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Needle penetration test: Evaluation of its performance and possible uses in predicting strength of weak and soft rocks

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ABSTRACT

High quality core samples recommended by testing standards or suggested methods for uniaxial compressive strength (UCS) determinations cannot always be obtained particularly from soft, weak-to-very weak and clay-bearing rocks. Due to this difficulty, some simple and cheap index test methods have been developed in order to indirectly estimate the UCS. However, preparation of smaller samples from such rocks even for some index tests is also difficult. In addition, sampling from historical sites, monuments and buildings for strength determinations in rock engineering studies is not allowed. To overcome these difficulties, a new and portable light-weight testing device, Needle Penetrometer (NP), has been developed in Japan. But there is no any standard or suggested method available for this test. It is a non-destructive test applicable both in the field and laboratory with minimum sample preparation. The use of NP was mainly concentrated on predicting the UCS of soft and weak-to-very weak rocks from the Needle Penetration Resistance (NPR) in Japan and more recently in Turkey by the authors, and a few empirical relationships between the UCS and NPR have been developed by some investigators. This most recent study aims to provide some new contributions to previous works on the NP test, to assess the performance of the test and to develop a more generalized empirical relationship for indirect estimation of the UCS from NPR based on the data obtained from a wider range of soft and weak-to-very weak rocks. In addition, the effect of penetration rate on test results was investigated and the possible uses of the NP test in geo-engineering with the recommendations of the authors were also briefly discussed. For these purposes, a database consisting of a total of 725 UCS–NPR data pairs from the previous studies of the authors and those from the investigators in Japan and additional new tests carried out in this most recent study was established. The experimental results suggested that the rate of penetration had no effect on the test results. This finding makes the use of NP advantageous both in the field and laboratory. Statistical analyses reveal that based on the database used, there is a significant relationship between UCS and NPR at the 95% confidence level and the UCS values predicted from the model recommended in this study show the best agreement with those experimentally determined when compared to those obtained from the existing models. Particularly 70% of the UCS predicted from this model fall into approximately ±7% scaled percent error. It was concluded that the NP tests can be applied to soft and weak-to-very weak rocks with UCS of up to 40 MPa to predict the UCS from NPR, however, its use on rock types consisting of coarse grains embedded in a cementing material, such as conglomerate, should be avoided.

1. Introduction

Unconfined compressive strength (UCS) is the most widely used property for the classification and characterization of rock material. It is also an important input parameter in rock mass classification methods and various design approaches. However, based on the standards and suggested methods such as ASTM (2000) and ISRM (2007), respectively, the UCS test requires high quality specimens. Therefore, the need for accurate preparation of the test specimen and heavy test equipment makes the UCS test expensive and difficult to perform in the field. In addition, core samples with suitable length-to-diameter ratios recommended by the standards and suggested methods cannot always be obtained particularly from weak, stratified and fractured rocks. Amount of time and labor necessary for sample preparation is another aspect of the UCS test. Therefore, time and effort has been expended in the past to develop simple, inexpensive and portable test equipment and associated strength indices for indirect estimation of the UCS of rock materials.

The Point Load Test (PLT) (Broch and Franklin, 1972; ISRM, 2007) is a well known strength index test and core samples or small irregular lumps of rock can be used. However, the test is confined to a

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specific field setup. It is customary to convert the point load strength index ($I_{s(50)}$) to an equivalent UCS by multiplying by a factor, k. Point load testing by Read et al. (1980) has shown that the factor k varies with both rock type and degree of weathering. Norbury (1986) and Topal (2000) also reported that a wide scatter of values of k ranging between 13 and 50, and 3 and 68, respectively, had appeared in the literature although there was an accumulation of values between about 16 and 24. It is now agreed that the suggested k value of 24 (Bieniawski, 1975) cannot be universally applied because it could lead to large and unacceptable errors in predicting the UCS.

The other equipment, widely used for the indirect estimation of UCS, the Schmidt hammer (SH), is a portable device (ISRM, 2007; Aydin, 2009). However, its high impact energy applied to rocks makes it less suitable for weak and extremely weak rocks. The Equotip hardness tester (EHT) which was originally developed in the field of metallurgical engineering, as an indirect method to predict the UCS of rock material, is another index test and a relatively new product (Equotip, 1977; Verwaal and Mulder, 1993). It is an electronic battery operated, spring loaded device. Aoki and Matsukara (2008), who carried out some tests using EHT and combined their data with those from Verwaal and Mulder (1993), suggested that the optimum correlation between UCS and Equotip hardness (EH) can be obtained by comparing the UCS measured with the UCS calculated by taking into account both the EH value and porosity, although a fairly good correlation was found between UCS and Equotip L-values obtained using the Single Impact Method and UCS. These investigators also considered that the EHT has a number of advantages over the Schmidt hammer. In addition, Meulenkamp and Alvarez Grima (1999) used a neural network for the prediction of UCS from Equotip hardness test on rock samples. These investigators used a dataset containing 194 rock sample records, varying from weak sandstones to very strong granodiorites, and trained the network to predict the UCS based on hardness, porosity, density, grain size and rock type information of rock sample. They concluded that using neural networks to predict the UCS of rock samples has some benefits compared to statistical predictions. But no standard or a suggested method has been recommended yet for the EHT.

Another simple index test method, first developed by Schrier van der (1988) and then based on some modifications accepted as an ISRM suggested method (Ulusay et al., 2001; ISRM, 2007), is the Block Punch Index (BPI) test. The BPI test is intended as an index test for the strength classification of rock materials and also used for predicting some strength parameters with which it is correlated, for example uniaxial compressive and tensile strengths. The test can be performed with a portable apparatus mounted to point load device, and so may be conducted both in laboratory and field if the facilities for cutting the specimen into small disks are available.

The abovementioned simple and inexpensive index tests have been mainly recommended for the estimation of the UCS of rock materials. However, preparation of suitable test specimens from weak-to-very weak and soft rocks is also difficult even for some of the abovementioned index tests. Such rocks, particularly clay-bearing rocks, heavily disintegrate due to wetting–drying and freezing–thawing processes within a relatively short time and are highly prone to weathering and often coring process and/or preparation of small specimens breaks up the weaker sample pieces, and they are too thin or fragmented even to be used for index tests. In addition, in the world, there are a huge number of natural and man-made historical rock structures and monuments or buildings. Geo-engineering and/or restoration studies at such structures may sometimes require the determination of strength properties. But samples from these ancient sites, under protection, necessary for strength determinations are not allowed due to the reasons for preservation, environmental and others, and this restriction results in a gap related to strength determinations. Due to the abovementioned issues, there is a need for a non-destructive and portable test device that can be used both in laboratory and field to estimate the strength of weak-to-very weak and soft rocks and artificial cement-based materials. For this purpose, a

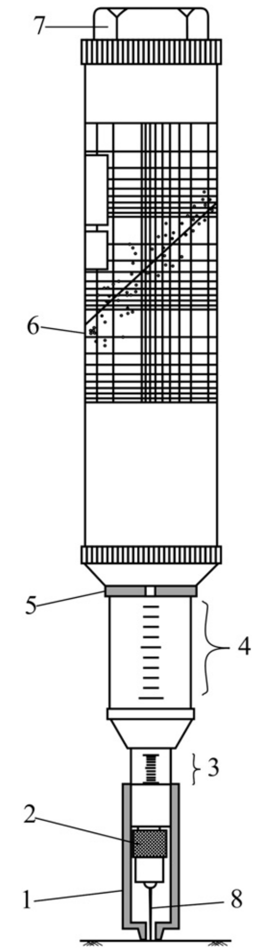

Fig. 1. Needle Penetrometer manufactured by Maruto Co. Ltd. (2006) and its parts: 1. presser, 2. chuck, 3. penetration scale, 4. load scale, 5. load indicating ring, 6. UCS–NPR correlation chart, 7. removable cap, and 8. penetration needle.

non-destructive portable testing device, called Needle Penetrometer (NP), has been developed in Japan in the eighties. This device is used to estimate the UCS from the Needle Penetration Resistance (NPR) quickly and inexpensively with minimum sample preparation. Any standard or suggested method for this test has not been recommended yet.

Mostly, the references to the NP test were in papers written in Japanese. The earliest reference to NP test was cited in the instruction manual of the manufacturer of the NP (Maruto Co. Ltd., 2006). This document mentions that the NP was designed for measuring the penetration of soft rock in accordance with the penetration testing method specified in the Japan Civil Engineering Society's "Guideline for Examination and Testing of Soft Rock (January, 1980)". In addition, JGS (2004) mentions that the NP testing method is applicable to soft rocks having UCS less than 10 MPa according to the recommendations of JSCE (1991). The use of the NP is mainly concentrated in the studies by the investigators from Japan (Okada et al., 1985; Yamaguchi et al., 1997; Takahashi et al., 1998; Naoto et al., 2004) on the performance of the NP test for the indirect prediction of the UCS from the NP. For this purpose, these investigators used NP manufactured by Maruto Co. Ltd. (2006) on weak-to-very weak sedimentary and volcanic rocks and artificial cement-based samples. More recently, Erguler and Ulusay (2007, 2009) carried out a series of NP and UCS tests on a total of 120 specimens of weak clay-bearing rocks (marl, mudstone, siltstone and tuff) for UCS and NPR determinations using a NP device manufactured by Maruto Co. Ltd. They combined