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Nondestructive Testing of Stabilized Soils and Soft Rocks via Needle Penetration

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TECHNICAL NOTE

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Abstract
Assessing the strength of hard soils and soft rocks is a pressing issue in geotechnical investigations, since high quality core samples recommended by testing standards for strength determinations cannot always be achieved. As a solution, a lightweight, non-destructive testing device, Needle Penetrometer (NP), was developed in Japan. It is not well known and standardized in other parts of the world. No sample preparation is required, and it is applicable both in the field and laboratory with minimum surface conditioning. This study aims to provide some new contributions to previous works on the NP test, including new rock types and stabilized soils. For these purposes, unconfined strength (UCS) and needle penetration resistance (NPR) values were determined for compacted clays, lime and cement stabilized clays, micritic tufa, microdetrital tufa and pumice. A database consisting of a total of 108 UCS–NPR data pairs was established. Regression analyses reveal that, there is a significant relationship between UCS and NPR. It is concluded that the NP tests can be applied to stabilized soils and soft rocks with UCS of up to 30 MPa to predict the UCS from NPR.

Keywords
needle penetration test, unconfined strength test, soft rock, stabilized soils

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1 Introduction

Hard natural soils, stabilized soils and soft rocks are intermediate geo-materials between a hard rock and a soil. They include hard clays and clay-shales, hard residuals soils, lime stabilized clays, cement stabilized soils, soft sedimentary rocks (mudstones, claystones, marls, shales, tufas and weak limestones), weak pyroclastic rocks (tuffs, pumices), weakly cemented sandstones and very weathered hard rocks. A rock material can be classified as a soft rock if it has a UCS between 1 MPa to 20 MPa [1]. Soils with a UCS higher than 400kPa are classified as hard soil. Compaction causes reduction of soil volume, and hence void ratio, without variation in its solid content. Stabilization of soils with additives can improve mechanical properties up to seven times higher than that of non-stabilized soil [2]. Chemically stabilized soil behaves more like soft rock than hard soil, because it gains tensile strength.

UCS is one of the most important parameters for characterization of geo-materials. Standard testing methods such as ASTM (2002) [3] and ASTM (2013) [4], requires high quality cylindrical samples. Moreover, heavy test machines are needed. Core samples with suitable length-to-diameter ratios recommended by the standards may not be obtained from hard soils and soft rocks. To overcome these difficulties, some predictive models utilizing some simple index parameters, such as point load, ultrasonic wave velocity and Schmidt hammer tests, were developed in order to estimate the UCS indirectly. However the Point Load Test [5] can be performed on small irregular lumps of rock, it cannot be classified as non-destructive. Moreover, the regression is widely scattered [6] and regression equation is dependent on rock type and degree of weathering [7]. The Schmidt hammer [5], which is widely used for the indirect estimation of UCS, is not suitable for soft rocks, because its high impact energy may cause indentation instead of rebound. Ultrasonic test is portable and non-destructive approach for UCS estimation. However, the ultrasonic pulse velocity values are affected by surface irregularities of rock, micro-cracks and discontinuities, moisture content and porosity [8]. The Pocket Penetrometer was defined by OSHA [9] for soil strength predictions, during evaluation of stability and safety of trench excavations. Eventhough it is a practical measuring tool for providing approximate values of UCS quickly, maximum reading of the penetrometer is 450 kPa.

Maruto Corporation (Japan) introduced the Needle Penetrometer (NP) for indirect estimation of the UCS of soft rocks. As opposed to the pocket penetrometer, the needle penetrometer has a sharp needle probe that is pushed into the geo-material. The main difference between this device and the pocket penetrometer is that the estimated strength was not shown directly in this instrument. Instead, it came with a formula to convert the needle penetration resistance (NPR) to the standardized UCS measurements. NPR is obtained by dividing the applied force in Newton (N) by the penetration in millimeter. As penetration causes a local damage in small volume, the test is said to be non-destructive. In general, the NP is best suited for field use on weak to very weak rocks [10]. The Japanese Geotechnical Society [11] suggested the NP testing for rocks having a UCS less than 10 MPa. Rock type, mineralogy and grain size are likely to affect NP readings [12]. As the damage caused by the needle penetration is negligible, the device can also be used to assess the properties in archeological remains [13]. It has been widely used in many engineering projects in Japan, however, it is not well known in remaining parts of the world. Outside Japan, some groups, specialized in soft rocks from Turkey, Holland, Spain, and Korea [14, 15, 16] studied the use of this device. ISRM suggested this device for indirect determination of UCS, in 2007–2014 year book [5]. There are similar needle penetration devices in the literature. Ngan-Tillard et al. [15] modified Eijkelkamp Hand Penetrometer [17] to use for penetration of soft rocks. The standard Eijkelkamp cone was replaced by a short needle, which is made of hardened steel. 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. Contrary to the Maruto Penetrometer, the Eijkelkamp Penetrometer does not allow the simultaneous measurement of the load and penetration depth. Heidari et al. [18] mounted a dial gauge to the end of the Eijkelkamp hand penetrometer to measure the penetration depth. However, due to the distance between the needle and the dial gauge tip, resolution is questionable.

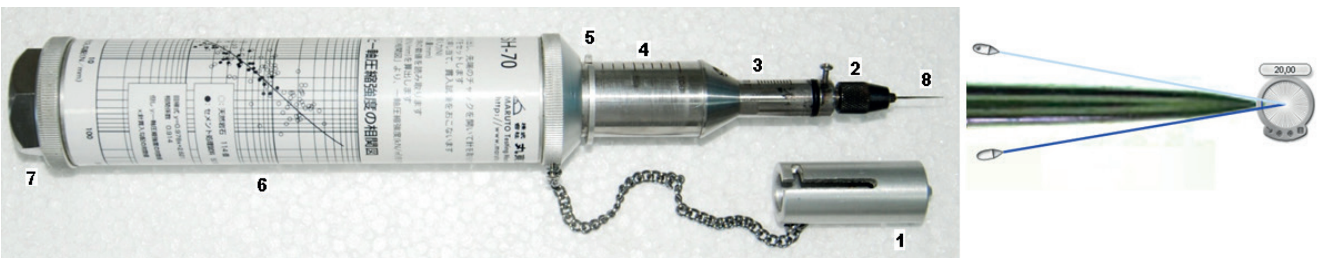
In this paper, a brief description of the needle penetration test and definition of the needle penetration index (NPI) is given, previous works were briefly evaluated, a new database was established based on new laboratory test results, and an empirical relationship was developed to estimate the UCS from NPR stabilized soils and soft rocks. Attempts were made to contribute literature on the application of the NP test in some geo-materials, including compacted soils, chemically stabilized soils, soft tufa facies and pumice.

2 NP device and test method

Needle Penetration device (Model SH-70) manufactured by Maruto Co. Ltd. (Japan), was used in this study (Fig. 1A). The needle used in the device is a thin, sharpened cone with a minimum diameter of 0.03 mm, a maximum diameter of 0.84 mm. The cone tip angle is 20° (Fig. 1B), and back of this tip along 10 mm the angle is 2.5°. It is a Japanese Industrial Standard (JIS) S3008 needle for cotton thread No. 5, which is cut to 40 mm. This is one of the disadvantages, because it is hard to supply spare needles outside Japan. Then, Hijnekamp [19] investigated the usability of needles which can be supplied easily in the European market, without a large deviation from the Maruto needles. Chenille 22 needle having 0.86 mm diameter was found to be the closest one of Maruto needles.

No sample preparation or strict sample shape conditions are required. The only requirement is that the surface of the material should be smooth, and if not, it should be smoothed by using a sander or grinder. When core sample is tested, it must be fixed to get reaction to apply force. Ulusay and Ergüler [14] reported that the rate of penetration had no effect on the test results, and this finding makes the use of NP advantageous both in the field and laboratory.

Principle of measurement is simple; the needle is pushed slowly into a material applying a load on the spring dynamometer on which the needle is attached. The NP can be used in any direction. The maximum depth of penetration is 10 mm and when this value is reached the loading is stopped and the force value (F) is read from the load scale. When the material is harder, the force value reaches to 100 N before the needle penetrates 10 mm, then the penetration value (D) is recorded. The NP test is carried out on the same surface between 3 and 10 times, and the Needle Penetration Resistance is calculated



A B

Fig. 1 A) Maruto SH-70 Needle Penetrometer; 1) presser, 2) chuck, 3) penetration scale, 4) load scale, 5) load indicating ring, 6) correlation diagram, 7) removable cap, and 8) penetration needle (Maruto 2006), B) Close up view of the needle as NPR = F/D. The unit of NPR is N/mm. The mean value represents the NPR of the sample. Okada et al. [20], Yamaguchi et al. [21], Takahashi et al. [22], Ergüler and Ulusay [23–24] and Uchida et al. [25] developed empirical relationships between UCS and NPR for soft rocks. There are a number of factors affecting the needle penetration test method, such as, calibration and malfunction of the instrument, rock surface irregularities, surface moisture content [14], spacing between penetration points, surface weathering [26, 27] and sample disturbance. The NPR parameter reflects the strength of thin crust of the material; hence a considerable uncertainty arises from the scale effect and heterogeneity.

3 Needle penetration mechanism

Researches about the mechanism of penetration of a sharpened rod into a softer medium go back to early 40's, especially to contribute to hardness testing. A mechanical model for indentation of ductile materials by cylindrical punches with conical heads was developed by Bishop et al. [28]. They proposed that the pressure required to expand a cavity into a material is proportional to the pressure to expand a cavity of the same volume. The developed model was named as cavity expansion model. The model account for both elastic and plastic soils, and has been applied to many practical problems of geotechnical engineering, such as pressuremeter test, cone penetration test and installation of driven piles. The spherical cavity expansion model was applied to estimate cone and pile end resistance [29, 30]. Pressuremeter test was interpreted by using the cylindrical cavity expansion model [31, 32].

The needle used in the Maruto device has two slopes. Therefore, 20° tip cone penetrates into the material according to spherical cavity expansion model. On the other hand upper portion of the needle has low angle, and obeys cylindrical cavity expansion model (Fig. 2A). Initial deformation caused by the initial conic tip. Low sloped longer portion has a secondary function, which is the displacement of failed chips laterally in brittle materials, and further compression in porous materials. At the beginning of penetration, indentation of sharp cone of the needle result in spherical pressure distribution. This pressure distribution causes to increase of compressive stress downward, and increase of shear stress laterally. In brittle materials this indentation results in shear failure, whereas compression in porous materials. As the needle penetrates deep inside a material, increased confinement reduces shear failures, then after some compression, the penetration stops. Similarly, compression in porous materials increases the density, then, strain hardening character of the material makes penetration harder. Fig. 2B shows computer tomography (CT) image of needle penetrated soapstone [16]. The drawing below the CT image is an interpretation by the author. Chipping due to shear failure is dominant at upper portion. As penetration depth increases, increased strength due to increased confinement prerevents further failure.

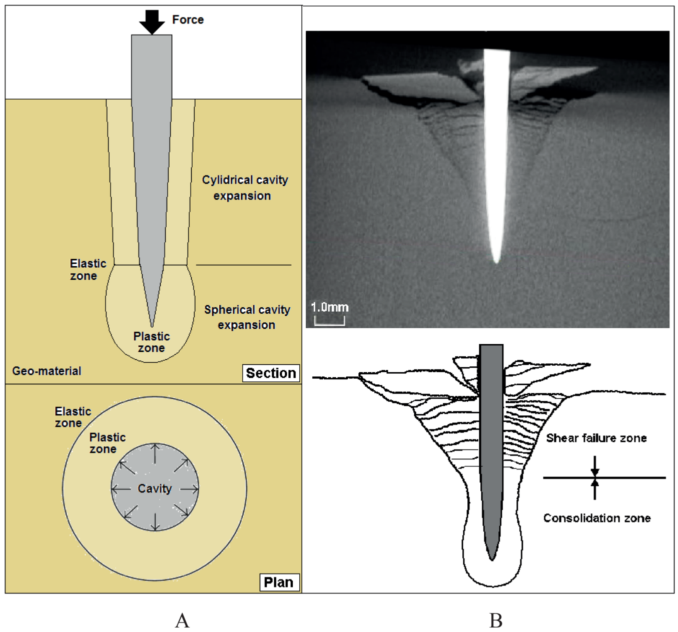


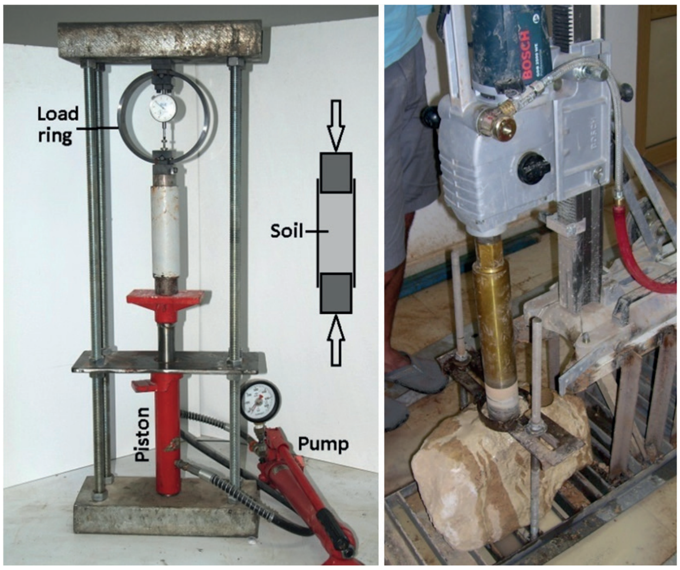
Fig. 2 A) Cavity expansion model for needle penetration, B) Computer tomography images of needle penetrated soapstone [16] (below drawing is an interpretation of the author)

4 Experimental studies

Laboratory tests were performed on six groups of geo-materials. The first three are stabilized soils; 1) compacted clay, 2) lime stabilized clay, and 3) soil-cement mix. Remaining samples are soft rocks; 4) micritic tufa, 5) microdetrital tufa, and 6) pumice.

Red and gray clays, used in soil stabilization, were obtained from Antalya (Turkey) city center. Gray clays are abundant in Bogacay coastal plain. These are silty clays of lagoon origin [33]. Red clays (terra-rossa) are residual soils observed on top of carbonate rocks in Antalya [34]. In preparation of the first group samples, soil samples were compacted using a static compaction device (Fig. 3A) at 1379 kPa which is a static equivalent of Standard Proctor [35]. Optimum water content values were estimated using Atterberg limits and according to [36]. In lime stabilized soils, hydrated lime contents were in between 2% to 8% of dry soil mass. 1% additional water was added to the lime-soil mixture for every 1% increase of lime content, to facilitate mixing and uniform distribution of the hydrated lime in the soil. Lime stabilized samples were wrapped with stretch film and left for 28 days curing period in an airtight chamber. In soil-cement mix samples, cement contents were in between 100% to 300% of dry soil mass, and water contents were in between 130% to 400% of dry soil mass. Gray clay and Type I Portland cement (CEM I) were first dry mixed in a cement mixer, then water added. Due to high water content, cement-soil mixed samples were not compacted, instead, they were molded in cylindrical PVC molds. The samples were cured 7, 14 and 28 days before the tests.

Two groups of soft rocks were obtained from Antalya tufa. Antalya Tufa is a carbonate rock which is deposited physico-chemically under cool water regime. Dipova [37] reported 1-100 MPa uniaxial strength for 8 different facies. Two facies of Antalya Tufa, which are clastic and micro-clastic tufas, are soft rocks. Clastic tufas are originated from mainly fluvial origin and related with flood seasons, whereas micro-clastic tufas are related to deposition in tufa pools [34]. The third group of soft rocks was obtained from Gölcük Volcanics (Isparta-Turkey). The Gölcük Volcano is located immediately South of Isparta city (Turkey). There is a large crater partly occupied by a lake and surrounded by a thick cone of pyroclastic deposits, mainly pumice. The pumice samples are highly porous and thereby have low density. These three groups of soft rocks were obtained as block samples from the field and using core drilling machine (Fig. 3B), core samples having 54mm diameter and 110mm height, were prepared.



A B

Fig. 3 Sample preparation, A) Static compaction, B) Soft rock coring

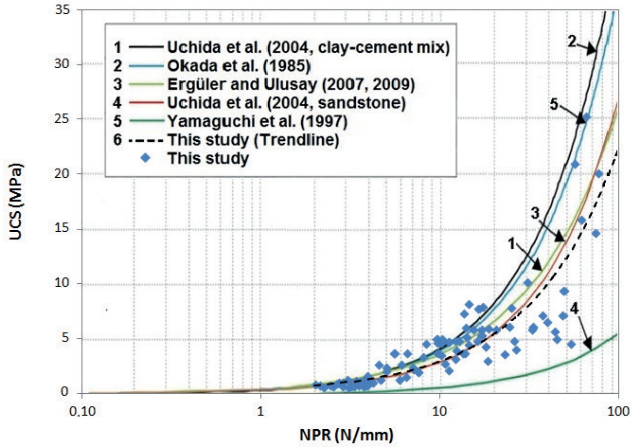
NP tests were performed at both top and bottom ends of cylindrical core samples. The circular area was divided into four approximately, and penetrations were performed at equal distances. Hence, for one sample eight measurements were taken, and the mean value was accepted as NPR. After needle penetration testing, unconfined strength tests were conducted to measure the unconfined compressive strength of all stabilized soil samples and rock cores using standard ASTM D2938 [3] and ASTM D2166 [4]. Rock samples were tested using hydraulic compression machine. To increase resolution, stabilized soil samples were tested on 50kN deformation controlled compression machine.

5 Results and discussion

The UCS and average NPR values were analyzed using the method of least-squares regression. Correlation between the UCS and NPR is shown in Fig. 4, and the predictive equation are given in Equation 1. Regression analyses reveal that there is a significant relationship between UCS and NPR, as expressed by a power curve, at the 83% regression coefficient.

$$UCS = 379.8 * NPR^{0.885} \quad (1)$$

where: UCS is in MPa and NPR is N/mm.



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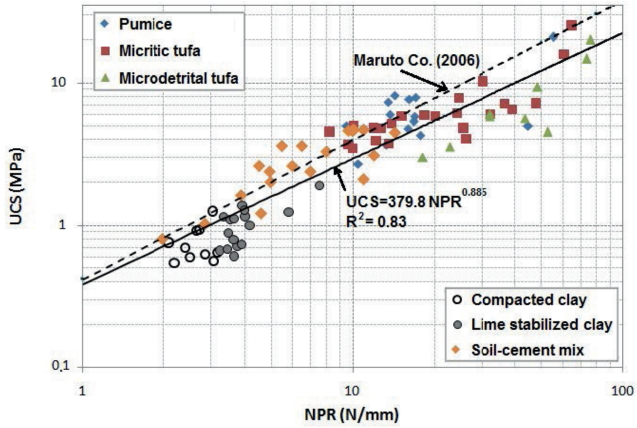

B

Fig. 4 A) Test results on semi-log scale and comparison with the previous studies, B) Test results on log-log scale and comparison with Maruto (2006) [10]

Any measurement has a degree of uncertainty associated with it. The main issue which should be regarded in needle penetration testing is uniformity of the sample. If there is doubt about sample uniformity, test number should be increased. On the other hand, large deviations between the test results may provide information about nonuniformity of the sample. Especially samples having larger grains in a matrix (such as conglomerate) are more problematic in NP testing. It can be thought that the NP test would provide the strength of matrix between larger clasts, such as block in matrix rocks, but it may be misleading if the penetration stops when the needle is stuck into a hard grain after passing a thin matrix. Mechanical properties of some geo-materials are affected from anisotropy, which is generally originate from the mineral foliation in metamorphic rocks and stratification in sedimentary rocks. Therefore, in schistose or thinly bedded rocks penetration direction should be considered.

Breaking or wear of the needle tip is always possible. Flat ended tip will eventually effect stress and stress distribution, hence NPR results. It is important to ensure that the original geometry of the needle is maintained. To verify this, a pocket microscope, such as used in the concrete crack detection, would be helpful.

Another uncertainty comes from the resolution of the loading system. Load and penetration depth values are read visually, and this makes a measurement low-resolution. The minimum resolution of the device is 10N, and values smaller than this value can only be predicted by interpolation visually. The loading system consists of a compressing spring type dynamometer. In these type systems the spring compresses in response to a force; the change in the length is measured and read as a force from markings on the scale. Spring dynamometers have three main sources of error: the measured value varies with the local gravitational force, the elasticity of the measurement spring can vary slightly with temperature, and the spring can permanently deform with repeated use. These would cause inaccurate readings resulting in misleading data. A modification, which provide force measurement via a load cell, penetration measurement via a displacement transducer, and allow automatic calibration will reduce above mentioned uncertainties.

6 Conclusions

In this study the relationship between UCS and NPI was investigated on 108 stabilized soil and soft rock specimens. The major conclusions are summarized below:

I. Research shows that the unconfined compressive strength of stabilized soils and soft rocks are a function of the needle penetration resistance. Regression analyses reveal that there is a significant relationship between UCS and NPR, as expressed by a power curve, at the 83% regression coefficient. Comparison of this relation with those in the literature, show reasonable agreement.

II. Being a light-weight, portable and simple device, the NP provides useful non-destructive site testing for stabilized soils and soft rocks. No specimen preparation other than surface smoothing is required, so it is an easy and quick test method.

III. The main limitation of the NP test method is scale effect such that the needle diameter and depth of penetration are beyond the scale of rock fabric. Therefore, the obtained UCS can only be representative for homogeneous rocks, otherwise it is representative for the outer crust of the material. Due to small diameter and sharp tip, it is not suitable for geo-materials consisting of coarse grains, such as conglomerate, or gravely soils.

IV. At present conditions, the device is manually operated, results are taken visually and recorded thereafter. Upgrade with electronic sensors, digital display and digital storage to a memory card will make the use of the device easier.

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