7	93·9	0·44	0·48	0·35	0·37	Av:
1	—	20′-0″	11·5	91·5					0·48
1	—	25′-0″	6·8	97·0					
104	14	28′-0″	15·5	99·6	0·40	0·47	0·32	0·54	

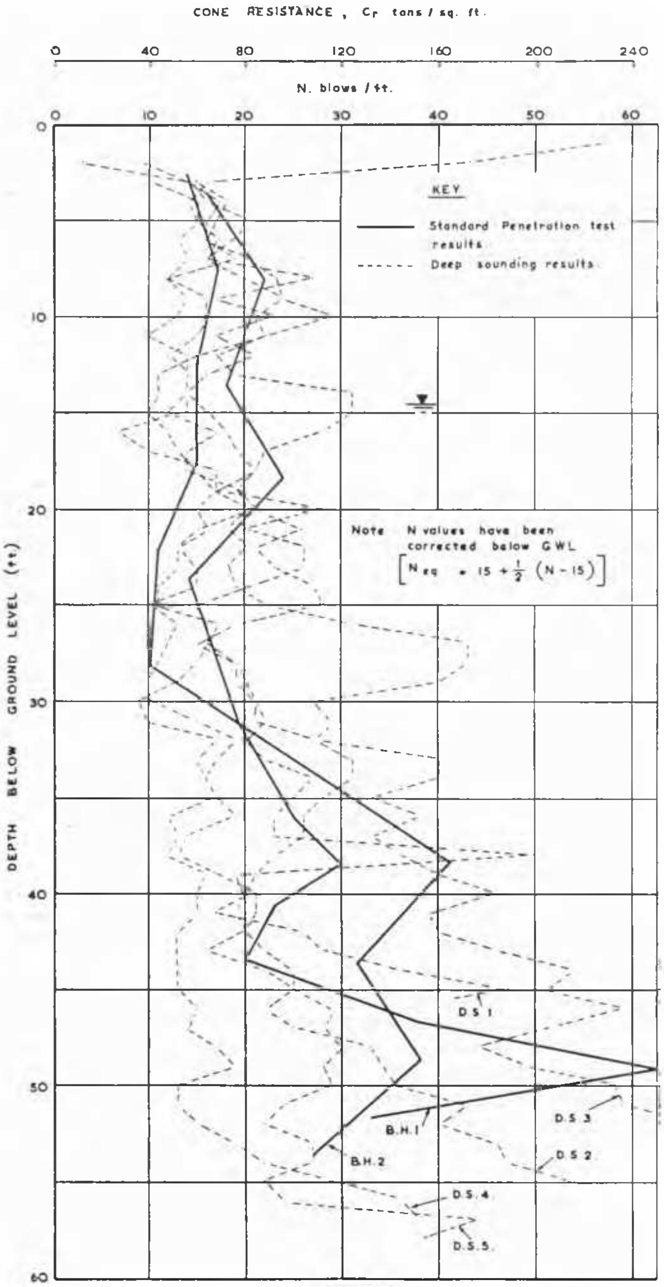

Fig. 2 Standard penetration test results and Dutch deep sounding results, Argyll Street, Glasgow.

Résultats d'essais de pénétration Standard et des essais de pénétration en profondeur suivant le système hollandais, à Argyll Street, Glasgow.

A comparison of the results of the plate loading tests and the Standard penetration tests is given in Table 2 in terms of the allowable bearing pressure to give 1 in. settlement of a 10 ft. square footing. From these it can be seen that the plate loading tests give somewhat higher allowable bearing pressures. Excluding the test at the lowest level which is complicated by considerations of the water table the ratio of allowable bearing pressures, q_{PLT} to q_{SPT} varies between 1·1 and 1·7 with an average of about 1·4, i.e. the plate loading tests give allowable pressures some 40 per cent in excess of those given by Standard penetration tests.

Dinslaken, Germany—At the site of a proposed oil refinery the investigation consisted of 17 soft ground borings with Standard penetration tests and 23 deep soudings. The soils concerned are principally river terrace sands and gravels (Fig. 5). These sands and gravels were very variable in grading (grading curves for 3 samples are shown in Fig. 5), and both the Standard penetration test results and the Dutch deep sounding results showed considerable scatter. The values for the whole site have been averaged and plotted against depth in Fig. 5, from which it can be seen that the Meyerhof relationship does not hold: for the first five metres C_r is approximately $8N$ and below this it increases to a maximum of $18N$.

Considering a 10 ft. square footing at approximately 1·5 metres below ground level the allowable bearing pressure from the Standard penetration test results is 1·0 tons/sq.ft. whereas the allowable bearing pressure from the Dutch deep sounding results is 3·0 tons/sq.ft. (Table 2). No calculations have been made for footings at lower levels, but it is clear that at lower levels the divergence between the allowable bearing pressures based on the two sets of data increases.

This is an interesting case in that much of the data applies to materials above ground water level (average ground water level was some five metres below ground level) and therefore there is no question of the Standard penetration results having been affected by piping in the boreholes.

Mammee Bay, Jamaica, B.W.I.—Seven borings revealed soft to firm clay overlying sandy gravel (Fig. 6). Standard penetration tests in the sandy gravel gave an average value for the whole site of $N = 12$. A plate loading test was carried out with a 26 in. diameter plate just below the top of the sandy gravel stratum at ground water level. A total settlement of nearly 1 in. occurred for a maximum load of 5 tons/sq.ft. (Fig. 6). Based on the plate loading test the allowable pressure (1 in. settlement, 10 ft. square footing) is 3 $\frac{1}{2}$ tons/sq.ft. Based on the Standard penetration tests for the two nearest boreholes $N = 14$, the allowable pressure, taking into account the proximity of the water table, is 0·6 tons/sq.ft. The ratio of allowable pressures, q_{PLT}/q_{SPT}, is therefore approximately 5 $\frac{1}{2}$.

Purley Way, Croydon, Surrey—At the site of a factory extension at Purley Way, Croydon, a borehole revealed Taplow gravel (gravel with flints and some fine sand) overlying Woolwich and Reading Beds. Ground water level was about 9 ft. below ground level. Standard penetration tests in the gravel gave an average of $N = 21$ blows per foot. Following this, excavations some 4 ft. deep for isolated footings were made and Standard penetration tests were made just below the bottom of these excavations. N was found to vary from 8 to 19 with an average of 13. This is somewhat less than the tests in the borehole but experience has shown that this is to be expected when these tests are carried out immediately below surface level. Two plate loading tests were also carried out using 12 in. square plates and the results are given in Fig. 7.

During construction settlement observation points were incorporated with three selected stanchion footings. Level readings were then taken at intervals for a period of some 4 months and the loads on the selected footings were estimated at each time readings were taken.

The footings were loaded to maximum intensities approaching 1 ton/sq.ft. The load/settlement curves are plotted in Fig. 8, together with a predicted load/settlement curve based on the plate loading tests, and curves based on the Standard penetration tests ($N = 13$ and $N = 21$). The actual settlements appear to exceed slightly those calculated from the plate loading tests. However, the movements involved were small, and not so much greater than possible errors in the plate loading test data and observed settlements. No precise comparison can be made therefore, but it can be seen clearly that although the settlements calculated from plate loading tests are of the same order as those observed, the

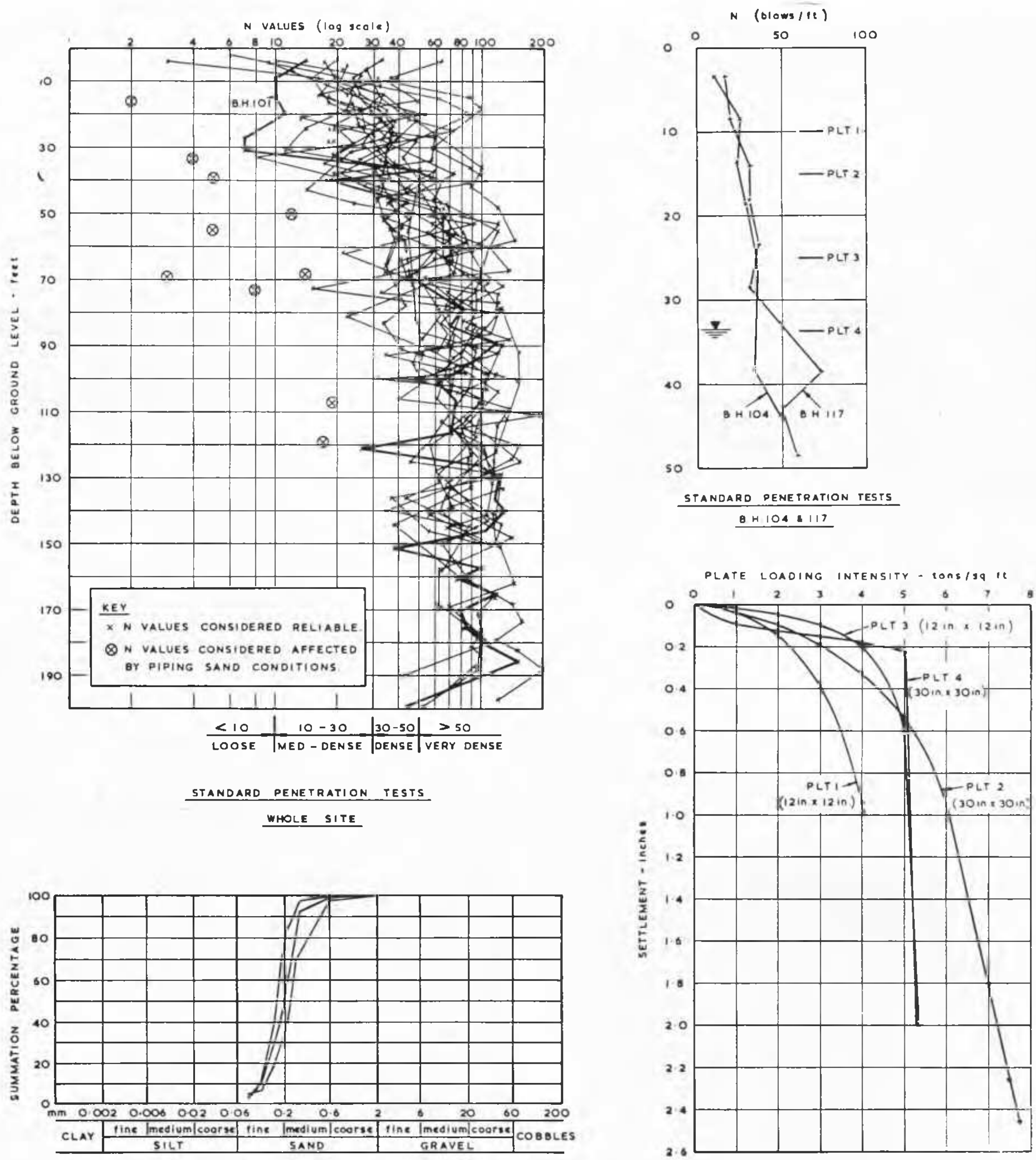

Fig. 3 Field test data, Sizewell, Suffolk.
Données des essais de chantier à Sizewell, Suffolk.

settlements calculated from the Standard penetration tests exceed them by a factor of 4 or more.

For comparison with other sites, the allowable loads corresponding to a 1 in. settlement of a 10 ft. square footing have also been calculated and these are shown on Table 2.

Dungeness, Kent—At Dungeness a site investigation for a proposed nuclear power station was carried out by George Wimpey & Company, Ltd. This showed a top stratum some 45 ft. thick consisting of beach deposits of fine, medium and coarse flint gravel becoming increasingly sandy below about 25 ft. to 30 ft. below ground level. Plate loading tests were made in a trial pit at levels varying between 16 ft. and 31 ft. below ground level with plates of 18 in. diameter and 30 in. diameter. Standard penetration tests were made in the boreholes. Subsequently Soil Mechanics Ltd. made static cone test measurements in the gravel (Fig. 9) and also in situ density measurements using a radio-isotope probe.

From the plate loading test results the allowable bearing pressure (10 ft. square footing, 1 in. settlement) is 7·0 and 10·5 tons/sq.ft. for foundation levels 15 ft. and 20 ft. below ground level respectively. For the same levels, the Standard penetration test values give allowable pressures of 1·4 tons/sq.ft. ($N = 28$) and 1·8 tons/sq.ft. ($N = 35$). The allowable bearing pressures calculated from the Dutch deep sounding results (Fig. 9) are 7·5 and 5·0 tons/sq.ft. which are in reasonable agreement with those calculated from the plate loading test results and are in strong disagreement with those calculated from the Standard penetration tests. (Table 2).

In situ density measurements using the radio-isotope probe were made at this site, and maximum and minimum

Table 2

Allowable bearing pressure, tons/sq.ft. (for 1 in. settlement of 10 ft. square footing)

(1) Site *	(2) Soil	(3) From plate loading tests q_{PLT}	(4) From Standard penetration tests q_{SPT}	(5) From Deep Soundings q_{DS}	(6) $\frac{q_{PBT}}{q_{SPT}}$	(7) $\frac{q_{DS}}{q_{SPT}}$	(8) $\frac{C_r}{4N}$	(9) Remarks
1. Motherwell, Lanarkshire	Fine Sand (very dense)	> 10	6·6	6·5	1·6	1·0	1 +	
2. Argyll St. Glasgow	Silty fine Sand (medium dense to dense)	—	1·4	1·4	—	1·0	1	Corrected N values below ground-water level.
3. Sizewell, Suffolk	Fine and medium Sand (medium dense)	At 10 ft. 2·7 At 15 ft. 5·2 At 20 ft. 4·5 At 34 ft. > 5·0	2·4 3·0 3·5 2·7	— — — —	1·1 1·7 1·3 (1·9)			Relative density, from undisturbed samples, about 60 %
4. Dinslaken, Germany	a. Medium and coarse Sand	—	1·0	3·0	—	3·0	2	
	b. Gravelly medium and coarse Sand	—	—	—	—	—	2 to 4·5	
5. Mammee Bay Jamaica, B.W.I.	Sandy, fine, medium and coarse Gravel with cobbles and silt	3·3	0·6	—	5·5	—	—	
6. Purley Way, Croydon	Sandy Gravel	6·8	1·1 to 2·0 (N = 13; N = 21)	—	3·8 to 6·2	—	—	Observed settlement of footings of same order as settlement predicted from plate bearing tests.
7. Dungeness, Kent	(Sandy) fine, medium and coarse Gravel	At 15 ft. 7·0 At 20 ft. 10·5	1·4 1·8	10·5 9·0	5·0 5·8	7·5 5·0	 3 to 4	

* Note : All the data given above is from site investigations by the authors' company, with the exception of Dungeness where the PLT and SPT data is from the site investigation by George Wimpey & Co. Ltd.

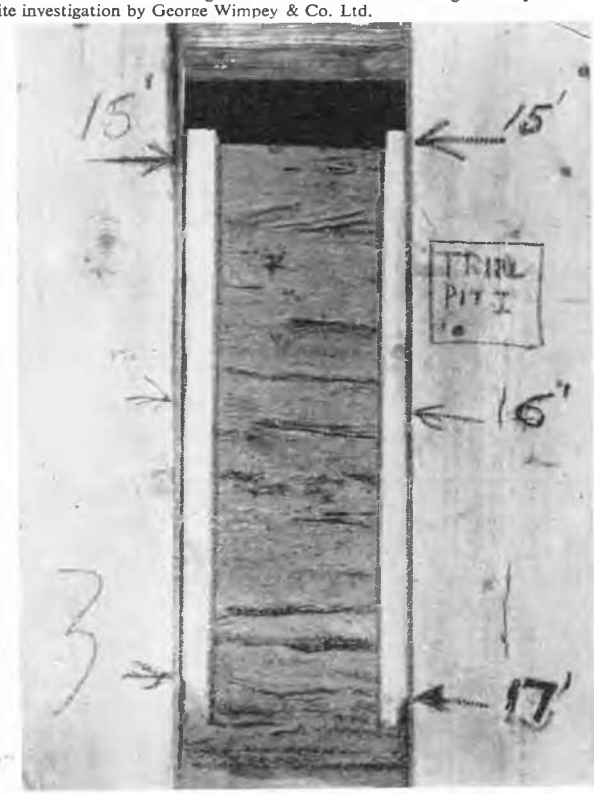

Fig. 4 Part of exposed face of trial pit at Sizewell, Suffolk.
Une partie de la face exposée d'un puits d'essai à Sizewell, Suffolk.

density measurements were made on disturbed samples. The results were erratic, but suggest a relative density of about 60-70 per cent, which for a sand would normally be considered to correspond to a Standard penetration test value of about 35, or to a static cone resistance of about 140 tons/sq.ft.

Discussion

The field test data has been summarised in Table 2 in which the sites have been placed in order of increasing particle size and wideness of grading. A study of columns 6 & 7, in which are given the ratios of allowable bearing pressures $\frac{q_{PLT}}{q_{SPT}}$ and $\frac{q_{DS}}{q_{SPT}}$, and of column 8, which gives the ratio $\frac{C_r}{4N}$, reveals a definite trend following the particle size and grading.

At three sites (Nos. 1, 2 and 3) there are fine sands including silty fine sand, and fine with some medium sand. At two of these sites (Nos. 1 and 2) Dutch deep soundings can be compared with Standard penetration results. The ratio of allowable bearing pressures for the two methods is 1. The results also confirm the Meyerhof relationship $C_r = 4N$. At two of these sites (Nos. 1 and 3) plate loading test results can be compared with Standard penetration test results. In each case the allowable bearing pressure from the plate loading tests is somewhat in excess of that given by the Standard penetration tests, about 40 per cent in the case of Sizewell, 60 per cent in the case of Motherwell.

At Dinslaken (Site 4) in the medium and coarse sand it was shown that Meyerhof's relationship is not valid and $C_r = 8N$ approximately. The allowable bearing pressure

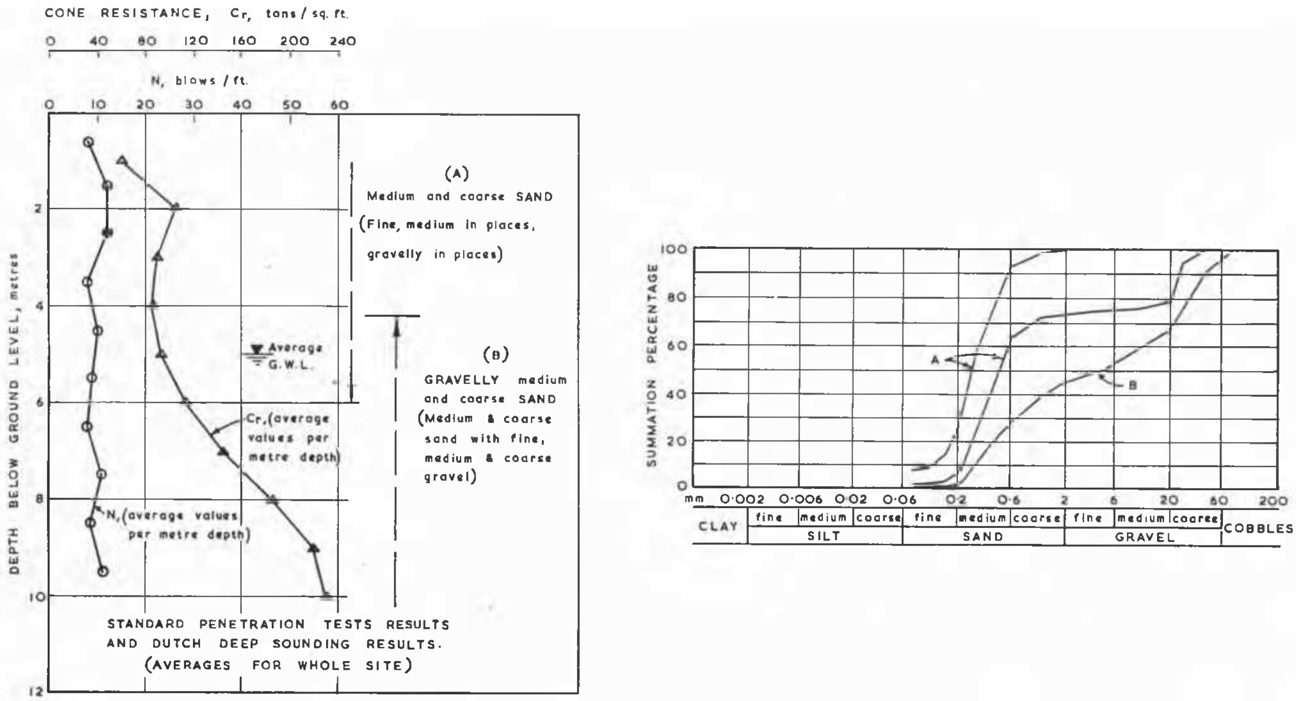

Fig. 5 Field test data, Dinslaken, Germany.
Données des essais de chantiers à Dinslaken, Allemagne.

calculated from deep sounding tests is some three times that calculated from the Standard penetration tests. In the gravelly sand C_r varied between $8N$ and $18N$.

At all the remaining three sites (Nos. 5, 6 & 7) there were sandy gravels and plate loading tests gave allowable bearing pressures some 4 to 6 times greater than those calculated from the Standard penetration tests. At Dungeness, Dutch deep soundings were also carried out and these gave allowable bearing pressure comparable with those given by the plate loading tests, i.e. some 5 — 7 ½ times greater than those given by the Standard penetration tests. At Purley Way settlements of footings were observed and appeared to be of the same order or slightly more than those predicted from the plate loading tests. It should be noted, however, that the movements were small and minor differences are of the same order as the errors in measurement.

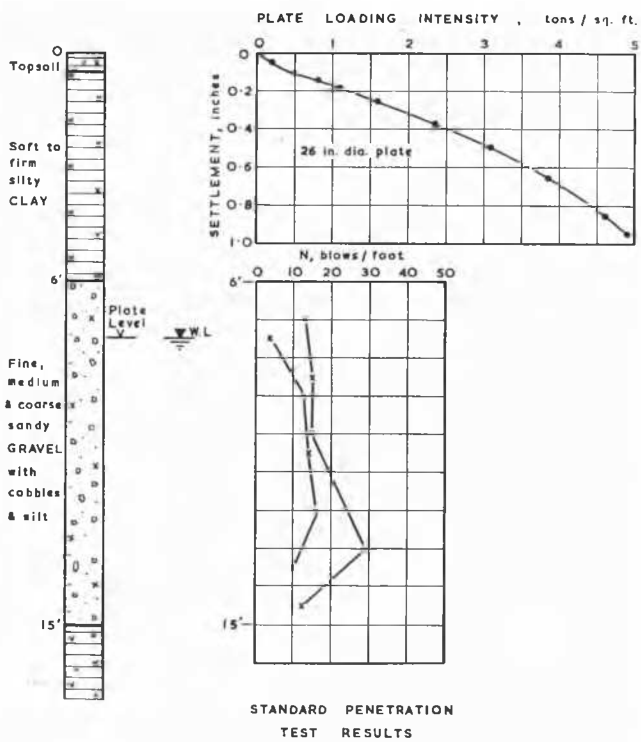

Fig. 6 Field test data, Mammee Bay Jamaica.
Données des essais de chantier à Mammee Bay, Jamaique.

The general trend of these results can be summarised by grouping them under the various soil types and rounding off the figures. This has been done in Table 3 below.

Table 3

Soil type	*Sites Nos.*	q_{PLT}/q_{SPT}	q_{DS}/q_{SPT}	$Cr/4N$
(Silty) fine sand	1, 2 & 3	1½	1	1
Medium and coarse sand	4	—	3	2
Gravelly sand	4	—	—	3
Sandy gravel	5, 6 & 7	4-6	5-7	3-4

q Allowable bearing pressure ; 10 ft. square footing, 1 in. settlement.
PLT Plate loading tests ; SPT Standard penetration tests.
DS Dutch deep sounding.

Conclusions

In order to assess the practical application of these results it is necessary to assume that allowable bearing pressures based on the plate loading tests are correct for practical purposes (as far as footings on medium dense and dense granular soils are concerned at least). This assumption appears to be justified for the following reasons :

(1) The original Terzaghi and Peck relationship between settlement of a plate and settlement of footings was based mainly on field data.

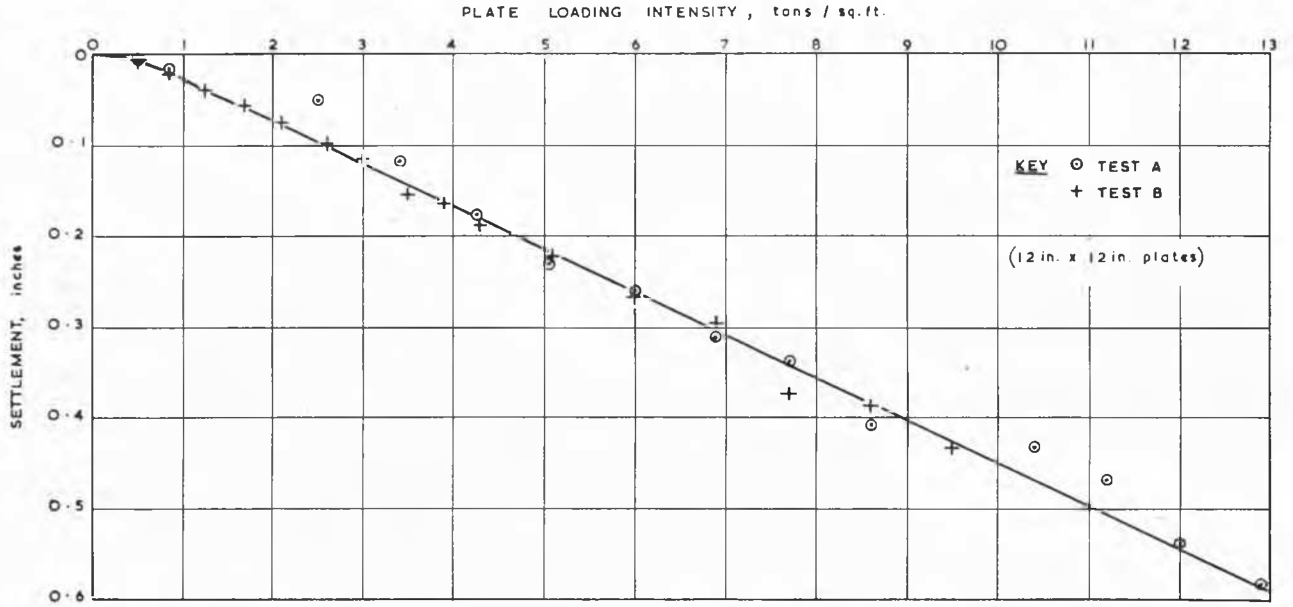

Fig. 7 Plate loading test results, Purley Way, Croydon, Surrey.
Résultats des essais de charge sur plaque, à Purley Way, Croydon, Surrey.

(2) The one case of observed settlements quoted above confirms approximately this relationship.

(3) Where plate loading tests were carried out with the two sizes of footings, the bigger size gave the same, or somewhat greater allowable bearing pressures (Sites Nos. 3 and 7).

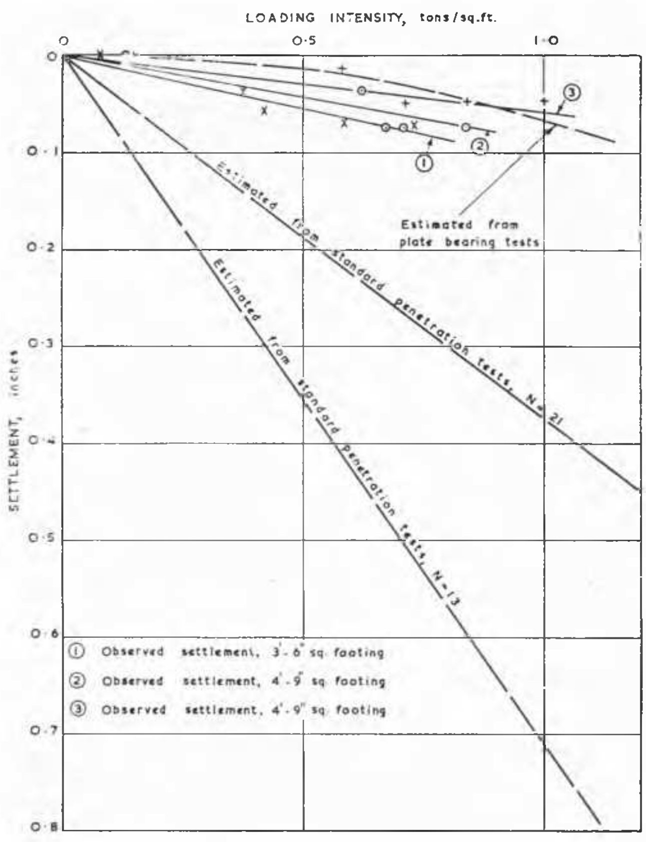

Fig. 8 Observed and estimated settlements, Purley Way, Croydon, Surrey.
Tassements constatés et calculés à Purley Way, Croydon, Surrey.

Working from this assumption, the suitability of Standard penetration tests and deep soundings have been assessed for the various soil types. For fine sand the Standard penetration tests and deep soundings give more or less the same allowable bearing pressures, and in both cases they are somewhat less than those given by the plate loading tests. An alaysis of settlements of bridge foundations on fine Sand by De Beer and Martens (1957) also showed that deep sounding results give a conservative estimate of allowable bearing pressure. This would seen to be a desirable feature of a test which is an indirect measurement of allowable bearing pressure. In the sandy gravels, however, it can be seen that the Standard penetration tests seriously under-estimate allowable bearing pressure by a factor of 4 or more. On the other hand the deep sounding does appear to give reasonable estimates of allowable bearing capacity.

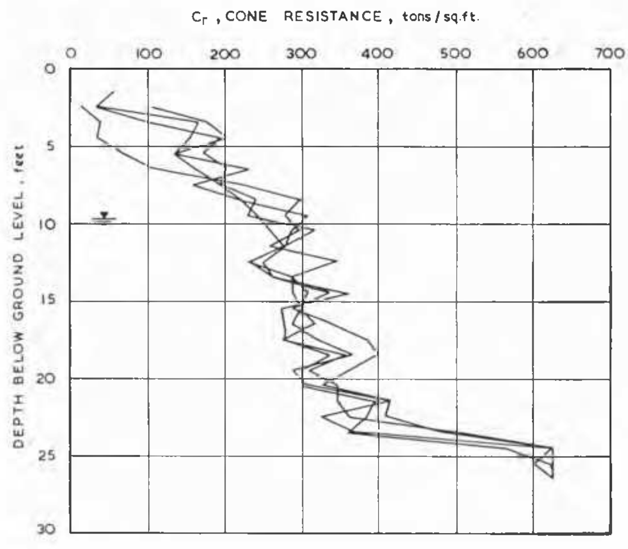

Fig. 9 Dutch deep sounding results in gravel, Dungeness, Kent.
Résultats des essais de pénétration en profondeur suivant système hollandais, effectués dans le gravier à Dungeness, Kent.

There is some indication from the test results that for materials intermediate between the fine sands and the sandy gravels there is a transition in which the deep sounding gives values which may represent reasonable estimates of allowable bearing capacity, whereas the Standard penetration test appears to be over-conservative.

If is not suggested that the full potential of these results can be utilised immediately. Further observations on actual structures are required. In the meantime the information should enable a designer working from Standard penetration test results for a gravelly sand or a (sandy) gravel to arrive at a more realistic estimate of allowable bearing capacity. It is, of course, necessary to check that there is an adequate factor of safety against ultimate bearing capacity failure in particular cases. Finally, the results emphasis the value of an adequate programme of plate loading tests as part of the investigation of foundation for important structures on coarse granular soils.

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