Geomechanics and Engineering, *Vol. 28, No. 6 (2022) 625-636*
https://doi.org/10.12989/gae.2022.28.6.625

Determining *N* value from SPT blows for 30 cm penetration in weathered strata

Chang-Guk Sun, Hyung-Ik Cho*, Han-Saem Kim and Moon-Gyo Lee

Earthquake Research Center, Korea Institute of Geoscience and Mineral Resources, 124 Gwahak-ro, Yuseong-gu, Daejeon 34132, Republic of Korea

(Received December 2, 2021, Revised January 20, 2022, Accepted January 24, 2022)

Abstract. The standard penetration test (SPT) obtaining the *N* value of the number of blows has been widely used in various subsurface conditions, including in weathered soil and rock on fresh bedrock, in geotechnical studies pertaining to the design of foundations and earth structures. This study examined the applicability of SPTs terminated conventionally after 50 blows for a penetration of less than 30 cm, particularly in weathered strata, at four sites in Korea. The *N* values obtained during practical SPTs are typically extrapolated linearly at 30 cm penetration, despite the possibility of a nonlinear relationship between blow counts and penetration. Such nonlinearity in weathered strata has been verified by performing special SPTs ensuring 30 cm penetration. To quantify the nonlinearity in dense strata, we conducted statistical regression analyses comparing the differences (*DN*) between the *N* values measured by the special SPTs and those extrapolated using the practical approach with the differences (*DP*) between the 30 cm penetration and the penetration during 50 blows. Bi-linear relationship models between *DN* and *DP* were subsequently proposed for determining the *N* values at 30 cm penetration in weathered strata. The *N* values reflecting nonlinearity could be determined from the linearly extrapolated *N* values by adding a modeled *DN* value.

Keywords: blow counts; geotechnical design; *N* value; standard penetration test; weathered strata

1. Introduction

Geotechnical field investigations are performed to characterize the subsurface soil and rock strata at a site, and borehole drilling is typically used to identify soils or rocks in geotechnical practice (Gui *et al*. 2002). The standard penetration test (SPT) is a simple in situ test that is typically conducted when approaching the bottom of a borehole. The blow count required to advance a sampler a total of 30 cm through soils and weathered rock strata (the second and third of three 15 cm increments) is termed the '*N* value'. The SPT has been utilized extensively in the design of foundations and other earth structures (Robert 1997, Dung *et al*. 2011, ErzÍn and Gul 2013, dos Santos and Bicalho 2017, Cho *et al*. 2018, Zhang *et al*. 2021), and has been standardized across many countries and regions (BSI 2007, KSA 2017, ASTM 2018).

The SPT is easy to perform and can be used not only to identify samples in the field but also to reconstitute test specimens in the laboratory, adopting a split-barrel hollow sampler. Given these advantages, the SPT has been widely applied such that vast quantities of data have been accumulated in the field of geotechnical engineering (Muduli and Das 2015, Mujtaba *et al*. 2018, Ghali *et al*. 2020, Han *et al*. 2022). Many geotechnical design codes and manuals describing various empirical methods have been developed based on the *N* values obtained from the SPT (Kulhawy and Mayne 1990, FHWA 2006, AASHTO 2007, Dung *et al*. 2011, ErzÍn and Gul 2013, Matsumoto *et al*. 2015, Zhang *et al*. 2019).

The SPT was originally developed in the late 1920s as a technique for geotechnical engineers to quantitatively measure the relative densities of granular soils (Bowles 1997, Guo 2012), and thereby empirically estimate the stiffness and strength parameters of soil deposits and weathered strata underlying bedrock strata. Weathered strata, composed of weathered residual soil and/or the underlying weathered rock, are extensively distributed between fill or alluvial soil layers and fresh parent rock layers in plains, as well as near the ground surface in hilly and mountainous areas (Sun *et al*. 2005, Anbazhagan *et al*. 2013, Jeong *et al*. 2017, Zaid *et al*. 2020, Goh *et al.* 2020). The weathered strata would be stiffer than the fine and sandy soil layers, and correspondingly have larger *N* values, and typically take more than 50 blows to penetrate 30 cm.

If the sampler is driven less than 30 cm until 50 blows during the last two 15 cm increments in a borehole, the *N* value is recorded as 50 counts per the penetrating depth (cm in units) (Sun *et al*. 2015, KSA 2017), for example, '50/22', '50/13', and '50/8', even though, in practice, as many as 100 blows may have been applied (BSI 2007, ASTM 2018). In geotechnical design practices, simple linear extrapolation is typically applied to convert the measured *N* values of 50 blow counts for less than 30 cm penetration into equivalent *N* values of more than 50 counts per 30 cm penetration in soil deposits and weathered strata despite the possibility of nonlinearity associated with the differences in subsurface constraint conditions and geotechnical structures (Oh and Sun 2008, Dung *et al*. 2011, Sun *et al*. 2013, 2015).

*Corresponding author, Ph.D.
E-mail: hicho@kigam.re.kr

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

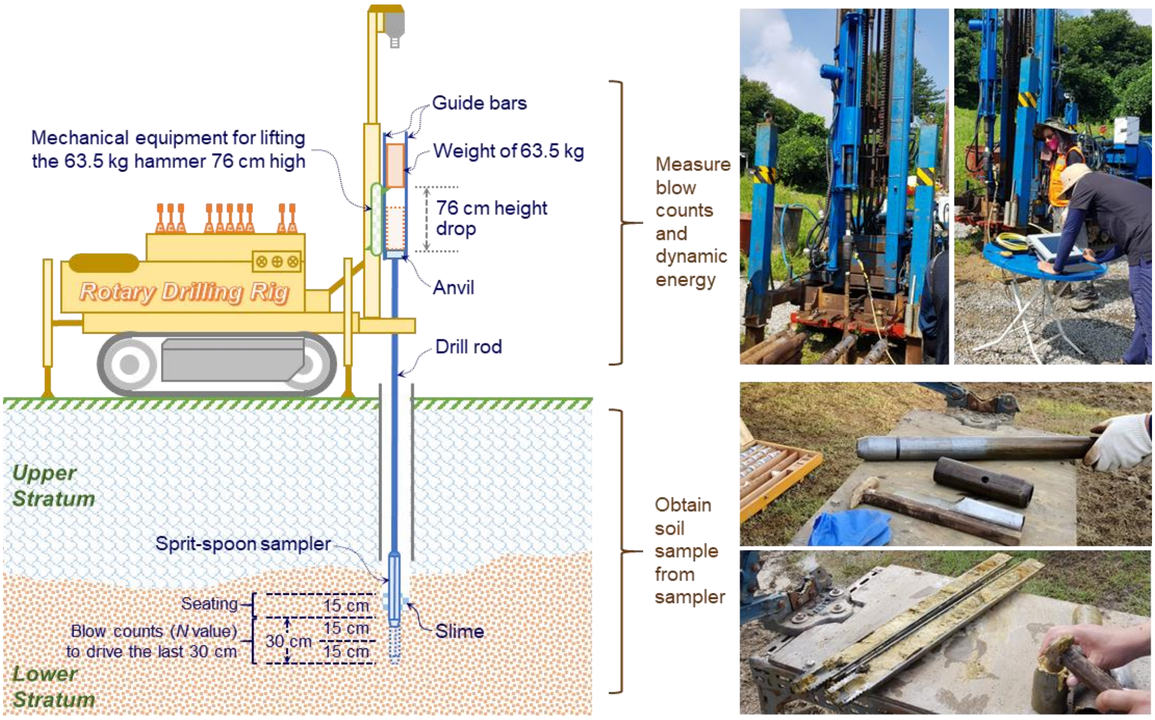


Fig. 1 Schematic of borehole drilling and performance of the SPT using a rotary drilling rig

The simple linear extrapolation approach might be useful in dense fine sand and silty soil deposits (Dung et al., 2011), but this can lead to underestimating N values in dense soil and decomposed or weathered rock layers. In this study, the nonlinear relationship between penetration and blow counts was investigated for weathered strata above fresh rock based on SPT data from four locations in Korea. An approach to preliminarily determine the N values for a 30 cm penetration from 50 blows of a penetration of less than 30 cm is introduced, in which several regressions are compared to solve the underestimation of the N value.

2. *N* values measured during the SPT

This study was conducted at four sites (DES, HAC, HDB, and KNUC) in inland South Korea with different parent rocks. Borehole drilling investigations of the casings of NX with SPT were carried out on the upper part of fresh bedrock through weathered soil/rock layers and a SPT was performed at 1.0 m intervals at the bottom of a borehole. For the in situ testing, a hydraulically operated rotary drilling rig, equipped with a mechanical device to ensure free fall of the 63.5 kg hammer from a height of 76 cm during the SPT was used (Fig. 1).

During the SPT in ordinary soil strata, the numbers of blows needed to drive a split-spoon sampler 15 cm increments into the ground were recorded; the sum of the numbers of blows required for the last two 15 cm increments (30 cm in total) was measured as the N value (i.e., N/30), allowing for the slime and seating of the first 15 cm increment (Bowles 1997, Oh and Sun 2008). For very dense or stiff soil and decomposed rock strata, the sampler might not achieve the required 30 m penetration (Sun *et al.* 2005, 2015). In practice, as regulated in KS F 2307 (KSA 2017), the SPT is typically considered complete when 50 blows have been applied, even if the penetration depth is less than 30 cm (defined as 'P_{50}' in this study) (Oh and Sun 2008, Dung *et al.* 2011), with the test result recorded as '50/P_{50}' and linearly extrapolated to the N value for 30 cm penetration (Dung *et al.* 2011, Sun *et al.* 2013). Fig. 2 shows an example of the in situ exploration results of borehole drilling and the practical SPT conducted at the DES site.

A plot of the linearly extrapolated N values with depth in the weathered soil layer is shown in Fig. 2, together with their corrected N_{60} and $(N_1)_{60}$ values. Since the original SPT hammer had a standard dynamic energy of approximately 60% of the hammer potential energy (475 J) (Ghali *et al.* 2020) and is composed of a donut hammer, a smooth cathead, and a worn hawser rope (Skempton 1986, Rogers 2006, ErzÍn and Gul 2013), the blow count measured with other recent hammers should be corrected to N_{60}, according to Eq. (1) for the field procedures (Skempton 1986, Bowles 1997).

$$N_{60} = C_{ER} C_B C_S C_R N \tag{1}$$

where C_{ER}, C_B, C_S, and C_R are the correction factors for the hammer energy efficiency, borehole diameter, sampling method, and rod length, respectively (Rogers 2006, Oh and Sun 2008, Dung *et al.* 2011).

The automatic trip hammer used in this study typically exhibited an energy ratio greater than 60%. The driving energy was measured for the automatic trip hammer during the SPT at each site by applying a section rod instrumented with two strain gauge bridges (Matsumoto *et al.* 2015). The energy transferred from the hammer to the driving rod was

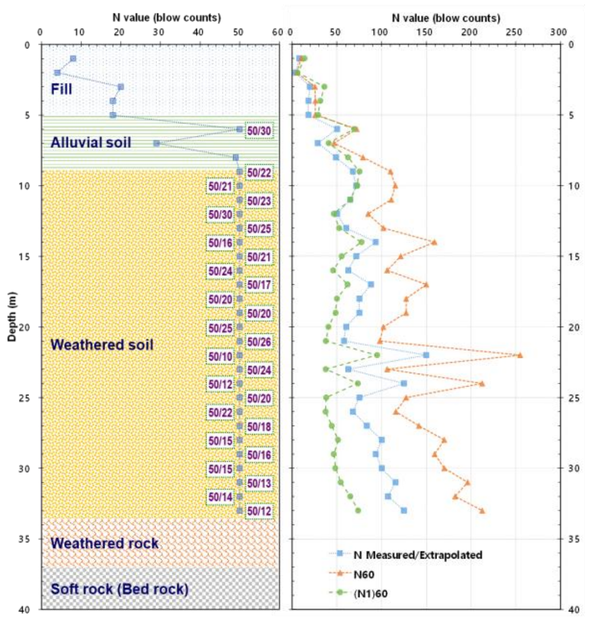


Fig. 2 Borehole drilling profile and measured N values during practical SPTs and corrected N values at DES site

estimated by measuring the force and velocity based on the strain and acceleration. The energy ratio and corresponding energy at the sites were determined using the mean value from 50 successive blows at the testing depth of each site. The driving energy ratio was deduced as 84–91% for the testing sites, and the C_{ER} was considered with 1.40 (= 0.84/0.60) to 1.52 (= 0.91/0.60) for this study.

The penetration resistance also varies with the stress level related to the overburden pressure of soils (Liao and Whitman 1986, Mujtaba *et al*. 2018), and increases with the depth from the ground surface. The N value measured at a deeper depth is generally greater than that at a shallower depth and is typically prominent in sandy soils rather than clayey soils (Bowles 1997, Oh and Sun 2008). Considering the overburden stress effect, the N_{60} value is corrected to $(N_1)_{60}$, expressed by

$$(N_1)_{60} = C_N N_{60} \tag{2}$$

where C_N is the correction factor for overburden stress. There are several expressions for C_N in the literatures (Liao and Whitman 1986, Bowles 1997, Rogers 2006, Oh and Sun 2008, Dung *et al*. 2011). In this study, the C_N suggested in ASTM D6066 was used (ASTM 2011), which is expressed as

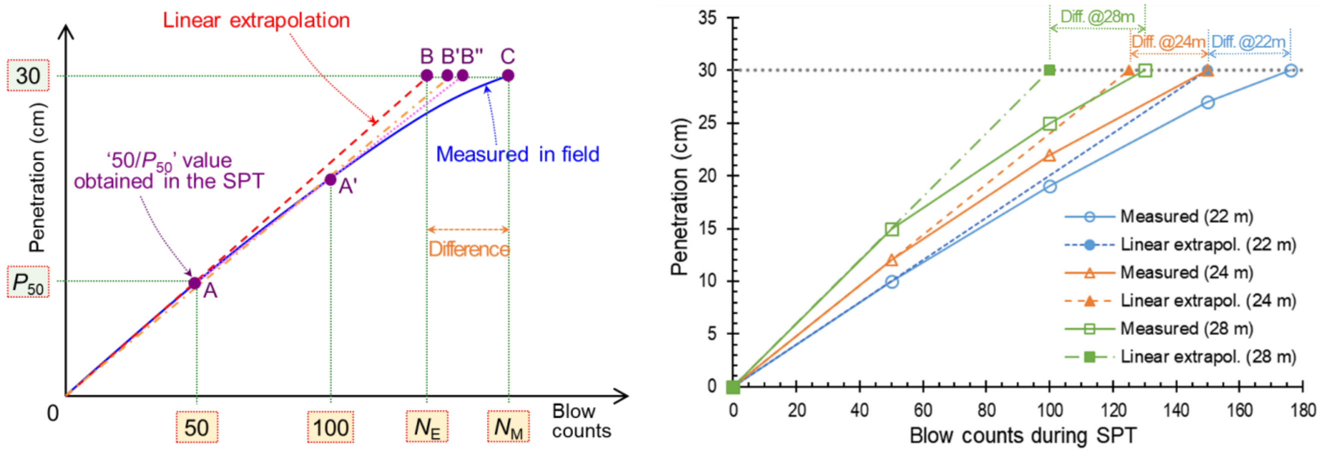
$$C_N = (p_a/\sigma'_v)^{0.5} \tag{3}$$

where σ'_v is effective overburden stress and p_a is reference stress of 100 kPa.

Instead of performing a routine SPT that terminates after 50 blows (KSA 2017), in this study, special SPTs were carried out in the weathered strata until a full penetration of 30 cm was reached, even if this required more than 50 blows. Most of these special SPTs required fewer than 100 blows, but in some cases, 150 to 250 blows were required for the necessary penetration. Data were obtained during the first, second, and third phases at a total of 41 testing locations across the four sites, as listed in Table 1. In this study, the N values measured for a 30 cm penetration during the SPT without correction were corrected to N_{60} and $(N_1)_{60}$, taking into account the field procedures and the overburden

Table 1 Blow counts (N values) measured through the SPTs in weathered strata at four study sites

Name of site	Depth (m)	N values (blow/cm)		
		1st ($50/P_{50}$)	2nd	3rd
DES	9	50/22	82/30	-
	10	50/21	87/30	-
	11	50/23	76/30	-
	13	50/25	62/30	-
	14	50/16	104/30	-
	15	50/21	88/30	-
	16	50/24	75/30	-
	17	50/17	97/30	-
	18	50/20	86/30	-
	19	50/20	95/30	-
	20	50/25	73/30	-
	21	50/26	74/30	-
	22	50/10	100/19	176/30
	23	50/24	78/30	-
	24	50/12	100/22	150/30
	25	50/20	87/30	-
	26	50/22	80/30	-
	27	50/18	100/30	-
	28	50/15	100/25	130/30
HAC	9	50/28	58/30	-
	10	50/26	69/30	-
	11	50/20	90/30	-
	12	50/18	102/30	-
	13	50/19	97/30	-
	14	50/18	95/30	-
	15	50/18	96/30	-
	16	50/18	96/30	-
	17	50/19	99/30	-
	18	50/21	90/30	-
	19	50/18	104/30	-
	20	50/18	104/30	-
	21	50/13	100/24	150/30
HDB	9	50/26	60/30	-
	10	50/28	56/30	-
	11	50/27	57/30	-
	12	50/27	60/30	-
	13	50/28	58/30	-
	14	50/26	64/30	-
KNUC	6	50/29	53/30	-
	8	50/11	100/18	244/30
	9	50/9	100/16	267/30



(a) Conceptual diagram (b) Example data obtained at the DES site

Fig. 3 Nonlinear relationship between penetration and blow count during the SPT

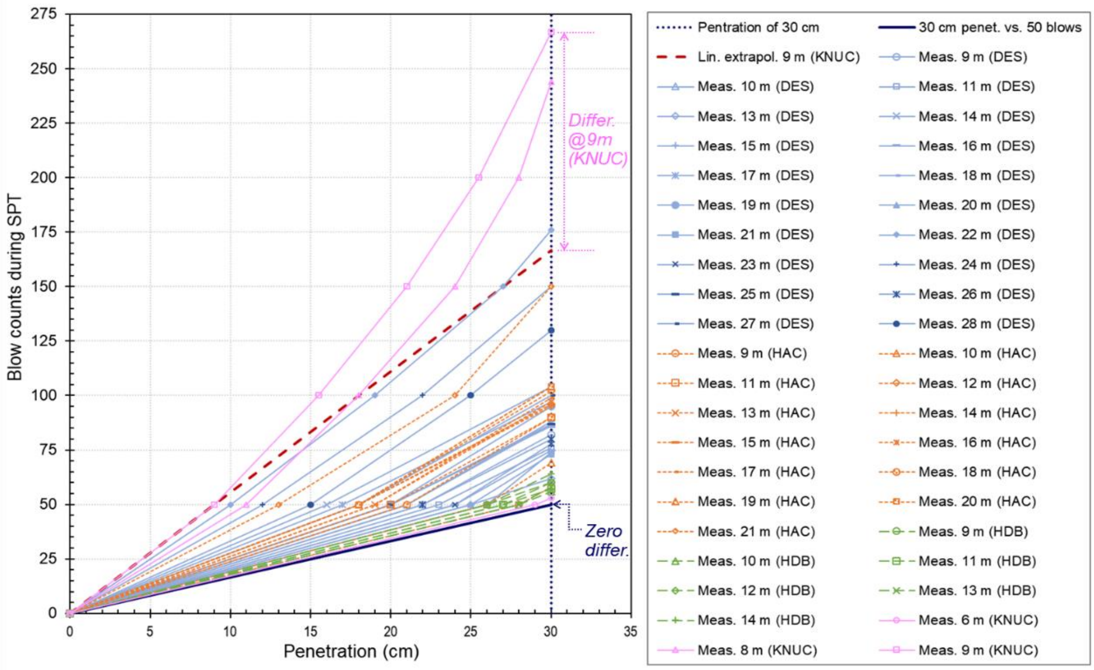


Fig. 4 Blow counts versus penetration for phases 1–3 during the SPTs at the four sites

stress, respectively. The three resistance values were considered to examine the relationship between the blow count and penetration in this study.

A general relationship between the penetration depth and number of blows during the SPT is illustrated conceptually in Fig. 3(a), assuming more than 100 blows, and the data measured at the DES site are presented in Fig. 3(b). The data indicate a nonlinear relationship between penetration and the number of blows, similar to a hyperbolic curve, where the gradient of the penetration gradually decreased with increasing blow count. The difference between the linearly extrapolated blow count at 30 cm penetration (defined as 'N_E') and the blow count measured in the field (defined as 'N_M') can therefore be determined. In Fig. 3(a), points A and A′ indicate the penetration after 50 and 100 blows, respectively. Three points (B, B′, and B′′) at a penetration of 30 cm were linearly extrapolated based on the gradients from the origin to point A, the origin to point A′, and point A to point A′, respectively. On comparing the blow count (N_M) measured in the field (point C) to the blow counts that were linearly extrapolated, the difference decreased in the order of points B, B′ and B′′, namely with decreasing extrapolation gradient, which was statistically analyzed by introducing new variables on the differences in this study.

3. Regression analysis to predict *N* value at 30 cm penetration

To investigate the nonlinear increase in the number of blows, the blow counts at 41 testing locations in weathered soil/rock layers across four sites, DES, HAC, HDB, and KNUC (Table 1), for phases 1–3, are plotted against penetration in Fig. 4. The line with 30 cm penetration, the gradient from the origin to the point of 30 cm penetration at 50 blows (no difference between N_M and N_E), and the maximum difference between N_M and N_E at a 9 m deep testing location at the KNUC site are also plotted. A general tendency towards greater nonlinearity in the relationship between the number of blows and penetration was observed as the penetration at 50 blows decreased, with some exceptions.

In weathered strata, the difference between N_M and N_E, denoted '*DN*' in the regression analysis, increases with the stiffness of the soil at the testing location, such that P_{50} was smaller for those testing locations in a borehole. The difference in penetration between 30 cm and P_{50} in a stratum was denoted as '*DP*' herein and used as the independent variable in the regression analysis. The *DN* and *DP* values for analyses in weathered strata were calculated with all three *N* values, such as the uncorrected *N* measured in the field, the corrected N_{60}, and the corrected $(N_1)_{60}$. An example profile of *N* values recorded after 50 cm penetration in weathered strata (9–28 m deep) and their corrected N_{60} and $(N_1)_{60}$ values at the DES site are presented in Fig. 5, which might be compared with the profile of the linearly extrapolated *N* values (see Fig. 2).

Various regression analyses were performed on a dataset comprising *DN* and *DP* variables for 41 testing locations across the four sites. The representative four relationships from the regression analyses on both the uncorrected *N* value and the corrected two *N* values (N_{60} and $(N_1)_{60}$) are shown in Fig. 6, together with the histogram of the *DN* data and the probability of lognormal distribution. Fig. 6(a) indicates the data and correlations for the uncorrected *N*, and Figs. 6(b) and 6(c) indicate the data and correlations for the corrected N_{60} and $(N_1)_{60}$, respectively. The coefficient of determination (R^2) in three types of *N* values showed the range from 0.32–0.60 for the linear model for poor cases to 0.54–0.65 for both the cubic and exponential models as good cases. In particular, the R^2 values for the uncorrected *N* and N_{60} were both nearly identical and significantly higher than those for $(N_1)_{60}$.

Despite small amount of data, the nonlinear regressions including the cubic, exponential, and power models showed a very steep increase in the *DN* values, particularly for larger *DP* values. For a cubic function, parts (approximately 5–12 cm in *DP*) decreasing *DN* with increasing *DP* in Figs. 6(a)-6(c) may not be acceptable for the nonlinear relationship between penetration and its resistance as bow count (e.g., Figs. 3 and 4). In addition, the value of *DN* was not equal to zero for the zero in *DP*, for an exponential function, and for a power function, the fitted values of *DN* were extremely low for less than 10 cm in *DP*, compared with the data from four sites. Although the cubic and exponential correlations yielded higher R^2 values compared to the linear correlation, a rational linear model would be considered for practical applications in the field of geotechnical engineering.

The cubic and linear regression models between *DN* and *DP* for the uncorrected *N* values are illustrated in Fig. 7 as

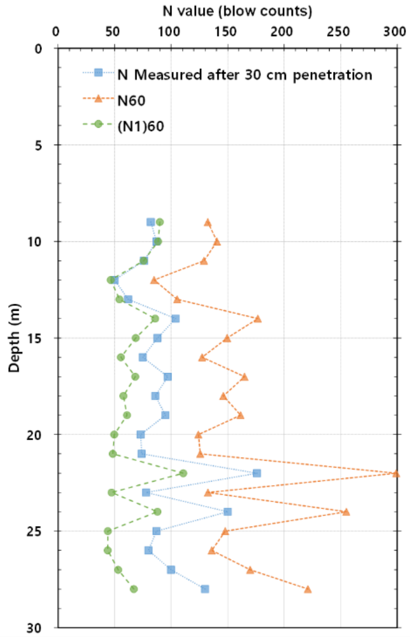


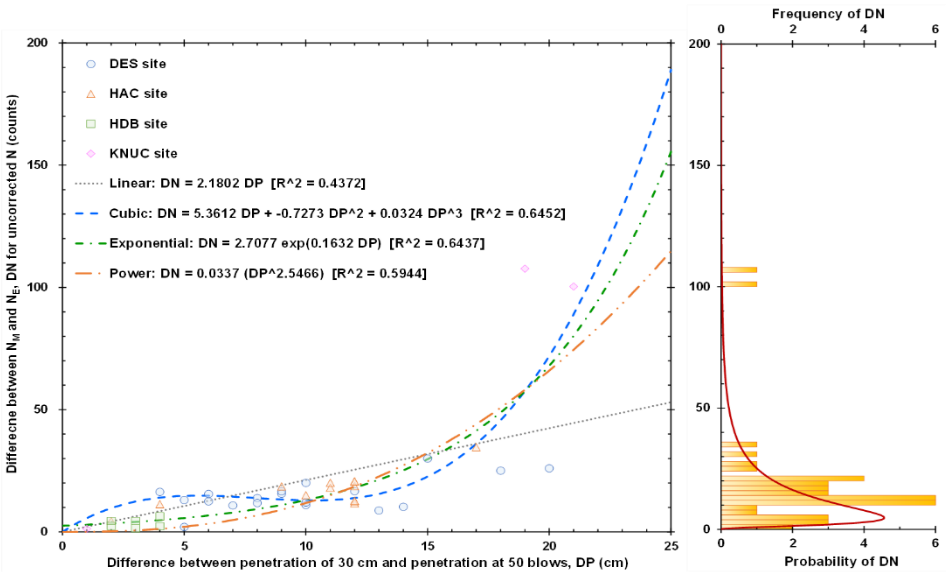
Fig. 5 *N* values measured after 30 cm penetration during special SPTs and their corrected *N* values in weathered strata at the DES site

example cases, together with their 95% confidence and residuals of *DN*. Based on the confidence of correlations as well as the residual of *DN*, the correlations between *DN* and *DP* for larger values of data may be considered less meaningful than those of smaller to intermediate *DN* and *DP* data owing to insufficient data in the range of more than 15 cm in *DP* and roughly 50 in *DN*. This indicate the need for more special SPTs in weathered rock strata and reserve their data in the future. However, the relationships between *DN* and *DP* in the range of < 15 cm are meaningful considering both the distribution of data and the residuals of *DN*.

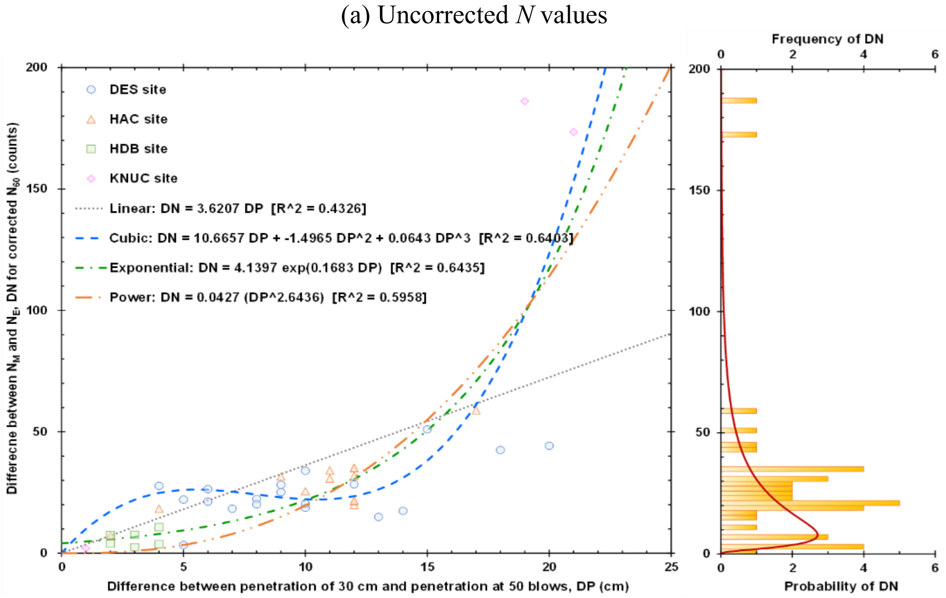
For these reasons, an alternative bi-linear function was developed that might be reasonable and simple with an intersection point of 15 cm in *DP*. To create the bi-linear regression model, first, a linear correlation passing through the origin was derived based on only data below 15 cm of *DP*, and as expected, the R^2 values based on the data below 15 cm in *DP* were higher than those for all data. Then, the other linear correlation intersecting at a point of 15 cm in *DP* with the former linear correlation was deduced using only the data above 15 cm of *DP*, and the two linear correlations were combined into a bi-linear relation model according to the ranges of their resource data. The bi-linear model for the uncorrected *N*, given by Eq. (4), may be useful for comparison with other nonlinear function models.

However, more SPT data should be acquired to enhance the reliability of the bi-linear regression model, particularly focusing on weathered rock for data of more than 15 cm in *DP*.

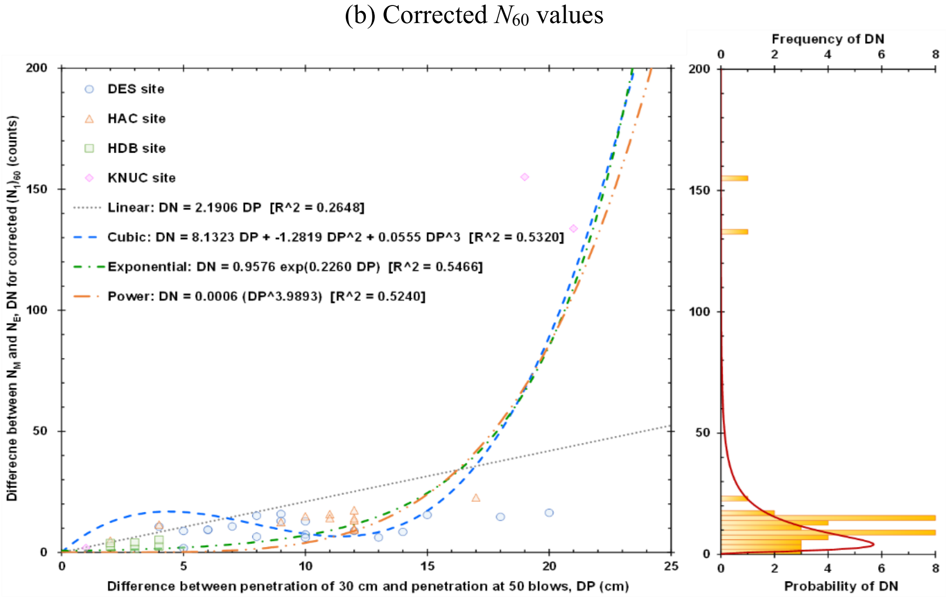
$$DN = \begin{cases} 1.47\ DP, & DP \le 15\ \text{cm (for uncorrected } N) \\ 9.61\ DP - 122.06, & DP > 15\ \text{cm (for uncorrected } N) \end{cases} \quad (4)$$



(a) Uncorrected N values

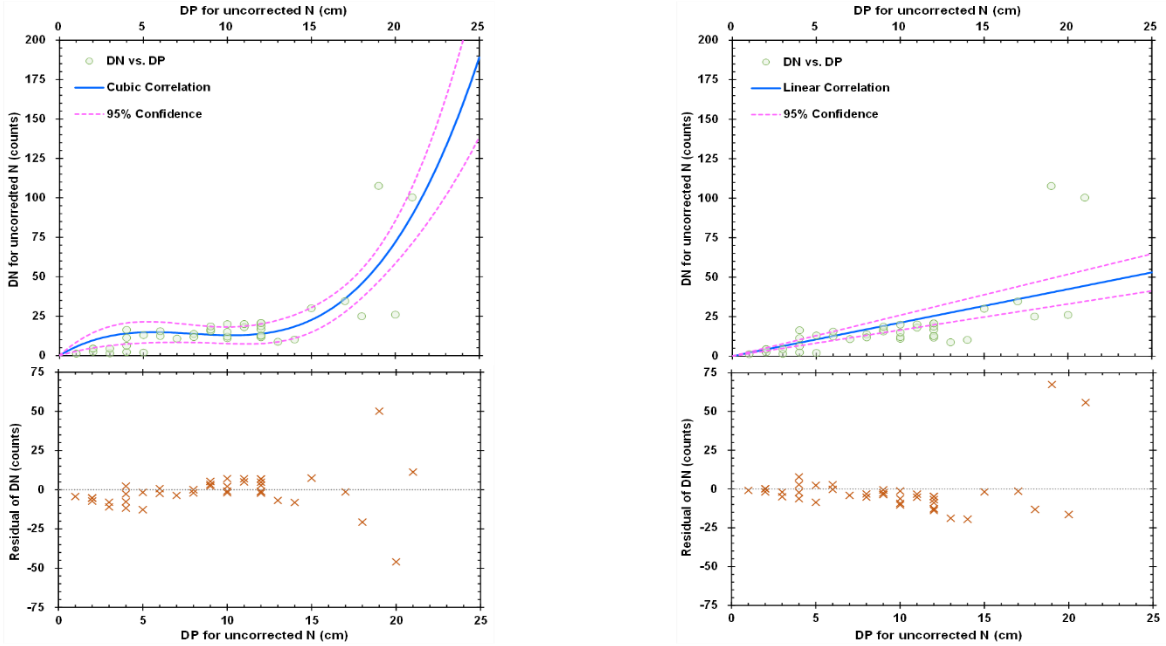


(b) Corrected N_{60} values



(c) Corrected $(N_1)_{60}$ values

Fig. 6 Correlations between DN and DP and the probability distribution of DN



(a) Cubic model (b) Linear model

Fig. 7 Representative regression models of *DN* by *DP* for uncorrected *N* with 95% confidence bands (upper panel) and residuals (lower panel)

In addition to the bi-linear correlations from the uncorrected *N* values measured in the field, in this study, bi-linear models for the corrected N_{60} and $(N_1)_{60}$ were also deduced for a variety of applications in dynamic as well as static conditions (Muduli and Das 2015, Bajaj and Anbazhagan 2019). Fig. 8 illustrates the bi-linear correlations based on the datasets of *DP* and *DN* suggested in this study, for the uncorrected *N* value and the corrected two *N* values (N_{60} and $(N_1)_{60}$). The histogram of the *DP* and its probabilistic distribution are also presented in Fig. 8. The derived bi-linear functions for corrected N_{60} and $(N_1)_{60}$ are given by Eqs. (5) and (6), respectively.

$$DN = \begin{cases} 2.50\ DP, & DP \le 15\ cm\ \text{(for corrected } N_{60}) \\ 17.70\ DP - 213.13, & DP > 15\ \text{cm (for corrected } N_{60}) \end{cases} \tag{5}$$

$$DN = \begin{cases} 1.08\ DP, & DP \le 15\ \text{cm (for corrected } (N_1)_{60}) \\ 14.11\ DP - 195.48, & DP > 15\ \text{cm (for corrected } (N_1)_{60}) \end{cases} \tag{6}$$

4. Determination of the *N* Value at 30 cm Penetration

The relationship between the penetration and number of blows obtained during the SPTs of weathered strata, exhibited a nonlinear curve (refer to Figs. 3 and 4). The bi-linear models between *DN* and *DP* were proposed by Eqs. (4)-(6), and Eq. (7) is the functional form used for determining the modeled *N* value (defined as 'N_P') at a penetration of 30 cm by adding N_E based on 50 blow counts in the practical SPT and the modeled *DN* (denoted 'DN_{PE}' in this study) indicating the difference between N_P and N_E.

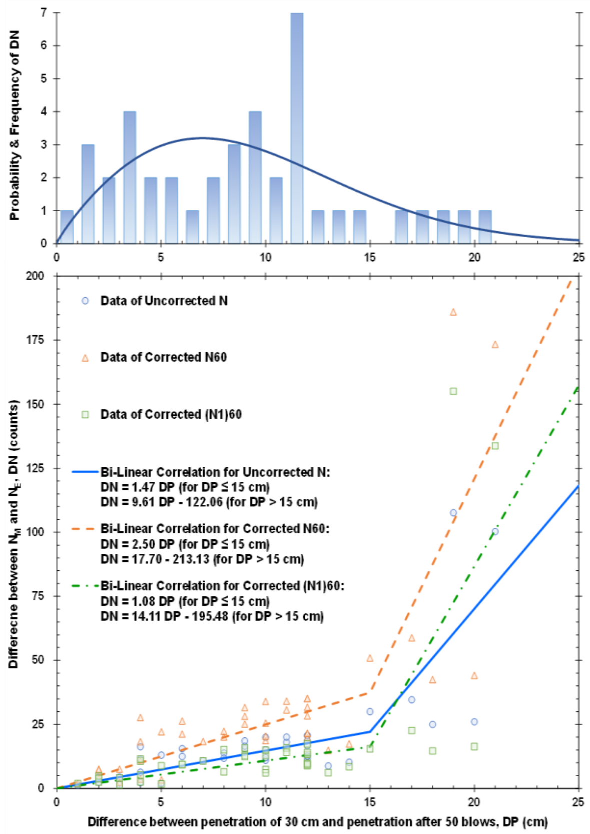


Fig. 8 Suggested bi-linear correlations between *DN* and *DP* and the probability distribution of *DP*

$$N_P = N_E + DN_{PE} \tag{7}$$

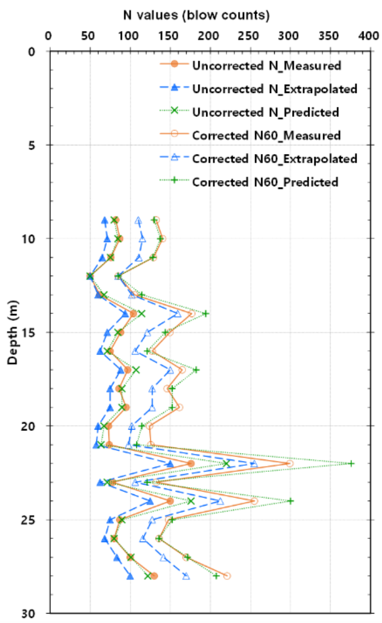
Table 2 Comparisons of uncorrected N values (N_M) measured after 30 cm penetration from the SPTs in weathered strata and linearly-extrapolated and predicted N values (N_E and N_P)

Name of site	Depth (m)	DP (cm)	N_M (blows)	N_E (blows)	N_P (blows)	Differences between N values		
						N_M & N_E	N_M & N_P	N_P & N_E
DES	9	8	82	68.2	80.0	13.8	2.0	11.8
	10	9	87	71.4	84.7	15.6	2.3	13.3
	11	7	76	65.2	75.5	10.8	0.5	10.3
	13	5	62	60.0	67.4	2.0	-5.4	7.4
	14	14	104	93.8	114.4	10.3	-10.4	20.6
	15	9	88	71.4	84.7	16.6	3.3	13.3
	16	6	75	62.5	71.3	12.5	3.7	8.8
	17	13	97	88.2	107.4	8.8	-10.4	19.1
	18	10	86	75.0	89.7	11.0	-3.7	14.7
	19	10	95	75.0	89.7	20.0	5.3	14.7
	20	5	73	60.0	67.4	13.0	5.6	7.4
	21	4	74	57.7	63.6	16.3	10.4	5.9
	22	20	176	150.0	220.1	26.0	-44.1	70.1
	23	6	78	62.5	71.3	15.5	6.7	8.8
	24	18	150	125.0	175.9	25.0	-25.9	50.9
	25	10	87	75.0	89.7	12.0	-2.7	14.7
	26	8	80	68.2	80.0	11.8	0	11.8
	27	12	100	83.3	101.0	16.7	-1.0	17.7
	28	15	130	100.0	122.1	30.0	7.9	22.1
HAC	9	2	58	53.6	56.5	4.4	1.5	2.9
	10	4	69	57.5	63.6	11.3	5.4	5.9
	11	10	90	75.0	89.7	15.0	0.3	14.7
	12	12	102	83.3	101.0	18.7	1.0	17.7
	13	11	97	78.9	95.1	18.1	1.9	16.2
	14	12	95	83.3	101.0	11.7	-6.0	17.7
	15	12	96	83.3	101.0	12.7	-5.0	17.7
	16	12	96	83.3	101.0	12.7	-5.0	17.7
	17	11	99	78.9	95.1	20.1	3.9	16.2
	18	9	90	71.4	84.7	18.6	5.3	13.3
	19	12	104	83.3	101.0	20.7	3.0	17.7
	20	12	104	83.3	101.0	20.7	3.0	17.7
	21	17	150	115.4	156.7	34.6	-6.7	41.3
HDB	9	4	60	57.7	63.6	2.3	-3.6	5.9
	10	2	56	53.6	56.5	2.4	-0.5	2.9
	11	3	57	55.6	60.0	1.4	-3.0	4.4
	12	3	60	55.6	60.0	4.4	0	4.4
	13	2	58	53.6	56.5	4.4	1.5	2.9
	14	4	64	57.7	63.6	6.3	0.4	5.9
KNUC	6	1	53	51.7	53.2	1.3	-0.2	1.5
	8	19	244	136.4	196.9	107.6	47.1	60.5
	9	21	267	166.7	246.4	100.3	20.6	79.8

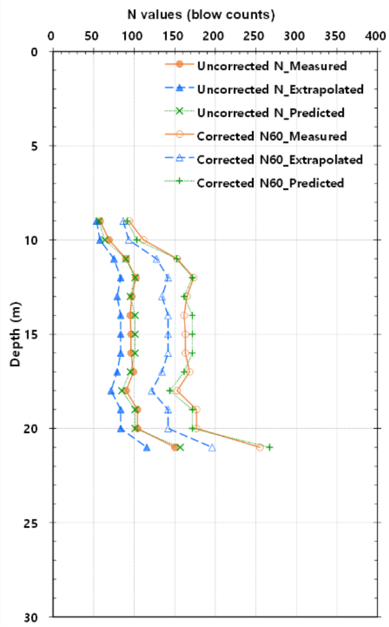
Based on the $50/P_{50}$ obtained by the practical SPTs conducted according to KS F 2307 (KSA, 2017) at four sites (see Table 1), the predicted N_P values were calculated by substituting the DN_{PE} in Eq. (7) with the DP relationships from Eqs. (4)-(6). The N values for the full penetration of 30 cm would be determined based on the N_E extrapolated linearly based on 50 blows from the conventional SPTs, for uncorrected N, corrected N_{60}, and corrected $(N_1)_{60}$, using Eqs. (8)-(10), respectively. The N_P and N_E associated with Eq. (8) for the uncorrected N values are listed in Table 2, together with the N values measured from the special SPTs and the differences between N values, among which the difference between N_M and N_E indicates the DN data for the statistical analyses. In addition, the N_M,

Table 3 Comparisons of linearly-extrapolated N values (N_E) based on 50 and 100 blow counts from the SPTs in weathered strata and measured and predicted N values (N_M and N_P) for uncorrected condition

Name of site	Depth (m)	DP (cm)		N_M (blows)	N_P (blows)	N_E (blows)	
		50 blows	100 blows			50 blows	100 blows
DES	22	20	11	176	220.1	150.0	157.9
	24	18	8	150	175.9	125.0	136.4
	28	15	5	130	122.1	100.0	120.0
HAC	21	17	6	150	156.7	115.4	125.0
KNUC	8	19	12	244	196.9	136.4	166.7
	9	21	14	267	246.4	166.7	187.5



(a) DES site



(b) HAC site

Fig. 9 Comparisons of N values (N_M) measured after 30 cm penetration from the SPTs in weathered strata with linearly-extrapolated and predicted N values (N_E and N_P) for the uncorrected N and the corrected N_{60} and $(N_1)_{60}$

N_E and N_P values for the uncorrected N and the N_{60} among two corrected values in weathered strata are plotted in Fig. 9 for representative cases of the DES and HAC sites.

According to Table 2 and Fig. 9, the N_E values are smaller than the N_M and N_P values, with a consistent discrepancy in DN_{PE}, regardless of the conditions of correction and DP value. Therefore, particularly for geotechnical studies of weathered strata (Seo *et al*. 2012, Sun 2015, Yoon *et al.* 2015), the N_P proposed herein can be used to determine the N value for 30 cm penetration, instead of the more commonly applied N_E. The corrected $(N_1)_{60}$ values, as well as the N_{60} depicted in Fig. 9, show the same pattern with depth as the uncorrected N values.

$$N_P = \begin{cases} N_E + 1.47\ DP, & DP \le 15 \text{ cm (for uncorrected } N) \\ N_E + 9.61\ DP - 122.06, & DP > 15 \text{ cm (for uncorrected } N) \end{cases} \tag{8}$$

$$N_P = \begin{cases} N_E + 2.50\ DP, & DP \le 15 \text{ cm (for corrected } N_{60}) \\ N_E + 17.70\ DP - 213.13, & DP > 15 \text{ cm (for corrected } N_{60}) \end{cases} \tag{9}$$

$$N_P = \begin{cases} N_E + 1.08\ DP, & DP \le 15 \text{ cm (for corrected } (N_1)_{60}) \\ N_E + 14.11\ DP - 195.48, & DP > 15 \text{ cm (for corrected } (N_1)_{60}) \end{cases} \tag{10}$$

Data in this study might be insufficient particularly for the very stiff subsurface conditions of larger than 100 blow counts after 30 cm penetration in the special SPTs, which results in larger DP values for 50 blows from the practical SPTs. To enhance the reliability of the regression models to determine the N_P from the N_E, more penetration data should be obtained by performing special SPTs at many sites, mainly developed by weathered soil and rock layers. However, the bi-linear regression models would be applicable for estimating the N values for 30 cm penetration instead of the existing linear-extrapolation approach in weathered subsurface layers in Korea. Table 3 summarizes the N values consisting of N_M, N_P, and N_E at the testing locations where the final penetration resistances were more than 100 blow counts. The *DP* values based on the penetration depth after 50 blows for the regression analyses in this study were compared to those of 100 blows, and the N_E values were calculated with different *DP* values.

The N_E values for 100 blows were larger than those for 50 blows because of the nonlinear relationship between penetration and blow counts (see Fig. 3), and were then quantitatively closer to the N_M values. This indicates the need to perform SPT in Korea up to 100 blows, as specified in ASTM D1586 (ASTM 2018). Furthermore, the regressions suggested in this study should be validated by compiling the SPT data generated in more tests involving more than 100 blows, and be improved by performing the special SPTs for wider range of site conditions.

5. Conclusions

Special SPTs ensuring that the penetration of 30 cm was reached were conducted in boreholes with weathered strata underlying fresh bedrock, in several inland sites in Korea. A nonlinear relationship between penetration and the number of blows was identified, similar to a hyperbolic curve that gradually decreases the gradient of the penetration, which is different from the linear relationship assumed previously in geotechnical practice. The *DN* data associated with measured N_M and extrapolated N_E values were analyzed, along with *DP* data associated with 30 cm penetrations and P_{50}. From various statistical regression analyses, bi-linear models intersecting at 15 cm in *DP* were derived not only for the uncorrected *N* values but also for the corrected N_{60} and $(N_1)_{60}$ values, to reflect the nonlinearity of the relationship between penetration and number of blows. The predicted *N* values (N_P) through the bi-linear regression models may be derived that could replace N_E when the penetration is less than 30 cm after 50 blows; this could be particularly useful for weathered strata.

Acknowledgments

This research was supported by the Basic Research Project of the Korea Institute of Geoscience and Mineral Resources (KIGAM).

References

AASHTO (2007), Standard specifications for highway bridge, 18th edition. American Association of State Highway and Transportation Officials, Washington DC, USA.

ASTM (2011), ASTM D6066–11: Standard practice for determining the normalized penetration resistance of sands for evaluation of liquefaction potential. American Society for Testing and Materials International, West Conshohocken, PA, USA.

ASTM (2018), ASTM D1586/D1586M–18: Standard test method for standard penetration test (SPT) and split-barrel sampling of soils. American Society for Testing and Materials International, West Conshohocken, PA, USA.

Anbazhagan, P., Sheikh, M.N. and Parihar, A. (2013), "Influence of rock depth on seismic site classification for shallow bedrock regions", *Nat. Hazards Rev.*, **14**(2), 108-121. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000088.

Bajaj, K. and Anbazhagan, P. (2019), "Seismic site classification and correlation between V_S and SPT-*N* for deep soil sites in Indo-Gangetic Basin", *J. Appl. Geophys.*, **163**, 55-72. https://doi.org/10.1016/j.jappgeo.2019.02.011.

Bowles, J.E. (1997), *Foundation Analysis and Design*. McGraw-Hill, Singapore.

BSI (2007), BS EN ISO 22476-3:2005+A1:2001: Geotechnical investigation and testing–Field testing–Part 3: Standard penetration test. British Standards Institution, London, UK.

Cho, H.I., Sun, C.G., Kim, J.H. and Kim, D.S. (2018), "*OCR* evaluation of cohesionless soil in centrifuge model using shear wave velocity", *Geomech. Eng.*, **15**(4), 987-995. https://doi.org/10.12989/gae.2018.15.4.987.

dos Santos, M.D. and Bicalho, K.V. (2017), "Proposals of SPT-CPT and DPL-CPT correlations for sandy soils in Brazil", *J. Rock Mech. Geotech. Eng.*, **9**(6), 1152-1158. https://doi.org/10.1016/j.jrmge.2017.08.001.

Dung, N.T., Chung, S.G., Kim, S.R. and Baek, S.H. (2011), "Applicability of the SPT-based methods for estimating toe bearing capacity of driven PHC piles in the thick deltaic deposits", *KSCE J. Civil Eng.*, **15**(6), 1023-1031. https://doi.org/10.1007/s12205-011-0801-0.

ErzÍn, Y. and Gul, T.O. (2013), "The use of neural networks for the prediction of the settlement of pad footings on cohesionless soils based on standard penetration test", *Geomech. Eng.*, **5**(6), 541-564. https://doi.org/10.12989/gae.2013.5.6.541.

FHWA (2006), Soils and foundations: Reference manual –Volume I. National Highway Institute, Federal Highways Administration, Washington DC, USA

Ghali, M., Chekired, M. and Karray, M. (2020), "Framework to improve the correlation of SPT-*N* and geotechnical parameters in sand", *Acta Geotechnica*, **15**(3), 735-759. https://doi.org/ 10.1007/s11440-018-0745-3.

Goh, A.T.C., Zhang, R.H., Wang, W., Wang, L., Liu, H.L. and Zhang, W.G. (2020), "Numerical study of the effects of groundwater drawdown on ground settlement for excavation in residual soils", *Acta Geotechnica*, **15**(5), 1259-1272. https://doi.org/ 10.1007/s11440-019-00843-5.

Gui, M.W., Soga, K., Bolton, M.D. and Hamelin, J.P. (2002), "Instrumented borehole drilling for subsurface investigation", *J. Geotech. Geoenviron. Eng.*, **128**(4), 283-291. https://doi.org/10.1061/(ASCE)1090-0241(2002)128:4(283).

Guo, W.D. (2012), *Theory and Practice of Pile Foundations*, 1st edition. CRC Press, Boca Raton, FL, USA

Han, L., Wang, L., Ding, X., Wen, H., Yuan, X. and Zhang, W. (2022), "Similarity quantification of soil parametric data and sites using confidence ellipses", *Geosci. Frontiers*, **13**(1), 101280. https://doi.org/10.1016/j.gsf.2021.101280.

Jeong, S., Park, J., Ko, J. and Kim, B. (2017), "Analysis of soil resistance on drilled shafts using proposed cyclic p-y curves in weathered soil", *Geomech. Eng.*, **12**(3), 505-522. https://doi.org/10.12989/gae.2017.12.3.505.

KSA (2017), KS F 2307: Standard test method for standard penetration test. Korea Standards Association, Seoul, Korea (in Korean)

Kulhawy, F.H. and Mayne, P.W. (1990), "Manual on estimating soil properties for foundation design", Electric Power Research Institute, Palo Alto, CA, USA.

Liao, S.S.C. and Whitman, R.V. (1986), "Overburden correction factors for SPT in sand", *J. Geotech. Eng.*, **112**(3), 373-377. https://doi.org/10.1061/(ASCE)0733-9410(1986)112:3(373).

Matsumoto, T., Phan, L.T., Oshima, A. and Shimono, S. (2015), "Measurements of driving energy in SPT and various dynamic cone penetration tests", *Soils Found.*, **55**(1), 201-212. https://doi.org/10.1016/j.sandf.2014.12.016.

Mujtaba, H., Farooq, K., Sivakugan, N. and Das, B.M. (2018), "Evaluation of relative density and friction angle based on SPT-*N* values", *KSCE J. Civil Eng.*, **12**(2), 572-581. https://doi.org/10.1007/s12205-017-1899-5.

Muduli, P.K. and Das, S.K. (2015), "Model uncertainty of SPT-based method for evaluation of seismic soil liquefaction potential using multi-gene genetic programming", *Soils Found.*, **55**(2), 258-275. https://doi.org/10.1016/j.sandf.2015.02.003.

Oh, S. and Sun, C.G. (2008), "Combined analysis of electrical resistivity and geotechnical SPT blow counts for the safety assessment of fill dam", *Environ. Geol.*, **54**(1), 31-42. https://doi.org/10.1007/s00254-007-0790-y.

Robert, Y. (1997), "A few comments on pile design", *Can. Geotech. J.*, **34**(4), 560-567. https://doi.org/10.1139/t97-024.

Rogers, J.D. (2006), "Subsurface exploration using the standard penetration test and the cone penetration test", *Environ. Eng. Geosci.*, **12**(2), 161-179. https://doi.org/10.2113/12.2.161.

Seo, M.W., Olson, S.M., Sun, C.G. and Oh, M.H. (2012), "Evaluation of liquefaction potential index along western coast of South Korea using SPT and CPT", *Mar. Georesour. Geotech.*, **30**(3), 234-260. https://doi.org/10.1080/1064119X.2011.614322.

Skempton, A.W. (1986), "Standard penetration test procedures and the effects in sands of overburden pressure, relative density, particle size, aging and overconsolidation", *Géotechnique*, **36**(3), 425-447. https://doi.org/10.1680/geot.1986.36.3.425.

Sun, C.G. (2015), "Determination of mean shear wave velocity to 30 m depth for site classification using shallow depth shear wave velocity profile in Korea", *Soil Dyn. Earthq. Eng.*, **73**, 17-28. https://doi.org/10.1016/j.soildyn.2015.02.011.

Sun, C.G., Cho, C.S., Son, M. and Shin, J.S. (2013), "Correlations between shear wave velocity and in-situ penetration test results for Korean soil deposits", *Pure Appl. Geophys.*, **170**(3), 271-281. https://doi.org/10.1007/s00024-012-0516-2.

Sun, C.G., Kim, B.H., Park, K.H. and Chung, C.K. (2015), "Geotechnical comparison of weathering degree and shear wave velocity in the decomposed granite layer in Hongseong, South Korea", *Environ. Earth Sci.*, **74**(9), 6901-6917. https://doi.org/10.1007/s12665-015-4692-0.

Sun, C.G., Kim, D.S. and Chung, C.K. (2005), "Geologic site conditions and site coefficients for estimating earthquake ground motions in the inland areas of Korea", *Eng. Geol.*, **81**(4), 446-469. https://doi.org/10.1016/j.enggeo.2005.08.002.

Yoon, S., Lee, S.R., Kim, Y.T. and Go, G.H. (2015), "Estimation of saturated hydraulic conductivity of Korean weathered granite soils using a regression analysis", *Geomech. Eng.*, **23**(3), 245-259. https://doi.org/10.12989/gae.2020.23.3.245.

Zaid, M., Sadique, M.R., Alam, M.M. and Samanta, M. (2020), "Effect of shear zone on dynamic behaviour of rock tunnel constructed in highly weathered granite", *Geomech. Eng.*, **9**(1), 101-113. https://doi.org/10.12989/gae.2015.9.1.101.

Zhang, R., Zhang, W. and Goh, A.T.C. (2021), "Assessment of wall deflections and ground settlements for braced excavations subjected to groundwater drawdown: Numerical simulations and design charts", *ISSMGE Int. J. Geoeng. Case Histories*, **6**(2), 67-80. https://dx.doi.org/10.4417/IJGCH-06-02-04.

Zhang, W.G., Zhang, R.H., Han, L. and Goh, A.T.C. (2019), "Engineering properties of the Bukit Timah Granitic residual soil in Singapore", *Undergr. Sp.*, **4**(2), 98-108. https://doi.org/10.1016/j.undsp.2018.07.001.

IC

Symbols

SPT Standard penetration test

N Number of blows during SPT

P_{50} Penetration measured at 50 blow counts during a practical SPT mostly in very dense soil and weathered strata

N_E Blow counts (N value) linearly extrapolated to full penetration of 30 cm using a ratio of $50/P_{50}$

N_M N value (more than 50 blows in this study) measured by advancing a sampler the 30 cm of penetration from the specified SPT in field

DN Difference between the N_M and N_E

DP Difference between the 30 cm as final penetration and the penetration advanced at the 50 blows in a field

R^2 Coefficient of determination from regression analysis

N_P N value predicted using a correlation between DN and DP suggested in this study

DN_{PE} Difference between the N_P and N_E