

Cone Penetration Testing – A Historic Perspective

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ABSTRACT: Penetration testing is a relatively recent geotechnical field investigation method, but which has become very popular during the past four decades. A historic overview of penetration testing methods is given, with emphasis on the development of cone penetration testing. The European Symposium on Penetration Testing, ESOPT I, held in 1974, was the platform, which initiated many positive developments, such as harmonization and standardization of penetration testing equipment and methods. The role of ISSMGE Technical Committees in this development is described, in particular the efforts by ISSMGE TC16/TC102 in organizing international symposia and conferences. The results of efforts to standardize penetration testing are presented. An effort was made to review the contents of papers published at symposia held during the past 40 years to detect major trends in testing and application of test results.

1 INTRODUCTION

The 3rd International Symposium on Cone Penetration Testing, CPT'14 is being held almost on the day forty years after the first European Symposium on Penetration Testing, ESOPT (ESOPT I) in Stockholm, Sweden, 1974. I was secretary of ESOPT I and have been asked to present my thoughts about the developments in cone penetration testing following the first conference. I have accepted this invitation with the reservation that I would not be able to provide a complete documentation of the many aspects of penetration testing that have taken place. Instead, I focus on a historic overview of the developments in terms of methods and equipment since 1974. This can help to explain the impressive progress, which has led to the impressive state of knowledge and the wide scope of practical application of penetration testing today. A review of recent developments in geotechnical and foundation engineering clearly shows that cone penetration testing (CPT) has indeed become one of the most widely used geotechnical investigation methods. Examples are different types of pressuremeter, the dilatometer, and geophysical methods. Some of the reasons are: - testing method and equipment are relatively easily standardized, - the test provides a continuous soil profile, compared to other, intermittent, tests, - different types of sensors can be incorporated in the same probe, - the method is relatively fast and therefore less expensive than most other in-situ methods, - the rapid development in electronic engineering has facilitated quick and efficient data acquisition and evaluation of large data volumes, and – the concerted effort by researchers and geotechnical practitioners from different

countries has helped to develop design concepts which can be used for the solution of many types of geotechnical, geo-environmental and earthquake-related problems. However, it is important to recognize that also other in-situ methods have become available and are widely used today. Examples are different types of pressuremeters, the dilatometer and geophysical methods.

Looking back at the developments over a time period of 40 years in a relatively young engineering discipline, such as geotechnical engineering, is fascinating. At the end of the 1960s, many of the engineering challenges of today did not exist or were just emerging. Heavy structures were either founded on rock or hard soil or supported by piles. The number and size of land reclamation projects was still small and their planning, design, and execution was often based on relatively unsophisticated concepts. Geotechnical earthquake engineering was emerging and offshore engineering was still in its infancy. The use of electronic equipment on a construction site was an exception and restricted to scientific projects. Data recording was often manual, by reading dial gages. Also the accuracy and reliability of field measurements was low and their quality depended to a large degree on the skills of the site crew. A factor, which limited the development of equipment and the application of penetration testing results in practice, was the variability of methods and equipment used in different parts of the world. Various types of in-situ tests had been developed, often in specific regions, and design tools based on local experience, which limited their wider application. In Europe, different types of static and dynamic penetrometers were used while the Standard Penetration Test (SPT) dominated outside Europe.

A main reason for arranging an international symposium on penetration testing was to assemble experts in penetration testing from Europe and a selected number of other countries for exchange of information and discussion of future needs of harmonization. Without the vision of a group of outstanding geotechnical engineers – most of them no longer active – who recognized the need of information exchange, the rapid progress in CPT accomplished during the past 40 years would not have been possible. This report is an attempt to pay tribute to their important contributions.

2 EARLY DEVELOPMENTS OF PENETRATION TESTING

In ancient times, it was common practice to locate temples and tombs in areas that were known to have stable ground conditions, where there was no need for extensive investigations. For instance, the greatest construction challenges in Egypt were associated with excavations in rock, such as the excavation of tombs and the building of pyramids and temples. About 2000 years ago, the Chinese installed boreholes - sometimes to depths of several hundred meters - and retrieved soil and rock samples to examine ground conditions. However, the most important progress in construction and foundation methods was achieved by the military. Military campaigns required sound knowledge of construction and foundation engineering, such as the construction of roads, bridges, aqueducts or fortifications. However, most of the construction work was carried out on a trial and error basis. About one millennium ago, the Vikings, who lived primarily along shores and coast lines in Scandinavia, were often confronted with difficult ground conditions and developed therefore extensive knowledge on how to build roads, fortifications and harbors on very soft, compressible ground. Engineering knowledge was important when combating neighbors or invading other countries, usually by attacking from the sea. Therefore, it is not surprising that Vikings used piling and soil reinforcement - such as bundles of wood - for strengthening paths and roads across wet terrain. Their superior engineering knowledge was an important advantage for successfully conquering foreign lands.

Penetration testing is a relatively new soil investigation method, compared to boring, excavation and visual site inspection. Comprehensive reviews of the history of site investigations have been published by for instance, Sanglerat (1972) and Broms and Flodin (1988). The first known, documented use of *penetrometers* for engineering applications was in the 14th century when the German military engineer, Konrad Kyeser (1366 – 1405?) began to write books on military and mechanical arts: *A medieval con-*

cept of ordered practices or skills. He showed examples of screw-type tools to test materials and probably also the ground, (Cambefort, 1955). Leonardo da Vinci (1452–1519) sketched a screw type implement which *may be advanced into the ground by means of turning the lever*. However, this screw was most likely never used during the lifetime of Leonardo da Vinci. Little evidence of the practical application of sounding tools can be found until the end of the 17th century.

A ram sounding device was invented in Germany by Nicolaus Goldmann (1611 – 1665) as described by Broms & Flodin (1988): *Hereto on the site at each place, a pointed rod can be driven, and one can notice the penetration depth for each blow, and in this manner one can find differences in the subsoil*, according to a translation from German by H. Zweck (1969). This is most likely the forerunner of the light German penetrometer, re-invented in the mid 1930s. Also in the 18th century, Germany dominated the development of new soil exploration tools. In Central Europe, with relatively favorable (hard) ground conditions, engineers worked mainly with auger tools. In France, different sounding devices were used to determine ground conditions. H. Gauthier (1660 – 1737) described the practical application of penetrometers for construction of bridges and fortifications. In northern European countries with many deep deposits of loose or soft soil, however, the simpler *rod penetration* concept was applied.

During the 19th century, several handbooks were published in Europe, mainly in Germany, which included chapters on soil, rock and foundation engineering (*Grundbau*). The continental philosophy of building on firm ground prevailed in many countries. Sounding rods (*Sondiereisen* or *Visitireisen*) were described for the first time in detail in *Handbuch der Tiefbohrkunde* by the German engineer Tecklenburg (1885/86). The sounding rod had a maximum length of approximately 4 m and was provided at the bottom with a point and an eye at the top for a wooden cross bar, intended for the withdrawal of the rod.

In England, different types of soil investigation tools were used. For the construction of the Westminster bridge, Charles Labelye, a naturalized Swiss engineer and architect, was employed. He used drill rods *to obtain information on the nature and consistency of the soil, determined by the resistance to the penetration of the boring rod*. Vibrations in the rod, and the noise it gave, was used to decide whether the bore was in mud, sand, clay, or gravel. Telford used sounding rods in connection with the construction of the Caledonian Canal in England in 1804.

In North America, wash borings was for a long time the most commonly used drilling method. A remarkable penetration testing campaign was carried out in Canada in 1872 in connection with the construction of the *Intercolonial Railway*. A major problem was the construction of bridges, several of them technically challenging, such as a railway bridge crossing the Miramichi River in New Brunswick. The chief engineer was Sir Stanford Fleming (inventor of the Standard Time Zones) who pioneered engineering techniques, including soil sampling and the prestressing of piers. Fleming suspected that earlier investigations at the bridge sites were incorrect. He proposed a new soil investigation method where a steel rod was pushed down into the soil and the required force was measured (Legget & Peck, 1973). The friction along the rod was eliminated by a 125 mm diameter steel casing. The rod used for the testing had a diameter of 75 mm and the end was blunt. The rod was loaded axially using weights. The time of loading was varied. This was probably the first application of a static penetrometer.

In Scandinavia, several handbooks, based mainly on the work by Tecklenburg, were widely used for military engineering projects. In the 1890s, almost everyone in charge of site investigations chose his own penetration testing method. In very soft soils, sounding rods were employed to investigate for instance areas where landslides had occurred. Rods were pushed into the ground, to depths of 10 to 12 m, often without reaching firm bottom. Svensson (1899), a Swedish railway engineer, was dissatisfied that the strength and the bearing capacity of soils could not be predicted quantitatively. He suggested that the penetration resistance should be measured more systematically and be expressed in terms of the number of men required to push down the rod. Grad 0 was used to indicate when the rod sunk by its own weight; Grade 1 when one man was required; Grad 2 when two man were required etc. Half-grades were also used. Ernst Wendel (1900), at the time head of the Harbour and River Works in Gothenburg, proposed to replace square sounding rods by a new type of *needle probe*, composed of several short pipe sections

which were connected using in-side couplings in order to achieve a smooth outside surface, shown on a drawing from 1914. Instead of expressing the soil resistance in terms of number of men, Wendel proposed to drive down the probe using a weight, which was dropped from a predetermined height, and to measure the penetration for each blow.

3 EMERGENCE OF MODERN PENETRATION TESTING

Although different types of penetration tests and sounding tools had been used during the past centuries, excavation and soil boring was the dominant method of soil investigation in Europe. However, at approximately the beginning of the 20th century, modern penetration testing methods started to develop in Central and Northern Europe where soft and loose soil deposits were encountered in connection with the development of the transportation infrastructures, such as railways, harbors, and roads.

3.1 *Dynamic Penetration Test*

Measuring the driving resistance of a steel rod, being rammed into the ground, has long been taken as an indication of the bearing capacity of the soil, and of piles. As mentioned above, Goldmann was probably the first to use the ram penetration method in Germany. The rod was driven down by a sledge hammer and the penetration for each blow was measured. However, the contribution by Goldmann was forgotten until the last half of the 19th century (Broms and Flodin 1988).

Records of the Swedish National Archives show that a *ram penetration test* was carried out in 1880 for a construction project in Stockholm. The main objective of the test was to determine the required length of piles to be driven into an esker. In 1910, penetration tests were again employed in the same area, using square (25 x 25 mm) steel rods, being driven by a 60 kg hammer which was probably made of wood. The stroke was 0.6 m. Penetration depth was recorded every 10 cm, and varied typically between 30 and 140 blows/10 cm. The simplicity of the equipment and of the testing method was probably the reason why the dynamic penetrometer became the most widely used testing method.

During the early 20th century in Germany, a light dynamic penetrometer was developed by Künzel (1936), known as *Künzel Prüfstab*. A hammer (5 kg, later increased to 10 kg) with a drop height of 50 cm was used to drive steel rods (16 to 20 mm) into the ground. The penetration for every 10 blows (originally, the number of blows to drive the penetrometer a certain depth, 10 cm) was recorded. The results were presented graphically, Fig. 1. Later, the penetrometer was provided with a conical point with a diameter of 35.6 mm. If needed, the friction along the rod could be reduced by a casing. The light penetrometer was standardized in Germany in 1964. This method is the forerunner of the modern light dynamic penetrometer and has become very popular in certain parts of Central Europe.

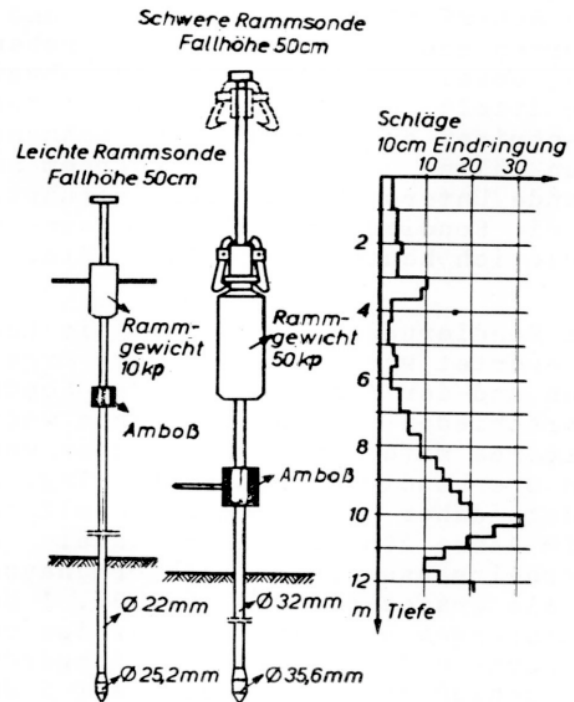
The first heavy dynamic penetrometer was developed in Sweden around 1935 by the company Borros and patented in 1942. A heavy dynamic penetrometer was also developed in the USSR in 1950 (Broms & Flodin (1988)). A hammer with a mass of 60 kg and a height of fall of 0.8 m was used to drive a steel rod, provided with a 74 mm diameter cone. The number of blows required to advance the penetrometer was counted. Heavy dynamic penetrometers were also developed and used in France, Germany and other countries.

3.2 *Swedish Weight Sounding*

At the end of the 19th century, an important development in geotechnical engineering took place when a commission consisting of geologists and engineers was appointed by the Swedish State Railways to investigate the cause of a number of embankment failures and landslides.



a) Light Dynamic Penetrometer

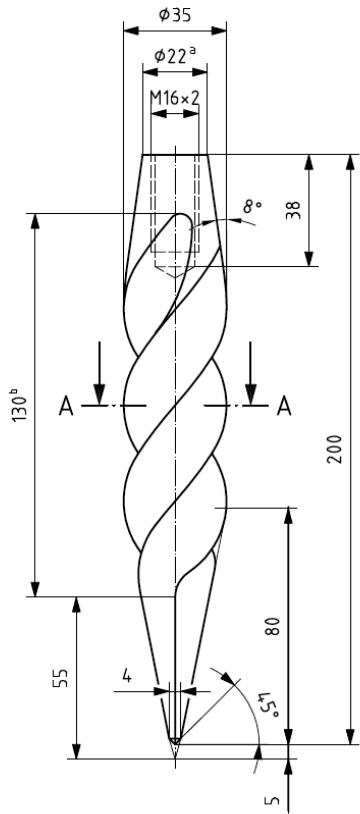


b) Examples of light and heavy dynamic penetrometer

Figure 1. Dynamic penetration testing in Germany around 1960, Zweck (1969)

The committee constituted itself as the *State Railways Geotechnical Commission* and worked between 1914 and 1922. In 1917, the Commission published its first report with the title *Soil investigations for Railways*, with John Olsson, secretary of the Commission, as its main author. Wolmar Fellenius was a member of the Commission from its start and chairman from 1919. In 1911, he signed a drawing which shows a penetrometer consisting of 1.0 m long solid steel rods, 19 mm in diameter with outside couplings and a 0.8 m long lower rod which was provided with a twisted screw point, 0.20 m in length, Fig. 2a. A drawing in the handbook by the secretary of the Commission, John Olsson (1915), describes the use of the weight sounding procedure: *The rod is first pressed down by the force of one man and the penetration depth recorded, then by two men and the depth recorded. After that the 90 kg weight is fastened to the handle (total mass about 100 kg), the rod is rotated and the penetration for each 25 turns (sic: half-turns) is recorded.* It is further pointed out that an experienced person can obtain additional information about the character of the soil from the noise and the penetration resistance. The final report by the Commission from 1922 - the first publication ever to use the word *geotechnical* - is regarded a milestone in modern geotechnical engineering, where the weight sounding method was described in detail. The single 90 kg weight of the penetrometer had been replaced by cast iron plates, with a total mass of 100 kg. The load was adjusted in order to keep the penetration speed constant, about 20 mm/s. The penetrometer was rotated when the rod stopped at the maximum applied load (100 kg). The penetration every 25 half-turns was then measured and recorded. The test was stopped at 100 half-turns when the penetration speed was approximately 10 to 20 mm. Refusal was checked by striking the penetrometer a few times with a sledge hammer. The type of soil layer penetrated by the point was determined from the noise generated by the twisted screw point. Figure 2b shows the performance of the weight sounding test in accordance with the instructions by the geotechnical commission. The engineer (the man to the right) touches the top of the sounding rod in order to detect rod vibrations when the sounding point penetrates

from soft clay to sandy layers, as this information was considered important for assessing drainage conditions.



a) Screw point of the weight sounding penetrometer b) Illustration of the weight sounding method (~1925)

Figure 2. Illustration of the weight sounding method around 1925

The Commission stated that the main purpose of weight sounding was to determine the strength and thickness of different soil layers. Also, embankments that had failed were investigated by the new, standardized method. Weight sounding was also used to determine the bearing capacity of piles in sand and gravel. The work of the Commission was of also of importance in the other Nordic countries with similar geotechnical conditions and foundation problems.

3.3 Standard Penetration Test

The Standard Penetration Test (SPT) can be traced back to around 1902, when Colonel Charles R. Gow in Boston began making exploratory borings using 1-inch diameter drive samplers. The sampler was driven by a 50 kg hammer into the bottom of the borehole, Fig. 3. Mohr (1940), one of Gow's engineers, then working at Raymond Concrete Pile Company, developed a slightly larger diameter split spoon drive sampler and recorded the number of blows per foot of penetration on an 18 inch deep sample, using a 140 lb. hammer dropped from 30 inches height. Karl Terzaghi and Arthur Casagrande supported adoption of the split-spoon sampling procedure through the auspices of ASCE's Committee on Sampling and Testing of the Soil Mechanics and Foundations Division of ASCE, formed in 1938 (Rogers 2006). The work of this committee was carried out at Harvard by Juul Hvorslev (1940) when writing *The Present Status of the Art of Obtaining Undisturbed Samples of Soils*. The SPT gradually replaced

the samples obtained from wash borings which were used almost exclusively at that time for the classification of soils.

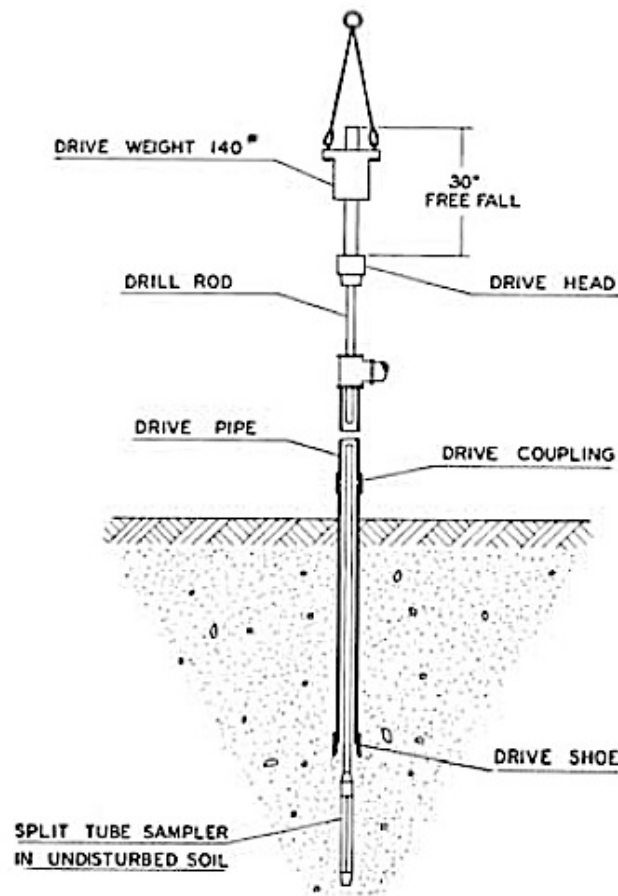


Figure 3. Original Gow Pipe sampler, introduced around 1902, utilizing 1-inch diameter drill rod and 1-inch diameter pipe with a beveled cutting tip, after Hvorslev (1949).

Terzaghi's concept of using *standard* blow counts to estimate soil properties was not utilized until 1947, when he, in collaboration with H. Mohr, developed correlations between allowable bearing stress and blow counts (*N*-numbers) for sands. Later that year Terzaghi christened the 2-inch Gow sampler the *Standard Penetration Test*, in a presentation titled *Recent trends in subsoil exploration*, which he delivered at the 7th Conference on Soil Mechanics and Foundation Engineering at the University of Texas. The first published SPT correlations appeared in the textbook *Soil Mechanics in Engineering Practice* (First Ed.), Terzaghi and Peck (1948). The original split spoon sampler was gradually improved and provided with a ball valve just above the sampling spoon to prevent loss of the sample during the retrieval. The Standard Penetration Test was used increasingly for the design of both deep and shallow foundations and spread rapidly after the publication of *Soil Mechanics in Engineering Practice*.

3.4 Cone Penetration Test

The concept to determine the strength of soils by pushing or dropping a cone into the soil was developed early. This method was used by John Olsson in 1915 to determine the undrained shear strength of very soft clay, (Massarsch & Fellenius, 2012). A pocket penetrometer was later developed by the Danish State Railroads in 1931, which is based on the principle of the fall cone test.

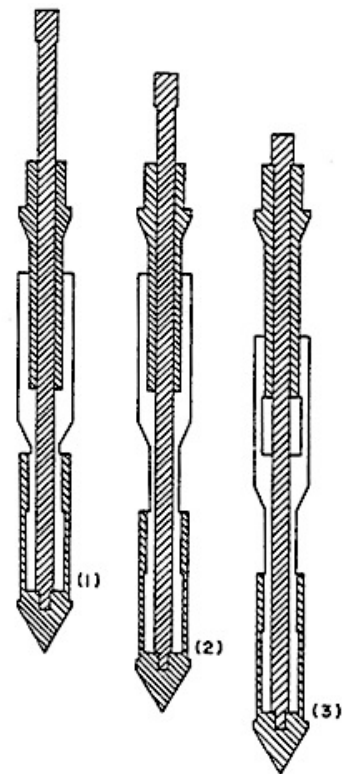
A predecessor of the mechanical cone penetrometer was the wash point penetrometer where a conical point with 70 mm diameter, attached to the lower end of a 50 mm diameter heavy wash pipe, is pushed

into the soil, Terzaghi & Peck (1948). A 75 mm diameter casing eliminated the skin friction resistance along the wash pipe. The force required to push the penetrometer 250 mm into the soil, using a hydraulic jack, was measured. Water jets were then turned on so that the casing could be driven down to the level of the cone. After the water had been turned off, the point was forced down an additional 250 mm and the corresponding force was measured. This penetrometer has not been used widely, probably because of the difficulty to operate the equipment.

The Dutch cone penetrometer was initially developed around 1930 by Pieter Barentsen, a civil engineer at the Department of Civil Works (*Rijkswaterstaat*) in the Netherlands (Barentsen, 1936). He invented a way to measure accurately the resistance of the soil reacting on the conical tip. He inserted an inner rod into the sounding tube and pushed with this inner rod manually on the interior part of the conical tip. The soil resistance was read out by means of a hydraulic measuring head provided with a pressure gauge, Fig. 4.



a) Mechanical cone testing around 1950



b) Begemann mechanical cone with friction sleeve

Figure 4. Early Dutch mechanical penetrometer, from History of Cone Penetration Testing - Gouda Geo-Equipment BV.

The purpose of penetration testing at the time was to determine the thickness and bearing capacity of approximately 4 m thick hydraulic fill near the town of Vlaardingen. The 10 cm² cone with a 60 degree apex angle was pushed down by two men and the penetration resistance was read on a manometer. A hand-operated cone penetrometer was first built by Goudsche Machinefabriek, Holland. Because the maximum force to push down the inner rod had to be delivered by the weight of the operator (approx. 80 kg), the maximum measurable cone resistance was often not sufficient to advance the penetrometer, which limited the application of the apparatus. In 1935, under the supervision of T.K. Huizinga, then director of Delft Laboratory of Soil Mechanics (LGM), the first deep cone penetration test with a pushing force of 10 tons was performed, as described by Platema (1948). The original cone penetrometer involved simple mechanical measurement of the total penetration resistance required to push a tool with a

conical tip into the soil. Different methods were employed to separate the total measured resistance into components generated by the conical tip (the *tip friction*) and friction generated by the rod string. In 1950, a jacket cone was developed by J. Vermeiden to avoid measuring errors that could occur when sand entered the cavity between the rods. However, this sleeve affected the measured penetration resistance, particularly in clay.

Static penetration testing equipment was also developed and used in other European countries. A cone penetrometer was developed at the Belgian Geotechnical Institute by DeBeer (1945). It was provided with a fixed cone and the total skin friction resistance was measured separately. The first mechanical cone penetrometer in the USSR was developed in 1953, with a maximum capacity of 100 kN (Broms & Flodin 1988).

In the early 1950s, another significant development was the *SGL cone penetrometer*, which was mounted on a vehicle. It was invented by Kjellmann and Kallstenius at the Swedish Geotechnical Institute. The penetrometer had a conical point with either 25 mm or 40 mm diameter. A special feature of this penetrometer was that the rod could be rotated as the point was pushed into the soil. From the torque measurement it was possible to separate the point resistance from the skin friction. This separation was done automatically by the machine.

A significant advancement of the static cone penetrometer by Begemann was to measure the skin friction resistance every 0.2 m with a separate friction sleeve located just above the cone (Begemann, 1965). He published graphs enabling the frictional load capacity for different sorts of piles to be deduced from the measured local friction resistance. Figure 4b shows the mechanical friction cone introduced by Begemann (1953).

The first experimental electric cone penetrometer dates back to the end of World War II in Germany, (Broms & Flodin, 1988); followed by prototypes developed by the Rotterdam civil servant Bakker and LGM, Delft, in 1949. Fugro was first to introduce the electric cone in 1965 for routine soil investigation.

In the mid 1970s, following research with pore pressure measurements in Norway, USA, and Sweden, standard electric penetrometers were equipped with sensors to measure the pore pressure during the penetration of the cone (Torstensson, 1975, Wissa et al., 1975). The *Piezocone* could measure in addition to the cone resistance and the sleeve friction also the pore pressure. The equipment was further developed by Fugro and other manufacturers. In Sweden, Torstensson (1975) was first to carry out a so-called *dissipation test*. From measured changes in pore pressure during a pause in the CPT test, it became possible to calculate the permeability of fine-grained soils.

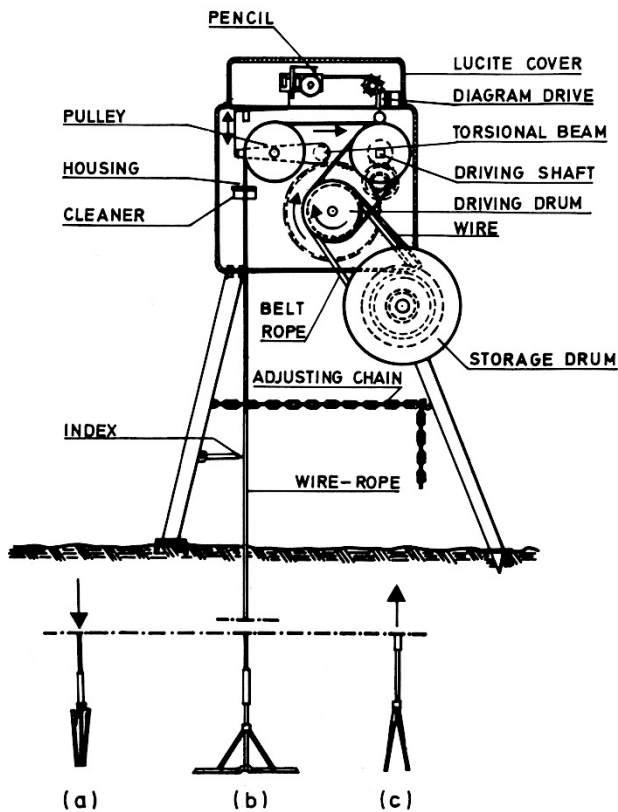
Inclinometers were incorporated in modern penetrometers to detect deviation of the penetration path from the vertical direction.

Campanella and Robertson (1984) integrated a small velocity seismometer into an electronic cone penetrometer. The cone penetration test is briefly stopped to conduct seismic down-hole tests at specific depths. Today, the seismic cone penetration test can be provided with one, or an array of seismic sensors. Performing seismic down-hole measurements during a penetration test is much quicker and less expensive than standard cross-hole tests or down-hole tests.

3.5 Full Flow Penetrometers

In 1940 Walter Kjellman and Torsten Kallstenius at the Swedish Geotechnical Institute, invented a pull-out device, the *Iskymeter* (Massarsch & Fellenius, 2012). The method is based on the umbrella principle as shown in Fig. 5. The Iskymeter concept - although relatively little used today - is an ingenious apparatus which consists of two wings, which can be retracted to form a penetrometer. The Iskymeter is pushed in the ground by a rod and the penetration resistance can be measured, providing approximate information on soil density. Once the maximum penetration depth has been reached, the Iskymeter probe is expanded and the pulling resistance is measured continuously, providing a measure of the undrained shear strength and soil stratification. The pushing rod is withdrawn and then the wire, which has very

low skin friction, is used to pull out the device. An advantage of the system is that pulling the Iskymeter does not require anchoring.



a) Principle of the Iskymeter



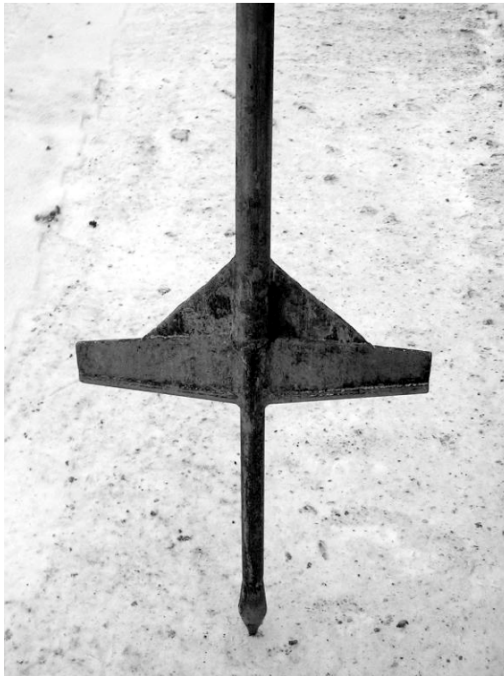
b) Iskymeter demonstrated at ESOPT I, 1974.

Figure 5. Pull-out penetration test – Iskymeter, developed at the Swedish Geotechnical Institute in early 1940s.

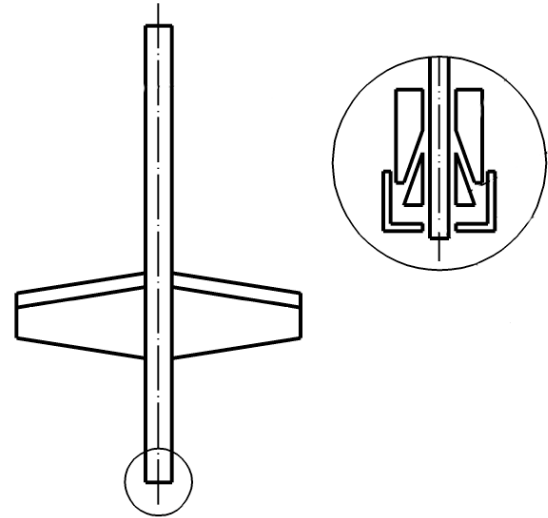
The Iskymeter can be seen as the forerunner of *full flow penetrometers* (Stewart and Randolph 1991). Two such devices, the *T-Bar* and the *Spherical Ball*, have been developed. The T-bar penetrometer was first introduced at the University of Western Australia. It consists of a short cylindrical bar measuring 250 mm in length and 40 mm in diameter. The ball cone is 163 mm in diameter. Both devices are attached at right angles to penetrometer rods, just below a calibrated load cell. The T-bar and the ball cone are pushed into the soil at the same rate as a conventional cone penetrometer, and the penetration resistance is measured using the cone-tip load cell. Full flow penetrometers attempt to combine the advantages of the cone penetration test and the in-situ vane shear tests. The in-situ vertical stress is equilibrated across the T-bar and thus there is essentially no correction for the ambient stress level to be included. Also included in the shaft of modern full flow penetrometers is an inclinometer to indicate any deviation from the vertical during insertion. The device can also incorporate pore water pressure transducers. Full flow penetrometers have gained acceptance in the offshore industry and their use for other applications has increased recently.

3.6 Column Penetration Testing

In Sweden, a common method for quality control of lime/cement columns, since the 1970's, is the Column Penetration Test (in Swedish called KPS). The test is carried out by pushing a probe with two wings through the center of the column with a speed of 20 mm/s, Fig. 6a.



a) Image of KPS probe



b) Sketch of pull-out column penetration probe

Figure 6. Column penetration test by penetrometer with two-bladed vanes.

The probe is pushed down the center of the column about one to two weeks after column construction. The width of the wings is less than the column diameter (normally 100 mm). The method can normally be used on columns with a maximum length of 8 m and with unconfined compressive strength < 300 kPa. In the case of longer columns the probe may deviate into the soil outside of the column. The penetration depth can be extended by pre-boring a vertical hole in the center of the column. By the use of preboring, the KPS can be used for columns with maximum unconfined compressive strength of 600 kPa to 700 kPa to a depth of 20 m to 25 m.

It is possible to carry out a reverse column penetration test, similar to the Iskymeter, where the uniformity of the column can be determined along its whole length, Fig. 6b. In this test, a probe, fitted with vanes equal to those used in the column penetration test, is attached to a wire placed below the bottom of the column while it is being constructed. The wire, having a strength of at least 150 kN, runs through the whole column up to the ground surface. The strength of the column is obtained by measuring the resistance obtained when drawing the probe up to the ground surface. The idea is to obtain a mean value of the shear strength for the larger part of the cross section. KPS is a frequently used method in Sweden and other Nordic countries for lime-cement columns, constructed by dry deep mixing.

3.7 Environmental and Multiple Penetrometers

Extensive research during the past decade, especially in the area of geo-environmental engineering, has led to the development of new, sophisticated penetrometers. Different types of sensors can be incorpo-

rated in the probe, for example laser-type and fiber-optical sensors, high-resolution ground-penetrating radar antennas and integrated opto-electronic chemical sensors. It is interesting to note that the cone penetrometer has evolved from a relatively simple, standardized geotechnical investigation tool into a multi-purpose testing instrument. The cone penetrometer has the potential of becoming a multi-purpose instrument, which offers new areas of application for geo-environmental investigations, Table 1.

Table 1. Sensors incorporated in CPT

Type	Description of Method
Dielectric constant	Dielectric constant is very sensitive to contamination, used in combination with CPT
Laser induced fluorescence (LIF)	Fluorescence emission can detect hydrocarbons, sensor mounted behind the tip of CPT
Magnetometer	CPT with a tri-axial magnetometer, used to attempt to ensure that tests, boreholes, and piles, do not encounter unexploded ordnance (UXB). The magnetometer in the cone detects ferrous materials of 50 kg or larger within a radius of up to about 2 m distance from the probe depending on the material, orientation and soil conditions.
Redox Potential	Measures organic exchange capacity Used in combination with CPT for identification of acids and inorganic substances
Optical	Vision Image of penetrated material, from borehole or mounted in CPT tip

4 EUROPEAN SYMPOSIUM ON PENETRATION TESTING, ESOPT

The (first) European Symposium on Penetration Testing, ESOPT I, was held at the Royal Institute of Technology (KTH) in Stockholm, Sweden from June 5-7, 1974. The symposium was organized by the Swedish Geotechnical Society (SGF). Conference chairman was Prof. Bengt B. Broms, then director of the Swedish Geotechnical Institute and professor at KTH. All European national geotechnical societies were invited to take part in the symposium, as well as a few societies from outside of Europe, with special interests in penetration testing. The response to the invitation was overwhelming and it was necessary to restrict the number of participants (originally estimated to be 80), primarily because of the limited facilities. The number of participants exceeded 200. A total number of 136 papers from 28 countries were submitted to the symposium.

The Organizing Committee believed that it would be valuable to have - as background material primarily for the group discussions - a description of the different penetrometers and the test procedures utilized in various countries, of the methods used in the interpretation of the test results and the need of standardization of different testing methods. National reports were prepared by 19 European countries and 8 countries from outside Europe. All national reports followed the same outline: - geological background, - description of penetrometers used in each country, - test procedures, - interpretation and evaluation of test results, and - needs of future developments including standardization. In this way, it was possible to obtain a comprehensive picture of the status of penetration testing at that time. State-of-the-art reports were presented at the symposium by four general reporters, representing Scandinavia, Central and Western Europe, Eastern Europe, and countries outside of Europe. The division into four groups was made primarily because equipment and testing procedures used in the interpretation of the test results differed between the various regions. The group discussions were considered an important part of the symposium. The following topics were chosen and divided into five discussion groups: 1) Planning of site investigations 2) Standardization of penetrometers and future cooperation in Europe 3) Future de-

velopments 4) Interpretation of static penetration tests 5) Interpretation of dynamic penetration tests. The results from the group discussions were presented on the last day of the symposium in connection with the panel discussion. An important objective of ESOPT I was to promote the needs in standardization of different penetration testing methods. Therefore, participating countries were invited to present their national standards or guidelines on penetration testing and/or to comment on existing standards used elsewhere. Contributions from 21 countries were received. General Reports, summaries of the group discussions and a listing of national standards were documented in Vol. 2:1. Accepted papers were published after the conference in Vol. 2:2. The ESOPT I proceedings are available from the CPT'14 conference website, thanks to the generosity of the Swedish Geotechnical Society (SGF). A field demonstration of penetrometers used in different parts of the world was arranged on the second day of the symposium, Fig. 7. Manufacturers of penetrometers, consulting and soil boring firms were invited to take part. An area with variable soil conditions close to the conference venue had been selected for the field demonstration. Investigations by the Swedish weight and ram sounding methods and standard penetration tests were carried out within the area in advance, as well as soil sampling. An exhibition on penetration testing was arranged just outside the conference hall. Research organizations, soil consultants and contractors had an opportunity to present new designs, examples of application of penetration testing and test results from soil investigations.



Site of field demonstration



Penetration testing in action



Bengt B. Broms (right)



E. DeBeer (left)



K. Senneseth and N. Janbu



E. deBeer, M. Fukuoka and A. Vesic

Figure 7. Field demonstration and participants at ESOPT I in Stockholm. (Photos K. Rainer Massarsch).

In hindsight, ESOPT I was a milestone in the development of penetration testing, and in particular that of cone penetration testing. For the first time, a comprehensive document became available which illustrated the practical application of different types of penetration tests. The information provided in the ESOPT proceedings formed the basis for harmonization of interpretation methods and future standardization.

5 EVOLUTION OF MODERN CONE PENETRATION TESTING

5.1 *The Role of ISSMFE/ISSMGE*

The International Society for Soil Mechanics and Foundation Engineering (ISSMFE), through its technical committees, has played an important role in promoting and developing the application of cone penetration testing. At the 4th International Conference on Soil Mechanics and Foundation Engineering in London in 1957 an ISSMGE Subcommittee on penetration testing was created for the purpose of studying static and dynamic penetration tests with a view to their standardization. At that time, it was not possible to reach an agreement within the committee on suitable standards for the different tests, particularly the standard penetration test (SPT). In Paris in 1961, Prof. M. Vargas, Brazil, then the chairman of the Subcommittee on penetration testing, reported that the SPT, as it was used at that time, was far from being a standard method and that the procedure to carry out the test varied between different countries. However, the Subcommittee felt that there was a real need for standardization of penetration testing methods and equipment, but could not agree on any recommendations.

The work of the Subcommittee was summarized in three reports. It was suggested that efforts should continue on a regional basis. Subsequently, a European Subcommittee on Penetration Testing was appointed at the 6th International Conference in Montreal in 1965 with Dr. H. Zweck of Germany, as chairman with the task to investigate the possibility of standardizing penetration testing methods commonly used in Europe.

In order to initiate and to stimulate the work on standardization and because of the rapid development of penetration testing during the past years, Prof. B. B. Broms, then chairman of the national Swedish Committee on Penetration Testing, offered to arrange a European symposium on penetration testing in Stockholm. The proposal was discussed with Professor de Beer, Belgium, at that time ISSMFE Vice President for Europe, during a visit to Stockholm in 1972. The proposed plan was approved with minor modifications and the (first) European Symposium on Penetration Testing (ESOPT-I) was held in

Stockholm in 1974. The stated aims of ESOPT I were: to document the use of penetration tests in soil investigations in different countries, to outline areas where further research is desirable, to stimulate the standardization of commonly used penetration testing methods, and to provide guidelines for future developments.

5.2 Emergence of Cone Penetration Testing from 1974

Since the first European Symposium on Penetration Testing, ESOPT I in 1974, major changes have taken place in civil and geotechnical engineering. Advanced numerical tools, such as Finite Element Analyses and other numerical methods have found increasing use in research but also for the solution of engineering problems. The reliability of numerical analyses depends to a large degree on the quality of chosen input parameters. Cone penetration testing (CPT) is one of several geotechnical investigation methods, which can provide information about strength and deformation parameters of soils, especially in soils which cannot be sampled or are difficult to sample. In the early 1970s cone penetrometers were rarely used in engineering practice in North America. During the early 1980s and thereafter, their use grew rapidly and spread to many new areas of application. New areas of CPT application emerged for the assessment of earthquake engineering problems (liquefaction susceptibility) and especially in off-shore engineering.

It is interesting to note that the first application of penetrometers in space engineering was reported to ESOPT I by Mitchell & Houston (1974).

On an international scale, penetration testing and in particular the CPT started to play a central role in the planning, execution, and supervision of very large land reclamation projects, required for the construction of new airports, harbors, or industrial and residential facilities.

During the past decade, cone penetrometers, provided with new types of sensors, have become increasingly important in environmental engineering. This development has only started and further progress can be expected in the years to come. Table 2 lists a range of areas where cone penetration testing is used today.

Table 2. Application of cone penetration testing in different technical disciplines (in alphabetical order).

• Archaeological investigations
• Earthquake engineering
• Environmental engineering
• Forensic studies
• Foundation engineering
• Land reclamation and ground improvement
• Military operations and transportation
• Mining and exploration
• Offshore and marine engineering
• Soil conservation and water regulation
• Space engineering
• Tunneling

5.3 ISSMGE Technical Committees

Until 2006, ISSMGE sponsored two technical committees, focusing on geotechnical and geophysical site characterization: TC 102, *Ground Property Characterization from In-Situ Test - formerly TC 16 In-Situ Testing* and TC 10, *Geophysical Site Characterization*. In 2006, ISSMGE transferred seismic and geophysical methods to TC 102/TC 16, with the task to cover all aspects of geotechnical and geophysical site characterization (GSC). The present chairman of TC 102 (up to September, 2013) is Prof. Paul Mayne, USA and Vice Chairman is Prof. Antonio Viana da Fonseca, Portugal. TC Secretary is Roberto Quental Coutinho, Brazil.

The objectives of TC 102 are to provide the geotechnical engineer (designer, contractor, owner or authority) - based on the results of field investigations - with sufficiently detailed information in order to plan, design, construct and operate structures on or below the ground. Site characterization has become one of the most important and rapidly developing areas of geotechnical engineering. One of the most important accomplishments of the ISSMGE Technical Committees is the organization and successful implementation of symposia, workshops, and conferences. TC 102 also operates a website where up-to-date information is made available to the professions.

5.4 The James K. Mitchell Lecture Series

A special series of keynote lectures were established by TC 102/TC 16 circa 2002 in the name of Professor James K. Mitchell (Univ. of California Berkeley and Virginia Tech) who was an early leader in the research areas of in-situ testing and site characterization, as well as other geotechnical topics involving ground modification, geo-environmental concerns, micromechanics, geochemistry, and soil behavior. TC 102 chooses a special lecturer every 2 years and the keynote address is presented at a major conference or symposium. The technical paper is published along with the proceedings. Including CPT'14, there have been six JKM Lectures, as summarized in Table 3.

Table 3. List of James K. Mitchell Keynote Lecturers 2004 – 2014.

Year	Lecturer	Conference Presentation
2004	Hai-Sui Yu, Univ. of Nottingham, UK	ISC-2 (2004), Porto, Portugal
2006	Paul W. Mayne, Georgia Inst. Technology, USA	GeoShanghai (2006), China
2008	Dick Campanella, Univ. British Columbia, Canada	ISC-3 (2008), Taipei, Taiwan
2010	Tom Lunne, Norwegian Geotech. Inst., Norway	CPT'10, Huntington Beach, USA
2012	Peter K. Robertson, Gregg Drilling, USA	ISC-4 (2012), Pernambuco, Brazil
2014	Michele Jamiolkowski, Professor Emeritus, Technical University of Torino, Italy	CPT'14, Las Vegas, USA

6 STANDARDIZATION OF PENETRATION TESTING METHODS

International, regional and national standards and reference procedures have been developed with respect to penetration testing in general, and cone penetration testing in particular. This section summarizes the most widely used standards, prepared by International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), American standards institute (ASTM International) and the International Organization for Standardization (ISO) in cooperation with the European Committee for Standardization (CEN).

6.1 ISSMFE/ISSMGE Reference Procedures on Penetration Testing

Following the discussions and reports at the European Symposium on Penetration Testing in Stockholm in 1974, the European Subcommittee on Penetration Testing submitted its final report at the 9th ICSMFE in Tokyo in 1977. The report also included reference procedures for the following penetration testing methods: Cone Penetration Testing (CPT), Standard Penetration Test (SPT), Dynamic Probing (DP) and Weight Sounding (WST). The proposal was approved by the ISSMFE Council with the recommendation that these recommendations should also be used outside Europe.

At the 10th ICSMFE in Stockholm in 1981, the Committee repeated its recommendation that *Papers to international conferences or journals should include results from at least one recommended standard penetration testing method*. The Subcommittee also recommended *Comparison between the different recommended standard penetration methods should be made in different soils to facilitate the evaluation of soil characteristics from different penetration testes*.

Work on developing reference procedures for penetration testing continued within Technical Committee, TC 16 and the results were presented in *Report of the ISSMFE Technical Committee on Penetration Testing of Soils - TC 16*, with International Reference Test Procedures (IRTP) for: CPT - SPT - DP - WST. The following reference test procedures were published in the Proceedings of the International Symposium on Penetration Testing – ISOPT 1, held in 1988:

Cone penetration test (CPT): International reference test procedure. De Beer, E.E., Goelen, E., Heynen, W.J. & Joustra, K. International symposium on penetration testing, 1, ISOPT-1, Orlando, March 1988. Proceedings, Vol. 1, 1988, pp. 27-51.

Standard penetration test (SPT): International reference test procedure. Decourt, L, Muromachi, T, Nixon, I.K., Schmertmann, J.H., Thorburn, S., & Zolkov, E. International symposium on penetration testing, 1, ISOPT-1, Orlando, March 1988. Proceedings, Vol. 1, 1988, pp. 3-26.

Dynamic probing (DP): International reference test procedure. Stefanoff, G, Sanglerat, G., Bergdahl, U., & Melzer, K.J. International symposium on penetration testing, 1, ISOPT-1, Orlando, March 1988. Proceedings, Vol. 1, 1988, pp. 53-70.

Weight sounding test, (WST): International reference test procedure Bergdahl, U, Broms, BB, Muromachi, International symposium on penetration testing, 1, ISOPT-1, Orlando, March 1988. Proceedings, Vol. 1, 1988, pp. 71-90.

The IRTP for the CPT was updated to include CPTU by TC16 in 1999 and published in the Proceedings of 12th European Conf. on Soil Mechanics and Geotechnical Engineering, Amsterdam. TC 16 also produced reports on the Pressuremeter in 1998 (ISC'98) and the DMT in 2001 (exist in, 2001).

As a supplement to the Reference test procedure for cone penetration testing, ISSMGE Technical Committee 10, *Geophysical Testing in Geotechnical Engineering* prepared Guidelines for execution of the seismic cone downhole test to measure shear wave velocity (SCPT). The document was presented at the 16th ICSMGE in Osaka in 2005, Butcher et al. (2005) but never officially published. Therefore, this document has been included in the proceedings of CPT'14. It provides guidance to practitioners and procurers on downhole seismic wave measurement using a seismic cone penetrometer. This guideline is a supplement to the International Reference Test Procedure (IRTP) for the electric Cone Penetration Test (CPT) and the Cone Penetration Test with Pore pressure (CPTU). The guideline therefore follows and should be used with the CPT IRTP.

6.2 Standards in United States of America

In the United States, the American Society for Testing and Materials (ASTM) has prepared standards for different types of penetration tests. The following standards apply to cone penetration testing:

ASTM, 2004, *Standard Method of Deep Quasi-Static Cone and Friction-Cone Penetration Tests of Soil*; ASTM Standard D 3441, ASTM International, West Conshohocken, PA, 7 pp., and

ASTM, 2012, *Standard Test Method for Performing Electronic Friction Cone and Piezocone Penetration Testing of Soils*. ASTM D-5778, ASTM International, West Conshohocken, PA.

6.3 ISO and CEN Standards (Eurocodes)

The International Organization for Standardization (ISO) has prepared standards in cooperation with the European Committee for Standardization (CEN). CEN members are bound to comply with the CEN/CENELEC Internal Regulations, which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. European Standard are published in three official versions (English, French and German). The following countries are CEN members: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, the Former Yugoslav Republic of Macedonia, Turkey and United Kingdom.

The first Eurocode 7 Working Group, in charge of drafting a European standard on geotechnical design, was created in 1981. It was composed of representatives of the National Societies for Geotechnical Engineering of the 10 countries forming the European Community at that time. A model code for Eurocode 7 was submitted to the European Commission in 1987 – it was not actually published. This had just one part. The next stage was the ENV, or trial, stage published by CEN, and it had 3 parts. The ENV version of Part 1 was published by CEN in 1994 and the ENV versions of Parts 2 and 3 were published by CEN in 1999. Details are given by Orr (2008), *The Story of Eurocode 7 in Spirit of Krebs Ovesen Session – Challenges in geotechnical engineering*. During the conversion phase, the two documents were merged into the single document called Eurocode 7 Geotechnical design - Part 2: Ground investigation and testing. The formal positive vote was obtained in May 2006 and the document was published in March 2007.

Eurocode 7, Part 2: deals with laboratory and field testing. It gives the essential requirements for the equipment and test procedures, for the reporting and the presentation of results, for their interpretation and, finally, for the derivation of values of geotechnical parameters for the design. It complements the requirements of Part 1 in order to ensure a safe and economic geotechnical design. Eurocode 7 – Part 2 includes the following Sections:

Section 1 – General

Section 2 – Planning of ground investigations

Section 3 – Soil and rock sampling and groundwater measurements

Section 4 – Field tests in soils and rocks

Section 5 – Laboratory tests on soils and rocks

Section 6 – Ground investigation report

Eurocode, Part 2 includes the following field testing procedures: cone penetration tests, CPT(U); pressuremeter tests, PMT; rock dilatometer tests, RDT; standard penetration tests, SPT; dynamic penetration tests, DPT; weight sounding tests, WST; field vane tests, FVT; flat dilatometer tests, DMT and plate loading tests, PLT.

The following CEN/ISO standards are relevant for cone penetration testing:

EN ISO 22476-12:2009. *Geotechnical investigation and testing - Field testing - Part 12: Mechanical cone penetration test* and

EN ISO 22476-1:2012. *Geotechnical investigation and testing - Field testing - Part 1: Electrical cone and piezocone penetration test*.

The standard on CPT deals with equipment requirements, the execution of and reporting on electrical cone and piezocone penetration tests as part of geotechnical investigation and testing according to EN

1997-1 and EN 1997-2. Within the electrical cone and piezocone penetration test, two subcategories of the cone penetration test are considered: electrical cone penetration test (CPT), which includes measurement of cone resistance and sleeve friction and piezocone test (CPTU), which is a cone penetration test with the additional measurement of pore pressure. The CPTU is performed like a CPT with the measurement of the pore pressure at one or several locations on the penetrometer surface.

EN ISO 22476-1:2012 specifies the following features: - type of cone penetration test; - application class; - penetration length or penetration depth; - elevation of the ground surface or the underwater ground surface at the location of the cone penetration tests with reference to a datum; - location of the cone penetration test relative to a reproducible fixed location reference point; - pore pressure dissipation tests.

7 CONFERENCES ON PENETRATION TESTING

A large number of conferences, symposia, meetings and workshops have been held since ESOPT I, in addition to larger ISSMGE international and regional conferences. Table 4 lists conferences and symposia, held since 1974, where cone penetration testing was the main focus. These meetings addressed different aspects of cone penetration testing, but had often a broader scope than cone penetration testing. In the Reference section of this paper, a comprehensive listing of conferences and symposia, covering different aspects of penetration testing and site characterization, is given.

In the following section, papers submitted to five international symposia/conferences on penetration testing since 1974 have been compiled in a database and evaluated with the objective of discerning trends and developments during the past 40 years:

- European symposium on penetration testing, ESOPT I - 1974
- European symposium on penetration testing, ESOPT II - 1982
- International symposium on penetration testing, ISOPT 1 - 1988
- Symposium on Cone Penetration Testing, CPT'95 - 1995
- 2nd International Symposium on Cone Penetration Testing, CPT'10 – 2010.

Table 4. International Conferences and Symposia addressing penetration testing held since 1974. For details, see the Reference section of this paper.

Title	Location	Year	Reference
European symposium on penetration testing, ESOPT I	Stockholm, Sweden	1974	June 5-7 1974. Swedish Geotechnical Society.
Cone penetration testing and experience	St. Louis, Missouri, USA	1981	October 26-30, 1981, ASCE national convention.
European symposium on penetration testing, ESOPT II	Amsterdam, Netherlands	1982	24-27 May 1982, Dutch Geotechnical Society.
International symposium on penetration testing, ISOPT-1	Orlando, Florida, USA	1988	20-24 March 1988.
Seminar on cone and pressuremeter testing	Sydney, Australia	1989	June 2, 1989 University of Sydney.
Pressuremeter, cone penetrometer, and dilatometer for foundation design	College Station, Texas, USA	1992	August 17-18, Texas A&M University.
Symposium on Cone Penetration Test-	Linköping, Sweden	1995	October 4-5, 1995, Sweden, Swedish Ge-

ing, CPT'95			otechnical Society.
International Conference on Site Characterization, ISC-1	Atlanta, USA	1998	April 19-21, 1998, ISSMGE TC 16.
2 nd International Conference on Site Characterization, ISC-2	Porto, Portugal	2004	September 19-22, 2004, ISSMGE TC 16 and TC 10, Portugal.
4 th International Symposium on Deformation Characteristics of Geomaterials IS-Atlanta 2008	Atlanta, USA	2008	September 22-24, 2008, Georgia Institute of Technology, USA.
3 rd International Conference On Site Characterization, ISC-3	Taipei, Taiwan	2008	Taiwan 1-4 April, 2008.
2 nd International Symposium on Cone Penetration Testing, CPT'10	Huntington, California, USA	2010	May 9 – 11, 2010, California.
4 th International Site Characterization, ISC-4	Pernambuco, Brazil	2012	September 18-21, 2012, Brazil.
3rd International Symposium on Cone Penetration Testing, CPT'14	Las Vegas, USA	2014	May 12-14, 2014, Nevada, USA.

All written contributions to these events have been classified as shown in Tables 5, 6 and 7, respectively.

Table 5. Categories of Site Investigation Methods

1. CPT	Cone Penetration Testing, including piezocone and seismic cone
2. DPT	Dynamic penetration test
3. SPT	Standard Penetration Test
4. WST	Swedish Weight Sounding
5. PT General	Other types of penetration tests, percussion, rotary etc.
6. SI General	Site investigation methods general, including pressuremeter and dilatometer
7. Other	Other in-situ methods (percussive, rotary methods)

All papers published were characterized according to their main topics according to the following groups, shown in Table 6.

Table 6. Topics of Papers

Comparison	Comparison between different penetration testing methods
Equipment	Development and use of penetration testing equipment
Execution	Execution of penetration tests
Future	Future development in penetration testing
General	General topics of penetration testing and in-situ testing
Reports	Regional or national reports, state-of-art reports and summary of discussions etc.
Standardization	Standardization of penetration testing

In order to evaluate trends with respect to the application of penetration testing, and cone penetration testing in particular, all published papers were classified according to the following types of applications, shown in Table 7.

Table 7. Geotechnical Application of Penetration Testing Methods

Classification	Soil classification
Clay	Strength and deformation properties of fine-grained soils
Environmental	Solution of environmental problems
Hard soil	Penetration testing in hard soil and soft rock
Interpretation	Interpretation of results from penetration testing
Laboratory	Laboratory investigations and correlation with model tests
Piles	Assessment of liquefaction problems, seismic response etc.
Pore pressure	Pore pressure during penetration testing
Properties	Soil properties - general
Sand	Strength and deformation properties of sand
Seismic	Seismic testing and liquefaction problems

7.1 *First European Symposium on Penetration Testing, ESOPT*

In the proceedings of ESOPT I, 136 papers from 28 countries were published, as shown in Figure 8. For clarification reference is made to Tables 5, 6 and 7. It is interesting to note the relatively even distribution of submissions, with the largest number of papers from France, Sweden and the USA. Figure 9 shows the distribution of papers addressing different penetration testing methods. The dominating topics were cone penetration testing and the comparison of different types of penetration tests (PT). The category *Other* included the pressuremeter tests.

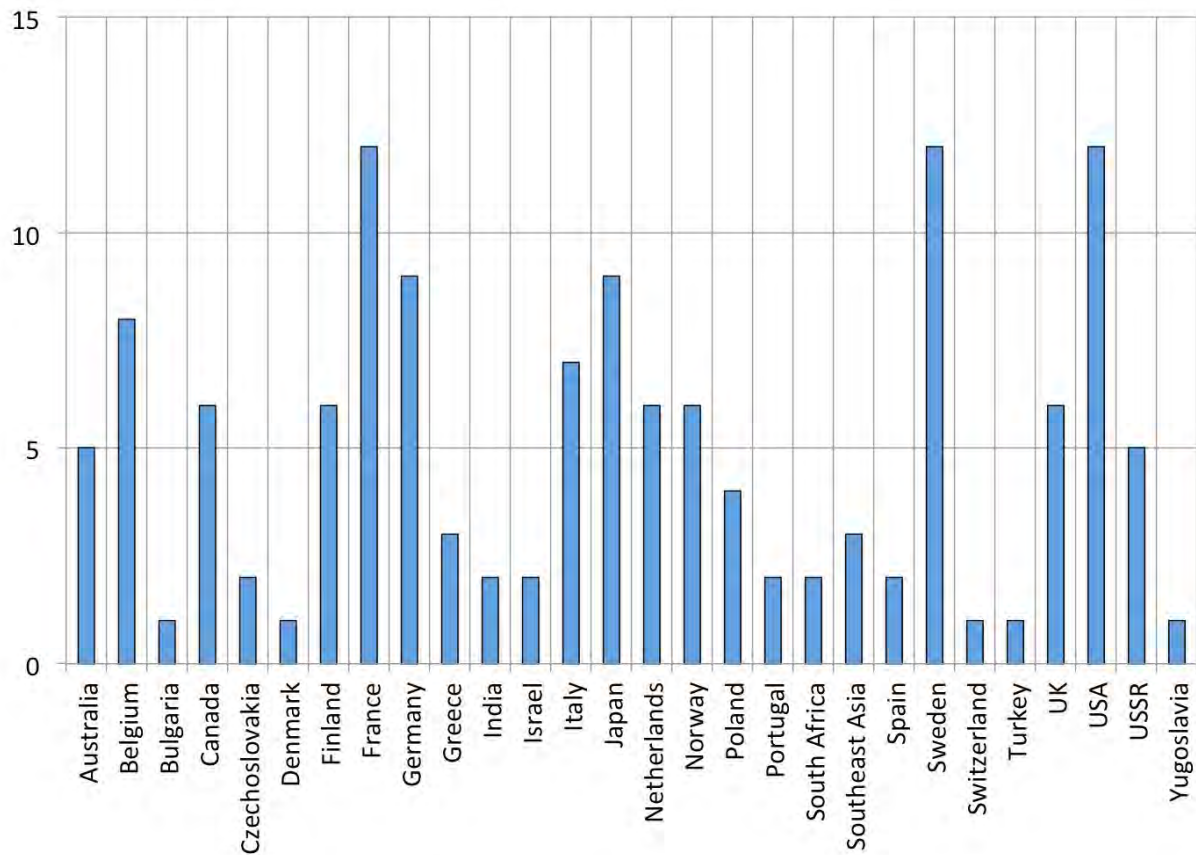


Figure 8. Countries and number of papers published in the proceedings of ESOPT I, Stockholm, 1974. Total number of published papers: 136.

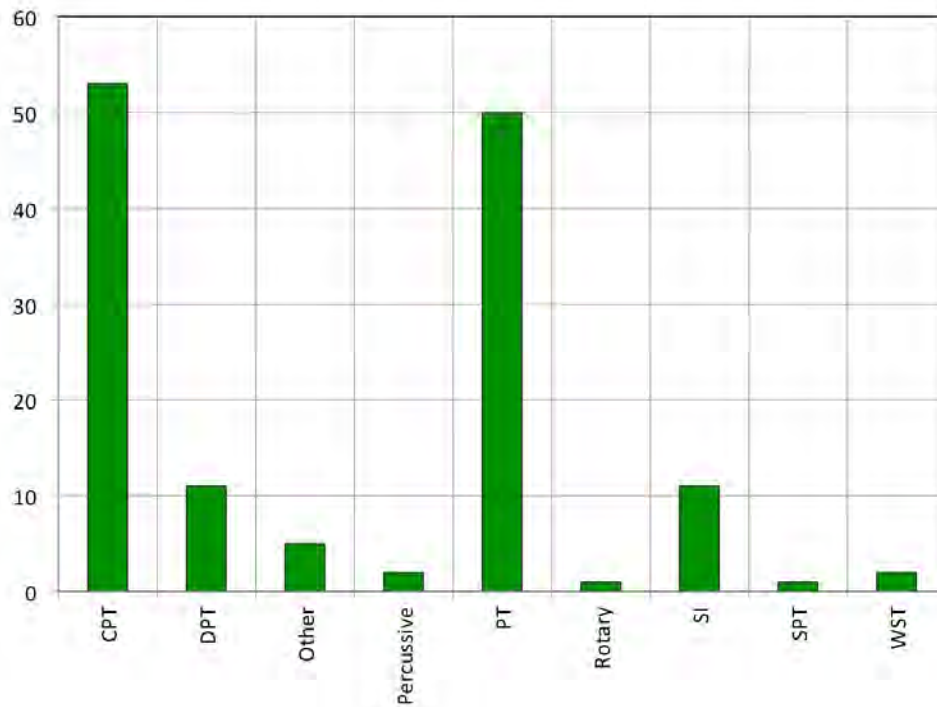


Figure 9. Number of papers discussing different penetration testing methods, ESOPT I, Stockholm.

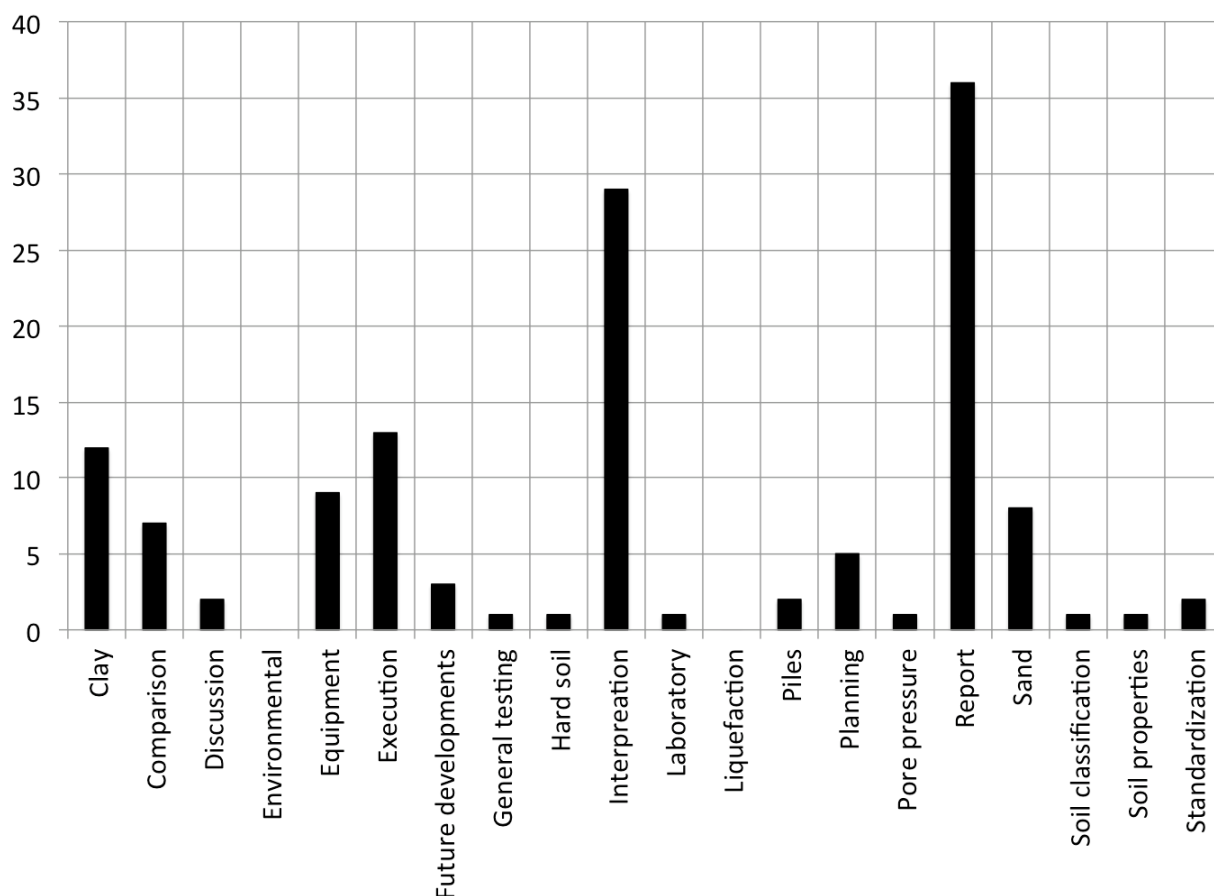


Figure 10. Number of papers addressing different applications of penetration testing, ESOPT I, Stockholm.

Figure 10 shows the topics covered by the papers. As the objective of ESOPT I was to compile national and state-of-practice reports, this category dominates. The second largest number of papers addressed the interpretation of results from penetration testing. The third largest number of papers referred to the execution of penetration testing.

7.2 European Symposium on Penetration Testing, ESOPT II

The total number of papers submitted to ESOPT II was 128, coming from 29 countries, cf. Fig. 11. As the symposium was held in the Netherlands, contributions from this country dominate. The second largest number of contributions came from the UK (a significant increase from ESOPT), followed by the USA and France, respectively.

The types of penetration testing methods covered by the papers in the proceedings are shown in Figure 12. Again, it is not surprising that the number of papers on cone penetration testing dominate. Similarly to ESOPT I, this symposium covered all types of penetration tests. The second largest number of papers addressed the comparison of different types of penetration tests (PT). Papers on pressuremeter tests are included in the group (*Other*).

The subject Determination of soil properties dominated the application of penetration testing, followed by a comparison of between different types of penetration tests, and the use for pile foundations. Again, determination of strength properties of clay by penetration tests was a popular subject.

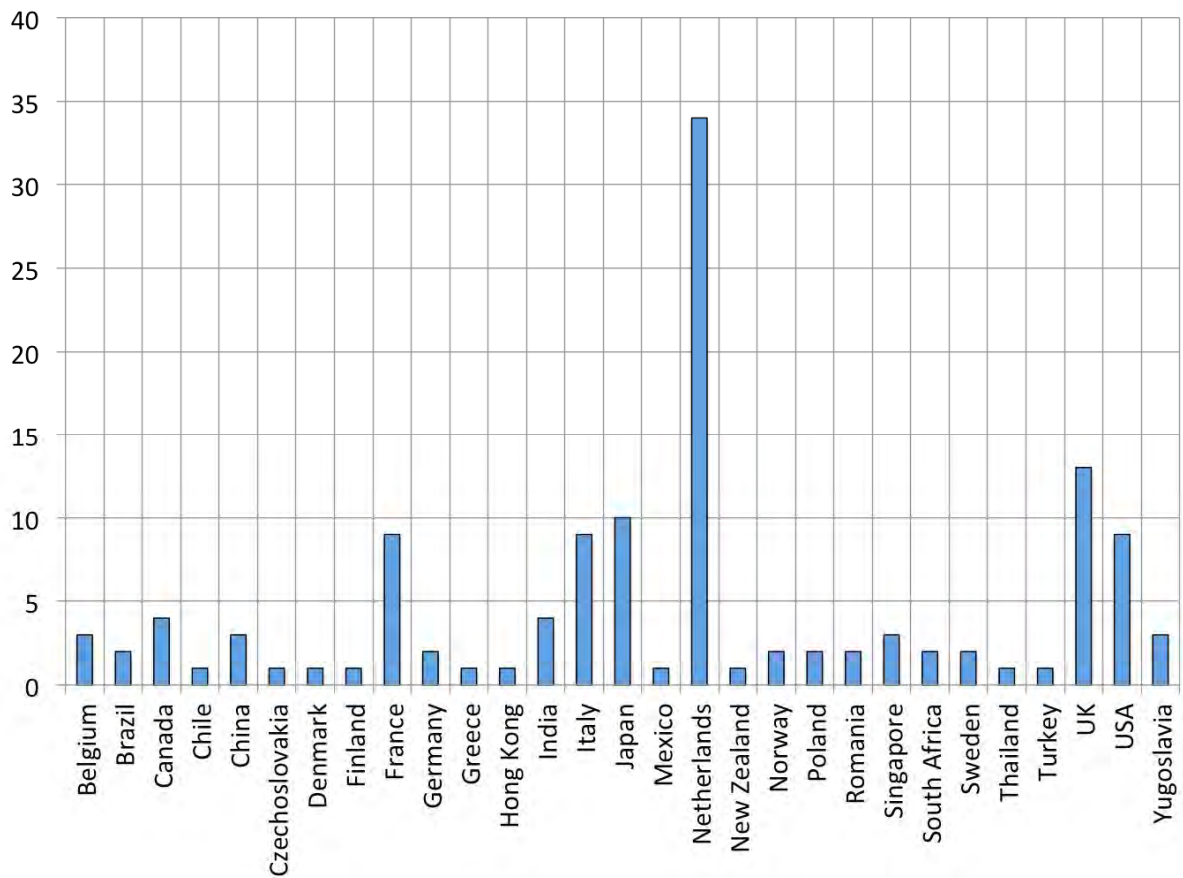


Figure 11. Countries and number of papers published in the proceedings of ESOPT II. Total number of published papers: 128.

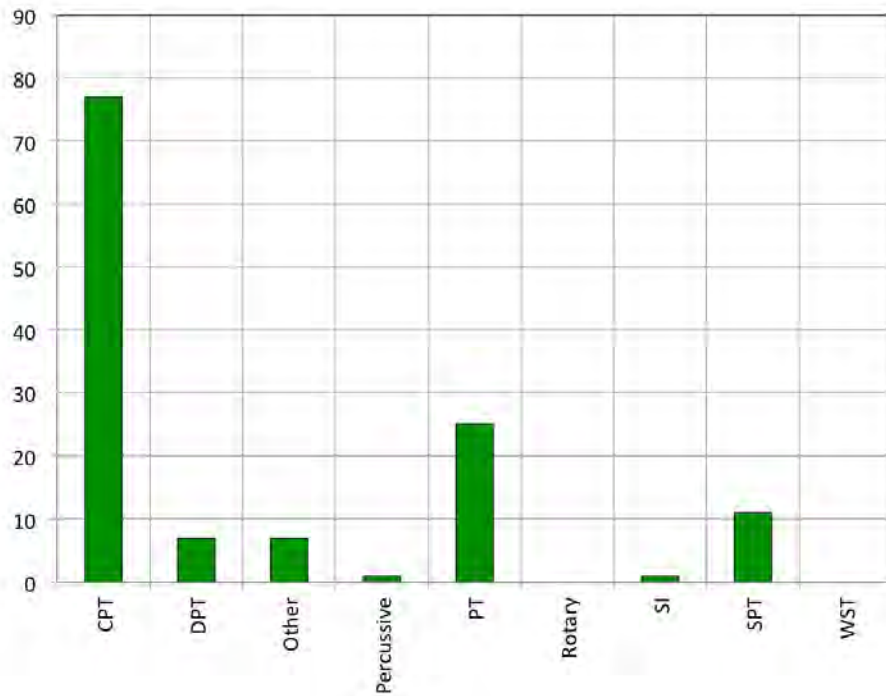


Figure 12. Number of papers discussing different penetration testing methods, ESOPT II.

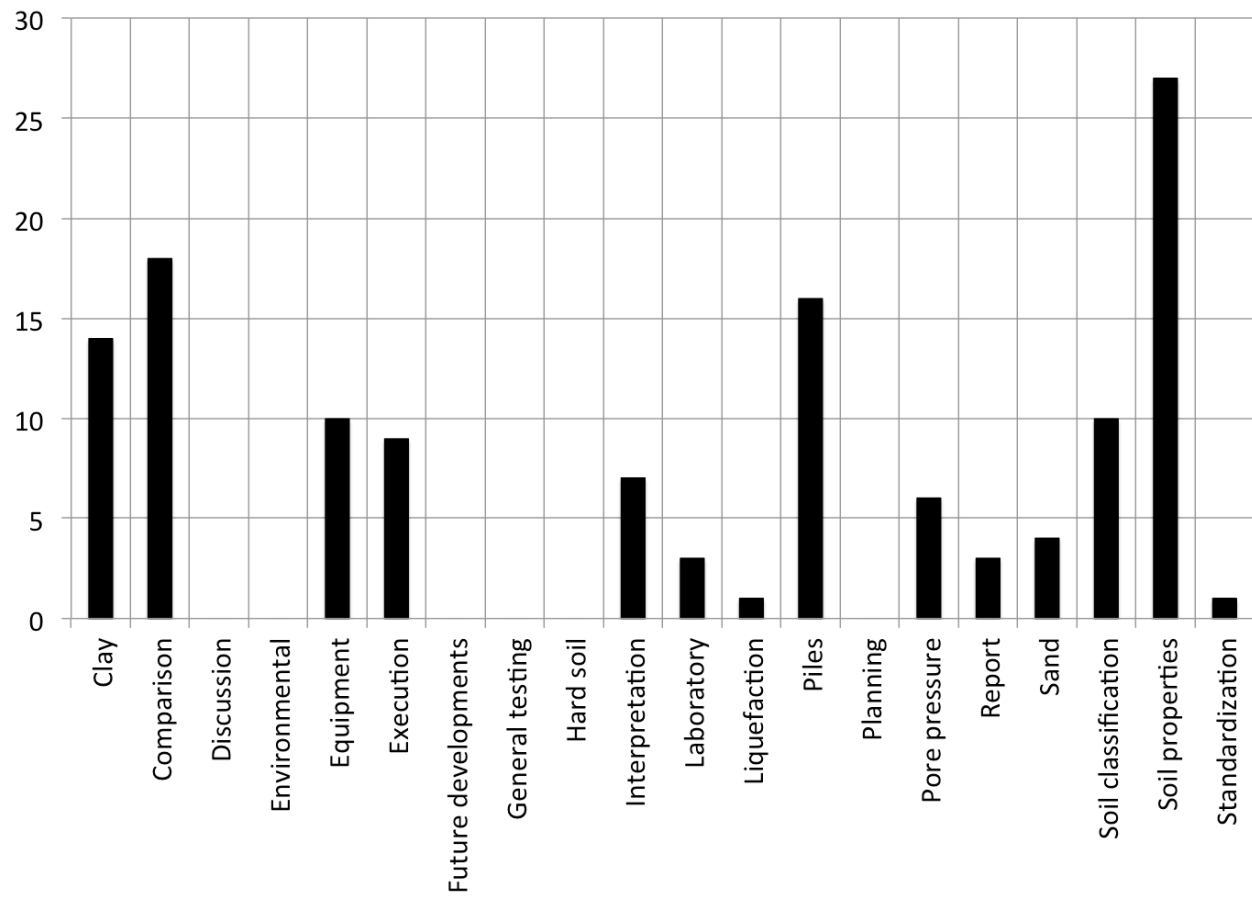


Figure 13. Number of papers addressing different applications of penetration testing, ESOPT II.

7.3 International Symposium on Penetration Testing, ISOPT-1

The International Symposium on Penetration Testing, ISOPT-1 was held in the United States of America in 1988. A total of 111 papers from 31 countries were included in the proceedings. The largest number of contributions came from the host country, followed by Canada, Japan and the Netherlands.

Figure 15 shows the number of papers for different penetration testing and site investigation methods. As the main subject of the symposium was explicitly cone penetration testing, it is not surprising that the largest number of papers belonged to this category. The second largest group of papers addressed the comparison of different types of penetration tests. It is interesting to note the increase of papers on the dilatometer (DMT), which is not a genuine penetration test. This category has been included in the comparison as the DMT is often compared with penetration tests.

Figure 16 displays the distribution of how penetration tests have been applied. The largest number of papers covered the determination of soil properties, followed by questions related to data interpretation. Again, the third largest number of papers addressed the determination of properties in clay. Note that not a single paper was concerned with geo-environmental problems.

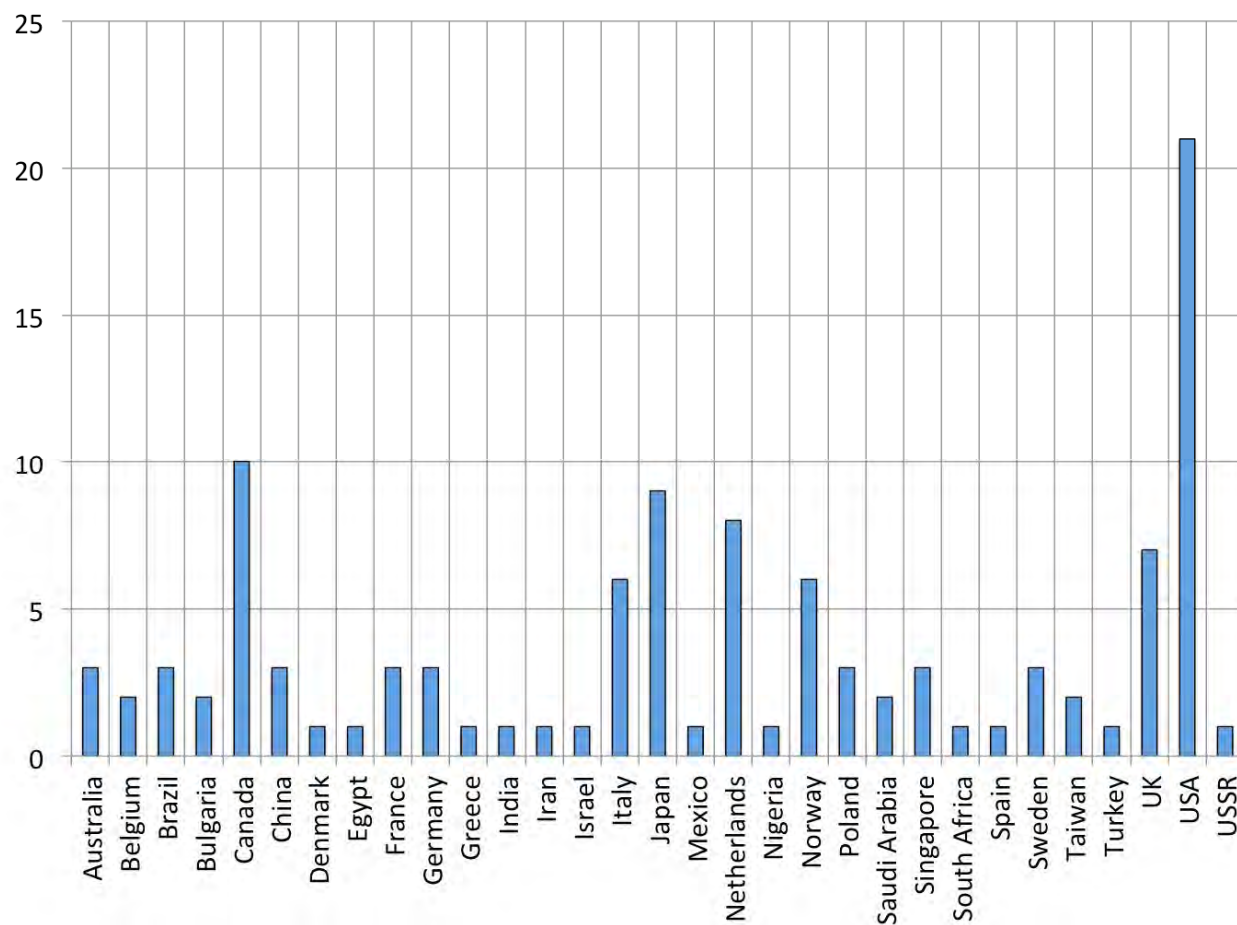


Figure 14. Countries and number of papers published in the proceedings of ISOPT-1. Total number of published papers: 111.

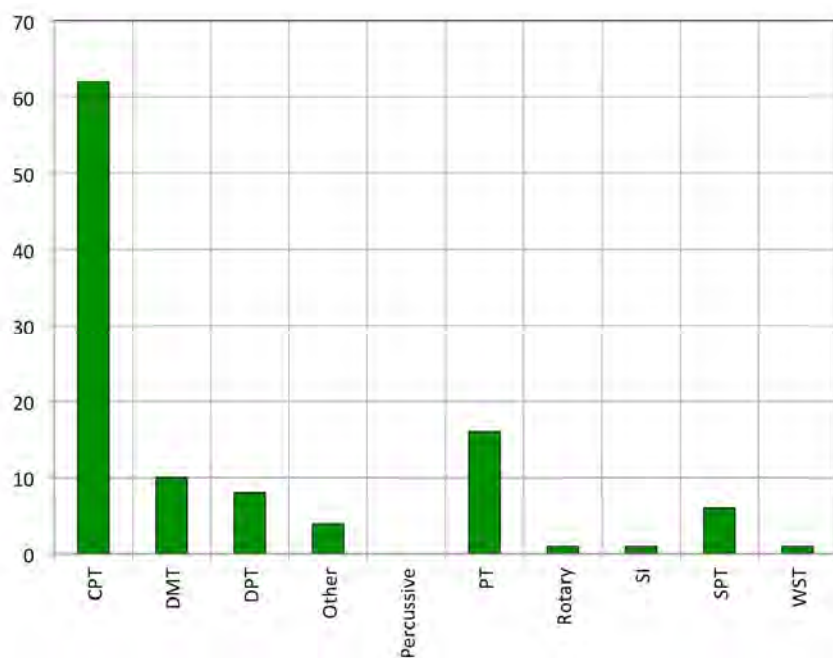


Figure 15. Number of papers discussing different penetration testing methods, ISOPT-1.

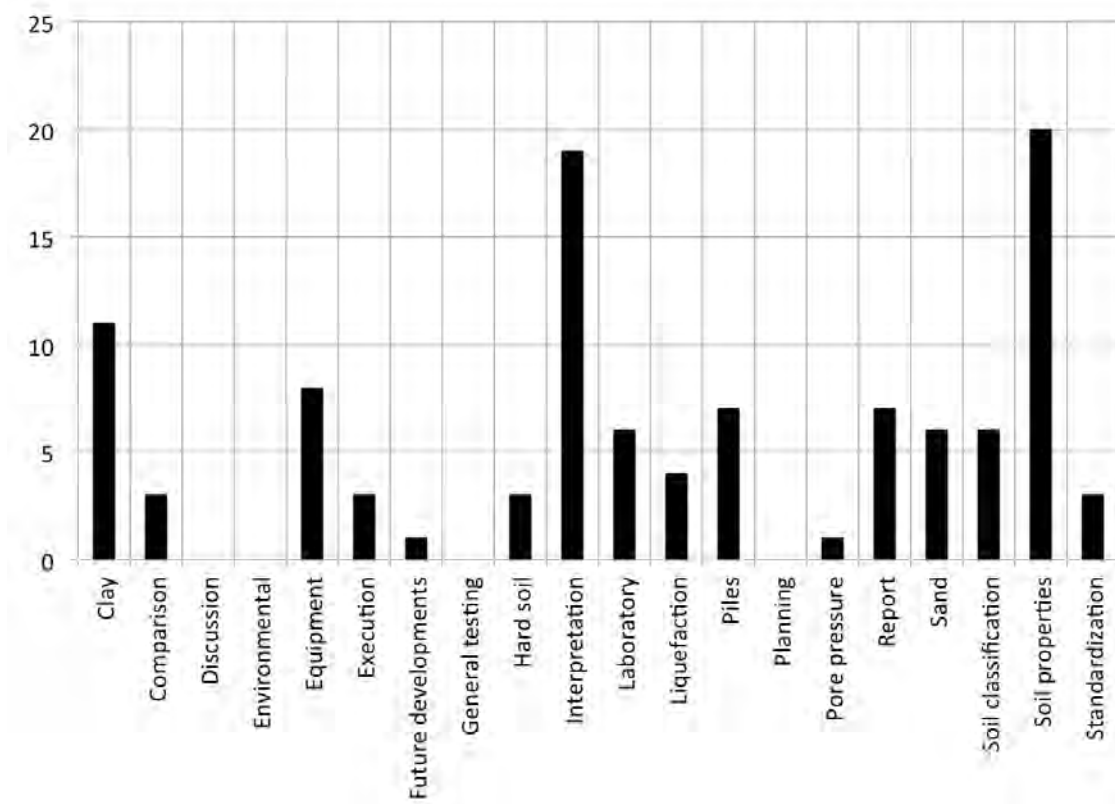


Figure 16. Number of papers addressing different applications of penetration testing, ISOPT-1.

7.4 *Symposium on Cone Penetration Testing, CPT'95*

CPT'95 was again held in Sweden, more than 20 years after ESOPT I. The scope of the conference was specifically devoted to cone penetration testing. A record number of 151 papers from 45 countries were received, as shown in Fig. 17. The proceedings of CPT'95 are available from the CPT'14 website.

The USA had by then become the leading contributor of papers to the symposium with 30, followed by a group of countries: Canada, Denmark, Japan, Russia, Sweden and the United Kingdom.

Figure 18 shows the distribution of papers addressing different penetration testing and site investigation methods. Of course, CPT dominated with more than 120 contributions. The second largest group (PT) covered different aspects of penetration testing, and in particular the comparison of CPT and other site investigation methods.

Figure 19 shows the distribution of papers addressing different applications of penetration testing. As one important aspect of CPT'95 was to document the progress of cone penetration testing since ESOPT I, emphasis was on national and regional reports. The second most important topic of papers was the determination of soil properties, followed by the developments of new equipment. Another popular topic was the interpretation of CPT data with respect to soil properties.

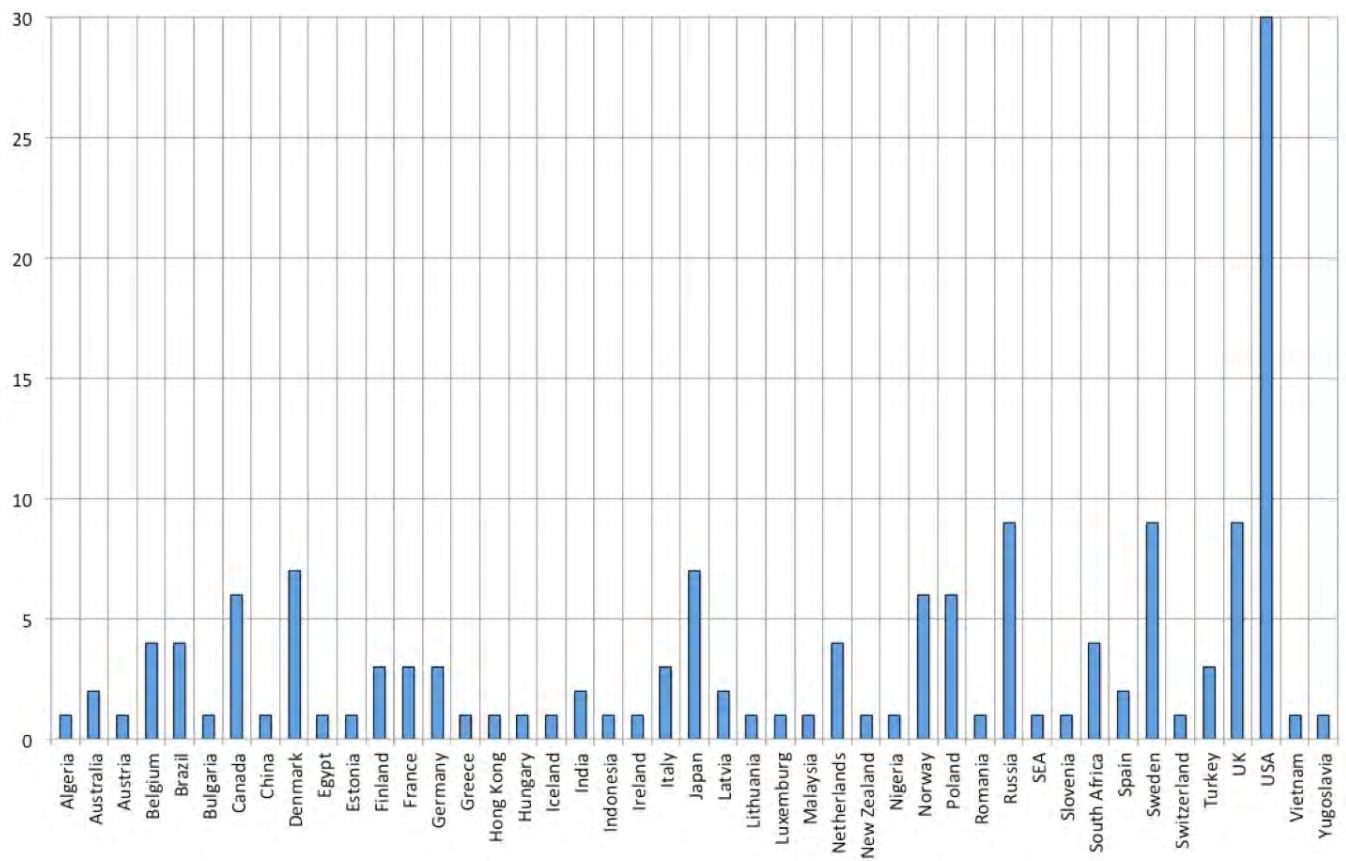


Figure 17. Countries and number of papers published in the proceedings of CPT'95. Total number of published papers: 151.

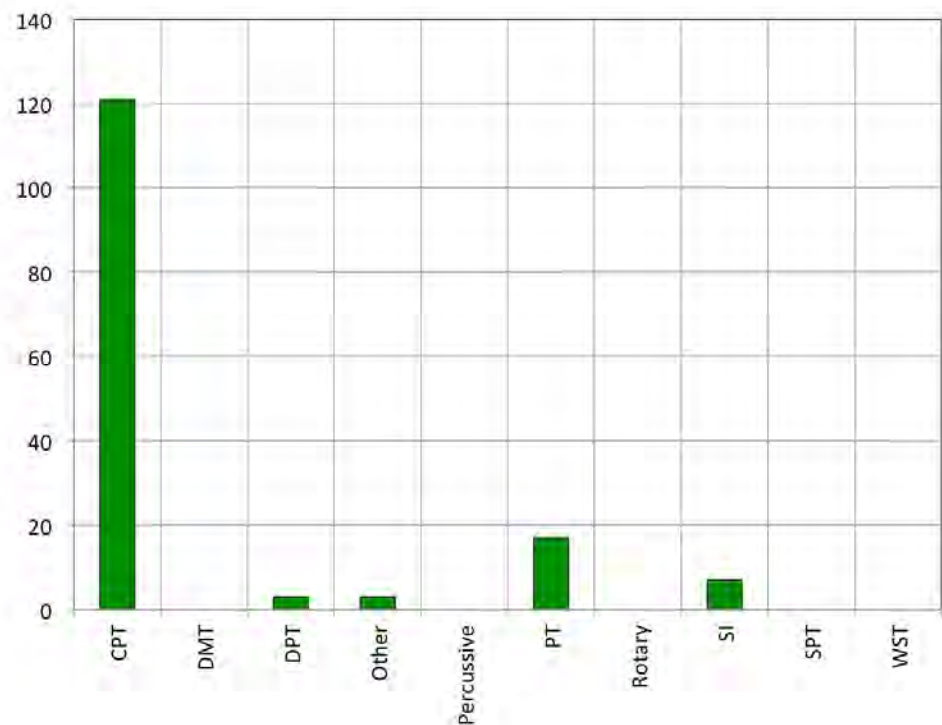


Figure 18. Number of papers discussing different penetration testing methods, CPT'95.

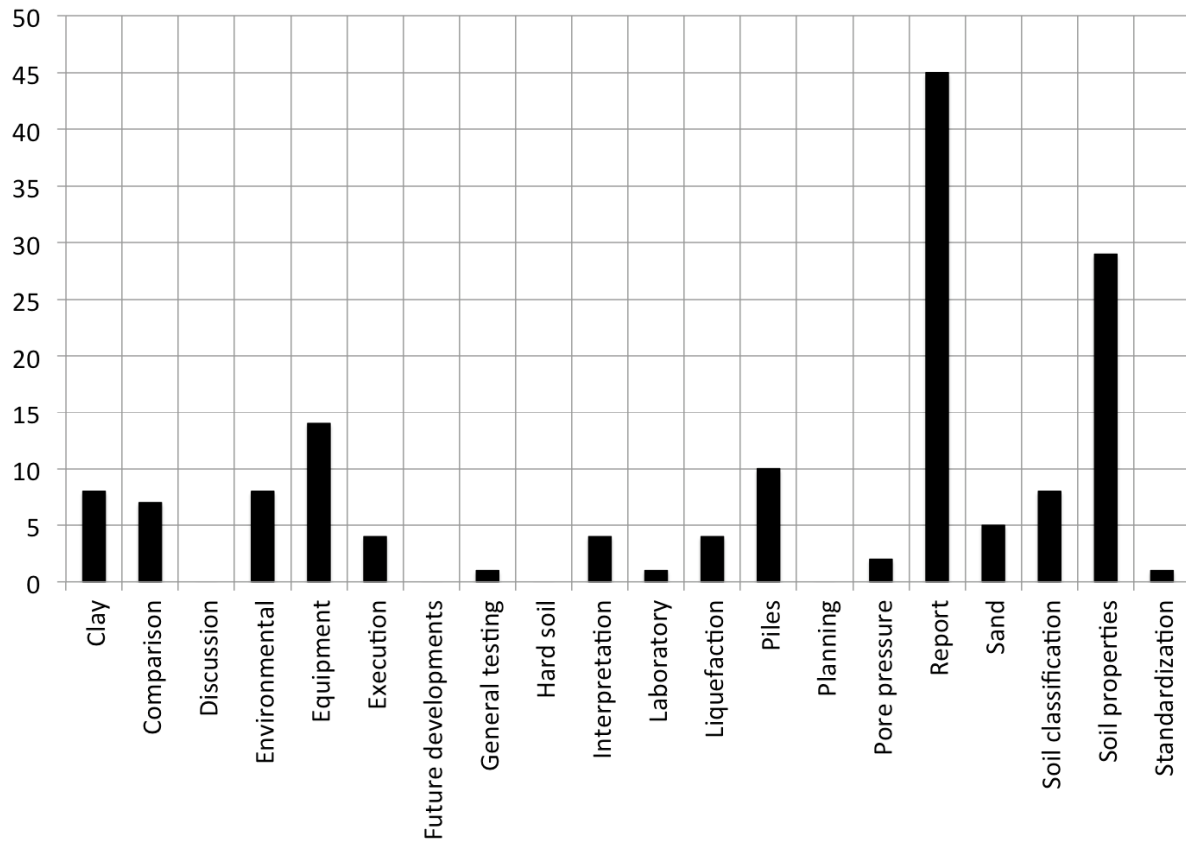


Figure 19. Number of papers addressing different applications of penetration testing, CPT'95.

7.5 2nd International Symposium on Cone Penetration Testing, CPT'10

The most recent symposium on cone penetration testing, CPT'10 was held in Huntington Beach, California in 2010, fifteen years after CPT'95. The total number of papers was 140, submitted from 31 countries, cf. Figure 20.

Again, the largest number of papers was from the USA (41). Then follow papers from a large number of countries from different parts of the world, including Australia, Brazil, Canada, Italy, Korea (!) and Turkey.

Figure 21 shows the distribution of papers addressing different types of penetrometers. Naturally, the largest number of papers was related to cone penetration testing, followed by a comparison between different types of penetration testing methods and the use of penetrometers in site investigation. Figure 22 shows the distribution of papers addressing different applications of penetration testing. Due to the fact that the symposium attempted to compile national and regional developments, the largest number of papers falls into the category Reports. Again, the determination of soil properties from CPT is the second largest category, followed by description and new developments of equipment.

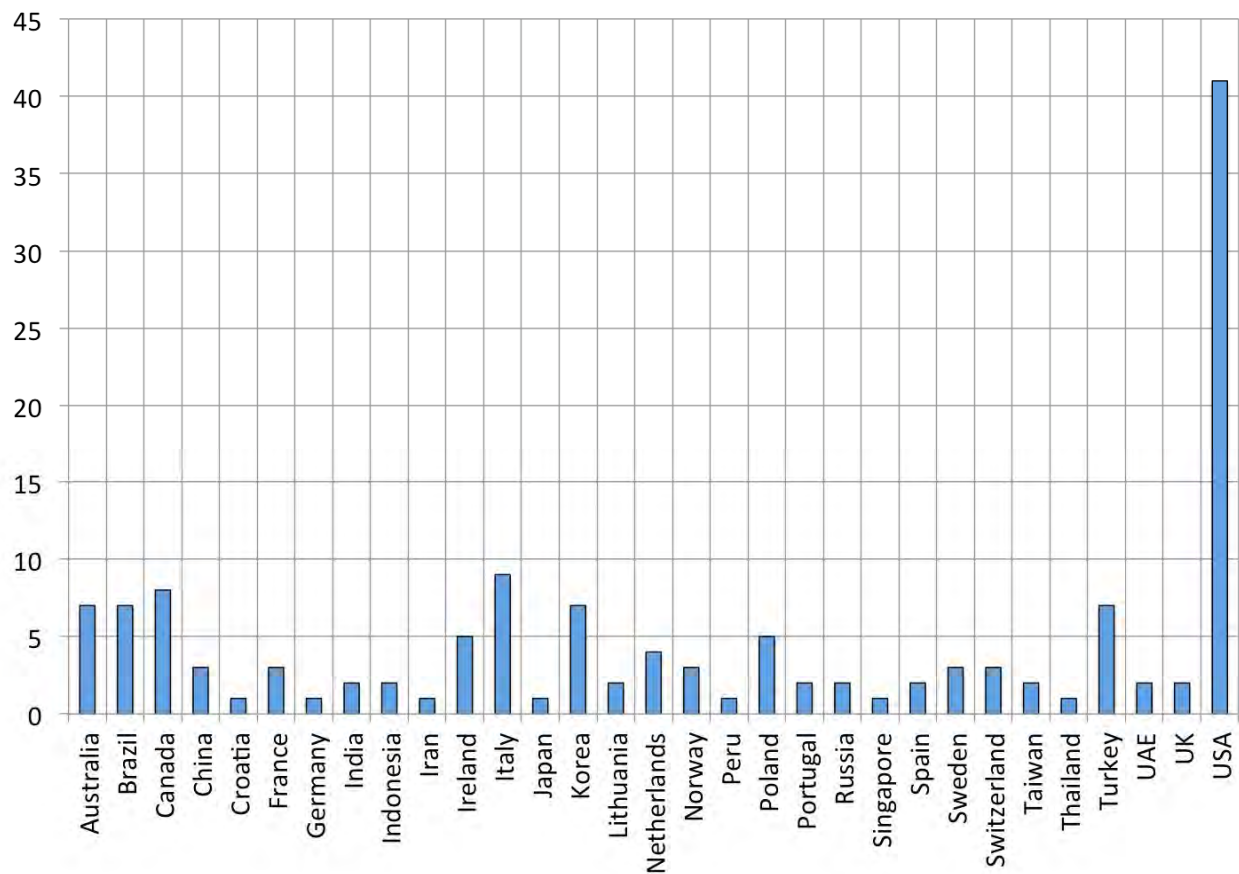


Figure 20. Countries and number of papers published in the proceedings of CPT'10. Total number of published papers: 140.

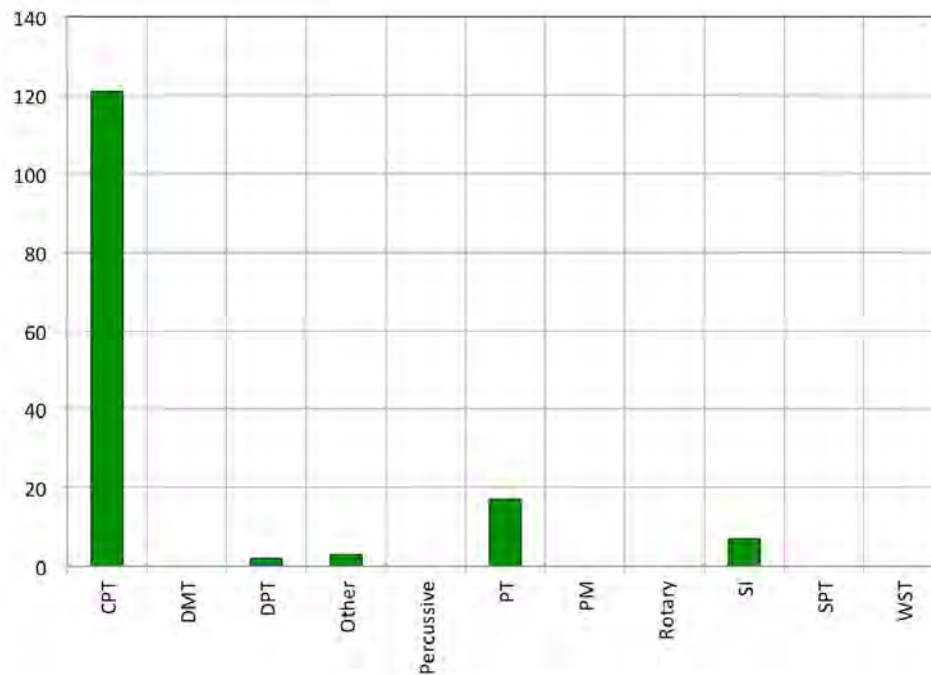


Figure 21. Number of papers discussing different penetration testing methods, CPT'10.

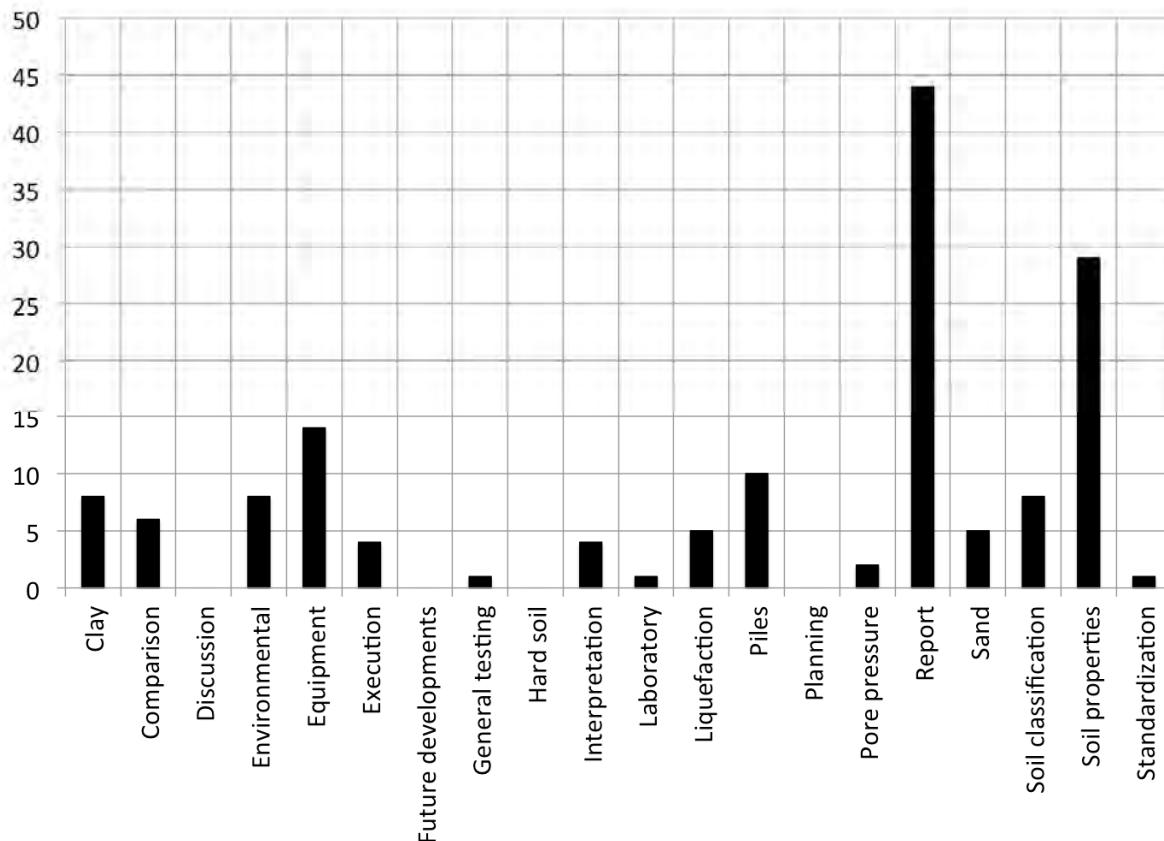


Figure 22. Number of papers addressing different applications of penetration testing, CPT'10.

8 TRENDS IN CPT APPLICATIONS DURING THE PAST 40 YEARS

The contents of papers published over a period of 40 years have been reviewed in the previous section. The papers were classified according to Tables 6 and 7. As the first two symposia (ESOPT I and ESOPT II) covered all types of penetration tests, it is not surprising that the number of papers related to CPT was initially comparatively low and increased with time. However, from the previous section, a clear trend can be seen regarding the increasing interest in symposia on penetration testing, with 100 to 150 papers submitted to the respective events.

The compilation of subjects of papers submitted to the symposia over the past 40 years can only give an approximate picture of the actual developments. The interest in the use of penetration tests for site investigation has steadily increased, which is not reflected in this summary. Also, other in-situ tests for site investigation, such as the pressuremeter, the dilatometer and geophysical tests, play an important role in geotechnical engineering, a fact which is not reflected in this summary. However, some interesting trends in the geotechnical industry can be detected.

Figure 23 illustrates the trend of different topics covered over the past 40 years. The largest number of papers addressed general trends (Reports) with an aim to document regional and national developments. Clearly, there appears to be a need for updated reviews of the state-of-practice of penetration testing, and cone penetration testing in particular, while the need for comparison between different types of penetration testing methods appears to have declined. There is an increasing interest in the development of new types of CPT equipment while the number of papers regarding the execution of penetration tests has decreased, most likely due to the introduction of standardized methods.

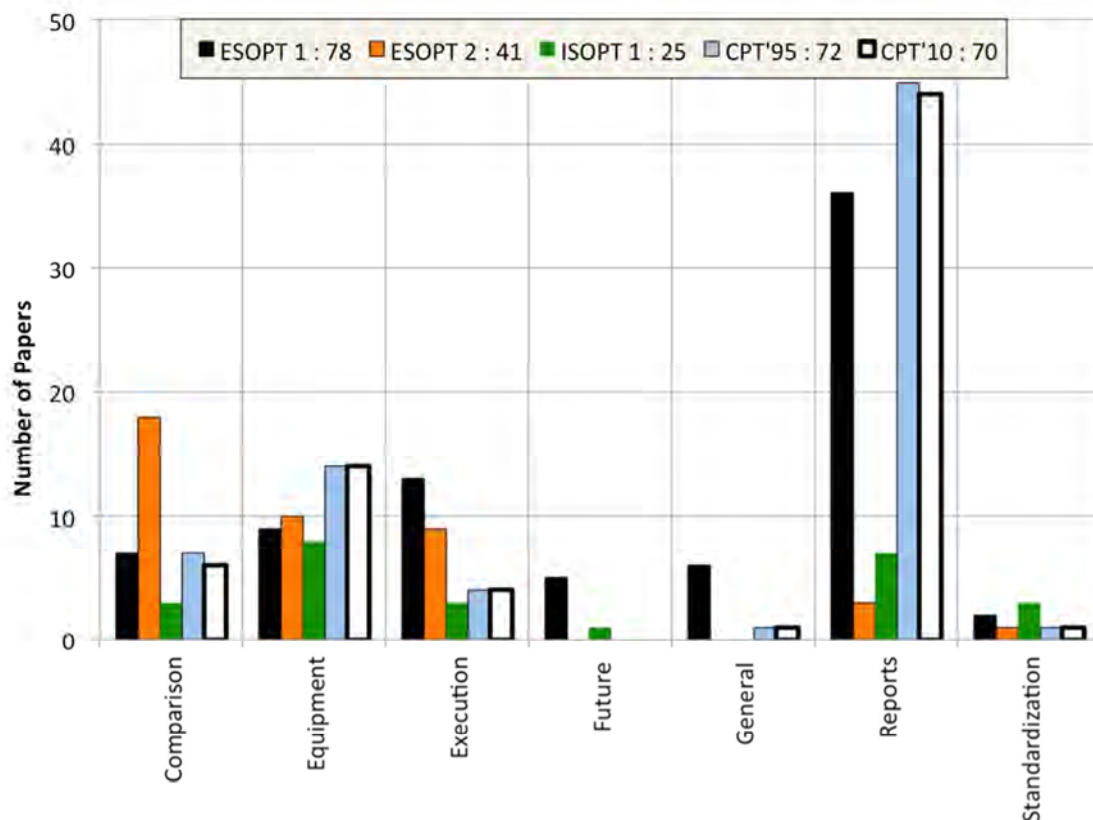


Figure 23. Topics of Papers (Table 6) since ESOPT Stockholm, 1974.

Figure 24 shows the distribution of papers on different topics related to penetration testing. While initially, focus has been on the interpretation of CPT and other penetration testing methods, the largest interest appears to be on the determination of soil properties. Also, there has been a steady interest in soil classification and the determination of the properties of clay soils. Another topic of great interest over the past 40 years has been the application of penetration tests with respect to the design of piles. The number of papers addressing seismic problems (liquefaction) has also increased. It should be pointed out that an increasing number of papers has been related to geotechnical offshore engineering, but it has been difficult to isolate this specific trend.

9 FUTURE TRENDS

After having presented the historic developments of penetration testing and describing the major trends over the past 40 years, it is tempting also to look ahead and try to identify future trends. However, considering the many unforeseen developments in the past, it becomes increasingly difficult to make any predictions. Still, an attempt will be made to identify future trends in penetration testing, being aware that these will not stand the test of time and probably will miss several new important aspects. Assessing future developments is of course made from a personal perspective. Future trends will be divided into four main categories: equipment and execution of penetration testing; interpretation of test data; standardization; communication and information exchange.

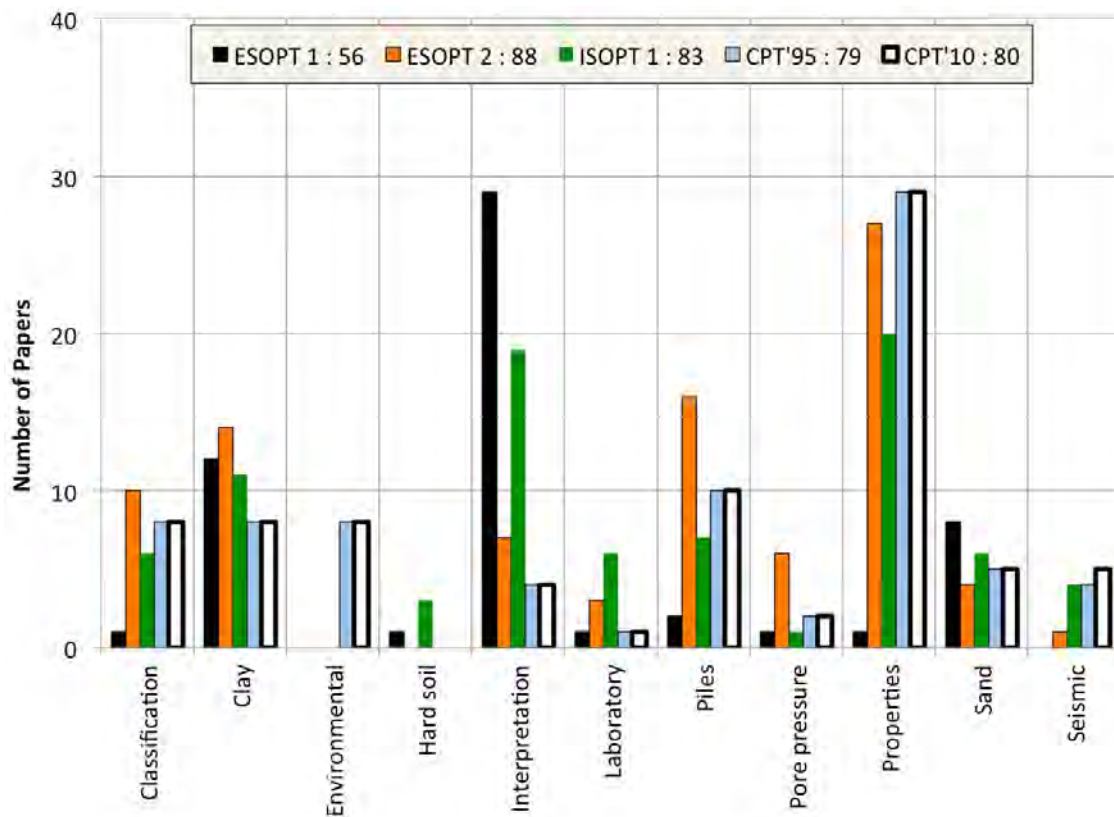


Figure 24. Geotechnical Application of Penetration Testing Methods (Table 7) since ESOPT Stockholm, 1974.

9.1 Equipment and Execution of Penetration Testing

If the past trend of equipment development and test execution continues, it is likely that cone penetrometers will become multi-purpose instruments applied to testing in different technical disciplines, c.f. Table 2, for which new types of sensors will be incorporated. One example is the measurement of sound during penetration testing (Villet et al., 1981, Tringale & Mitchell, 1982 and Massarsch, 1986). When initially introduced in the mid 1970s, the volume of recorded data was too large to take advantage of the high resolution of sound recordings (thousands of values per second/cm). Today, it is possible to record and store large quantities of various acoustic signals (amplitude, frequency etc.) and to correlate these with other parameters, soil type and/or soil properties.

Full-flow penetrometers and push-pull type methods, such as the Iskymeter, have a potential for combined penetration and extraction testing. This trend has started within the offshore industry but may well spread to other areas of application.

Another positive trend, which is expected to continue, is the use of multiple testing methods, incorporated into one device. The seismic CPT (SCPT) is an example of such an application, where - in the same test location - deformation properties of soils can be determined by different methods.

It is also likely that the rapid development in the electronic industry will have a profound impact on penetration testing equipment. The accuracy of sensors is expected to increase and electronic equipment will become more rugged and suitable for site applications. Also the cost of electronic components, such as pressure or acoustic sensors, will decrease, making equipment more affordable. For instance, the price of accelerometers has fallen dramatically with the incorporation of seismic sensors in the automotive industry (air bags) and the installation of accelerometers in computers and hand-held communication devices. To leave a sensor in the ground may become cheaper than recovering it, as is already the case in seismic testing. This development may become even more important for field monitoring.

The sensitivity of sensors and thus the accuracy of measured data will continue to improve, making measurements possible also in difficult site conditions, independent of background noise or disturbance.

It is also envisaged that the transmission of measured data from the sensor (e.g. incorporated in the cone tip) to the crew on the ground, and from there to any office world-wide, will make measured data instantly available to experts located anywhere. Sensors may become increasingly *intelligent*, becoming able to identify between multiple measured signals. The accuracy of sensors and thus that of measured data will be enhanced, making measurements possible also in difficult site conditions, deep below sea level or in urban areas, independent of background noise or disturbance.

9.2 Interpretation of Test Data

Past trends suggest that the interest in the interpretation of penetration test data will continue. The popularity of penetration testing will depend on its ability to relate measured data either to soil parameters (stiffness, strength etc.) or directly to the performance of the ground (soil compaction) or geotechnical structures (pile capacity etc.).

Another likely trend will be the development of knowledge bases for different penetration testing methods, incorporating also probabilistic data interpretation models. Expert systems, which are widely used in other scientific areas, have not yet made a major impact on geotechnical engineering.

The comparison of results from different penetration testing methods will offer new possibilities for data interpretation and assessment of geotechnical parameters.

The computing power of even small hand-held devices will continue to increase, making it possible to treat and evaluate large data quantities rapidly and to correlate these with other soil data.

9.3 Standardization

The most commonly used penetration testing methods have been standardized, for instance in the CEN standards. Similar, though slightly different, standards or guidelines are used elsewhere. There is a continued need for integrating the different types of penetration tests (equipment specifications and test execution).

With the incorporation of new sensors in the cone penetrometer and the introduction of new measuring systems, there will be a need for future standardization or harmonization.

9.4 Communication and Information Exchange

It is interesting to note that at the time of ESOPT I (1974), the facsimile machine (fax) did not yet exist! With the introduction of the fax, it became possible to transmit drawings and sketches. Even more important developments were the introduction of cellular phones and the PC. The internet – and access to the World Wide Web - have fundamentally changed the ways of social and professional communication.

At CPT'95, all submitted abstracts and papers were published on a password-protected website and the contents made accessible to symposium participants. Although in its infancy, the symposium website made it possible to discuss with the authors the contents of papers in advance of the symposium. One session of CPT'95 was devoted to the demonstration of how the internet could be used in the future for engineering applications. But even the most visionary person could not have envisaged the actual developments which have taken place during the past 20 years.

Following CPT'95, a research project was started at the Royal Institute of Technology (KTH) with the objective of publishing a book on pile installation methods on the internet. Due to the instant success of this (now perceived as) relatively simple web application, Geoforum.com was started (www.geoforum.com), into which PileInfo was incorporated.

One of the most comprehensive geotechnical information systems is SGI Line (www.swedgeo.se), developed and operated by the Swedish Geotechnical Institute (SGI).

An important issue, recognized by the ISSMGE, is copyright to published information. ISSMGE has adopted a policy whereby the author gives exclusive publishing rights but retains copyright. This will allow the author to post publications on his website. Recognizing the importance of free information dissemination, several personal websites (google for example: either Campanella; Fellenius; Mayne; In situ GeoLinks; or Robertson, etc.) and public websites provide free access to published information (papers, reports etc.).

ISSMGE and other professional organizations publish technical articles which are accessible free of charge, such as SGI Line or the GeoEngineer: *International Journal of Geoengineering Case Histories*.

ISSMGE Technical Committees and others are offering short courses (Webinars) on the internet, which can be a powerful tool of information dissemination, especially in countries where access to higher education still is limited.

In spite of the increasing number of communication channels, it is obvious that the need for personal meetings and direct exchange of information and opinion will remain an important aspect of professional interaction. Participation of individuals in workshops, symposia or conferences will remain one of the most important aspects of scientific and social communication.

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Prof. Bengt B. Broms convinced this author about the importance of becoming actively involved in the planning and organization of ESOPT in 1974. His vision and encouragement in connection with the planning and implementation of ESOPT I has been of great importance for the success of the symposium and the future of penetration testing.

CPT'95 was organized on behalf of the Swedish Geotechnical Society (SGF) with the support of the Nordic sister societies from Denmark, Finland, Iceland and Norway. CPT'95 became an important milestone in the development, application and information dissemination of cone penetration testing. CPT'95 was organized at the emergence of new fields of CPT applications, such as the use of the CPT for environmental testing and the routine use of the CPT in seismic and earthquake engineering. The contributions by Mr. Bengt Rydell, symposium co-chairman and Mr. Gunnar Westerberg, symposium secretary, were important for the success of the symposium.

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