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Application of the needle penetration test to a calcarenite, Maastricht, the Netherlands

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ABSTRACT

In this paper, first, the needle penetrometer test is briefly presented and experience gained, mainly in Japan and Turkey, with a model manufactured in Japan is reviewed. Second, the needle penetrometer test is used successfully to distinguish qualitatively carbonate sands from very weak and weak calcarenites in borehole cores recovered for cut-and-cover tunnel projects in Maastricht. Third, the relation between UCS and needle penetration resistance (NPR) for the Maastrichtian limestones is further analyzed. Needle penetration tests are conducted with the help of a loading frame. Results suggest that there is a statistically significant relationship between the UCS and NPR, that leaves however to high predictive uncertainty. During testing, very high compressive and shear stresses develop under the needle and stresses normal to the needle shaft increase. Microscopic observations show the extent of grain crushing and compaction ahead and around the needle. Nevertheless, resistance to needle penetration and UCS values are somehow related. The needle penetrometer is recommended as an index test rather than a way to determine accurately the UCS of the Maastrichtian limestones.

1. Introduction

The needle penetrometer test is a non-destructive test that has been designed to provide quick and cheap strength estimation for extremely weak to strong rocks, with minimum preparation of the material tested. The most common model is the SH-70 penetrometer (Figure 1, left) manufactured by Maruto Corporation, Ltd, Tokyo, Japan (http://www.maruto-group.co.jp/products/rock_asphalt/SH-70.htm). The test equipment and procedure have been presented by Erguler and Ulusay (2008). The equipment is housed in a light weight portable device and consists primarily of a 0.84 mm diameter needle which can be pushed slowly into a rock. The penetration force is recorded as function of the penetration depth. In weak and saturated rocks, the needle can penetrate up to a maximum depth of 10 mm whereas in hard rock, maximum allowable penetration force is set to 100 N before the needle penetrates for 10 mm. The 100 N threshold protects the thin needle from buckling. After slowly pulling out the needle, both the load and penetration depth are read from the needle penetrometer. The needle penetration resistance (NPR_M) is obtained by dividing the penetration load, i.e., 100 N or, the maximum load at a penetration depth of 10 mm, by the penetration depth, i.e., the penetration depth at a penetration load of 100 N or, respectively 10 mm. The resolution of the load and penetration depth measurements is 10 N and 1 mm, respectively. In the literature, NPR_M is also named needle penetration hardness and needle penetration gradient.

The needle penetrometer is a versatile tool. It can be used, in any direction, both in the field on outcropping rocks or loose blocks and in the laboratory on borehole cores. When a block or core sample is tested in laboratory, it must be clamped to prevent its movement and the rock surface that is perforated must be smooth. If needed, asperities are sanded or cut off. The test requires neither sample preparation nor stringent conditions on sample size and shape. When carrying out needle penetrometer testing, it is recommended to repeat readings between 3 and 10 times and calculate the mean of the readings for each specimen.

The needle penetrometer test has been developed to overcome shortcomings of index strength tests such as the point load, indentation hardness, Schmidt hammer, (ISRM, 2007) Block Punch (van der Schrier, 1988; Ulusay et al., 2001; ISRM, 2007; Sulukcu and Ulusay, 2001) and equotip hardness (Verwaal and Mulder, 1993; Aoki and Matsukura, 2008) tests. It operates successfully, according to the manufacturer on extremely weak and/or very weak rocks where the point load, indenter, Schmidt hammer and the equotip do not (Figure 2). Contrary to the block punch strength test, the needle penetration test does not require the fabrication of a thin disk. In clayey rocks sensitive to water and rocks prone to fracturation during sample fabrication, the needle penetration test is probably the most adequate strength estimation test (Erguler and Ulusay, 2008).

The performance of the needle penetrometer at predicting the strength of various rock types, mainly sedimentary and volcanic rocks ranging from very weak to strong, has been reported in the

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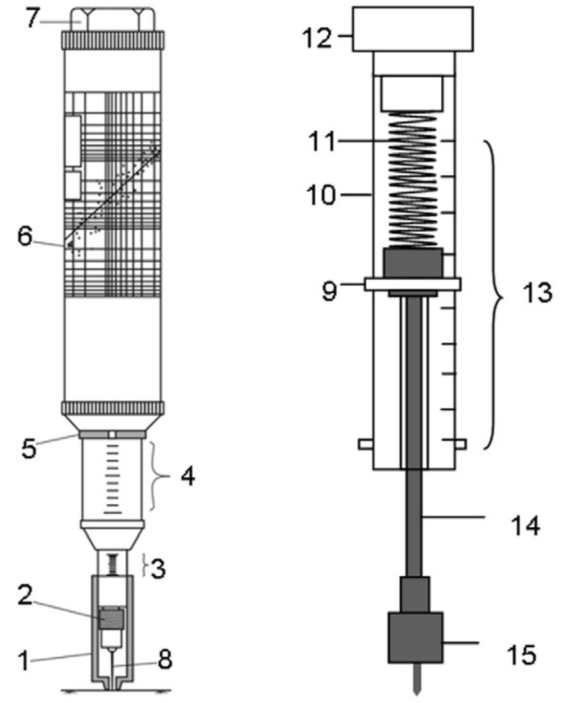

Fig. 1. General view of the Maruto (left, from Erguler and Ulusay (2008)) and modified Eijkelkamp (right) penetrometers and their parts. (1) presser, (2) chuck, (3) penetration, (4) load scale, (5) load indication ring, (6) UCS–NPR correlation chart given by the manufacturer, (7) removable cap, (8) penetration needle produced according to the Japan Civil Engineering Society's guideline, (9) indicator ring, (10) penetrometer tube, (11) spring, (12) end cap, (13) scale, (14) extension rod, and (15) needle block.

literature for a variety of applications ranging from structural mapping (Kawamura et al., 2009) to rapid strength prediction for dam foundation (Yamaguchi et al., 1997 and Yamaguchi et al., 2004) and tunnel support (Okada et al., 1985), quality control of construction material, estimation of weathering profiles and weathering rate (Hachinohe et al., 1999; Oyama and Chigira, 1999) and sample quality (Okada et al., 1985).

UCS can be estimated from NPR_M readings using the correlation introduced by the SH-70 manufacturer (Maruto Corporation, 2006):

$$\log UCS = 0.978 \log (NPR_M) + 2.621 \quad (1)$$

where UCS is expressed in kPa and NPR_M in N/mm.

Eq. 1 was established for natural and artificial stones with UCS values ranging from 0.3 to 40 MPa (Maruto Corporation, 2006). Yamaguchi et al. (2005) quoted variations of Eq. 1 that have been developed for other data sets by Japanese researchers (Okada et al., 1985), (Ref. 3 and Ref. 5 in (Yamaguchi et al., 2005), all except one with a r above 0.87 (Figure 3). Erguler and Ulusay (2008, 2009) measured NPR_M on thinly bedded and clay-bearing rocks, marls and tuffs and proposed a power relation between the UCS and NPR_M values that fits their data, all with UCS in between 1 and 35 MPa, combined with the Maruto Corporation calibration data set.

$$UCS = 0.51\ NPR_M^{0.8575} \quad (2)$$

where UCS is expressed in MPa and NPR_M in N/mm. This correlation has a r of 0.87.

UCS values predicted by Eqs. 1 and 2 up to 5 MPa show a negligible difference (Figure 3). Nevertheless, the predictive capability of both relations is reduced in this strength range as NPR_M values are widely spread for very weak and extremely weak rocks. As NPR_M reaches its upper limit, 100 N/mm, the relative difference between both UCS predictions increases to 30%.

Hachinohe et al. (1999) and Oyama and Chigira (1999) used NPR_M as an indicator of weathering, but did not convert it into a UCS value.

Rock type and especially, mineralogy and grain size are expected to affect NPR readings and spreading. Analogous to cone penetration testing, scale effects are anticipated when the ratio of needle diameter to grain diameter is below 6 to 10. Grain crushing is likely to occur when carbonate rather than quartzic rocks are tested. NPR results from coarse rocks such as conglomerates obtained by Takahashi et al. (1998); from Osada et al. (2005) are questionable. For pyroclastic fall and flow deposits with a UCS less than 2 MPa, Yamaguchi et al. (1997) fitted a relation that plots below the relations established by Erguler and Ulusay and Maruto Corporation (Figure 3).

In this paper, the performance of the needle penetration test for indirect estimation of the UCS is investigated for extremely weak to very weak (according to ISRM, 2007) carbonate materials originating from the same geological formation, the Maastrichtian limestones. In addition, needle penetrometer values have been measured on borehole cores recovered during the site investigation of a tunnel. The data are used to identify objectively carbonate sands, very weak and weak calcarenite. The presence of thick sand bodies in the borehole cores is tentatively related to faulting. Sand is assumed to result either from the destructuration of the calcarenite subjected to high tectonic stresses during faulting or from the weathering of the calcarenite by high ground water flowing through the fault zone. A modified version of the 06.06 surface hand penetrometer, which is a name of equipment manufactured by Eijkelkamp, the Netherlands (http://www.eijkelkamp.com/Portals/2/Eijkelkamp/Files/P1-53e.pdf) is used instead of the Maruto penetrometer (Figure 1, right). The standard Eijkelkamp cone has been replaced by a short needle made of hardened steel. Needles with a diameter of 1 or 1.4 mm and with a flat or a conical tip are available. It should be noted that their conical part (if any) is less than 1.3 mm long while the shaft of the Maruto needle increases slowly from 0 to 0.84 mm diameter over about 10 mm. The needle of the Eijkelkamp penetrometer is pushed until a constant compression of the spring is observed or the maximum needle penetration (8.5 mm) is reached. The spring compression is read with the help of an indicator ring on the millimeter scale of the penetrometer. The maximum spring compression is 8.5 cm. By similarity with cone tip resistance, the needle resistance, NPR_E is calculated by multiplying the spring stiffness by the observed spring compression and by dividing the calculated force by the needle cross section. The sensitivity of the Eijkelkamp penetrometer can be optimized by adjusting the spring stiffness. Springs with a capacity of 50, 100, and 150 N are available. Contrary to the Maruto penetrometer, the Eijkelkamp penetrometer does not allow the simultaneous measurement of the load and penetration depth.

2. Description of the studied material and application of needle penetration in a tunnel

This section explains how needle penetration testing contributed to the lowering of geo-risks associated to the construction of the A2 cut-and-cover tunnel in Maastricht, the Netherlands through the Maastrichtian limestones. The A2 motorway will be buried in Maastricht, in order to reduce traffic congestion and improve quality of urban life. The building pit will be excavated in dry conditions between sheet piling walls. Groundwater will be pumped out of the excavation pit using a deep well dewatering system. The presence of a thick layer of gravels overlaying the limestones and chert layers within the limestones will prevent sheet pile driving. The sheet piling walls will be inserted and cemented inside slurry trenches excavated with the help of a grabber and a rock breaker. First, the geology of the Maastrichtian limestones is briefly outlined. Then, difficulties associated to tunneling through these formations are listed and the necessity to perform a varied and intensive site investigation to evaluate these difficulties is highlighted. Finally, focus is put on the clustering of the A2 cores based on needle penetrometer resistance values in