Penetrability of sandstones with a CPT cone

Pénétration d'un grès avec une pointe de sondage

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ABSTRACT: The mechanisms acting during the penetration of stones and rock layers are not well known, resulting in discussions during the interpretation of geotechnical investigations and during excavations or other civil engineering projects. The research presented in this paper aims to answer the question if the penetration of a rock layer by a CPT cone can go by unnoticed on the sounding diagram. Laboratory and numerical simulations have been conducted addressing this problem. During the penetration of a rock layer tensile and shear fractures are induced and the rock beneath the cone is crushed. The authors hope that in future in-situ observations can be conducted to confirm these findings.

RESUME: Les mécanismes présents lors de la pénétration d'une pointe de sondage dans une pierre ou un banc rocheux ne sont pas bien connus.Il en résulte des discussions lors de l'interprétation des diagrammes de sondage et lors des travaux de génie civil. La recherche présentée dans cet article a comme but de répondre à la question suivante: est-il possible qu'une pointe de sondage traverse la roche ou un banc de roche sans que cela ne soit visible sur un diagramme de sondage. Des essais en laboratoire et des simulations numériques ont été réalisés et ont indiqué que cette question est justifiée. Lors de la pénétration d'une pointe de sondage dans une roche, des fractures de tension et de cisaillement sont induites. Sous la pointe, la roche est pulvérisée. Les auteurs souhaitent faire des essais in-situ dans le futur pour confirmer ces résultats.

1 INTRODUCTION

The presence of stones, rock layers and concretions pose practical problems during civil engineering works. There is a wide range of geological conditions, in which such rocks can be formed or deposited. In the subsoil of the Belgium territory, the occurrence of most of these rocks are related to transgressions and regressions of the sea in combination with periods of erosion. This results in several different geological formations present in the top 20 m of the subsoil. In the northern part of Belgium, Cretaceous, Tertiary and Quaternary formations are observed. In the Cretaceous deposits mainly silex concretions are present, while in the Tertiary and Quaternary deposits chalk and sandstone are present.

For large civil engineering projects, the geotechnical pre-investigation consist mainly of deep cone penetration tests (CPT). During such tests, a rod with at the end a steel cone is pushed into the ground by hydraulic forces. While testing, the cone resistance to penetration and the frictional resistance of the rod are measured. The frictional resistance is caused by the contact with the soil and possible rocks. The presence of a rock should result in a sudden increase of the cone resistance. In Figure 1, an example is given of a sounding diagram and a significant increase is noted when making contact with the sandstone layer. Such a distinct indication is not always observed. Hence, in the past, regular discussions were held on the incorrect estimation of the composition of the subsoil based on a geotechnical pre-investigation. Two situations could occur:

(i) The presence of stones or rock layers is not or at least insufficiently detected by cone penetration tests. Possible causes (Figure 2) are the pushing away of the rocks, the deflection of the rods by the presence of the rock and the holing of the rocks. While excavating the soil or building piles or foundations, rocks are then unexpectedly encountered.

(ii) The maximum force is reached, while only locally a small rock is present or only a thin insignificant rock layer occurs. In such situations, stability problems could later occur, for example when foundations are built on strongly weathered rock.

To improve the knowledge of perforating stones or rock

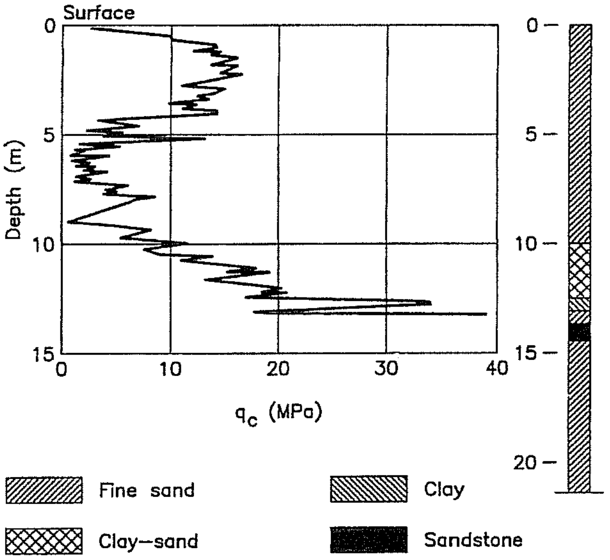

Figure 1. Typical sounding diagram of a CPT test.

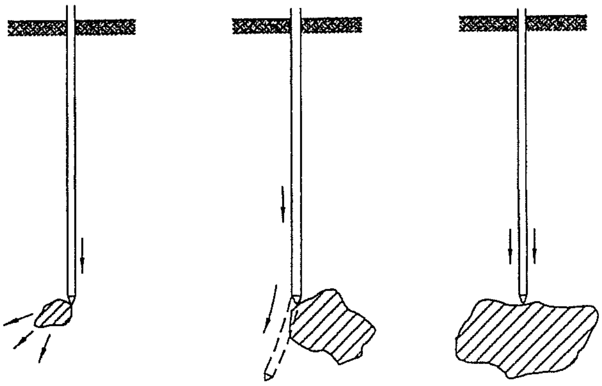

Figure 2. Possible causes of not detecting rocks during a CPT test.

layers, the problem was approached in a systematic way, by conducting laboratory experiments and numerical simulations.

The rock layer investigated belongs to the Brusselian formation and is a sandstone rich in chalk (Figure 3). The samples were taken on the site of a train tunnel to the airport of Brussels. The main rock mechanical properties of the rock are:

-Tensile strength: between 3 and 5 MPa,
-Uni-axial compressive strength: between 40 and 100 MPa,
-Modulus of Young: between 10 and 20 GPa,
-Poisson's ratio: between 0,2 and 0,3.

2 SIMULATIONS

2.1 Laboratory experiments

The laboratory experiments aim at simulating the in-situ conditions and circumstances of deep penetration tests (CPT). Such experiments have additional advantages. First of all, perforated or broken rock samples can be further investigated, resulting in a better knowledge of the mechanisms of failure. Movements of blocks can also be observed. Secondly, the boundary or surrounding conditions can be studied and the effect on the results analysed. Thirdly, experiments can be repeated under similar conditions.

The following experiments were conducted in a first phase of research:

(i) Rock positioned freely on a sand layer (see Figure 4),
(ii) Rock clamped in a steel drum, covered by a sand layer (above and below; Figures 5 and 6).
(iii) Rock clamped in a steel drum, positioned on a layer of cement (below and around) and covered by sand.

The successive experiments are characterized by a decrease of degrees of freedom of movement. For all experiments the same testing equipment was used. The range of the compressive forces varies between 0 and 20 ton; the diameter of the rod is 35,7 mm and the cone is manufactured out of hardened steel. The diameter of the cone is also 35,7 mm and its top angle is 60°. The contact area is 10 cm^2, as specified by the norms. The rods were kept short, so that no deflection due to irregularities of the rock samples would occur. The investigation concentrated on the maximum force to perforate the rock.

For the experiments with the stone positioned freely on the sand layer, the stones were splitted by the applied pressure of the cone. The rock material was crushed where the cone made first contact with the rock, due to high stresses. This was followed by the formation of a tensile fracture with a vertical orientation (Figure 7). The maximum force varied between 4 and 14 ton for rock layer thicknesses between 8 and 19 cm. In other words the assumption that a rock layer can be perforated without being observed on a sounding diagram is realistic. After splitting the rock, the cone and rod had no problem to further penetrate as the blocks could be pushed horizontally without any restrictions. In-situ, such freedom is non-existant.

In the second set of tests, the stones were clamped at three corners in a steel drum. Hence, the horizontal movement was heavily restricted even in some cases eliminated. The rocks were buried under a sand layer of 0,6 m thickness. Maximum forces of 11 to 14 ton were recorded for thicknesses of the rock lay between 12 and 15 cm. These forces are still situated within t range of CPT equipment. In these experiments the rocks fail and the cone also holed through the rock. The fracture mechanis is presented in Figure 8 and is more complex than in the first s of tests. At the first contact between cone and rock, the rock crushed by sufficiently high stresses. Once the rock is local crushed, the cone penetrates over a small distance, followed by new increase in the force and a further crushing of the rock. Th process repeats itself several times, till the tensile stresses in t remaining part of the rock layer are sufficiently large to split t rock. Similar to the first set of experiments, a vertical tensi fracture is induced. Due to the clamping, no or an insignifica amount of horizontal movement occurs. The cone penetrat further, though due to the occurrence of a second type of fractu the cone can eventually hole through the rock. When the distan between the cone position and the bottom of the rock sufficiently small, a shear fracture is induced and a block with t shape of a cone or of half a cone is pushed out of the rock.

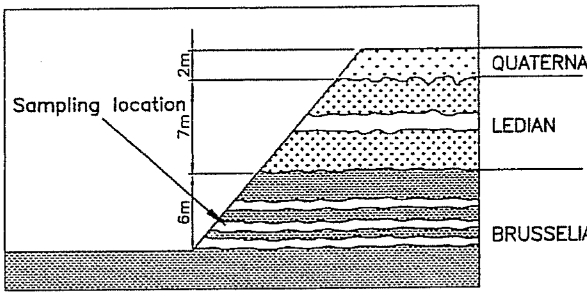

Figure 3. Vertical cross-section at the sampling location.

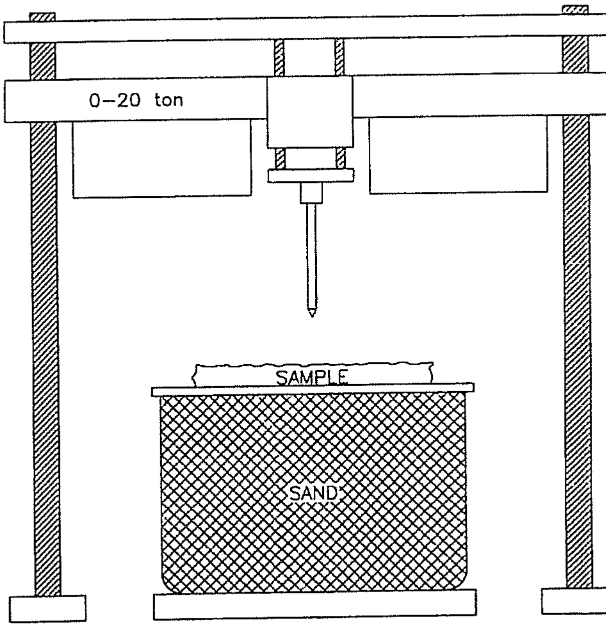

Figure 4. Set-up of laboratory experiments, with rock samp positioned freely on a sand layer.

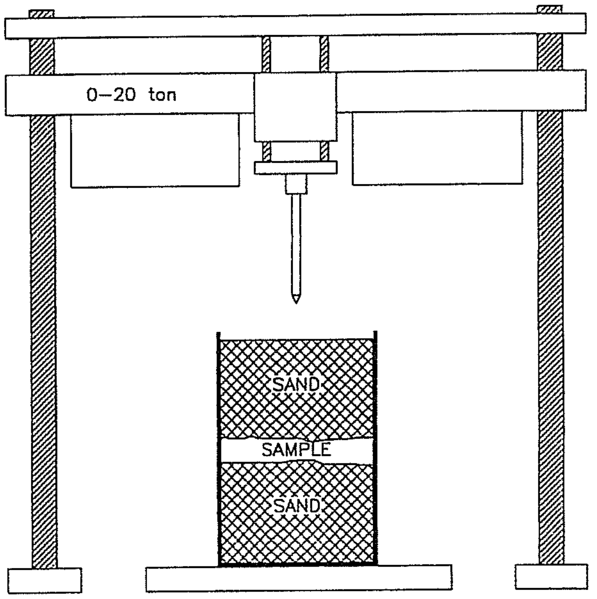

Figure 5. Set-up of laboratory experiments, with rock samp clamped in a steel drum.

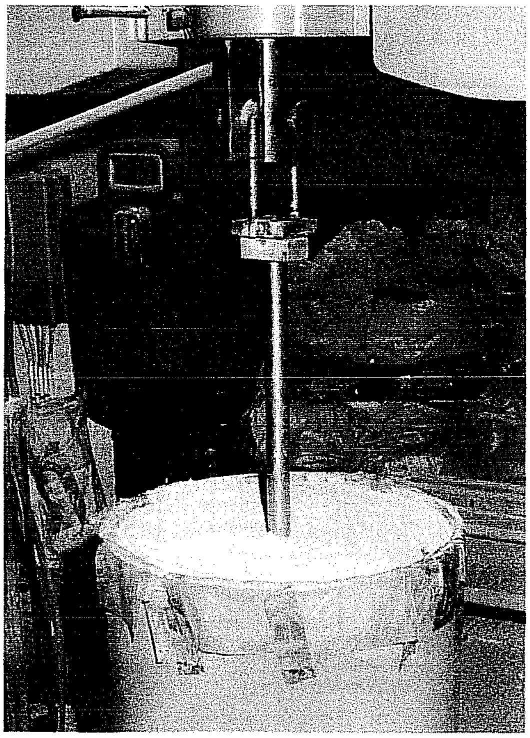

Figure 6. View of laboratory set-up (second and third set of experiments).

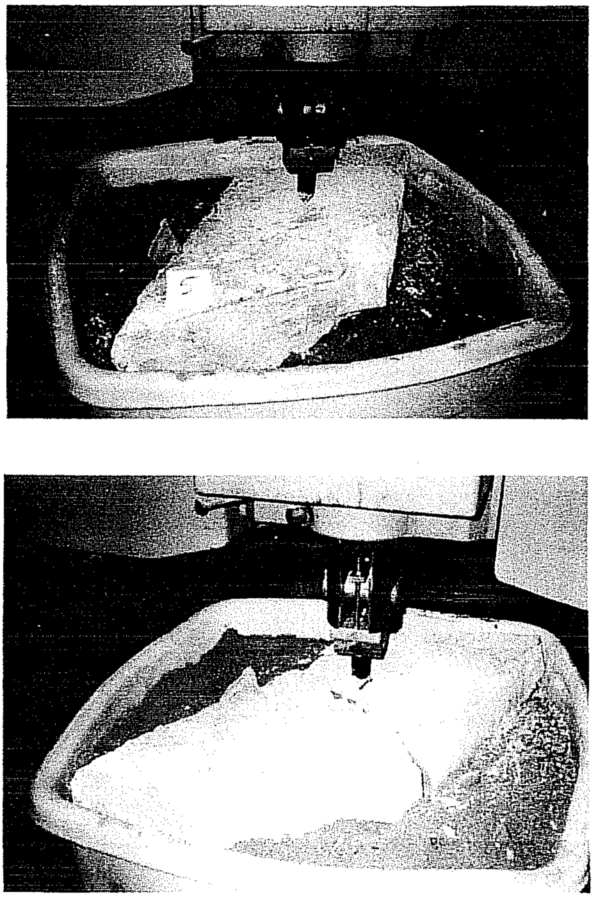

Figure 7. Example of first set of experiments (see Figure 4): before (top) and after (bottom) experiment.

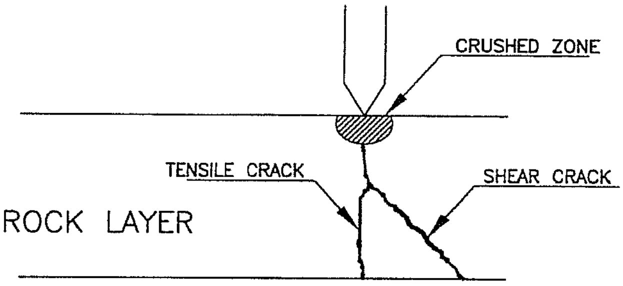

Figure 8. Schematic overview of fracture mechanism (second set of tests).

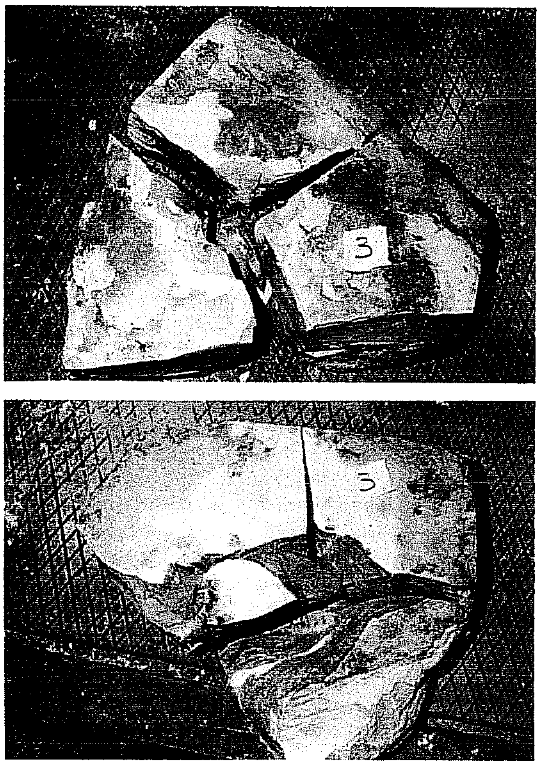

Figure 9. Example of second set of experiments (see Figure 5): top view (top) and bottom view (bottom) of fractured rock.

During this process the rock cone is further destroyed. On Figures 9 and 10, the tensile fractures and the rock cone surface can be well observed.

During the experiments of the second type, the cover of sand was smaller than in-situ and the possibility of a vertical movement of the rock due to deflection is not eliminated. Hence, tensile fractures are much easier induced. Therefore a third set of experiments was conducted, in which the stones were placed on a layer of cement (thickness of 8 cm) and surrounded by cement. The stones were again covered by a sand layer of 0,6 m. Three experiments were carried out. In the first one, cement with an UCS-value of 50 MPa was used and the rock layer had a thickness of 8 cm. The cone penetrated the rock and a tensile failure occurred at a force of 12,5 ton. Without further penetration of the cone, additional fractures were induced at a force of 15 ton. After that the force was increased to 20 ton, but no further vertical movement took place. By pumping the cone could penetrate a few millimeters further but the rock was not holed through. The bottom part of the rock was not damaged or affected by this action. For the next two tests a weaker cement was used (UCS of 15 to 20 MPa). In one of these two tests similar

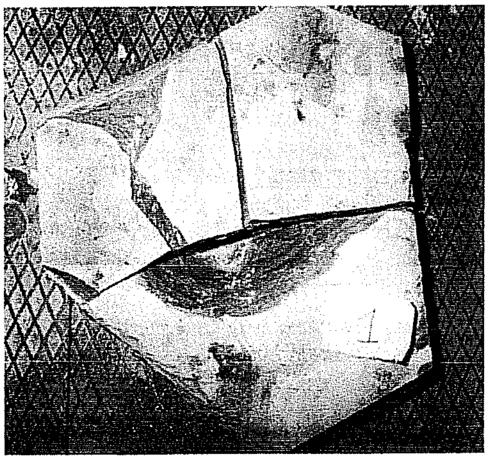

Figure 10. Example of second set of experiments (see Figure 5): bottom view of fractured rock.

observations were made, but in the other the rock was perforated and a maximum force of 13 ton was recorded. The material of the rock in the latter test was, however, weaker as the chalk content was larger.

2.2 *Numerical simulations*

To better understand the laboratory experiments, some numerical simulations were conducted using the finite element method. Only the situation before fracture initiation was considered. The main aim was to calculate the order of magnitude of the stresses present during such experiments and to verify the failure mechanisms as discussed above. For details of the simulations, reference is made to Nulens, 1996.

First of all the simulations confirm the possibility that tensile fractures are induced along a vertical plane below the cone. For example for a 20 cm thick rock layer at a depth of 10 m, the maximum tensile stress calculated was 5,7 MPa for an applied force of 10 ton. In other words for the rock material tested with a tensile strength between 3 and 5 MPa, the rocks are splitted when the force reaches the 10 ton level.

3 CONCLUSIONS AND DISCUSSION

The investigation presented in this paper shows that a systematic and scientific approach of a practical problem in geotechnics can result in additional information on the failure mechanisms occurring in-situ. The study shows that during cone penetration tests (CPT) it is possible that a rock layer or any other rock material is not detected in a distinct way on a sounding diagram. The failure mechanism related to the perforation of rocks is however complex. First of all, under the cone the rock is crushed. Secondly, a vertical tensile failure is induced throughout the rest of the rock. And finally, if a certain degree of freedom of movement is allowed, the cone pushes a cone or half a cone of rock material out of the rock. The latter happens by means of shear fractures.

This research cannot be considered to be final. The authors consider the presented results rather as a first step. As well by conducting more experiments in laboratory, as by conducting more simulations, numerous parameters can be investigated, which all should result in a better understanding. But apart from these experiments and calculations, detailed in-situ observations are also required. While a good parametric study can only be conducted in a laboratory environment or on a computer, the in-situ observations are necessary to check the results of the simulations and if necessary to improve them. The in-situ observations are not simple and are time consuming. To determine the fracture mechanisms in-situ, the soil around a perforated rock should be excavated with great care. As such, th number of in-situ observations will be limited.

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