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Forensic engineering in geotechnics, the Dutch approach on CPT interpretation

Forensic Ingénierie en Géotechnique, l'approche Hollandais de l'interprétation CPT

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ABSTRACT In the Dutch geotechnical engineering practise it is common to perform a large number of Cone Penetration Tests (CPT) at every new building site. Especially since the development of electric registration methods in the early 1980's, CPT's have become the "working horse" among site investigation techniques. Nowadays we trust the information of CPT's in such a manner that we only perform additional boreholes for very specific reasons. CPT's are cheap, easy to perform and have a well known result and reliability. Since the nineteen sixties over 5 million CPT's have been carried out in the Netherlands, and of course, every now and again we encounter "strange" results. Sometimes these results can be explained with a new calibration of the equipment itself, but most of the time we are dealing with irregularities in the actual soil conditions. These irregularities, especially in deeper soil formations, can have a geological explanation, an anomaly to a geotechnical engineer is sometimes a logical consequence for a geologist. However, in recent years we perform a large number of CPT's for urban regeneration projects and highway extensions that show irregularities at lesser depths and are frequently the result of earlier manmade alterations in the subsoil. This paper describes over 25 years of personal experiences with "explaining" the results of CPT's carried out in different parts of the Netherlands, both on a geological and historical perspective.

RÉSUMÉ Dans la pratique de la Géotechnique ingénierie Hollandaise il est usage de réaliser un grand nombre de Conus Penetration Tests (CPT) sur chaque nouveau chantier. Surtout depuis le développement des méthodiques d'enregistrement électrique au début des années 1980's, les CPT sont devenus les chevaux de travail parmi les techniques d' investigation sur location. Aujourd'hui nous avons une telle confiance dans l'information des CPT que seulement pour des raisons spéciales on fait des forages complémentaires. Les CPT ne sont pas cher, facile á réaliser et donnent un bon et fiable résultat. Depuis les années '60 plus de 5 million de CPT ont été réaliser en Hollande et évidemment de temps en temps il y a des résultats étranges. Parfois ces résultats peuvent être expliquer par un nouveau étalonnage de l'appareil lui même, mais souvent on á faires á des irrégularités dans la condition du sol même. Ces irrégularités, spécialement en formations terrestres les plus profondes, ce qui est une anomalie pour un ingénieur géotechnique mais parfois une conséquence logique pour un géologue. Néanmoins dans les années récentes nous réalisons un grand nombre de CPT pour des projets de réalisation urbaines et extensions d'autoroutes qui montrent des anomalies dans les formations terrestres les moins profondes et qui sont la plus part du temps les conséquences de changement dans le sol, causer par l'homme. Ce document décrit 25 ans d'expériences personnelles en expliquant des résultats des CPT exécutés dans différents parts de la Hollande, vue du perspectif géologique et historique.

1 INTRODUCTION

Since the first Cone Penetration Tests were performed in the 1930's, this measurement technique has developed into a reliable, cost effective and worldwide accepted standard test for soil investigations in soft soils. Since 2012 an international standard is available; EN-ISO-22476-1 "geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone penetration test".

A cone penetration test (CPT) is an in-situ test where a cone penetrometer (the cone) on the end of a series of rods is pushed vertically from a hydraulic rig into the ground at a constant rate of 20 mm per second, to depths of up to 100 m (depending soil conditions).

During a standard test, the forces on the cone and the friction sleeve above the cone, are measured every 20 mm to obtain detailed information about the soil conditions. The almost instant results can be used to determine soil parameters including soil type, soil density, in-situ stress conditions and shear strength for use in geotechnical design.

The most common cones used are the standard cone and the piezocone, the latter measuring porewater pressure. A large number of special cones have been developed over the years that can be run concurrently with the standard cone test to cope with different geological environments, to evaluate a huge range of soil parameters, as well as to take samples and install geotechnical instrumentation.

The Advantages of CPT can be summarized as follows:

- Greater delineation of strata, as readings taken every 20 mm;
- Repeatable, high quality and reliable results available in real time;
- Electronic data transfer means more manageable data handling;
- Test is quiet, produces no vibrations and creates minimal soil disturbance;
- High productivity (up to 150 m tested per day);
- Instant results allow on-site selection of the best locations for sampling, testing and monitoring;
- Huge range of cones for geotechnical investigations, contaminated land studies and unexploded ordnance detection;
- CPT platform can be used for obtaining high quality samples and installing instrumentation.

The down side is that test results do not always meet our expectations. Due to all kind of disturbances test results show irregularities that need further study to understand why the CPT-result is the way it is. The mentioned irregularities can be the result of incorrect measuring or processing of the data, the result of "unknown" geological site conditions or the result of manmade alterations to the soil conditions.

Explaining CPT-results is a type of forensic engineering that is common in the Netherlands where approximately 1000 tests are performed every day.

2 CPT-INTERPRETATION

For a correct interpretation of CPT results one needs to understand the theoretical back-ground of the soil behaviour during execution of the test, one needs to understand the vulnerability of the test equipment (cones, data acquisition and transport) and one should consider the "human errors" that can occur during processing of the data. Furthermore we should consider geological circumstances that influence CPT-data and the more recent history of the site with respect to previous building activities or other manmade changes to the soil conditions.

Lunne et al (1997) is considered the definitive textbook on CPT execution and interpretation. However, the book primarily covers "normal" CPT-results and does not consider all external influences that have been mentioned previously.

2.1 Data acquisition and processing

Although CPT's in the Netherlands are a standard product of which the quality is generally beyond any doubts, there is still a considerable difference between results from different CPT performing companies.

In 2004 11 Dutch companies took part in a trial test in which they performed a number of CPT's on a test site near Almere (Tiggelman & Beukema 2006 and 2008). Each company used their own equipment and procedures and measured cone resistance and sleeve friction. As a result also the friction ratio was presented.

After statistical analyses it was concluded that especially the friction ratio can vary significantly depending on the company. Even more dramatic was the conclusion that all CPT's individually complied with the former Dutch standard NEN 5140 class 2, the class in which 95% of all CPT's were executed.

It became transparent that data acquisition and processing needs continuous focus on calibration and quality. However "human errors" will now and again result in CPT results as presented in figure 1.

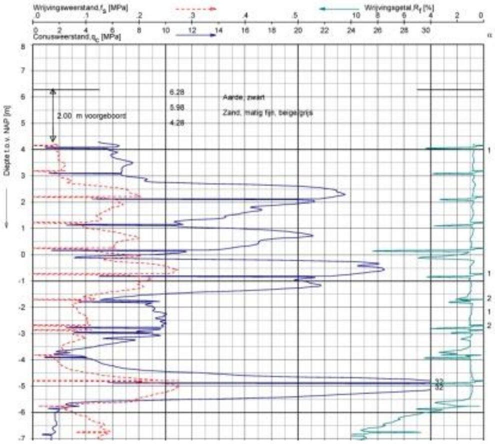

Figure 1. Typical data-processing failure ("meter" peaks due to stops for positioning next rod). The blue line represents the cone resistance (tip), the dotted redline shows the local friction and the green line on the right the friction ratio.

2.2 *Geological influences*

The main geological influences on CPT-results in the Netherlands have their origin in the last ice-ages, over 10.000 years ago. The northern half of the Netherlands, roughly above the artificial line Amsterdam – Nijmegen, was covered with ice with a thickness of up to 200 meters.

In 2011 a soil investigation was commissioned by the Dutch Ministry of Public Works for the extension of the A9 highway just south of Amsterdam. This site is located on the edge of the former glaciers and the Cone resistance can vary significantly between CPT's, see figure 2.

All presented CPT's were carried out within a distance of 100 m and therefore the results will have a large impact on the foundation design of the tunnel that has to be constructed as part of the works. Understanding the origin of the variations also means knowing how to deal with these variations in the design.

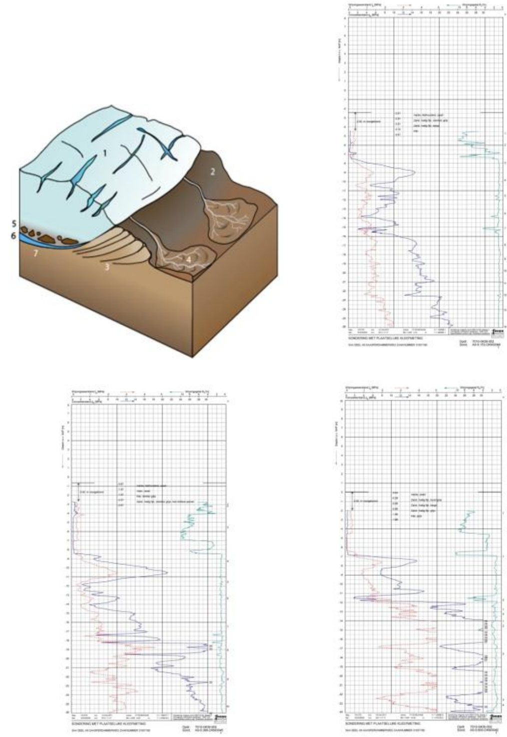

Figure 2. Variation in cone resistance (blue line) as a result of horizontal stresses in Pleistocene sand layers due to glacial surge.

2.3 *Man-made influences*

Building activities, like driving piles, excavations for underground structures or large fills, all have an influence on soil conditions and therefore on CPT results. Sometimes these influences are obvious, for example if the works are still visible or structures are still present. This may seem evident, but even in that situation it is possible that these influences are neglected. If excavations or fills have been carried out decades or even centuries before, or structures have been demolished years ago, than further investigation is necessary.

Until 10 years ago we had to rely on old photographs, local knowledge, geological maps and historical maps and documents to able to explain the influences from the past. The internet changed all that. Nowadays a number of public databases are available in which all kind of general data and historical data has been collected.

In The Netherlands we are fortunate to have access to the following public information:

- www.ahn.nl: this website presents the ground-level of the whole of the country related to NAP, the Dutch ordinance date. The accuracy of this information is quite astonishing, every 5 m a level is available with an accuracy of 5 cm;
- www.dinoloket.nl: a large part of all soil investigations done in the past 30 years have been collected in this database, including groundwaterlevels. In general there is at least one CPT or borehole within a maximum distance of 500 m to every possible location in the country. The site also contains geological information;
- www.waterbase.nl: With the amount of water in The Netherlands you would expect us to have a system that monitors and present the actual water levels;
- www.watwaswaar.nl: the title of this websites translates to "what was where" and contains a large number of historical maps, from the middle-ages to more recent years;
- A large number of websites show historical photographs, f.e.www.beeldbank.amsterdam.nl, the archive of the city of Amsterdam.

This also means that geotechnical engineers in The Netherlands have no excuse, they you should use this information when relevant. In the next paragraphs some examples are given.

2.3.1 Gelredome stadium Vitesse FC Arnhem

For the design and construction of the Gelredome stadium, home to footballclub Vitesse, an extensive soil investigation was carried out, consisting of numerous CPT's and several boreholes. This multifunctual stadium has a pitch that can be shoved to the outside of the actual structure in order to limit the damage to the grass and to make optimal use of the indoor space. As a result of this design the settlement requirements for the foundation were very strict. The CPT result on the right site of figure 3 was very unwelcome.

After several discussions between the structural designer and the geotechnical engineer it became clear that the "disturbed" CPT had been executed on the exact position of a borehole, that had been carried out only two years prior to the CPT.

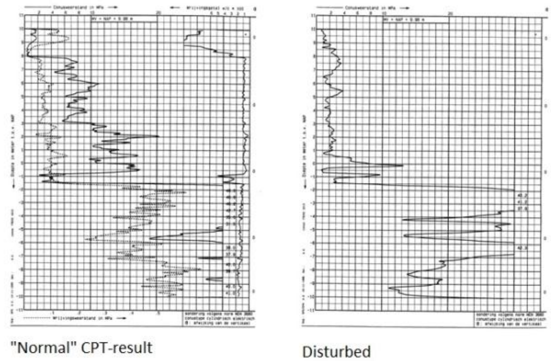

Figure 3. Variation in cone resistance (solid line) as a result of disturbance due to a former borehole.

Since the disturbance was limited to this 323 mm borehole there was no need to change the design and the stadium was completed successfully.

2.3.2 Industrial area Rotterdam Noord-West

In the 1980's the municipality of Rotterdam started developing the industrial area Noord-West (north-west). This area had been a polder since the year 1600 and had been filled during a period of 20 years (between 1960 and 1980) with material dredged from the port of Rotterdam. A typical CPT for this area is shown in figure 4.

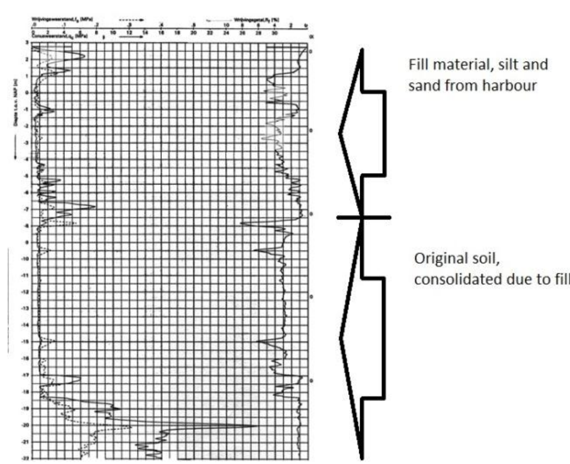

Figure 4. CPT-result Rotterdam Noord-West.

A geotechnical engineer from the east of The Netherlands was not aware of this fact and figured it would be possible to use a piled foundation with the pile tip at NAP -7 m, a level that according to geological information could be a holocene sand layer. Fortunately his mistake was corrected before the actual constructing or there would have been serious consequences.

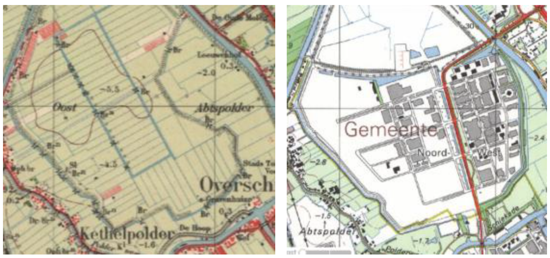

Figure 5. The original polder (left 1939) and the industrial area (right 1995); *source* www.watwaswaar.nl.

If the engineer had been able to consult the internet he would have found figure 5, showing the original polder with a groundlevel of NAP -5,5 m, the modified city maps form the period 1960 to 1980 and the actual heights (grounlevels) from www.ahn.nl that are presented in figure 6.

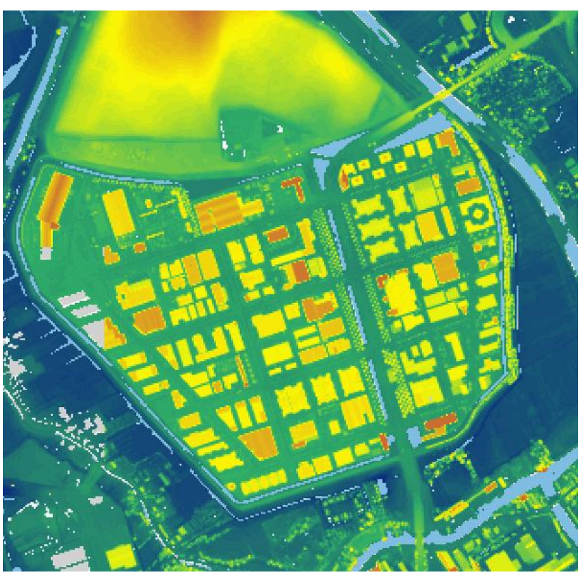

Figure 6. Groundlevel Rotterdam Noord-West (2012); *source www.ahn.nl.* The dark blue areas are situated well below NAP, the green areas are raised to approximately NAP +1,5 m.

As a result of the fill with material form the Rotterdam harbour the area to this day shows a "background" settlement (creep) of more than 20 mm each year.

2.3.3 *Highway A9 and polder Bijlmermeer*

In chapter 2.2 the geological history of this site was already discussed. However, the irregularities in the CPT's did not end with these geological phenomena. The polder "Bijlmermeer" was created in 1627 and the oldest available map of the polder dates back to 1650.

Figure 7. Polder Bijlmermeer 1650; *source www.watwaswaar.nl.*

In the 1960's the urban area of Amsterdam expanded to this area and highway A9 was opened in 1982, more or less on the exact location of the former Bijlmer Ringsloot, the canal that surrounded the polder.

Figure 8. Polder Bijlmermeer 1969. The dotted line represents the A9 highway; *source www.watwaswaar.nl.*

The new highway A9 will be situated in a tunnel for which large excavations are necessary. As a result the material present at excavation level, approximately NAP -5 m, became of considerable interest to the geotechnical engineers.

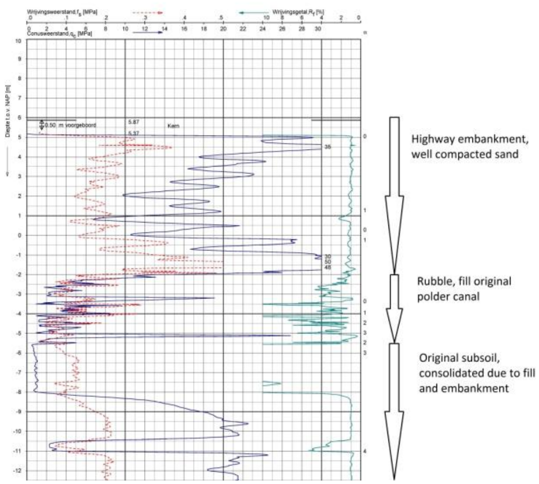

Figure 9. CPT former Bijlmer Ringsloot.

Only through extensive research we were able to conclude that the former canal was filled with debris from demolished local farm houses such as shown in figure 10.

Figure 10. Farmhouse Polder Bijlmermeer, appr. 1950; *source* www.beeldbank.amsterdam.nl.

3 CONCLUDING REMARKS

When interpreting CPT results one should always consider:

- Interpretation requires knowledge, or at least understanding, of CPT equipment, data acquisition and data processing;
- Try to avoid using different suppliers of CPT's in your project. Results from all suppliers could be within requirements and still be incomparable;
- When classifying soils based on CPT results use more than one source;
- If soil classification is really important to your project than make a borehole and perform laboratory tests;
- Always check the results with your own or available experience. If the CPT looks strange, it probably is.

ACKNOWLEDGEMENT

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