Chapter 46
Soil Exploration

In this chapter some of the most effective or popular methods for soil exploration, or soil investigations in the field will be described.

46.1 Cone Penetration Test

A simple, but very effective method of soil investigation consists of pushing a steel rod into the soil, and then measuring the force during the penetration, as a function of depth. This force consists of the reaction of the soil at the point (the cone resistance), and the friction along the circumference of the rods. The method was developed in the 1930s in the Netherlands. It was mainly intended as an exploration tool, to give an indication of the soil structure, and as a modelling tool for the design of a pile foundation. This *sounding test*, *cone penetration test*, or simply CPT, has been developed from a simple tool, that was pushed into the ground by hand or a manual pressure device, into a sophisticated electronic measuring device, with an advanced hydraulic loading system. The load is often provided by the weight of a heavy truck.

Originally the CPT was a purely mechanical test, as shown schematically in Fig. 46.1. The instrument consists of three movable parts, with a common central axis. The upper part is connected, by a screw thread, to a hollow rod, that reaches to the soil surface, using extension rods of 1 m length. The procedure was that pressure was alternately exerted upon the central axis or the outer rods. When pushing on the internal axis at first only the cone is pushed into the ground, over a distance of 35 mm. The other two parts do not move with respect to the soil (by the friction of the soil), so that the force represents the cone resistance only. When pushing the instrument beyond a distance of 35 mm the second part, the *friction sleeve*, moves with the cone, so that in this stage the force consists of the cone resistance plus the friction along the friction sleeve. The upper part of the instrument is still stationary in this stage. If it is assumed that the cone resistance is still the same as before, the sleeve friction

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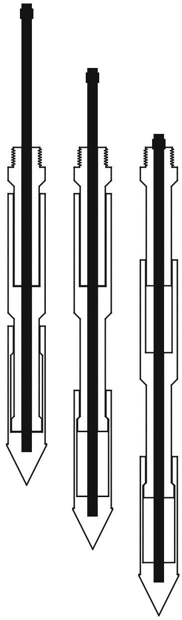
Fig. 46.1 Mechanical CPT

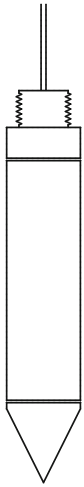


can be determined by subtraction. If in the next step the force is exerted on the outer rods, the cone remains stationary and the system is compressed to its original state, but at a greater depth (10 cm). The diameter of the lowest part of the sleeve, which is attached to the cone and moves with it, was sometimes reduced, to ensure that in the first stage only point resistance is measured.

Modern versions of the CPT use an electrical cone, see Fig. 46.2. Both the cone resistance and the friction are measured continuously, using a system of strain gauges in the interior of the cone. The instrument again consists of three parts, that are separated by thin rings of rubber. The very sensitive strain gauges can measure the forces on the lower two parts of the instrument independently. The results of a cone penetration test give a good insight into the layered structure of the soil. Clay layers have a much smaller cone resistance than sand. A typical cone resistance for a sand layer is 5 MPa or 10 MPa, or even higher, whereas the cone resistance of soft clay layers is between 0.01 and 0.1 MPa. If the local friction is also measured the difference is even more pronounced. The ratio of friction to cone resistance for clays is much higher than for sand. In sands the friction usually is only 1% or 2% of the cone resistance, whereas in clays this ratio usually is about 5%. Higher values (8–10%) may suggest a layer of peat. In peat the friction usually is substantial, but it has a very small cone resistance.

Recent developments are to install additional measuring devices in the cone, such a pore pressure meter. This type of cone is denoted as a *piezocone*. A small chamber inside the cone is connected to the pores in the soil by a number of tiny holes in the cone. This enables to measure the local pore water pressure. This pressure is

Fig. 46.2 Electrical cone



determined by the actual pore water pressure in the soil, but also by the penetration of the cone in the soil, at least in materials of low permeability. In a very dense clay the material may have a tendency to expand, which will lead to and under pressure in the water, with respect to the hydrostatic pressure. This enables to distinguish very thin layers of clay. In measuring the cone resistance or the friction such thin layers are not observed, because of the averaging procedure in measuring forces.

An example of the results of as cone penetration test is shown in Fig. 46.3. At a depth of 7 m a sand layer of about 2 m thickness can be observed. At a depth of 18 m the top of a thick sand layer is found. The low values above the first sand layer, and between the two sand layers indicate soft soil, probably clay. A simple building (a house) can be founded on the top sand layer, provided that the presence of this layer is general. A single CPT is insufficient to conclude the existence of this layer everywhere, having it observed in 3 CPT's at practically the same depth (and at about the same thickness) usually is sufficient evidence of its general existence. A heavy foundation, for a large building, usually requires a foundation reaching into the deep sand.

In the Netherlands the cone penetration test is mainly used as a model test for pile foundations. In the Western parts of the Netherlands the soil usually consists of 10–20 m of very soft soil layers (clay and peat), on a rather stiff sand layer. This soil structure is very well suited for a pile foundation, of wooden or concrete piles of about 20–40 cm diameter, reaching just into the sand. The weight of the soft soil acts as a surcharge on the sand, which has a considerable cone resistance. The allowable stress on the sand depends upon its friction angle ϕ, its cohesion c (usually very small, or zero), and the surcharge q, as explained in Chap. 42. The dimensions of the foundation pile have very little influence, because this parameter appears only in the third term of Brinch Hansen's formula, which is a small term if the width is less than, say, 1 m. This means that the maximum pressure for a large pile and the

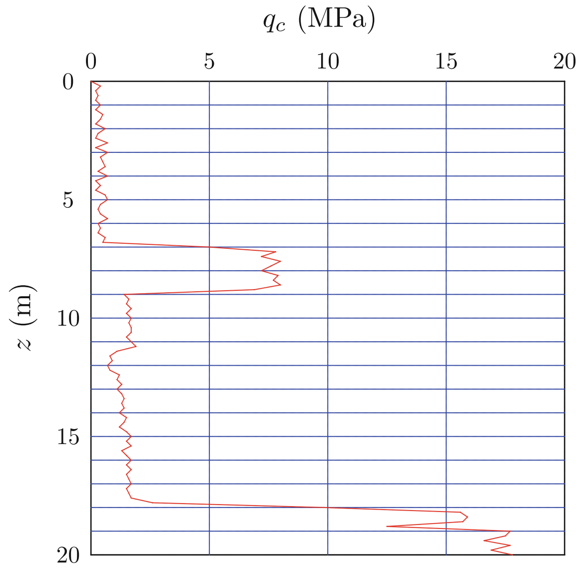


Fig. 46.3 Result of CPT

thin pile of a cone penetrometer will be practically the same, so that the allowable pressure on a pile can be determined by simply measuring the cone resistance. This will be elaborated in Chap. 48.

The cone penetration test can also be used to determine physical parameters of the soil, especially the shear strength. It can be postulated, for instance, that in clays the cone resistance will be determined mainly by the undrained shear strength of the soil (s_u). In agreement with the analysis of Brinch Hansen, see Chap. 42, the relation will be of the form

$$q_c - \sigma_v = N_c s_u, \tag{46.1}$$

where σ_v is the local vertical stress caused by the surcharge, and N_c is a dimensionless factor. For a circular cone in a cohesive material a cone factor N_c of the order of magnitude 15–18 is usually assumed, on the basis of plasticity calculations for the insertion of a cone into a cohesive material of infinite extent. By measuring the cone resistance q_c the undrained shear strength s_u can be determined. The results are not very accurate, because of theoretical shortcomings and practical difficulties, but the measurement has the great advantage of being done *in situ*, on the least disturbed soil. The alternative would be taking a sample, bringing it to a laboratory, and then doing a laboratory test. This process includes many possible sources of disturbance, that are avoided by doing a test in situ.

46.2 Vane Test

The shear strength of soils can be measured reasonably accurately in situ using the *vane test*. In this test a small instrument in the shape of a vane is pushed into the ground, through a system of rods, just as in the cone penetration test. The vane is connected, by a central steel axis, to a screw at the top of the rods. This screw can be rotated, so that the soil in a cylindrical element of soil is sheared along its surface, against the soil outside the cylinder. Measuring the moment necessary for the rotation enables to determine the average shear stress along the boundary, which is about equal to the (undrained) shear strength of the soil. The vane test is very popular in Scandinavian countries, where the soil very often consists of thick layers of clay of reasonable strength (Fig. 46.4).

46.3 Standard Penetration Test

In many parts of the world, especially in Anglo-Saxon countries, the properties of the soil are often determined by using a *Standard Penetration Test*, or SPT. In this test a sampling tube is driven into a borehole in the ground using a standardized hammering weight. The actual test consists of measuring the number of blows needed to achieve a penetration of 300 mm (1 foot) into the ground. This is denoted as N, the *blow count*, the number of blows per foot. An advantage of the SPT is that no heavy equipment is needed, as for instance in the CPT, which has to be pushed into the ground statically, and thus requires a large counter weight. Another advantage of the SPT is that it immediately provides a soil sample. The sample is perhaps not of the best quality, because of the disturbance of the soil during the dynamic hammering, but at least there is a sample that can be inspected. The reproducibility of the SPT usually is not so very good, and the difference between sand and clay is not so pronounced as it is in the CPT. It is also not possible to immediately derive the shear strength from the blow count.

For many projects the initial soil data often may be restricted to a series of SPT-results. Then it is useful to know that a characteristic blow count for sand is $N = 20$,

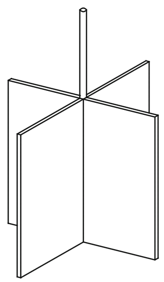


Fig. 46.4 Vane test

Table 46.1 Interpretation of SPT according to Terzaghi and Peck

Sand		Clay	
N	Density	N	Consistency
<4	Very loose	<2	Very soft
4–10	Loose	2–4	Soft
10–30	Normal	4–8	Normal
30–50	Dense	8–15	Stiff
>50	Very dense	15–30	Very stiff
		>30	Hard

and that for soft clay the value may be $N = 5$, or even lower, down to $N = 1$. A first indication can be obtained from Table 46.1, derived from Terzaghi and Peck. Many researchers have tried to obtain a correlation with the CPT, but their results are not very consistent.

46.4 Soil Sampling

For many engineering projects it is very useful to take a sample of the soil, and to investigate its properties in the laboratory. The investigation may be a visual inspection (which indicates the type of materials: sand, clay or peat), a chemical analysis, or a mechanical test, such as a compression test or a triaxial test.

A simple method to take a sample is to drive a tube into the ground, and then recovering the tube with the soil in it. The tube may be about 1 m long, see Fig. 46.5, and may have a valve at its bottom, to prevent loosing the sample. The tube may be brought into the soil by driving it into the ground using a falling weight, or a hammer. An advantage of this method is that it does not require heavy equipment. It is possible to take a sample in a terrain that is inaccessible to heavy vehicles. The sample is somewhat disturbed, of course, during the sampling process, but even so, a good impression of the composition of the soil can be obtained. The sample is not very well suited for a refined test, however, as the initial state of stress is disturbed, and perhaps also the density. To take a deep sample the sampling tube may be of smaller diameter than the borehole, which is supported and deepened by a special boring tube.

An alternative method is to push the sampler into the ground, by using hydraulic equipment, mounted on a heavy truck. In this case the sampling process is somewhat more careful, and the disturbance of the sample is less. Due to friction of the sample with the wall of the sampling tube, however, the samples are not undisturbed.

Various institutes have developed systems in which the sample is almost undisturbed. A completely undisturbed sample is impossible, but some procedures come very close. Some methods are, for instance, to take a very large block of soil, and use the inner part only, or freezing a block of sand, and then cutting a sample from the

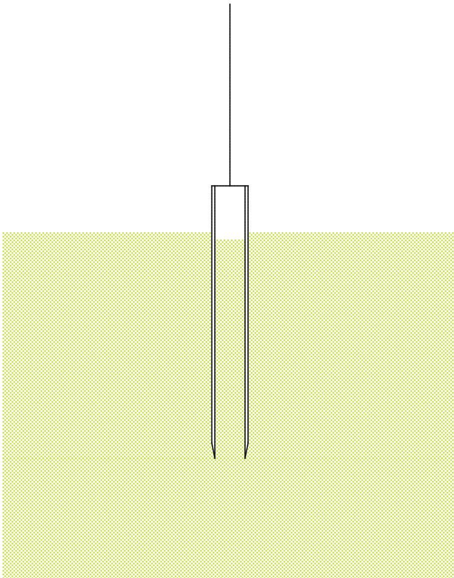


Fig. 46.5 SPT

frozen soil. Good quality samples can also be obtained using the Begemann sampler, developed at Deltares and managed by Fugro, see Fig. 46.6. This sampler consists of two steel tubes, that are being pushed into the soil together. The sample is cut by the outer tube, which immediately widens behind the cutting edge, and the sample is surrounded by a nylon stocking, that initially is rolled up on the inner tube. The end of the stocking is attached to a plate at the top of the future sample, so that, when the tubes are pushed down, the stocking gradually displace downward the stocking is gradually stripped off the inner tube. The final result is a very long soil sample (for instance 20 m long), enclosed by a nylon stocking. Around the stocking the sample is supported by a heavy fluid (of unit weight $\gamma \approx 15\ \text{kN/m}^3$), that simulates the original lateral support of the soil. This fluid also reduces the friction along the circumference of the sample. The samples produced by this sampler are of high quality. Very thin layers of all sorts of materials can be identified, including loose sand. The quality of the samples is good enough to be used for accurate laboratory testing, in compression tests or triaxial tests. The results of a boring may be presented in the form of a color photograph of one half of the sample, cut along its length. That the thin layers are not disturbed near the boundary confirms that there is very little friction.

It may be interesting to note that samples can also be taken from the bottom of the sea. One possible method is by using a diving bell, in which the air pressure is kept at the same level as the water pressure. From this diving bell a sample can be taken by the operators, or they can make a cone penetration test. Another method is to use a heavy frame, that is submerged in the water from a ship. Using a remote

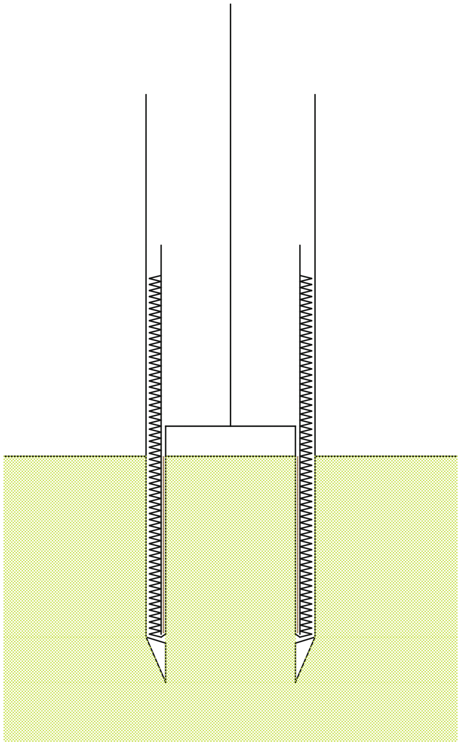


Fig. 46.6 Begemann sampler

control system a cone can be made to penetrate the soil, or a sample can be taken. This method can even be used in water depths of 1000 m, or more.

An example of a continuous Begemann boring, made from the bottom of the Eastern Scheldt, is shown in Fig. 46.7. The lighter and darker colors of the soil in the boring indicate a variation of sand and clay layers. Also, some of the sand layers appear to be composed of thin layers of different soils.

Investigating the sea bottom is of special interest in offshore engineering, of course. For the production of oil and gas from the sea bottom large platforms are constructed, which usually need a pile foundation to withstand the extreme wave load conditions during a storm. The piles usually are steel tubular piles, of large diameter (one meter or more), and very large length (50 m or more). These piles derive their bearing capacity mostly from the friction along the shaft, and not from the point resistance (as most piles in Western Netherlands). It is of great importance to predict the maximum shearing resistance along the pile shaft. This can be measured very well by a cone penetration test, from the bottom of the sea. Even though this is a costly operation, it gives very valuable information about the soil structure, and it gives numerical values for the cone resistance and the friction, as a function of depth.

Example 46.1 In formula (46.1) the total stress σ_v appears. It might be argued that this should be the effective stress σ'_v, because the shearing resistance of a soil is

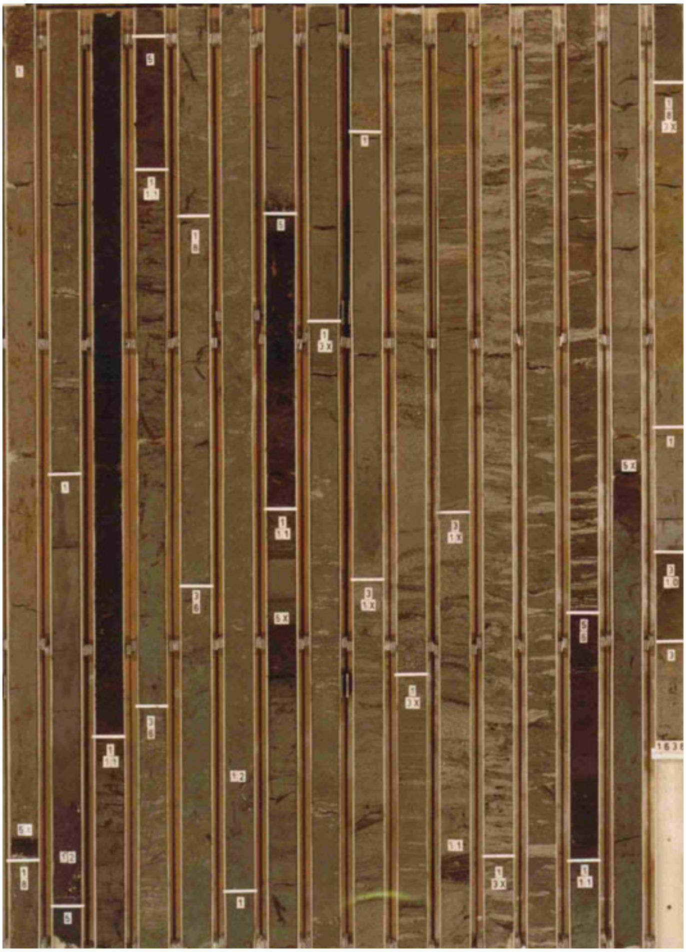


Fig. 46.7 Begemann boring

determined by the effective stresses and not by the total stresses. However, the cone resistance is also a total stress (and includes the local pore pressure), and in the formula the strength is the undrained strength, which also indicates a total stress analysis.