Experiences with Penetrometers

Expériences avec Pénétromètres

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Summary

In order to identify the apparatus best suited for the requirements of different subsoil conditions, comparative tests have been conducted with three static and six dynamic penetrometers of conventional types. The present report does not deal with the evaluation of measurements but solely with the behaviour of different penetrometers.

The advantages and shortcomings of individual apparatus as revealed by their practical application are discussed and the possible range of application which, apart from the intended purposes, depends on soil conditions and the importance of the company undertaking the work is stated. The behaviour of the apparatus in the principal types of soil is described. Comparison of the results obtained from different penetrometers admits of some conclusions regarding the correlation of measurements.

Sommaire

Avec trois pénétromètres statiques et six pénétromètres dynamiques il a été procédé à des expériences comparatives pour déterminer les appareils qui conviennent des sols différents. Le rapport ne se charge pas d'interpréter les résultats de mesures; il étudie seulement le comportement des différents pénétromètres.

Il expose les avantages et les inconvénients que présentent les pénétromètres à l'utilisation et indique leurs possibilités d'application, celles-ci variant suivant le but recherché, la nature du sol et l'importance de l'entreprise qui veut employer le pénétromètre. Le comportement des appareils dans les principaux types de sol y est décrit. Un tableau comparatif des résultats qui ont été obtenus avec les différents pénétromètres permet quelques conclusions sur les rapports entre les valeurs trouvées pour chacun de ces appareils.

Introduction

Subsoil conditions are to an increasing extent examined with the aid of penetration tests with a view to forming an idea not only on stratifications but also on the compactness and/or consistency of soils in order to be able to make conclusions as to the bearing capacity of different types of subsoils. It was felt it would be useful to resort to comparative tests by using different types of penetrometers in order to establish the apparatus best suited for the requirements of different subsoils and practical work on the site. At 20 different places several penetrometers have been applied side by side. Undisturbed samples were taken in order to establish in more detail the relations that exist between subsoil coefficients and recordings of penetrometers. As the work in these fields has not yet been completed the present report is confined to the behaviour of penetrometers.

Apparatus

Only simple and sufficiently approved apparatus were used, the dimensions of which have been partly modified.

The technical data of the penetrometers applied (Fig. 1) can be seen from Table 1.

With standard penetration tests in gravel, the split spoon sampler is closed with a detachable cone in order to prevent damage to the edge (Fig. 1d).

The cone resistance and the total resistance on static penetrometers are recorded in kg/cm². The number of blows on dynamic penetrometers required to obtain a penetration depth of 20 or 30 cm is indicated.

Application of Different Penetrometers

Time required and performance—Table 2 indicates the testing time required and the performance obtained from hand-

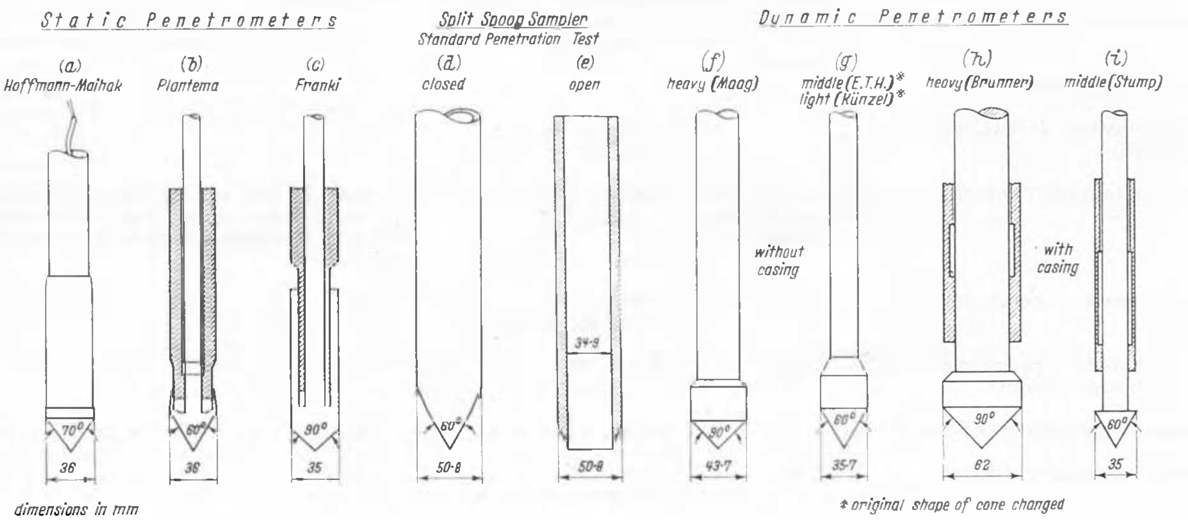

Fig. 1 Illustration of static and dynamic penetrometer cones
Cones de pénétromètres statiques et dynamiques

Table 1

Technical data of different static and dynamic penetrometers
Caracteristiques des pénétromètres statiques et dynamiques utilisés

Penetrometer	*of*	*Diameter of rod*	*Diameter of casing*	*Cross-section of cone*	*Drop weight*	*Weight of moved mass*	*Height of fall*	*Method of operation*	*Driving speed*
		cm	cm	cm^2	kg	kg	cm		*blows*/min m/min
Static penetrometer	Hoffmann	3·0		10				Resistance measured on cone with Maihak string	0·40
Static penetrometer	Franki	3·5		10				Resistance measured on ground level with dynamometer	0·45
Static penetrometer	Plantema			10					
Standard penetrometer	Terzaghi	5·1		Open 10·7 Closed 20·2	63·5	42	76·2	Without casing in bore hole	
Heavy dynamic penetrometer	Maag	3·2		15	50	25	50	Without casing	13
Middle dynamic penetrometer	Haefli–Amberg–von Moos	2·0		10	30	9	20	Without casing	16
Light dynamic penetrometer	Künzel	2·0		10	10	9	50	Without casing	30
Heavy static penetrometer	Brunner	4·2	6·0	30	50	92·5	33	With casing	
Middle static penetrometer	Stump	2·0	3·0	12·3	25·4	11·5	20	With casing	

Table 2

Data on time and capacity with hand-operated penetrometers
Poids, temps de montage, puissance des pénétromètres utilisés

Penetrometer	*Total weight of apparatus with 20 m rod inclusive, cases*	*Weight of auxiliary equipment*	*Erection of apparatus*	*Average driving capacity*	*Average retraction capacity*
	kg	kg	min	m/h	m/h
Static penetrometer (Hoffmann)	138	Loading frame with winch, 643	150	4	4
Static penetrometer (Plantema)					
Static penetrometer (Frankipfahl–Baugesellsch)		Sounding truck, 10,000	30		
Standard penetrometer (Terzaghi)	Drop weight with casing, 350; without casing, 310	Tripod with rope winch, 284	Drop weight in bore hole, 20 min/single penetration, drop weight over ground level, < 12 m depth 30 min/single penetration, > 12 m depth 45 min/single penetration		
Heavy dynamic penetrometer (Maag)	326	Tripod, 178 Chainblock, 70	30	5·5	12
Middle dynamic penetrometer (Haefli–Amberg–v. Moos)	123	Winch, 32	10	6	12
Light dynamic penetrometer (Künzel)	95	Winch, 32	10	6	12
Heavy static penetrometer (Brunner)	898	Tripod, 178 2 winches, 52	40	1	3
Middle static penetrometer (Stump)	187	Winch, 32	20	1·5	9

operated penetrometers. In order to ensure proper evaluation of the tests, the recording accuracy of individual apparatus should be taken into account.

Here is what has been ascertained.

Static penetrometers—Static penetrometers (Fig. 1a–c) present the advantage of recording the static soil resistance, whereas the necessary anchorage or counterweight which, in the central part of middle and western Germany, should weigh 7 tons if tests exceed depths of 10 m is considered a disadvantage. Owing to weight, the loading appliances are difficult to handle for transportation: time-taking erection is another disadvantage. Sounding trucks facilitate a quick starting operation but on the other hand are less manoeuvrable off the road. Their applicability to soils other than soft ones is limited due to the facts that loading frames with ground anchors are hardly liable to support more than 5 tons and that heavy surcharges (for instance the sounding trucks of the Frankipfahl–Baugesellschaft in Düsseldorf, which weigh more than 10 tons) are available only in exceptional cases. The cones of static penetrometers should have slightly larger diameters than the shafts so that the shaft resistance is largely eliminated, which results in the pressure being almost wholly transmitted to the cone (Fig. 2). This, of course, is not applicable if the shaft resistance is to be determined. Reading from the receiver of a static penetrometer according to the Maihak testing method is rather a laborious task and the measuring element is sensitive. Static penetrometers designed to transmit the pressure over an inside rod to the dynamometer or pressure gauge arranged under the press or the spindle are not so sensitive.

Dynamic penetrometers in bore holes—Static penetration tests that cannot be carried out on compact soils may be conveniently replaced by the U.S. Standard Penetration Test (Fig. 1d and e) (TERZAGHI and PECK, 1948; and HVORSLEV, 1949); but in this case a bore hole is required. Since, generally, bore holes cannot be dispensed with in the case of large building projects, this can be considered a disadvantage in very few cases. It should be remembered that with individual penetrations the boring operation is to be interrupted at intervals, as indicated in Table 2. By means of a watertight, encased drop weight, standard penetration tests in bore holes can be performed at any depth. The casing has proved successful even in a 50 m bore hole under water. The drop weight fell without meeting with any appreciable air resistance since, owing to the dropping operation, there existed a vacuum in the casing.

Penetrometers without casing—Penetrometers without casing are easily operated. Even the 'heavy penetrometer' (Fig. 1f) is easily transportable. It can be used without difficulty under all off-road conditions and is, because of its high dynamic energy and the reduced or often entirely eliminated shaft resistance, due to the enlarged cone, applicable to any soil up to a maximum depth of 25 m. The rod is pulled out by means of a chain block and a tripod, the operation taking only a little time since the enlarged cone is but loosely fastened to the rod and remains in the soil so that the use of such penetrometers is exceedingly economical (PECK, HANSEN and THORNBURN, 1953 and PECK). Removal of static penetrometers and of such dynamic penetrometers to which the 'lost cone' principle is not yet applied depends on the capacity of the hand winches or presses.

Middle penetrometers without casing (Fig. 1g) can be easily transported in a passenger car and can be used under all off-road conditions. They can be applied to soils of medium

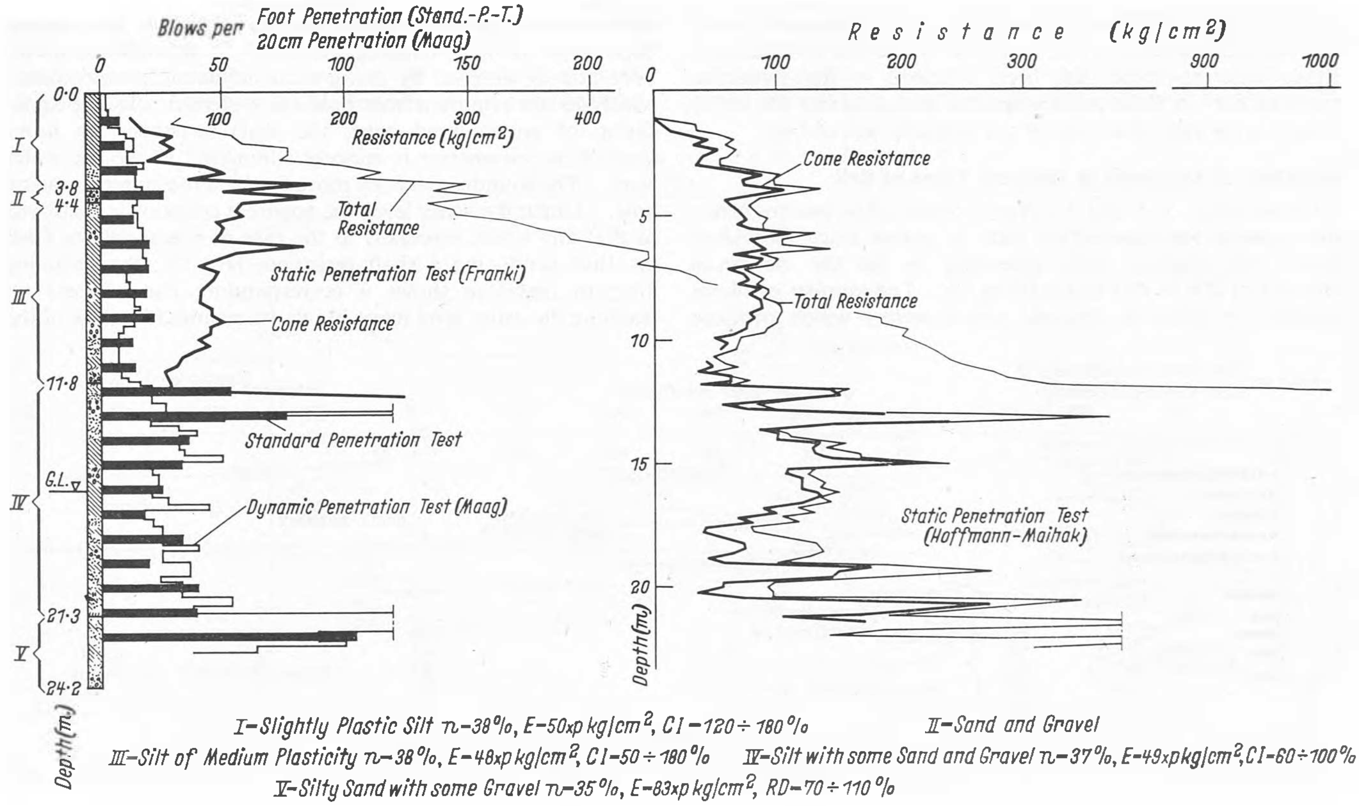

Fig. 2 Results obtained both from a bore hole and from penetrations with two static penetrometers, a standard penetrometer and a dynamic penetrometer

Comments on soil coefficients:
n = average porosity; CI = average consistency index; E = average stiffness coefficient with initial load; p being the load in kg/cm²; RD = average ratio of compaction

Résultats obtenus dans un trou de sondage avec deux pénétromètres statiques, un pénétromètre standard et un pénétromètre dynamique

n = porosité moyenne; CI = indice moyen de consistance; F = coefficient de rigidité moyenne sous charge initiale; p = la charge en kg/cm²; RD = densité relative strength and, in local conditions, ensure economical operation at moderate depths (< 15 m).

In dense soil, the *light penetrometers* (Fig. 1g) are inferior to middle penetrometers. They can be used to merely probe quickly into the uppermost layers and will fail in stony soil (Fig. 3). A depth of 10 m has occasionally been reached.

The performances of light and middle penetrometers without casing appear, as may be seen from Table 2, to be unduly favourable compared with those obtained with heavy penetrometers without casing, since the first-mentioned apparatus is applied to soft and compact soils only. In case of harder resistance, heavy penetrometers without casing must be used.

Dynamic penetrometers with casing—The application of penetrometers equipped with a casing requires much more time. *Heavy penetrometers with casing* (Fig. 1h) are difficult to operate by hand; this is especially so in soils producing an appreciable shaft resistance, owing to the large cone and casing cross-section (Fig. 3). In order to reach depths of 20 m a great amount of labour is required. If exact measurement of the shaft resistance is not required the cone should have a larger section than the casing. The cost of dynamic penetrometers with casing are not profitable for small companies: the apparatus is more suitable for companies that can afford motor-operated application.

Middle dynamic penetrometers with casing (Fig. 1i) are considerably lighter in weight and more easily transported. Although their use does not take so much time, driving them into soils presenting a dense state of packing or into stony subsoils requires a certain expenditure of work.

Much trouble has been taken to improve the shape of single parts and the material of which the dynamic penetrometers are made, since at first the continuous dynamic strain on the apparatus frequently led to breakage. In co-operation with appropriate institutes of the Technical University of Aachen, a higher wear resistance has been obtained so that breakage occurred only in those cases where the sounding rod was either locked in the cleft of a rock or not properly screwed up.

Behaviour of Apparatus in Different Types of Soil

Gravel (Figs. 3, 5 and 6)—Very robust *static penetrometers* are required for penetration tests in gravel since individual stones will produce loads exceeding by far the maximum pressure of 200 to 400 kg/cm² (Fig. 3). The number of blows required to drive in *dynamic penetrometers* which produce practically no shaft resistance in gravel when equipped with an enlarged cone (Figs. 3 and 6) depends, apart from the load (depth), on the compactness and grain size of the gravel. Dynamic penetrometers react very sensitively to any changes of compactness or grain size, this was also observed by SCHUBERT (1955) who explained this phenomenon by the decreasing number of contacts with an increasing size of grains which is important for the displacement by the penetrometer. In loose, coarse gravel and pebbles this nevertheless have a good bearing capacity, the number of blows is generally low. Heavy dynamic penetrometers can be driven even into loose pebbles of the size of an orange without much difficulty. Favoured by the dynamical principle of penetration, the penetrometer slides into more or less large voids, subject to grain size and distribution, the pebbles acting like a ball bearing. This advantage becomes more marked under water. The shortcomings of penetration tests in coarse gravel and pebbles, which differ from those observed in dense sand or cohesive soils, were hinted at by MEYERHOF (1956).

The number of blows required on closed cones exceeded that required on open cones by one-fourth. This increase represents only one-half of that stated by Meyerhof. The diagrams of the penetrometers equipped with a casing used in gravel show that with penetrometers having a uniform section all along shaft and cone only little resistance is produced.

Sand (Figs. 5 and 6)—The results obtained from penetration tests made in sand depend on factors similar to those obtained with gravel. The surcharge—according to Schubert, who thereby confirms former tests made in the U.S.A. (Bureau of Reclamation, 1953)—sometimes leads to the deceptive conclusion that the compactness is denser than it actually is. TSCHEBOTARIOFF (1956) reported an increase in the number of blows in a deep, non-cohesive layer, the upper mud layer having been filled up with pugging material. If the bottom of the bore hole is softened by rising water, dynamic penetrometers which do not require a bore hole are preferred. By the application of an enlarged cone, the shaft resistance on *heavy dynamic penetrometers* is entirely eliminated above the water level. The sounding rod can move freely in the larger sounding hole. Under the water level, the apparent cohesion is destroyed so that any voids, especially in the case of fine sand, are filled up, thus producing a shaft resistance (Fig. 5): the sounding diagram therefore shows a corresponding rise whereas on reaching the water level fewer blows are required because of the

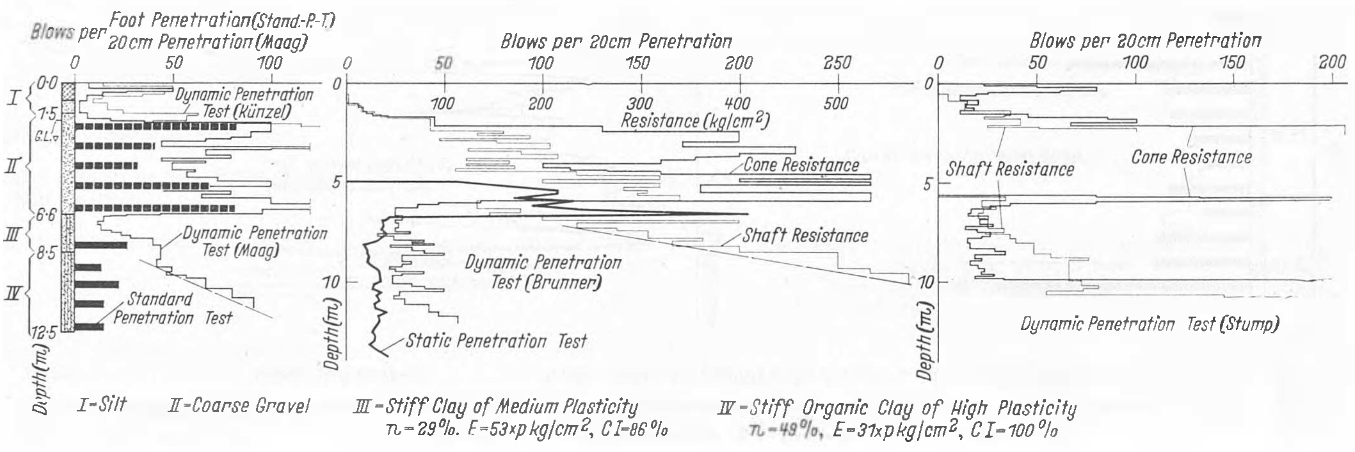

Fig. 3 Results obtained both from a bore hole and from penetrations with one static penetrometer, a standard penetrometer and several dynamic penetrometers

Comments on soil coefficients:
n = average porosity; CI = average consistency index; E = average stiffness coefficient with initial load; p being the load in kg/cm²

Résultats obtenus dans un trou de sondage avec un pénétromètre statique, un pénétromètre standard et plusieurs pénétromètres dynamiques

n = porosité moyenne; CI = indice moyen de consistance; E = coefficient de rigidité moyenne sous charge initiale; p = charge en kg/cm² better transmission of grain motion. This confirms some results obtained in the U.S.A. according to which all fine sands and to some extent silty sands require a reduced number of blows if the sand is saturated with water. In the case of fine sands, the rod is virtually gripped by the slurry so that a high shaft resistance is produced and removal of the rod is rendered more difficult in spite of the 'lost cone'.

Silt (Fig. 2)—Also in silt the water level is shown in the sounding diagram by a reduction in the number of blows. The measurements obtained from *static cone penetrometers* ranged from 10 to 40 kg/cm² (in clay 40 to 70 kg/cm²). The same measurements were made with a Proctor needle horizontally introduced into a steep excavation slope. In such cases the needle can replace a static penetrometer (Fig. 6). Driving diagrams plotted before and after the excavation work (Fig. 6) illustrate the negligible influence of shaft resistance and rod mass. Dynamic penetrometers without casing deliver satisfactory recordings, since a slightly enlarged cone will entirely eliminate the shaft resistance (Fig. 2).

Clay (Fig. 3)—In highly cohesive soils results obtained from *static penetrometers* with a cone resistance of 20 to 40 kg/cm² (Fig. 3) have proved too low as compared with the actual bearing capacity of clay, in spite of their reliability due to the elimination of the shaft resistance in other types of soil. Both the examination of soil samples (consolidation test) and the evaluation of static penetration tests by means of shear failure terms resulted in pressures on the soil that are far inferior to those found, according to Terzaghi, by an evaluation of unconfined compression tests. This difference may perhaps be explained by the sample in the consolidometer being more easily dehydrated than is possible under natural conditions, and because the impact strain produces a considerably larger range of disturbance than does the comparatively smooth motion of the static penetrometer. Schubert explains the easy advance of penetrometers into cohesive soils by the slow pressure compensation as compared with the motion of the penetrometer, and by the lubricating effect of the void water. The conventional evaluation of *standard penetration tests* produces bearing capacities which conform better to practical experience. In spite of all the arguments raised against dynamic penetration tests in cohesive soils, the results obtained just in this case seem to be satisfactory. The tests revealed an existing relation between the results obtained from the standard penetrometer and those obtained from the unconfined compression tests, which corresponds to the statements presented by Sowers (1954).

In spite of the enlarged cone, penetrometers without casing have a high shaft resistance; the cones appear to be circumfused by the clay. If the different drop energies are taken into account, it can be seen from the degree of inclination of the dashed lines in the driving diagram of Fig. 3 that both heavy dynamic penetrometers with and without casing show the same specific shaft resistance. Better results are obtained with *heavy dynamic penetrometers* in clayey soil. The falsification of results obtained from dynamic penetrometers without casing can be discovered only by means of static or standard penetrometer tests made in a bore hole after previous calibration, which as a simultaneous key test will indicate the types of soil. Therefore, penetrometers with casing are to be preferred in this case, the cone being driven in a short distance in advance of the shaft, since otherwise the inside rod will be subject to friction.

Organic soils (Fig. 4)—*Dynamic penetrometers without casing* failed in organic soils since peat, for instance, practically produces nothing but a shaft resistance, i.e. the shafts are blocked up. The influence of time, as already mentioned in the section dealing with clay, i.e. slow release by blows of the rod blocked during breaks, is felt in the case of mud to such an extent that by suitable breaks any driving diagram may be obtained. *Light dynamic penetrometers* having a small drop energy and presenting a small ratio of drop weight to moved mass have proved unsuitable. On the other hand, *dynamic penetrometers*

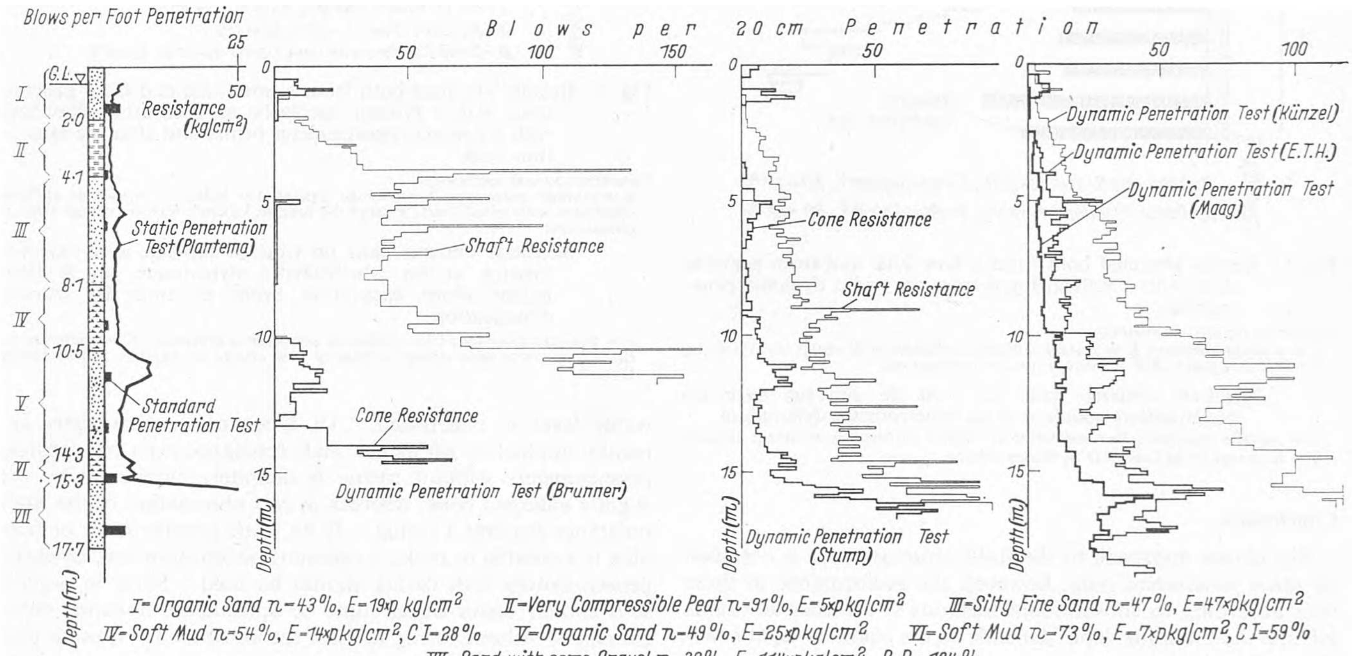

Fig. 4 Results obtained both from a bore hole and from penetrations with a static penetrometer and several dynamic penetrometers

Comments on soil coefficients:
n = average porosity; CI = average consistency index; E = average stiffness coefficient with initial load; p being the load in kg/cm²; RD = average ratio of compaction

Résultats obtenus dans un trou de sondage avec un pénétromètre statique et plusieurs pénétromètres dynamiques

n = porosité moyenne; CI = indice de consistance moyenne; E = coefficient de rigidité moyenne sous charge initiale; p = la charge en kg/cm²; RD = densité relative *equipped with a casing*, with which the above effects influence solely the shaft diagram, have proved all the more suitable. The assumption that in peat there exists no cone resistance is confirmed by the fact that the inside rod together with its cone penetrates the soil without any blows being necessary (Fig. 5).

Comparing Static with Dynamic Penetration Tests

Different dynamic penetration tests have been compared with static penetration tests effected in close vicinity of the former. The results obtained by MEYERHOF (1956), according to which the cone resistance of static penetrometers in non-cohesive soils, measured in kg/cm², is about four times the number of blows n required with standard penetrometers to effect a penetration of 30 cm have been confirmed. The results obtained in clay were about half that ratio. The corresponding factors for the other dynamic penetrometers range from about 0·5 to 3·5.

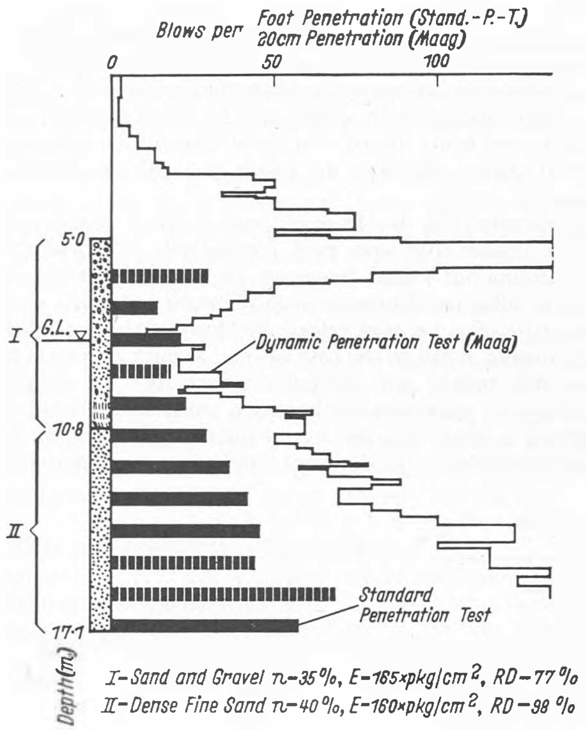

Fig. 5 Results obtained both from a bore hole and from penetrations with a standard penetrometer and a dynamic penetrometer

Comments on soil coefficients:
n = average porosity; E = average stiffness coefficient with initial load; p being the load in kg/cm²; RD = average ratio of compaction

Résultats obtenus dans un trou de sondage avec un pénétromètre standard et un pénétromètre dynamique

n = porosité moyenne; E = coefficient de rigidité moyenne sous charge initiale; p = la charge en kg/cm²; RD = densité relative

Conclusions

The closest approach to the static structure load is obtained by *static penetration tests*: however, the performance of these tests according to conventional methods is a rather laborious job and the sounding depth depends on the counterweight available. *Standard penetration tests* in the bore hole are, apart from layers that are greatly disturbed by the drilling process, the most reliable dynamic penetration tests and represent a satisfactory substitute for static penetration tests; they cannot, however, be performed without a bore hole. By means of *dynamic penetrometers without a casing* the sequence of layers is readily determined and interpolation of layer sequence between individual bore holes, where the distance from one another is not so much restricted, is easily effected. Besides, the number of blows required leads to conclusions as to compactness or consistency of the soil. Heavy dynamic penetrometers are suitable for depths of up to 20 m, whereas middle and light dynamic penetrometers can be used only for lesser depths. Measurements obtained from *dynamic penetrometers equipped with a casing* in any type of soil may be relied upon. In soils producing a shaft resistance, dynamic penetrometers with a casing are superior to ordinary dynamic penetrometers. The time required to apply them to soils not producing any shaft resistance may in some cases render their employment uneconomical.

The application of static penetrometers to *gravel* requires both a heavy counterweight and a very robust construction of the apparatus. The shaft resistance on dynamic penetrometers without casing and with enlarged cone is very low or does not exist at all so that penetrometers equipped with a casing can be dispensed with. In *sand*, static penetrometers are not subject to surcharges. If dynamic penetrometers advance beyond the water level, apparatus with casing should be preferred to those without casing as the bore hole is liable to collapse when the

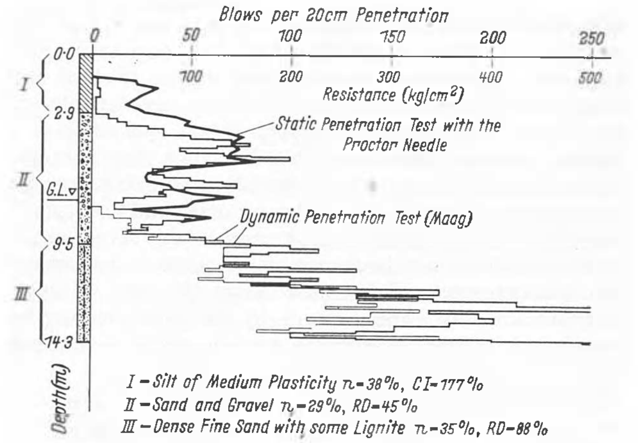

Fig. 6 Results obtained both from a bore hole and from penetrations with a Proctor needle on an excavation slope and with a dynamic penetrometer before and after the excavation work

Comments on soil coefficients:
n = average porosity; CI = average consistency index; E = average stiffness coefficient with initial load; p being the load in kg/cm²; RD = average ratio of compaction

Résultats obtenus dans un trou de sondage avec l'aiguille Proctor et un pénétromètre dynamique sur le plan incliné d'une excavation avant et après les travaux d'excavation

n = porosité moyenne; CI = indice de consistance moyenne; E = coefficient de rigidité moyenne sous charge initiale; p = la charge en kg/cm²; RD = densité relative

water level is penetrated. All types of penetrometers are readily applied to *silt* as the shaft resistance even on dynamic penetrometers without casing is definitely eliminated by the slightly enlarged cone, whereas in *clay* elimination of the shaft resistance requires a casing. If no static penetrometer or bore hole is available to make a standard penetration test, dynamic penetrometers with casing should be used. Since in *organic soils* similar disturbances must be considered, dynamic penetrometers without casing are not recommended. Comparison of the results obtained from different penetrometers leads to conclusions as to the relations existing between measurements taken with the various instruments used.

The research described has been accomplished with the aid of means made available by the Federal Minister for Economics and Communications of the Land Nordrhein-Westfalen.

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