Reliability assessment of Needle Penetration Index for estimating compressive strength of some sedimentary rocks from the Qom Formation, Central Iran

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Abstract

In this paper, the needle penetrometer test was utilized to explore the reliability of the Needle Penetration Index (NPI) for estimating the Unconfined Compressive Strength (UCS) of sedimentary rocks including gypsum, marl, siltstone and sandstone collected from the Qom Formation. Following the UCS and NP test, regression analyses were carried out to control the predictive performances of NPI. Statistic performance indices such as determination coefficient (R^2) the Root Mean Square Error (RMSE) and Variance Account For (VAF) are calculated. Regression analyses suggest meaningful relationships between UCS and NPI, for gypsum, marl, siltstone and all rock types as whole. The results are reasonably meaningful, excluding for sandstone which NPI does match with values of UCS prediction. As NPI could only penetrate to a maximum of 10 mm depth, it is not representative of intrinsic properties (e.g. texture and mineralogy) that control their UCS. Cross-plot of UCS/NPI vs. UCS and regression analysis was carried out to overcome this uncertainty. Results obtained from this purposed approach suggest that it is more reliable than those achieved from UCS vs. NPI. The derived equations are in good corresponding with those suggested by other researchers. Additionally, control data test was applied to make sure their validation.

Keywords: *Uniaxial Compressive Strength; Needle Penetration Test; Needle Penetration Index; Qom Formation.*

Introduction

The Unconfined Compressive Strength (UCS) of a rock widely used in tunnel excavations (Bieniawski, 1976 in rock, mining works (Ozkan *et al.,* 2009), the slope stability (Okubo, 2004; Gurocak *et al.,* 2008), weathering classification (Ceryan *et al.,* 2008), petroleum engineering (Uboldi et al., 1999; Garcia et al., 2008), well bore stability (Zhang *et al.,* 2010), infrastructure projects (Barton et al., 1974; Bieniawski, 1976; Hoek, 1977), rock classification and failure criteria (Bieniawski, 1989; Dehghan *et al.,* 2010; Beiki *et al.,* 2013) etc. Determination of uniaxial compressive strength is sometimes difficult due to the required samples; while it is simply achievable via index tests such as point load (ISRM, 2007), Ultra sonic wave velocity (ISRM, 2007), equotip hardness (Verwaal & Mulder, 1993; Aoki and Matsukura, 2008), Schmidt hammer (ISRM, 2007) and Block punch (ISRM, 2007). However, preparation of suitable test specimens from weak-to-very weak, heavily disintegrated due to wetting–drying and freezing–thawing processes, highly prone to weathering and soft rocks is also difficult. Meanwhile, there are numerous natural and man-made historical rock structures and monuments or buildings which require detailed but non-destructive studies by portable test device that can be used both in laboratory and field to estimate the strength of weak-to-very weak and soft rocks. For this purpose, a cheap, simple and portable light-weight (about 600–700 g) testing device, called Needle Penetrometer (NP), has been developed in Japan. The needle penetration test is intended for the determination of the needle penetration index (NPI). The needle penetration index (NPI) is calculated from the applied load (N) to the depth of penetration (mm). The unit of NPI is N/mm. This device is used to quick estimate of UCS from Needle Penetration Index (NPI) with minimum sample preparation (e.g., Okada *et al.,* 1985; Yamaguchi *et al.,* 1997; Takahashi *et al.,* 1998; Uchida *et al.,* 2004; Aydan *et al.,* 2008; Aydan, 2012; Erguler & Ulusay, 2007; Park *et al.,* 2011; Ulusay & Erguler, 2012).

The performance of the needle penetrometer for predicting the strength of various rock types from very weak to strong, has been reported in literatures for a variety of applications including tunnel support and sample quality (Okada *et al.,* 1985) to strength prediction of conglomerates (Takahashi *et al.,* 1998), quality control of construction material, estimation of weathering profiles and weathering rate (Hachinohe *et al.,* 1999; Oyama & Chigira, 1999), rapid strength prediction for dam foundation (Yamaguchi *et al.,* 1997; Yamaguchi *et al.,* 2004), strength estimation of clay-bearing rocks (Erguler and Ulusay, 2007), structural mapping (Kawamura *et al.,* 2009), cut and cover construction (Ngan-Tillard *et al.,* 2011), strength prediction of medium and high strength rocks, Young's modulus, P-wave velocity, cohesion of material of failed slopes, friction angle, S-wave velocity and relaxation and creep characteristics of some soft rocks (Ayden, 2012; Aydan *et al.,* 2014). Despite these advantages, uncertainties arise from lack of an established standard method; ignoring intrinsic characteristics, and insufficient data to draw statistical analysis. Literature review also revealed that, a few empirical equations exist; which relate UCS to NPI for intact rocks. However, derived relationships mostly do not constitute a unique model. The correlations between NPI and UCS are not only evaluated in a linear model, but also curvilinear was reported. Furthermore, these relationships were also developed for both single rock types and all rock types as whole. This means that there is no unique relationship between the NPI and UCS for all rock types, while they only provide a preliminary estimate for UCS of intact rocks (Ulusay & Erguler, 2012). There are also a number of factors affecting the needle penetration test method. Some of which are calibration and malfunction of instrument, rock surface irregularities, surface moisture content (Aydan, 2012), spacing between penetrations points reported that even slight weathering is capable of significant increase in NPI (Hachinohe *et al.,* 1999; Oyama and and Chigira, 1999). The main objective of this study study is to evaluate the ratio of UCS/NPI as a function of UCS of intact rock. The needle penetrometer reflects the strength of thin crust of maximum10 mm depth; hence it is not sensitive to the inherent properties of the rocks such as cementation, saturation, porosity, grain size and micro-fractures which control the UCS of rocks. Uncertainty arises from the survey scale of this method which is mm size, while size and distribution of grains and frequency of matrix impact considerable influence on the degree of scatter of NPI. Assuming the surface covered by large grains, the needle tip diameter could only give responses of those grains, rather than the expected values from all grains and interstitial matrix. Seemingly, the ratio of UCS/NPI is a suitable indicator to assess the UCS of rock materials. A total of 273 UCS–NPI data pairs obtained from four various sedimentary rock types were used in current study to obtain this parameter. The ratio of UCS/NPI defined as a function of UCS and regression analysis was carried out using experimental data to evaluate the ratio of UCS/NPI for prediction of UCS. Attempts were made to contribute previous works on the application of the NP test in rock mechanics, to assess its performance and developing a more generalized empirical relationship for indirect estimation of the UCS from NPI.

Materials and methods

Material identification and Sampling

Various rock block samples including (gypsum, marl, sandstone and siltstone) were collected from the Qom Formation in Iran. Geological map and the sampling points in the study area are shown in Fig. 1 and were numbered randomly (Table1). The Qom Formation was deposited during Oligo-Miocene in a shallow marine realm in Central Iran (Furrer and Soder, 1955; Bozorgnia, 1966; Reuter *et al.,* 2009) and consists of various rock types with more than 9 lithostatigraphic members designated from a through f. This Formation comprises a variety of different rock types including gypsum, siltstone, sandstone, marl and limestone, as well as volcanic rocks. The best outcrops of the Formation are well exposed around the Qom City, approximately 130 km south of Tehran. A number of rock outcrops were visited to collect suitable rock blocks for investigation. The intact rock blocks free of macroscale discontinuities were collected and transferred to the laboratory to conduct the UCS and NP tests. Attempts were made to check out the validity of results, hence some extra 11 rock block samples including two types (e.g. clayey marl and marl) were also collected from outcrops of the Qom Formation along the mid-way of the Hamedan – Saveh highway.

Methods

Needle penetrometer and method

In order to examine the performance of the Needle Penetrometer (NP) to estimate the UCS, a modified Eijkelkamp (Ngan-Tillard *et al.,* 2011) hand penetrometer which was also used in Netherlands (Fig. 2) was used in present study.

This equipment is less sophisticated than penetrometer manufactured by Maruto Corporation Ltd NP model.

Table1. Sampling numbers, measured UCS and NPI from laboratory tests and physical properties of samples.

Specimen No.	UCS (MPa)				NPI (N/mm)				Density (KN/m^3)	Porosity (%)	Absorption (%)
	Min	Max	Mean	n	Min	Max	Mean	n			
G1	11.25	14.21	12.86	3	38.51	43.82	41.98	7	21.87	1.24	0.95
G2	12.3	15.78	13.99	3	40.9	43.2	42.63	7	22.02	1.19	0.66
G3	13.32	16.89	15.11	3	41.1	45.87	43.28	7	22.17	1.14	0.57
G4	14.84	17.95	16.24	3	41.4	45.23	43.93	7	22.30	1.09	0.41
G5	16.55	18.15	17.36	3	42.17	46.21	44.58	7	22.50	1.04	0.38
G6	17.38	19.54	18.6	3	42.47	49.12	45.51	7	22.60	0.99	0.35
G7	18.45	20.36	19.66	3	42.45	48.12	45.52	7	22.77	0.94	0.26
G8	19.18	22.01	20.89	3	43.12	49.21	46.31	7	22.92	0.89	0.25
G9	19.85	22.65	20.95	3	44.28	49.98	47.69	7	23.07	0.84	0.25
G10	22.15	24.51	23.58	3	46.1	49.21	47.69	7	23.22	0.79	0.22
G11	22.35	26.8	24.58	3	45.95	49.11	47.69	7	23.37	0.74	0.20
G12	23.21	26.55	24.73	3	47.28	52.89	50.08	7	23.52	0.69	0.20
G13	26.55	28.42	27.02	3	48.52	53.21	50.08	7	23.67	0.64	0.15
G14	27.13	29.68	28.55	3	48.95	54.11	51.75	7	23.82	0.59	0.14
G15	7.24	11.35	9.89	3	23.25	28.15	25.56	7	21.50	1.10	0.42
G16	10.25	12.47	11.46	3	25.27	31.12	28.26	7	21.70	1.03	0.41
G17	12.47	14.21	13.04	3	28.55	32.68	30.97	7	21.90	0.96	0.37
G18	13.65	15.25	14.62	3	31.58	35.86	33.67	7	22.10	0.89	0.37
G19	15.39	17.52	16.19	3	34.25	38.95	36.38	7	22.30	0.82	0.36
G20	17.64	19.2	18.61	3	35.68	41.28	38.14	7	22.50	0.75	0.34
G21	17.21	19.63	18.61	3	39.27	45.36	42.87	7	22.70	0.68	0.32
G22	19.24	21.87	20.11	3	42.87	48.35	45.05	7	22.90	0.61	0.31
G23	20.35	24.1	22.94	3	44.87	48.99	47.03	7	23.10	0.54	0.29
G24	22.84	26.34	24.33	3	46.22	51.05	48.57	7	23.30	0.47	0.27
M1	0.81	1.15	0.93	3	18.56	25.68	22.55	7	21.20	15.80	9.90
M2	3.15	4.21	3.59	3	24.68	30.15	27.08	7	22.50	14.10	9.79
M3	4.2	6.97	5.12	3	28.26	34.97	31.4	7	22.90	13.85	9.20
M4	7.1	9.62	8.3	3	34.21	38.95	36.57	7	23.00	13.64	8.71
M5	11.35	13.51	12.69	3	37.85	43.28	40.47	7	23.10	13.12	8.67
M6	15.28	17.91	16.27	3	41.96	48.28	45.21	7	23.10	12.36	8.29
M7	16.98	19.54	18.05	3	46.95	52.84	49.74	7	23.20	11.77	8.11
M8	8.85	11.78	10.27	3	25.56	31.05	28.08	7	23.20	11.19	7.31
M9	11.41	13.58	12.4	3	28.52	34.68	31.31	7	23.20	10.61	7.20
M10	11.96	15.68	14.52	3	31.18	37.65	34.53	7	23.30	10.03	6.91
M11	15.24	17.82	16.65	3	34.85	39.89	37.76	7	23.73	9.45	6.85
M12	17.12	19.51	18.77	3	38.56	43.25	40.99	7	23.89	8.86	6.64
M13	19.23	22.17	20.9	3	41.35	48.11	44.21	7	24.05	8.28	6.58
M14	17.22	21.47	19.04	3	45.25	49.98	47.44	7	24.20	7.70	6.30
M15	25.36	29.1	27.43	3	47.56	53.21	50.67	7	24.36	7.12	5.71
S1	11.61	18.74	15.78	3	39.75	45.86	42.45	7	21.80	16.55	8.94
S2	16.81	20.12	18.35	3	40.11	46.51	43.61	7	21.90	16.10	8.72
S3	19.17	23.28	20.93	3	41.98	47.85	44.77	7	21.90	15.50	7.96
S4	22.69	25.1	23.5	3	42.78	49.12	45.94	7	22.00	15.20	7.38
S5	24.38	28.23	26.08	3	44.28	50.65	47.1	7	22.05	15.00	7.16
S6	27.21	29.89	28.66	3	45.23	52.13	48.26	7	22.11	14.87	6.88
S7	27.58	30.41	29.18	3	45.87	53.56	49.36	7	22.17	14.34	6.21
S8	15.29	17.83	16.39	3	31.86	38.78	35.79	7	22.23	13.99	6.08
S9	15.98	19.1	17.49	3	33.85	39.84	36.73	7	22.29	13.65	6.05
S10	17.18	20.12	18.59	3	33.28	41.15	37.66	7	22.35	13.31	6.04
S11	18.25	21.17	19.69	3	35.79	40.56	38.6	7	22.41	12.97	6.03
S12	19.58	22.37	20.79	3	36.22	43.87	39.54	7	22.47	12.62	6.00
S13	18.89	23.58	21.89	3	36.56	44.85	40.48	7	22.53	12.28	6.00
S14	20.75	25.18	23	3	37.65	45.12	41.41	7	22.59	11.94	5.75
S15	22.49	24.87	23.4	3	36.58	46.08	41.82	7	22.65	11.59	5.48
S16	23.84	27.19	25.73	3	39.85	47.17	43.7	7	22.71	11.25	5.44
S17	25.13	27.86	26.78	3	40.41	48.07	44.8	7	22.77	10.91	5.36
S18	25.22	29.64	27.64	3	41.25	48.53	44.86	7	22.83	10.57	5.16
S19	25.87	29.94	27.95	3	42.58	48.98	46.03	7	22.89	10.22	5.03

S20	28.45	31.14	29.6	3	42.58	50.21	46.97	7	22.95	9.88	6.28
SS 1	7.14	10.27	8.71	3	28.74	35.68	32.84	7	19.38	25.58	12.13
SS 2	4.52	6.87	5.61	3	18.85	24.5	21.14	7	20.73	19.95	9.75
SS 3	11.02	14.36	12.21	3	42.58	49.56	46.02	7	19.38	22.05	10.88
SS 4	9.35	12.58	10.89	3	39.56	42.59	41.04	7	22.36	18.83	9.38
SS 5	2.86	4.25	3.43	3	16.89	21.05	18.94	7	15.85	31.35	13.38
SS 6	2.1	3.68	2.57	3	13.58	15.97	14.7	7	19.65	26.33	12.75
SS 7	4.23	7.12	5.54	3	18.52	22.86	20.9	7	20.46	20.70	7.75
SS 8	6.87	10.14	8.38	3	28.86	33.69	31.59	7	21.14	20.63	10.50
SS 9	12.48	15.97	14.12	3	43.59	46.96	45.23	7	19.92	15.23	10.13
SS 10	9.58	12.19	10.43	3	36.51	43.21	39.3	7	25.61	11.03	10.50
SS 11	4.89	7.98	6.53	3	20.15	28.35	24.63	7	19.51	21.68	7.75
SS 12	8.75	10.86	9.31	3	32.39	38.84	35.07	7	16.67	26.85	10.88
SS 13	8.76	12.29	10.36	3	36.89	42.52	39.05	7	19.78	18.98	9.75
SS 14	10.24	14.56	12.08	3	37.12	41.99	39.52	7	21.68	20.70	10.25
SS 15	6.28	10.12	8.18	3	28.64	33.04	30.85	7	21.95	17.85	9.38
SS 16	3.85	6.35	4.88	3	19.86	24.12	22.41	7	16.40	29.33	10.50
SS 17	6.16	9.86	8.18	3	27.26	33.24	30.85	7	20.60	23.93	7.63
SS 18	1.18	2.09	1.45	3	8.98	12.08	10.47	7	10.98	30.00	11.63
SS 19	5.17	8.2	6.8	3	23.85	27.81	25.62	7	21.41	19.05	10.88
SS 20	4.65	8.13	6.01	3	19.68	25.19	22.64	7	19.11	21.68	12.00
SS 21	4.35	7.71	5.61	3	18.73	23.56	21.14	7	18.70	21.75	10.75
SS 22	4.15	6.58	5.21	3	17.35	21.14	19.65	7	18.56	22.50	9.75
SS 23	4.59	6.78	5.81	3	18.35	24.75	21.89	7	18.83	21.00	10.88
SS 24	14.1	17.03	15.07	3	41.96	47.68	44.79	7	27.13	5.38	2.78
SS 25	12.45	16.54	14.1	3	45.12	47.36	46.13	7	27.40	4.38	2.83
SS 26	10.58	14.24	12.98	3	37.52	44.1	40.91	7	20.49	9.11	6.35
SS 27	13.22	16.05	14.55	3	37.36	43.21	40.83	7	21.17	8.02	5.35
SS 28	6.95	9.42	8.45	3	29.52	33.64	31.84	7	20.49	11.66	7.25
SS 29	9.68	13.26	11.58	3	40.58	47.15	43.66	7	19.54	11.00	6.00
SS 30	13.17	16.21	14.36	3	38.11	44.35	41.1	7	20.89	10.88	7.13
SS 31	24.53	27.96	26.1	3	45.12	51.27	48.36	7	22.40	11.06	6.75
SS 32	10.81	14.25	12.69	3	35.58	40.05	37.81	7	23.67	11.51	7.00

G: Gypsum, M: Marl, S: Sandstone, SS: Siltstone, According to table (Min= minimum; Max= maximum; Ave = Average), n= number of samples.

The equipment is housed in a light weight light-weight (about 600–700 g) portable device and consists of a needle which is pushed slowly into a rock. The penetration force should be manually recorded, until reaches a steady state. The needle is hardened steel, with a 1 mm diameter, 8 mm long cylindrical needle having an apex angle of 60 (resulting in a conical end height of 0.87 mm).

The surface on which the test would be carried out, should be clean and smooth before testing. Then by holding rather tightly the removable cap and the main body, the load is perpendicularly and slowly applied to rock surface. In case of laboratory, the specimen should be fixed to prevent its movement during penetration. For weak rocks, no more penetration could be applied after a maximum depth of 10 mm and the needle should be slowly pulled out. For hard rock, if the penetration force reaches up to 100 N, the needle must be withdrawn before penetrates 10 mm. After the test is completed, the needle is slowly pulled out and the penetration load value and penetration depth are recorded from the load scale (Ulusay et al., 2014). The NP test is carried out repeatedly on the same surface between 3 to10 times (Ulusay and. Erguler, 2012), the mean of the readings for each specimen or outcrop are recorded to calculate the NPI from the following equation:

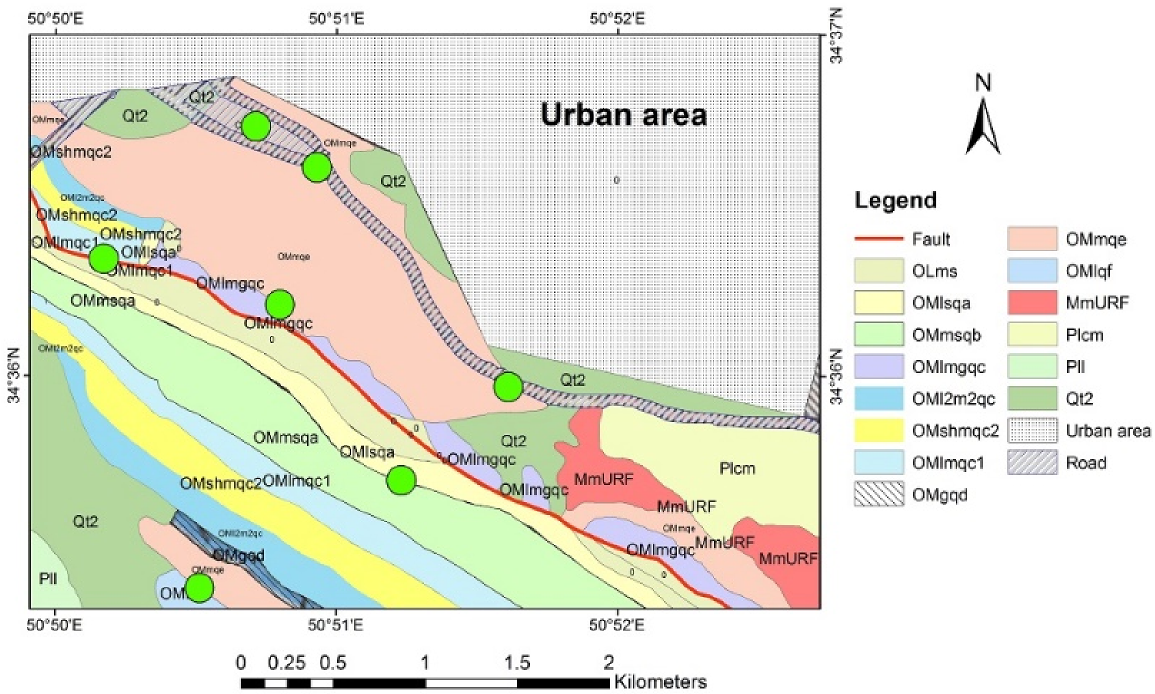
$$NPI = F/D \quad (1)$$

Where F is the penetration load (N) and D is the depth of penetration (mm). The unit of NPI is N/mm.

For $F = 100$ N and $D \leq 10$ mm $\quad NPI = 100/D$ (2)

For $D = 10$ mm and $F \leq 100$ N $\quad NPI = F/10$ (3)

Some fractures may develop during penetration, which may create a weak zone which causes an abnormal fracture. Considering this, the Ulusay and Erguler, (2012) suggest that when the test is carried out on core specimens in laboratory (Fig. 3a), the test results are not reliable and should be discarded if some fractures develop around the penetration hole as illustrated in Fig. 3b. In addition, if needle penetration causes tensile splitting of the core along a weakness plane, such as bedding plane, the test should be omitted. As these damage are local in small scales, the test is said to be non-destructive (Okada *et al.,* 1985; Ngan-Tillard *et al.,* 2011; Ayden, 2012; Ulusay & Erguler, 2012). In this study, needle penetration test is carried out on block and core samples in the laboratory. The NPI obtained from both block and core samples are identical.



Olms: Alternation of Red and dark grey silty shale, sandy marl, green marl with intercalation of sandstone, gypsum "Lower Red Formation". OMslqa: Fossiliferous sandy Limestone, calcareous sandstone "a. member". OMmsqb: Marl with intercalation of sandstone "b. member". OMlmqc1: Alternations of marl and limestone "c1. member". OMlmgqc: Limestone, marl with intercalation of gypsum and gypsiferous marl "c1-4. member". OMl2m2qc: Limestone with bryozoa oolitic limestone and green marl "c3-4. member". OMgqd: Gypsum and gypsiferous marl "d. member". OMmqe: grey green marl with intercalation of argillaceous limestone and locally gypsum "e. member". OMlqf: Light grey to cream think bedded limestone with marl "f. member". MmURF: Red marl. Shale, siltstone, dark and gypsiferous sandstone, gypsum and dark green sandstone in some localities. Pll: Conglomerate with calcareous pebbles. Plcm: Conglomerate with intercalations of sandstone and clay "Hezar Darreh Formation.

Figure 1. Generalized geological map of the study area in which the sample locations are shown (modified after Zamani & Hoseini, 1999).

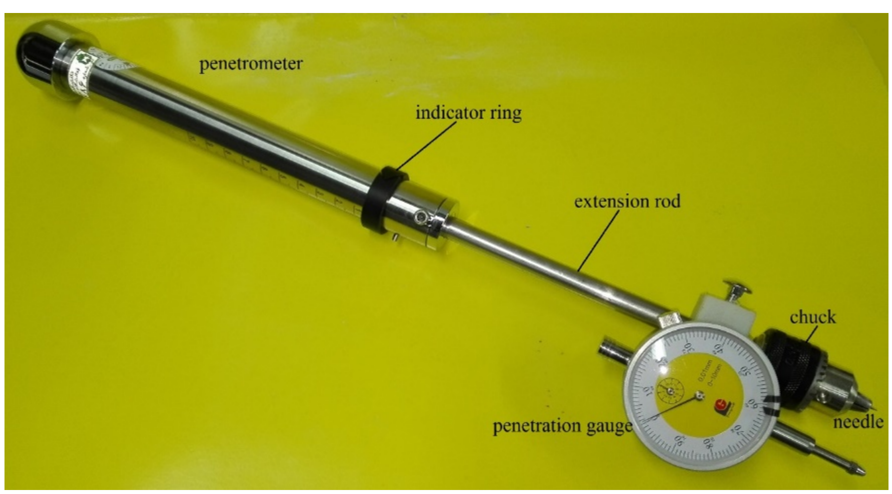


Figure 2. Modified Eijkelkamp Needle penetrometer device.

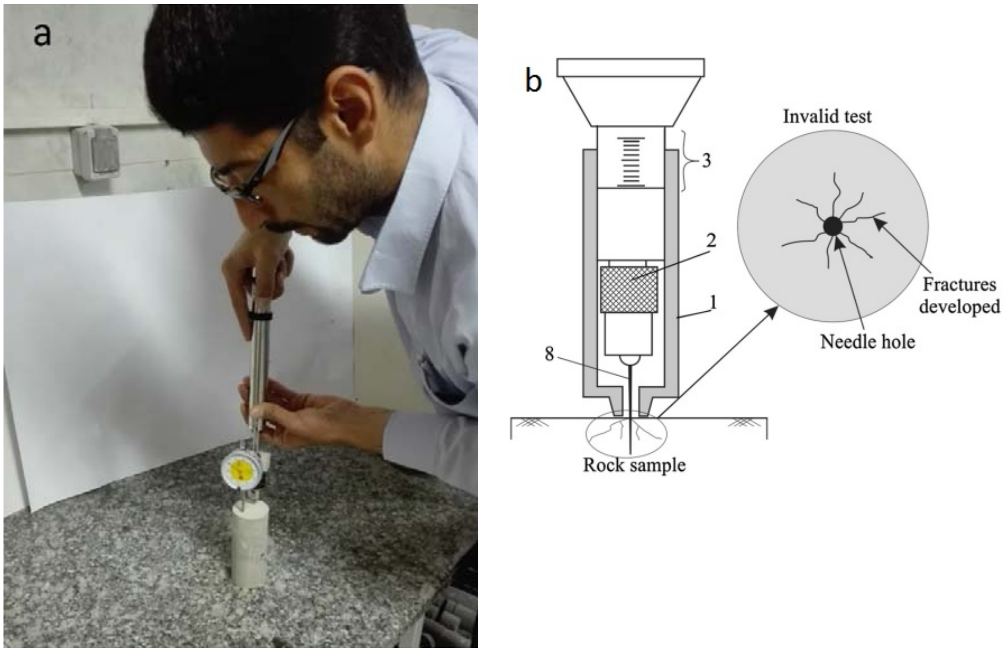


Figure 3. a:Application of the needle penetrometer in laboratory on core, b: Schematic illustration of an invalid NP test (Ulusay & Erguler, 2012).

Uniaxial compression test

The ASTM 7012 (04) standard was applied for the uniaxial compression test. Sample tests were performed at the Rock Mechanics Laboratory of the Engineering Geology Department of Bu-Ali Sina University in Hamedan, Iran. Rock samples were cored from each intact rock block and their ends were machined flat. Their length was kept in the interval between 2 and 2.5D. Each core was placed between the platens of the loading frame and the loading was applied for failure of NX core samples within 2–15 min (Fig. 4).

Results and Discussions

Test results

A series of NP and UCS tests were carried out on a total of 273 specimens of sedimentary rocks for the UCS and the NPI determinations. The range and mean of the NPI, UCS, density, porosity and water absorption of intact rocks are presented in Table 1.

Correlations between UCS vs. NPI and UCS/NPI vs. UCS

The limitation of NP test method e.g. the needle diameter is beyond the scale of rock fabric and limited depth of penetration (max. 10 mm), sounds that the obtained UCS is only representative of the outer crust of rack sample. Hence, we prefer to insert the UCS/NPI vs. UCS rather than UCS vs. NPI in order to consider prominent inherent properties of the rocks such as cementation, saturation, porosity, grain size and micro-fractures.

In order to determine the best empirical relationship between NPI-UCS and UCS/NPI versus UCS for gypsum, marl, sandstone, siltstone and also for all rocks, results of simple regression were drawn in Fig. 5 (a, b, c, d and e) and Fig. 6 (a, b, c, d and e) respectively. During the simple regression analyses, linear, power and exponential relationships were considered and the equation with the highest correlation coefficient was used for estimating UCS. The relationships between NPI – UCS and UCS/NPI vs. UCS of specimens and their determination coefficients (R^2) for simple regression analysis are presented in Table 2. The R^2 values between the NPI vs. UCS and UCS/NPI vs. UCS for all rock types as whole specimens are 0.72 and 0.90 respectively. Apparently, for gypsum, marl marl and siltstone, performances of NPI give reasonable results to predict the UCS. In comparison, the NPI of sandstone seems to be an improper index for UCS prediction, as R^2 value derived from NPI vs. UCS is less than 0.65. These results are in close correspondence with published data summarized in Table 3, however the sandstone is excluded. Many researchers applied similar approaches for deriving these relationships for a single rock type or all rock types as whole. Fig. 6 depicts strong relation between UCS/ NPI vs. UCS of rocks. Briefly, R^2 values between the ratio of

UCS/NPI and UCS is higher than R^2 values derived between UCS and NPI for same experimental data (Table 2).

In this research, the determination coefficient between measured and predicted values was used to check the prediction performance of the equations. In addition, the root mean square error (RMSE) (Eq. (4)) and variance account for (VAF) (Eq. (5)) (Makridakis and Hibon, 1995) indices were also calculated to control the performance of the prediction capacity of equations developed in the study.

Table 2. Correlation coefficients of the simple regressions between NPI and the UCS of rocks.

Rock type	**Equation**	R^2
Gypsum	UCS= 0.6106NPI - 7.1715	0.72
Gypsum*	UCS/NPI = 0.0107UCS + 0.236	0.71
Marl	UCS = 0.7251NPI - 13.794	0.77
Marl*	UCS/NPI = 0.0184UCS + 0.0891	0.87
Sandstone	UCS = 0.9263NPI - 16.755	0.65
Sandstone*	UCS/NPI = 0.0143UCS + 0.2028	0.84
Siltstone	UCS = 0.4085NPI - 3.7178	0.80
Siltstone*	UCS/NPI = 0.0126UCS + 0.1597	0.84
All rock types	UCS = 0.6715NPI - 10.075	0.72
All rock types*	UCS/NPI = 0.0164UCS + 0.1311	0.90

* Data derived from UCS/NPI vs. UCS.

UCS = compressive strength (MPa), NPI =Needle penetration index (N/mm).

Figure 4. a: The uniaxial compressive strength test setup, b: some of core samples used for laboratory tests.

$$\mathrm{RMSE} = \sqrt{\frac{\sum (Q_i - p_i)^2}{n}} \quad (4)$$

$$VAF = \left(1 - \frac{\mathrm{var}(Q_i - p_i)}{\mathrm{var}(Q_i)}\right) \times 100 \quad (5)$$

Where Q_i is the measured value, P_i is the predicted value from regression equation and n is the number of experimental data. When an RMSE value approaches zero, the predicted values from the regression equation are closer to the measured values. Also, if the VAF is 100, then the model will be excellent.

A series of equation fitting between NPI vs. UCS and UCS/NPI vs. UCS for all rock types as whole and gypsum, marl, sandstone and siltstone were performed (Table 4). The correlation coefficients (R^2) between measured UCS in the laboratory (Table1) and predicted UCS from equations developed in this study (Table 2) are illustrated in Tables 4. The predicted versus the true measurements by UCS vs. NPI plots and UCS/NPI vs. UCS plots, as well as the real data and the predicted values of UCS for all rock types as whole, are presented in Fig. 7. The correlation coefficient (R^2) between the measured and the predicted UCS from the equations (Table 4), for all rock types, is 0.72 and 0.90, respectively (Figs. 7a and 7b). The R^2 value is reasonable for relationship between the ratios of UCS/NPI vs. UCS plots in compare to the UCS vs. NPI plots. Also, for a more accurate performance evaluation of these two type plots, the RMSE and the VAF were computed (Table 4). Accordingly, the VAF and the RMSE indices were obtained as 72.20 % and 2.12 for the UCS calculated from UCS vs. NPI plots and 90.07% and 3.41 for the UCS calculated from the UCS/NPI vs. UCS regression analyses. It can be asserted that the reliability and the accuracy of UCS/NPI vs. UCS for estimating the UCS are high (Table 4).

Table 3. Previous investigations on the correlations between NPI and the UCS of rocks.

Investigator(s) or Company	Equation	R^2	Rock types tested	Penetrometer Type
Okada *et al* (1985)	log UCS=0.978 log NPI+1.599 (kgf/mm)	0.84	Artificial cement-based samples and mudstone	Maruto
Yamaguchi et al (1997)	log UCS (kgf/cm2) = 0.982 logNPI-0.209 (Kg/cm)	0.76	Artificial cement-based samples and Mudstone	Maruto
Takahashi *et al* (1998)	UCS (MPa) = 1.539 NPI $^{0.9896}$ (N/mm)	0.81	Sandstone, mudstone, conglomerate, greywacke, tuff	Maruto
Maruto Corporation (2006)	UCS (MPa) = 0:978 log NPI (N/mm)	0.84		Maruto
Erguler and Ulusay (2007, 2009)	UCS (MPa) = 0.51 NPI 0.8575 (N/mm)	0.76	Marl, siltstone, mudstone, tuff	Maruto
Ngan-Tillard *et al* (2011)	UCS (MPa) = 0.0731 NPI (N/mm)	0.70	Calcarenite	Eijkelkamp
Ulusay & Erguler (2012)	UCS (MPa) = 0.4 NPI0.929 (N/mm)	0.79	Marl, tuff, mudstone, siltstone, sandstone, greywacke, very stiff clay; data from Japan	Maruto
Aydan (2012)	UCS (MPa) = 0.2 NPI (N/mm)	-	Tuff, sandstone, pumice, limestone, lignite	Eijkelkamp & Maruto

UCS = compressive strength, NPI =Needle penetration index.

Table 4. R^2, RMSE and VAF values between measured and predicted UCS for equations given in Table 2.

Rock type	Equation	R^2 values between measured and predicted UCS	VAF %	RMSE
Gypsum	Y = 0.7281x + 5.1409	0.72	72.81	2.57
Gypsum	Y* = 0.9071x* + 2.0885	0.71	77.87	2.34
Marl	Y = 0.7765x + 3.0547	0.77	77.64	2.57
Marl	Y* = 1.9245x* - 7.8482	0. 75	82.54	3.54
Sandstone	Y = 0.657x + 7.9132	0.65	65.69	2.33
Sandstone	Y* = 0.9866x* + 0.6129	0.67	51.10	2.79
Siltstone	y = 0.8015x + 1.8741	0.80	80.15	2.12
Siltstone	Y* = 0.9574x* + 0.7018	0.84	82.27	2.02
All rocks	y = 0.7201x + 4.3777	0.72	72.20	3.92
All rocks	y*= 1.0781x* + 0.2784	0.90	90.07	3.41

UCS = compressive strength (MPa), NPI =Needle penetration index (N/mm).

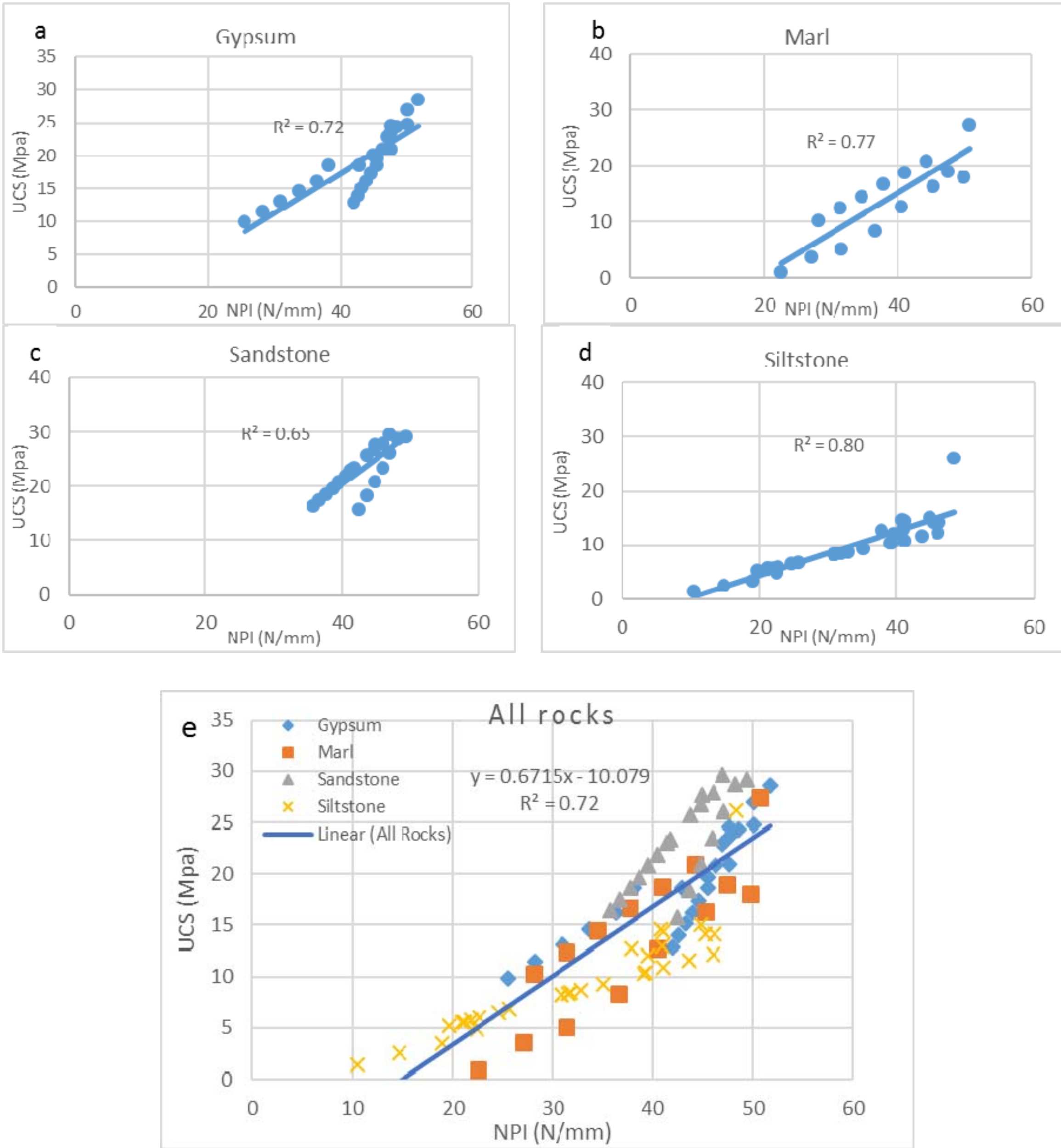


Figure 5. Simple regression analyses between the NPI and the UCS for a: Gypsum, b: Marl, c: Sandstone, d: Siltstone and e: all rock types.

For siltstone, the correlations between predicted and measured UCS values depict a R^2 value of 0.80 and 0.84 from UCS vs. NPI plots and UCS/NPI vs. UCS plots, respectively (Table 3). The root mean square error index was 2.12 from UCS vs. NPI regression analyses and 2.02 from UCS/NPI vs. UCS regression analyses. The R^2 between measured and the predicted UCS for sandstones is moderate (Table 4). Furthermore, the UCS of sandstones is more than the rest of rock types (>2o MPa, Table 1). Thus, the NP test is not a reliable method for UCS prediction of rocks with UCS higher than 20 MPa. These results are in line with Ulusay and Erguler, (2012).

As it can be seen in Table 4, the RMSE index for the all rocks is smaller than 3.92 MPa. This indicates that the UCS vs. NPI plots and UCS/NPI vs. UCS plots give prominent accuracy. Also, for all rocks, VAF index calculated from UCS/NPI vs. UCS plots is higher than that calculated from UCS vs. NPI plots. The overall conclusion deduced from these comparisons is that the ratio of UCS/ NPI appears to provide relatively better estimates for the UCS than those of the usual correlations between the UCS and the NPI. The results are reasonably meaningful, excluding for sandstone, which NPI does match with values of UCS prediction.

Likewise, the reliability and accuracy of the UCS vs. NPI for intact rocks were also within the expected data range of previous studies (Table 3). When each data group is assessed within the UCS vs. NPI, the values of RMSE are smaller than10MPa (Table 5). The range of standard error is reasonable for the relationship between the NPI and the UCS of intact rocks. The overall conclusion from these comparisons is that the UCS vs. NPI appears to provide somewhat well estimates for the UCS of intact rocks (Table 5), excluding for the prediction equations of Maruto Corporation, 2006.

After developing derived equations (Table 4), additional new data (Table 6) from samples collected along the mid-way of the Hamedan – Saveh highway, were used to validate the accuracy of each equation. The calculated statistical indices are presented in Table 7.

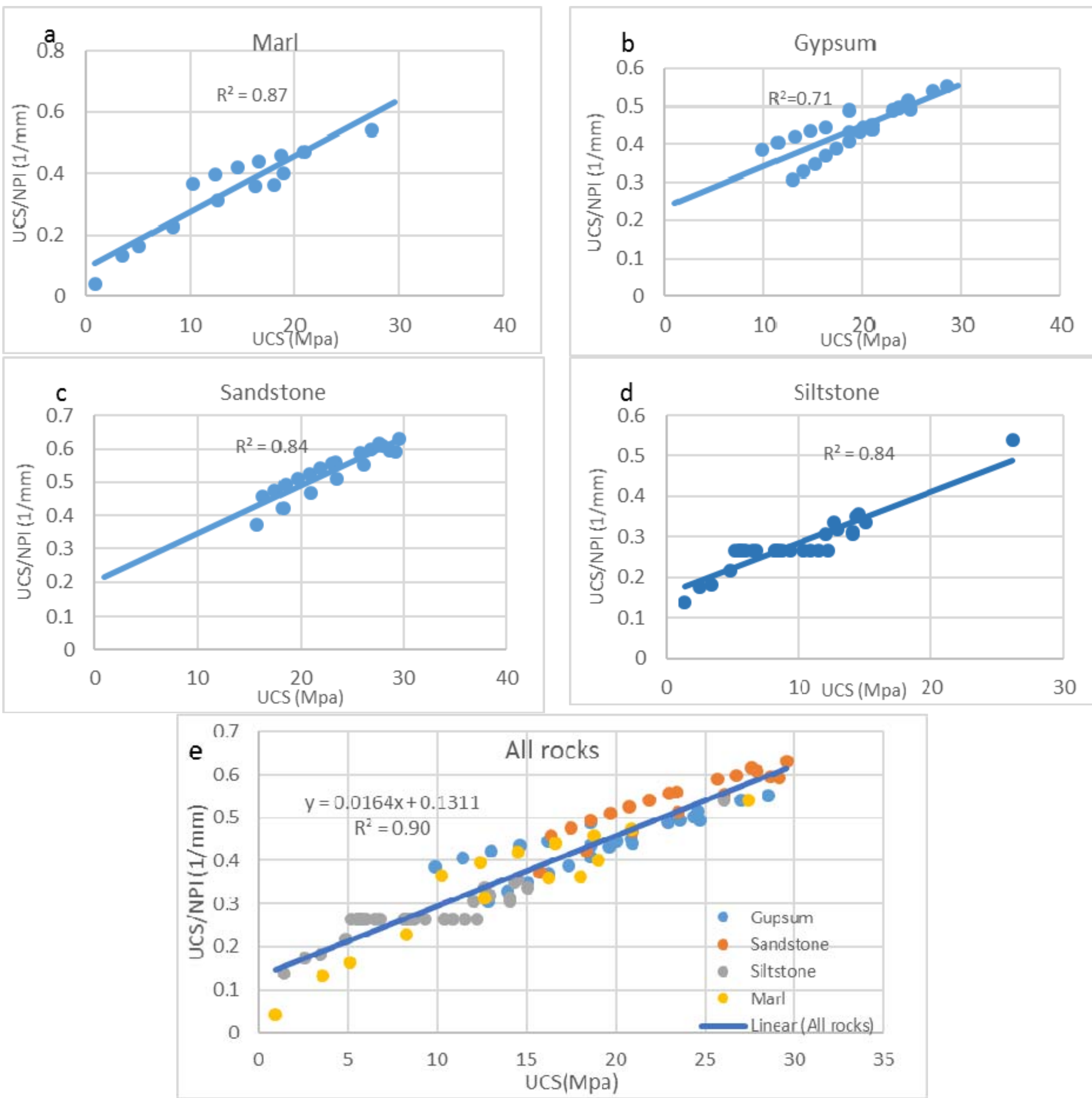


Figure 6. Relationship between the ratio of UCS/NPI and the UCS of intact rocks for a) Marl, b) Gypsum, c) Sandstone, d) Siltstone and e) all rock types.

Table 5. R^2, RMSE and VAF values between measured and predicted UCS for equations given in Table 3.

Recommended by	Equation	Relation between measured and predicted UCS	R^2	VAF %	RMSE
Ulusay, Z.A. Erguler 2012-2	UCS (MPa) = 0.4 $NPI^{0.929}$ (N/mm)	y = 0.3119x + 6.9789	0.71	48.81	6.53
Ulusay, Z.A. Erguler 2012-1	UCS (MPa) = 0.8244 $NPI^{0.6975}$ (N/mm)	y = 0.2131x + 7.07	0.70	36.18	7.92
Aydan (2012)	UCS (MPa) = 0.2 NPI (N/mm)	y = 0.2145x + 4.3043	0.72	36.50	9.94
Erguler and Ulusay (2007, 2009)	UCS (MPa) = 0.51 $NPI^{0.8575}$ (N/mm)	y = 0.2841x + 7.1259	0.71	45.50	6.83
Maruto Corporation, (2006)	UCS (MPa) = 0.978 log NPI+2.621 (N/mm)	y = 0.014x + 3.9341	0.65	2.76	13.62

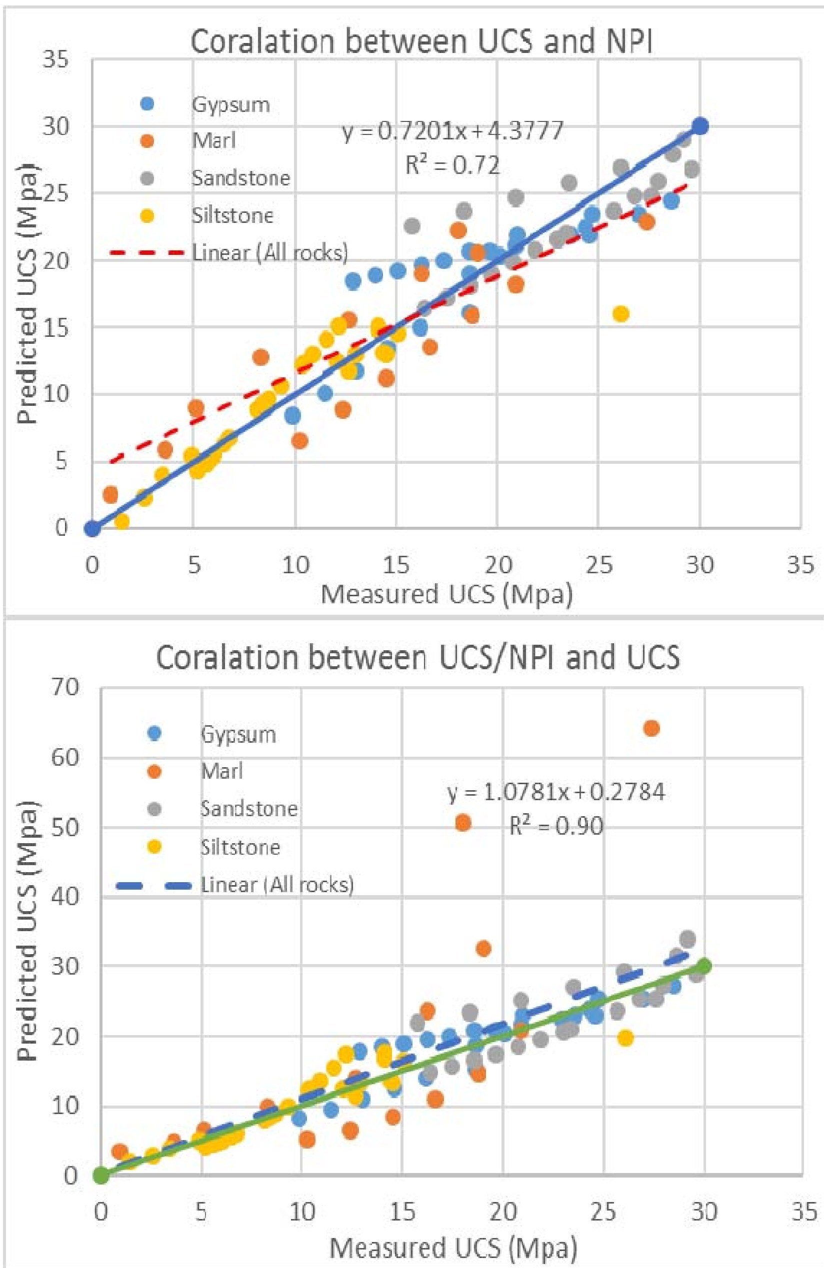


Figure 7. Comparison between the measured and the computed UCS from a) NPI vs. UCS plot and b) UCS/NPI vs. UCS plot.

Table 6. Additional new test data.

Specimen No.	UCS (MPa)				NPI (N/mm)			
	Min	Max	Mean	n	Min	Max	Mean	n
CM1	20.15	24.37	22.54	3	40.28	44.57	42.15	7
CM2	13.28	17.18	15.68	3	33.58	37.21	35.85	7
CM3	21.31	24.02	22.4	3	38.85	43.35	41.21	7
CM4	24.56	29.24	26.88	3	40.87	45.74	43.39	7
CM5	21.98	25.87	24.08	3	40.42	45.52	42.58	7
M1	30.21	33.25	31.5	3	45.68	49.12	47.95	7
M2	40.67	46.58	43.68	3	49.14	53.46	51.65	7
M3	37.45	42.08	39.62	3	50.36	52.65	51.07	7
M4	26.82	31.19	29.12	3	42.59	46.23	44.89	7
M5	26.28	29.74	28	3	42.71	45.98	44.19	7
M6	5.71	7.69	6.3	3	21.12	25.35	23.51	7

CM= clayey marl, M= Marl, n= number of samples.

Table 7. R^2, RMSE and VAF values between measured and predicted UCS for new additional data.

No	Equation	R^2 values between measured and predicted UCS	VAF %	RMSE
1	UCS = 0.6715NPI - 10.075	0.92	71.37	9.43
2	UCS/NPI = 0.0164UCS + 0.1311	0.94	91.00	4.84

Accordingly, the R^2 and VAF values derived from eq. 2 are more than those ones obtained from eq. 1 (see Table 7). Furthermore, less RMSE value of eq. 2 also support the better operation of this new inferred method.

Conclusions

Here, we have studied the relationships between UCS and NPI on 273 sedimentary rock specimens. The major conclusions of this study are summarized as follow:

The simple regression analyses for all rock types as whole and individual rock samples, show that empirical relationship between the NPI and the UCS based on UCS/NPI vs. UCS plot, gives better correlations than UCS vs. NPI. Although, both approaches give similar R^2 values only for gypsum.

For all rock types as whole, the VAF, RMSE, R^2 indices between the measured and the predicted UCS, is 90.5%, 3.41 MPa and 0.90, respectively obtained from UCS/ NPI vs. UCS plots and 70.20%, 3.92 MPa and 0.70 from UCS vs. NPI plots, respectively.

Despite high correlation coefficients (R^2) between the measured and the predicted UCS, the NPI gives only a rough estimate for the UCS for all rock types as whole. The NPI values reflect the thin crust of rocks and doesn't reflect the intrinsic properties of the rocks such as grain size, saturation, saturation, porosity, cementation and micro-fractures which could control their UCS. The results show that UCS/ NPI vs. UCS plots provide better results than UCS vs. NPI plots.

The root mean square error index is similar for both UCS/NPI vs. UCS plots and UCS vs. NPI plots which is less than<3.92 MPa. As a result, performance index revealed that these plots have high prediction potential.

In case of sandstone, NPI shouldn't be considered as an index for UCS prediction, as the R^2 <0.67, VAF<65%. The data presented here, suggest that NP test may give some over and underestimates for UCS values higher than 20 MPa for sandstone samples.

The VAF index calculated from UCS/NPI vs. UCS plots, was higher than that calculated from UCS vs. NPI plots. The conclusion deduced from these comparisons (excluding few exceptions), is that the ratio of UCS/ NPI apparently provide relatively better estimates of UCS than those of the usual correlations between the UCS and the NPI.

Some simple relationships are proposed to estimate the UCS of some rock specimens of the Qom Formation in Iran. Although empirical equations developed for determining the uniaxial compressive of four sedimentary rock types (gypsum, sandstone, siltstone and marlstone), more experiments are necessary to investigate and verify the relationships represented by these equations. It is particularly important to note that the purposed equations are stand on their initial steps, so they are valid only for those rocks from the Qom Formation and are not recommended for generalized purposes.

The derived equations compared with those published by different researchers, reveal reasonable agreement between them.

According to results obtained from control data used to validate the accuracy of the purposed equations, the R^2 and VAF values derived from UCS/NPI vs. UCS are more than those ones obtained from UCS vs. NPI. Less RMSE value for UCS/NPI vs. UCS also support the better operation of this new inferred method.

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