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Estimation of Pressuremeter Modulus and Limit Pressure in Weathered Granite Based on the SPT-N Value and Chemical Weathering Index: A Case Study in South Korea

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Abstract: A pressuremeter test (PMT) is a representative and highly reliable in situ test for assessing the stress–strain behavior of weathered granite. Its application, however, is restricted by its cost and time requirements. Many researchers have also investigated the correlations between the SPT-N value and the pressuremeter modulus (E_m) and limit pressure (P_L) of soils, but they have mostly focused on sand, silt, and clay and have employed simple regression analysis. In this study, equations for E_m and P_L were derived for weathered granite through multiple nonlinear regression analyses using a chemical weathering index that quantitatively represents the degree of weathering. Nonlinear multiple regression analyses were conducted by combining the allometric models that produced the optimal correlations between E_m , P_L , energy corrected SPT-N ($SPT-N_{60}$), and *normalized VR* (Vogt' ratio) with vertical effective stress. The obtained equations for E_m and P_L had higher R^2 values (0.76 and 0.46, respectively) compared with the simple regression equations reported in previous studies. Because local characteristics are important determinants of the engineering properties of geo-materials, the E_m and P_L equations proposed in this paper are intended for use in geotechnical surveys of weathered granite in South Korea.

Keywords: weathered granite; geotechnical property; standard penetration test; pressuremeter test; chemical weathering index



Citation: Lee, S.-H.; Kwak, T.-Y.; Park, K.-H. Estimation of Pressuremeter Modulus and Limit Pressure in Weathered Granite Based on the SPT-N Value and Chemical Weathering Index: A Case Study in South Korea. *Appl. Sci.* **2021**, *11*, 3411. <https://doi.org/10.3390/app11083411>

Academic Editor: Daniel Dias

Received: 18 February 2021

Accepted: 6 April 2021

Published: 10 April 2021

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1. Introduction

Weathered granite, including residual soil and highly and completely weathered rocks, is widespread in South Korea and is used as the support base in the construction of major roads, bridges, and tunnels. It is therefore important to assess the geotechnical properties of weathered granite to ensure satisfactory structural performance and safety. Although geotechnical properties are typically assessed by in situ testing, sampling techniques that minimize the disturbance of the weathered granite sample, such as the triple core barrel method, have been in limited use more recently. However, it is challenging to secure sufficient undisturbed samples that are suitable for laboratory testing due to the frequent occurrence of disturbance during the transportation and fabrication of the test specimens. Clayton et al. [1] have recommended that in situ testing should be performed to obtain proper geotechnical properties in the case when it is difficult to retrieve an undisturbed sample.

The representative in situ tests applied to weathered granite are the standard penetration test (SPT) and pressuremeter test (PMT). The SPT, which is conducted simultaneously with a borehole investigation, is most widely used in the geotechnical field due to its convenience and economic feasibility. It is used to estimate geotechnical properties such as friction angle, unconfined compressive strength, and elastic modulus based on accumulated data and may also be used to calculate the bearing capacity of the foundation

and assess ground liquefaction [2–4]. However, the equations currently used to determine the geotechnical properties should be used with caution because most empirical equations are proposed based on the SPT- N values measured from soils, and penetration into the highly and completely weathered granite during an SPT is quite subtle. The PMT is used to assess the radial stress–strain behavior of the ground around a borehole and can also be applied for the calculation of the pressuremeter modulus (E_m) and limit pressure (P_L) of the base ground according to the obtained stress–strain curve. The E_m is used to calculate the settlement of a shallow foundation and the coefficient of the horizontal subgrade reaction, as well as the strength parameter of the ground, the bearing capacity of a shallow foundation and a pile foundation using the limit pressure. It is applicable to a wide range of ground types, ranging from soils to weak rocks, and particularly to geo-materials in a transition state between rock and soil, such as weathered granite [5]. However, it is more time-consuming and costly than the SPT and thus its use is limited and it is often omitted in small-scale projects.

Researchers have used simple regression analyses to investigate the correlation between SPT- N values and the E_m and P_L interpreted from PMTs to assess the geotechnical properties of grounds with a high degree of reliability, because SPTs are relatively convenient and economical. For example, Chiang and Ho [6] proposed nonlinear relationships between N and E_m and between N and P_L for weathered granite, including highly weathered granite and residual soil, in Hong Kong. Yagiz et al. [7] proposed linear relationships between N and E_m and between N and P_L based on the results of a test conducted in sandy silty clay developed at a shallow depth (within 2 m) in Denizli, Turkey. Bozbeý and Togrol [8] proposed nonlinear relationships between the same parameters for sandy soil and clayey soil using the results of tests conducted in Istanbul, Turkey, while Cheshomi and Ghodrati [9] did the same for silty sand and silty clay based on SPTs and PMTs conducted in Mashhad, Iran. However, most of these previous studies dealt with soils with SPT- N values of ≤ 50 ; none considered weathered granite with an N value of ≥ 50 . SPT is not recommended for hard geo-materials such as hard soil, soft rock, and highly weathered rock because its penetrability is not sufficient [5]. However, conventionally SPT rather than PMT is used in field practice to estimate the geotechnical properties of weathered granite because of time consuming process and high cost of PMT. Therefore, it is important to suggest the correlation between the SPT and PMT results conducted in weathered granite with N value ≥ 50 (i.e., hard residual soil, completely weathered rock, highly weathered rock).

Meanwhile, many studies have been conducted on the variation of the engineering properties of rocks due to weathering. The feasibility of representing the engineering properties of a rock by a chemical weathering index has also been suggested through a correlation analysis of the index with the engineering properties (unconfined compressive strength, dry density, shear strength, etc.) [10–14]. This index quantitatively describes the degree of weathering based on the changes in the chemical composition of the rock constituent minerals.

In the present study, empirical equations for determining E_m and P_L based on an SPT- N value and chemical weathering index were derived through a case study of weathered granite, including highly weathered granite and residual soil, in South Korea. The results of SPTs and PMTs conducted at three sites were used, and the equations of E_m and P_L were derived through the multiple nonlinear regression analysis of the SPT- N value and chemical weathering index, respectively. The values of E_m and P_L determined by the proposed equations were compared with those obtained in previous studies and by field measurements.

2. Study Area

The present study was conducted at three sites in the central and western parts of South Korea where weathered granite is commonly found (Figure 1). The study areas were selected based on a review of geotechnical investigation reports for the adjacent areas as roughly identified from a geological map of South Korea provided by the Korea Institute

of Geoscience and Mineral Resources. The three sites, identified in this paper as sites A, B, and C, were all within Jurassic granite areas, and weathered granite (i.e., residual soil, highly and completely weathered granite rock) was thickly developed with thicknesses of 14, 25, and 23 m, respectively, according to a borehole investigation (Figure 2). The samples retrieved by triple core barrel from each test site shows similar condition; the samples were brown, and their rock texture and structures were preserved especially in highly and completely weathered granite (Figure 3). An SPT and PMT were conducted at each site, and samples were collected for assessment of the chemical weathering indices. The details of the test methods and the obtained data are provided in Sections 3 and 4.

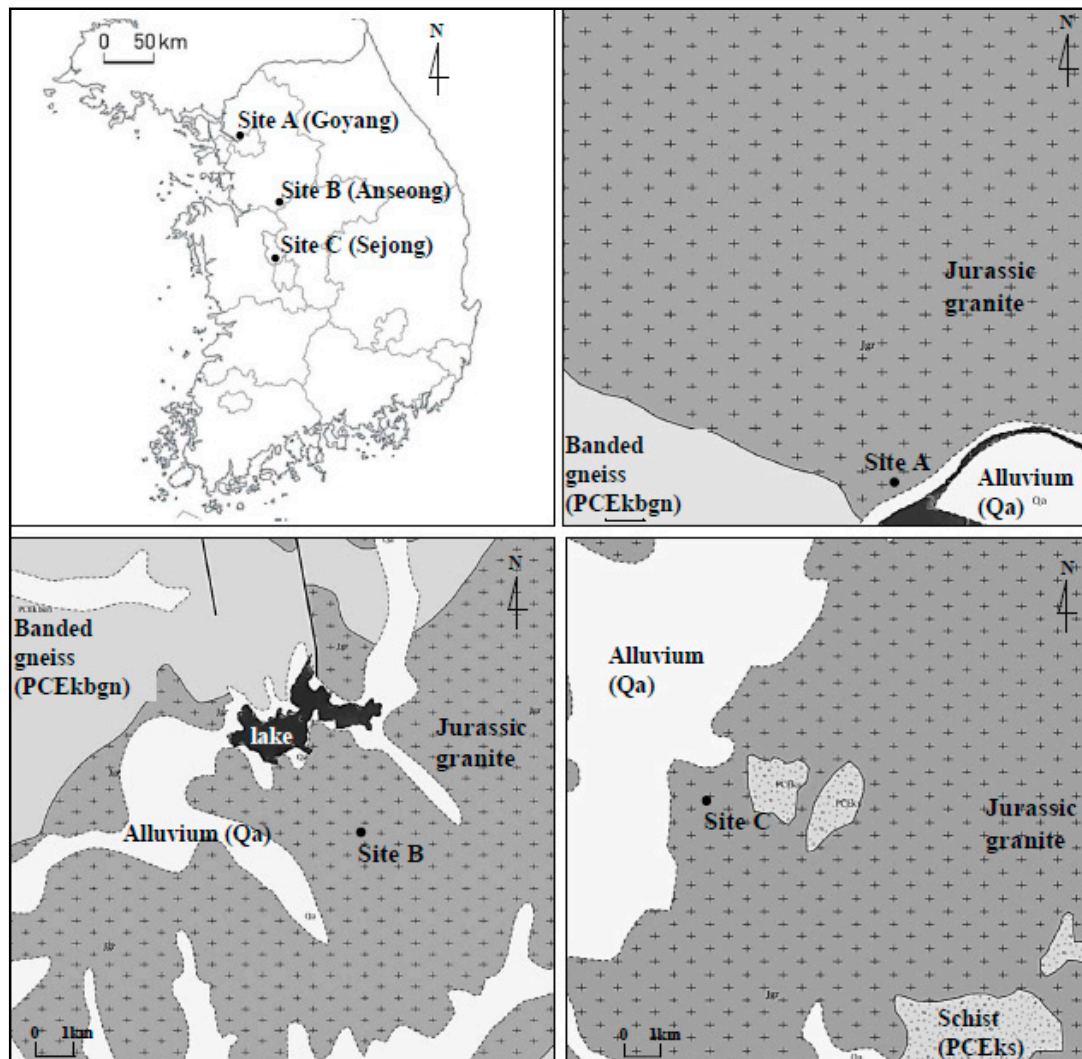


Figure 1. Locations of the study sites.

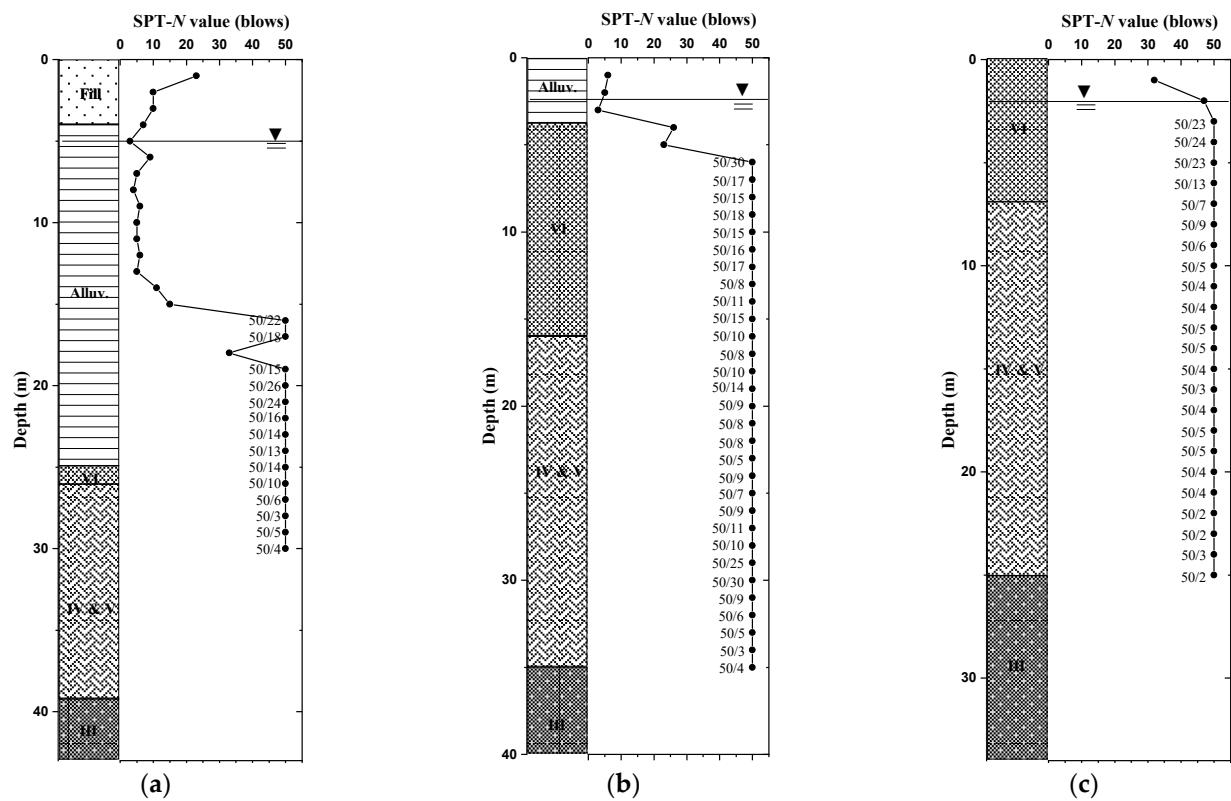


Figure 2. Boring logs of the test sites: (a) Site A, (b) Site B, and (c) Site C (Fill = fill material for developing agricultural land, Alluv = alluvium, III = moderately weathered granite, IV = highly weathered granite, V = completely weathered granite, VI = residual soil).

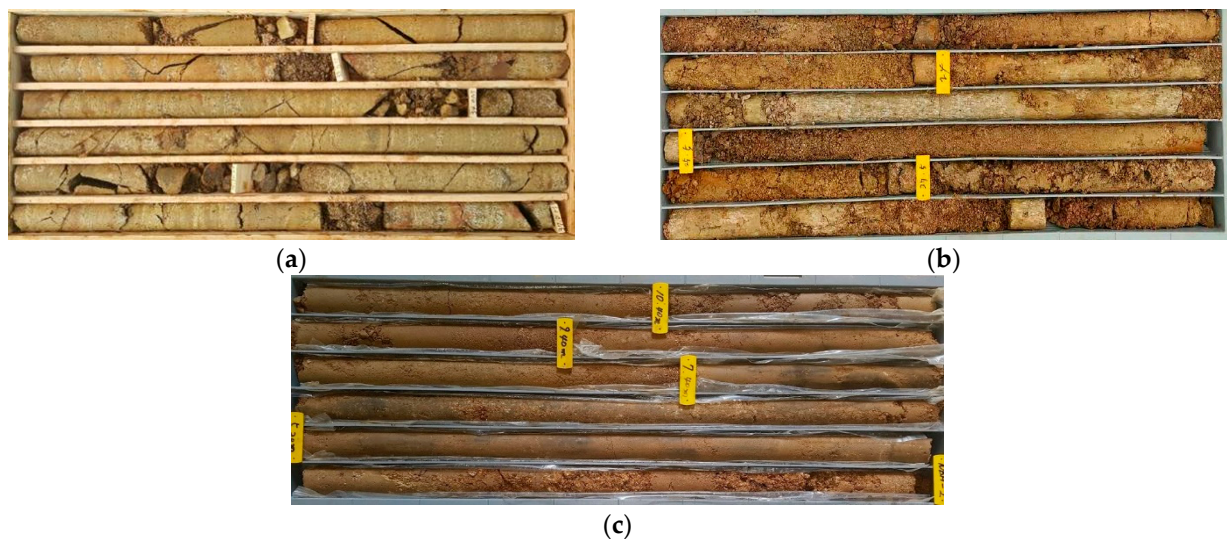


Figure 3. Samples retrieved from each test site: (a) Site A, (b) Site B, and (c) Site C.

3. Methodology

3.1. SPT and PMT

The SPT was conducted in three steps, namely the preliminary blows, main blows 1, and main blows 2, according to ASTM D1586 [15]. The preliminary blows are the number of blows required to penetrate 15 cm in the initial stage of the test. When the two main blows produced a combined penetration of <30 cm after 50 or more blows, the penetration produced by the first 50 blows was measured. If penetration was not achieved after

10 consecutive blows, the SPT was terminated. The SPT results for the weathered granite layer revealed a penetration of <30 cm after 50 blows because of the insufficient penetrability of the SPT device. Despite this limitation, the geotechnical properties of weathered granite (especially highly and completely weathered granite rock) are generally evaluated by SPT in practice field. Thus, many studies have used the converted SPT- N values linear extrapolated to the N value representing the number of blows required to penetrate 30 cm [16–18]. In the estimation of the geotechnical properties using the N value, an energy correction is necessary in order to obtain reliable results. Accordingly, the converted SPT- N value was corrected to SPT- N_{60} , which corresponds to 60% of the energy efficiency for the energy transfer rate of the equipment used in the test.

The PMT was conducted using an Elastometer-2 (OYO Corporation, Japan) in compliance with ASTM D4719 [19]. The test was conducted at the depth intervals of approximately 2 m in the weathered granite layer, and E_m and P_L were determined from the obtained pressure–radius curve. E_m is the modulus of the pseudo-elastic range and represents the deformation characteristic in the initial linear section under the horizontal pressure on the borehole wall. P_L represents the pressure at which the ground of the borehole wall reaches the state of destruction and is defined as the pressure that causes a continuous displacement without increasing the loading pressure beyond the initial elastic zone and plastic zone in the pressure–radius curve. In an actual test, however, it is difficult to reach P_L , due to the limited capacity of the testing equipment. Thus, in this study, the loading pressure was determined as the P_L at which the volume of the probe is twice the initial soil cavity volume (V_i) following the recommendation in ASTM D4719 [19]. The details of the PMT test and the methods for determining E_m and P_L are available in ASTM D4719.

3.2. Geochemical Analysis for Determination of Chemical Weathering Index

A chemical weathering index was calculated based on the weight percentage of the major oxides in the rock formed by weathering through the X-ray fluorescence (XRF) analysis. The index enables the evaluation of the degree of weathering regardless of the physical disturbance of the samples and is therefore appropriate for weathered granite, which easily shatters during sampling. In this study, the XRF analysis was conducted on weathered granite samples collected at the depths of the SPTs and PMTs at the three study sites. The chemical weathering index was calculated by converting the determined weight percentage of the major oxides into the molecular ratio.

Various chemical weathering indices have been proposed [12,20–23]. However, in this study, the representative chemical weathering index (Vogt's ratio (VR , Equation (1)) [24]) was used to conduct a nonlinear multiple regression analysis based on the study by Lee [25], in which eight types of chemical weathering indices and geotechnical properties of weathered granite in South Korea were analyzed; the assessment revealed the adequacy of the engineering property and degree of weathering based on VR . VR is the index which is calculated by considering the mobility of alkali and alkaline oxides during the weathering process, with a larger VR corresponding to a more weathered state.

The results of the SPTs and PMTs conducted at the three sites and the VR values of the collected samples determined by the XRF analysis are presented in Table 1.

$$VR = (Al_2O_3 + K_2O)/(MgO + CaO + Na_2O) \quad (1)$$

Table 1. Data for nonlinear multiple regression analysis.

No.	E_m (MPa)	P_L (MPa)	SPT- N_{60} (Blows)	VR	Normalized VR *
1	29.9	2.4	61	2.185	6.580
2	7.8	1.2	84	1.799	2.167
3	133.4	11.3	121	3.568	1.763
4	33.4	6.7	161	3.785	1.486
5	604.8	19.8	215	2.539	0.570
6	302.4	12.6	242	3.480	1.542
7	300.3	13.3	242	2.725	1.000
8	88.3	15.4	276	1.605	1.359
9	307.6	13.3	276	3.536	1.420
10	446.7	12.9	322	2.127	0.739
11	85.7	18.4	322	1.676	1.220
12	395.4	17.0	322	2.316	0.719
13	205.5	20.6	387	1.505	0.843
14	498.1	25.3	387	2.159	0.886
15	388.1	19.7	387	2.441	0.821
16	363.2	22.2	387	2.362	0.681
17	481.9	9.4	387	2.118	0.450
18	718.9	50.5	483	1.594	0.496
19	714.3	50.1	483	1.762	0.526
20	94.0	10.6	483	1.937	1.228
21	458.7	29.1	483	1.824	0.911
22	478.6	22.9	483	1.625	0.732
23	283.7	25.2	483	1.405	0.529
24	649.2	26.0	483	2.497	0.631
25	536.3	78.2	644	1.655	0.537
26	864.2	18.3	644	1.620	0.436
27	730.9	24.9	644	2.729	0.648

* $\frac{VR}{\sigma_v'/P_a}$, σ_v' = vertical effective stress, P_a = 1 atm.

4. Analysis

4.1. Test Data

The E_m values determined by the PMTs were between 7.8 and 864.2 MPa and generally increased with depth at each test site. The E_m at site A dramatically increased and those at site B decreased with depth below 29 m (Figure 4a). This tendency was also found for P_L (Figure 4b). The SPT- N_{60} determined by linear extrapolation conversion for a penetration of 30 cm corresponded to blows of between 61 and 644 at the three sites. Overall, SPT- N_{60} tended to increase with increasing depth at each test site, but those at site B decreased with depth below 29 m (Figure 5). As shown in Figures 4 and 5, the measured geotechnical properties showed different distribution due to different site conditions. Site A is near the riverside, so that it is rarely affected by the geological forces making fold and fissure. On the other hand, sites B and C are located in mountain areas that experienced complex geological forces (Figure 1).

The VR values, indicating the degree of weathering generally decreased with increasing depth at each test site. Weathering was affected by the vertical effective stress. Therefore, to exclude the effects resulted from the different depth and thickness at which the weathered granite layer was developed, VR was normalized using vertical effective stress and atmospheric pressure (Figure 6b); the vertical effective stress was calculated based on the results of in-situ density logging conducted at each test site. This is consistent with the results suggested in many studies and the theoretical trend of VR, that is, the increase of VR with greater weathering [25–28]. In this study, nonlinear multiple regression was used to estimate E_m and P_L based on SPT- N_{60} and the *normalized VR*. The details of the analysis and the results are presented in the next section.

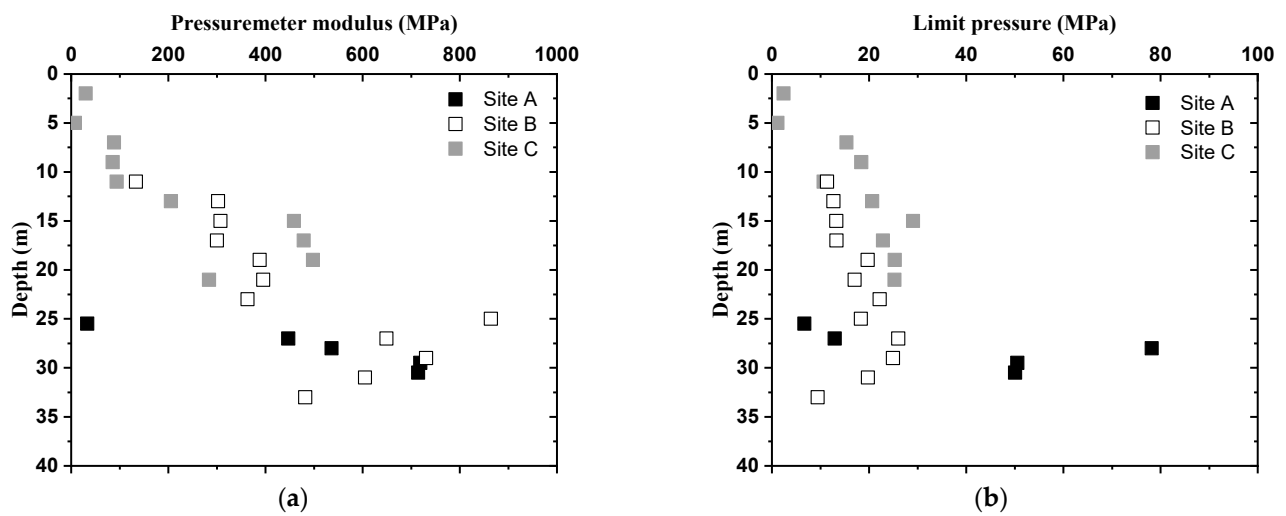


Figure 4. Variations of the (a) pressuremeter modulus and (b) limit pressure with depth.

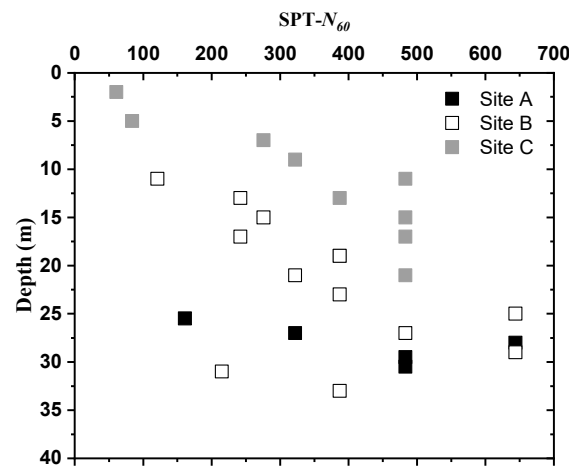


Figure 5. Variation of SPT- N_{60} with depth.

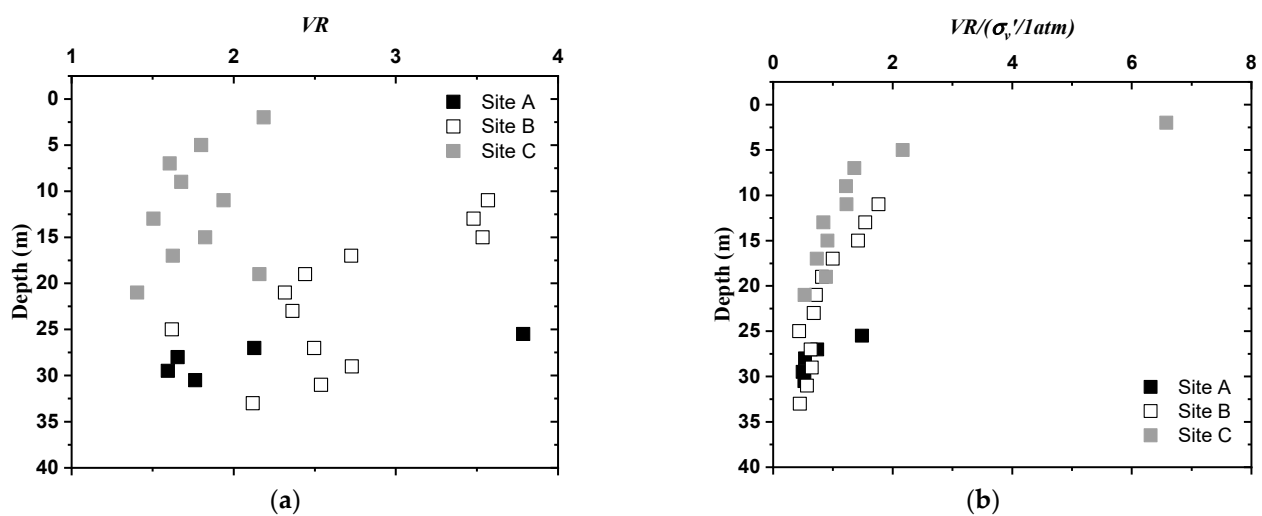


Figure 6. Variations of (a) VR and (b) normalized VR with depth.

4.2. Nonlinear Multiple Regression Analysis

To derive the equations for estimating E_m and P_L based on the chemical weathering index (VR) determined by the XRF analysis of the collected samples and the results of the PMTs and SPTs conducted at the three considered sites, nonlinear multiple regression analysis was performed using the following three steps:

- (1) Deduction of the relationships between E_m and SPT- N_{60} and between P_L and SPT- N_{60} by simple regression analyses;
- (2) Deduction of the relationships between E_m and *normalized VR* and between P_L and *normalized VR* by simple regression analyses;
- (3) Nonlinear multiple regression analysis using the relationships deduced in steps (1) and (2) above.

In the implementation of the first step, the relationship between the PMT results (E_m or P_L) and SPT- N_{60} was derived through a simple regression analysis. The aim of this step was to determine the basic function of the independent variable (i.e., SPT- N_{60}) to be used for the nonlinear multiple regression analysis. Empirical relationships between E_m and SPT- N_{60} and between P_L and SPT- N_{60} obtained in related research are presented in Table 2. Based on these several empirical relationships, simple regression analysis using an allometric model and a linear model was employed to derivate each of the equations. E_m increased with increasing SPT- N_{60} , with both the allometric and linear models revealing relatively high correlations as shown by the coefficient of determination (R^2) of 0.71 and 0.71, respectively (Figure 7). P_L exhibited lower correlations in the empirical equations compared with E_m ($R^2 = 0.44$ and 0.43, respectively) (Figure 8).

Table 2. Empirical equations for the relationships of E_m and P_L with SPT- N_{60} .

Geo-Material	Empirical Equations		Researchers
	E_m	P_L	
weathered granite	$E_m \text{ (MPa)} = 0.5832(N_{60})^{0.9687}$	$P_L \text{ (MPa)} = 0.1668(N_{60})^{0.7307}$	Chiang and Ho [6] *
sandy soil	$E_m \text{ (MPa)} = 1.33(N_{60})^{0.77}$	$P_L \text{ (MPa)} = 0.33(N_{60})^{0.51}$	Bozbey and Togrol [8]
silty sand	$E_m/P_a \text{ (MPa)} = 9.8N_{60} - 94.3$ **	$P_L/P_a = N_{60} - 20.8$ **	Cheshomi and Ghodrati [9]

* The empirical equations were digitized regression lines in the original works. ** $P_a = 1 \text{ atm}$.

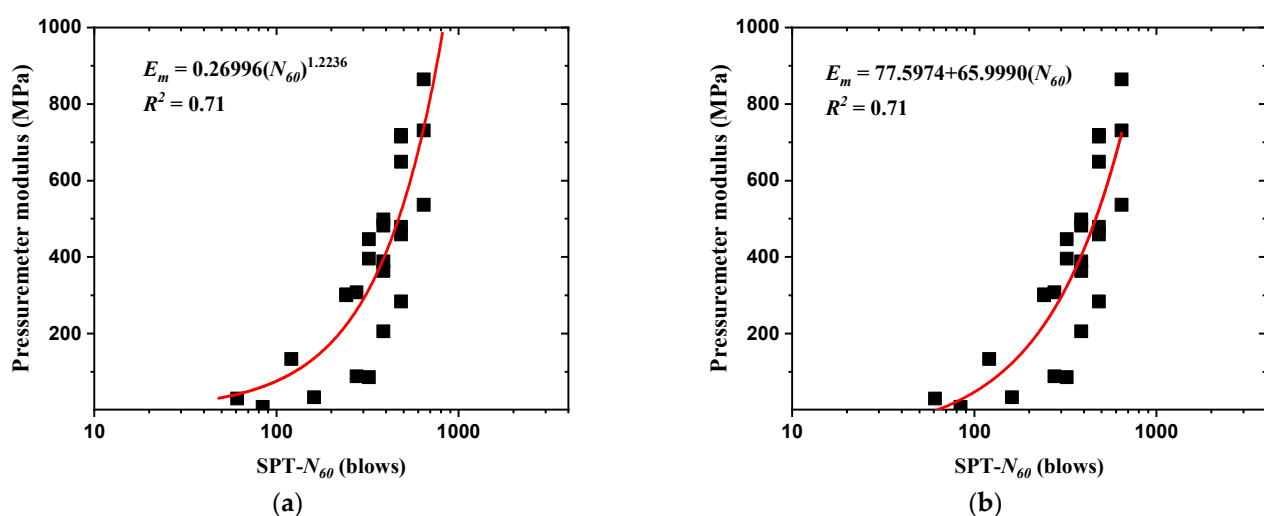


Figure 7. Correlations between E_m and SPT- N_{60} determined by simple regression analyses using an (a) allometric model and a (b) linear model.

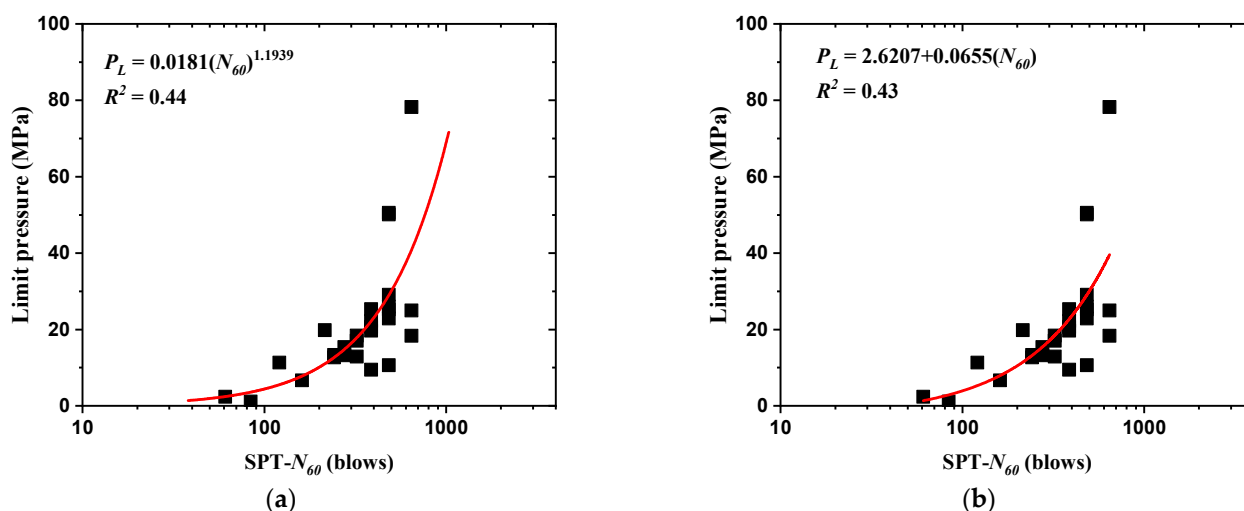


Figure 8. Correlations between P_L and SPT- N_{60} determined by simple regression analyses using an (a) allometric model and a (b) linear model.

In the second step, the procedure of the first step was applied to *normalized VR*. E_m was decreased with increasing *normalized VR*, with a higher correlation coefficient obtained for the allometric model ($R^2 = 0.67$) than for the linear model ($R^2 = 0.31$) (Figure 9). The correlation of P_L with *normalized VR* was also higher for the allometric model compared with the linear model, although the R^2 values (0.33 and 0.18, respectively) were lower than that for the correlation between E_m and *normalized VR* (Figure 10).

Subsequently, the nonlinear multiple regression analysis models of E_m and P_L were established by combining the allometric model, which produced the better correlations between the PMT results (E_m and P_L) and SPT- N_{60} and *normalized VR*. The obtained models are:

$$E_m = f(N_{60}, \frac{VR}{\sigma'_v/P_a}) = a_1 + a_2(N_{60})^{a_3} + a_4\left(\frac{VR}{\sigma'_v/P_a}\right)^{a_5} \quad (a_n = \text{const.}) \quad \text{and} \quad (2)$$

$$P_L = f(N_{60}, \frac{VR}{\sigma'_v/P_a}) = b_1 + b_2(N_{60})^{b_3} + b_4\left(\frac{VR}{\sigma'_v/P_a}\right)^{b_5} \quad (b_n = \text{const.}). \quad (3)$$

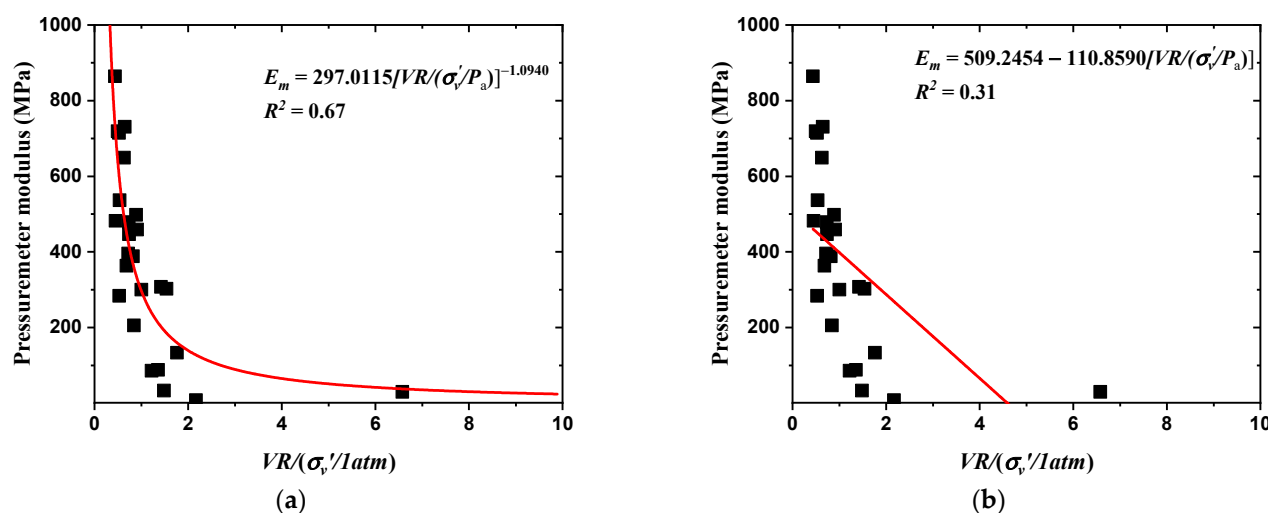


Figure 9. Correlations between E_m and *normalized VR* determined by simple regression analyses using an (a) allometric model and a (b) linear model.

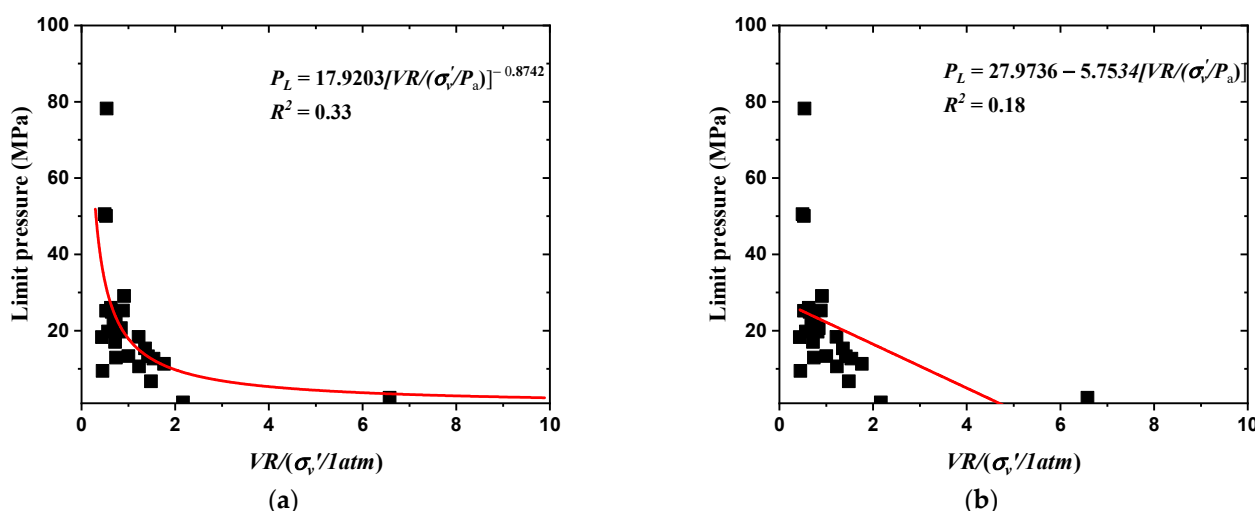


Figure 10. Correlations between P_L and *normalized VR* determined by simple regression analyses using an (a) allometric model and a (b) linear model.

The results derived by nonlinear multiple regression analysis revealed improved correlations compared with those from the equations derived by simple regression analysis. Even though the obtained slight increase in the coefficient of determination was lower than expected, this study is meaningful in that it demonstrates that improved prediction of the E_m and P_L values of weathered granite can be obtained by additionally considering the VR , chemical weathering index that represents the physical properties of weathered granite. The equation for E_m as a function of $SPT-N_{60}$ and *normalized VR* is presented in Equation (4), for which $R^2 = 0.76$, which is larger than that for the simple regression analysis equation (Figures 7a and 9a). The equation for P_L derived by nonlinear multiple regression analysis is presented in Equation (5) and, also has a higher R^2 of 0.46 compared with the corresponding simple regression equation (Figures 8a and 10a):

$$E_m = -35.1588 + 0.11367(N_{60})^{1.2859} + 136.3515\left(\frac{VR}{\sigma'_v/P_a}\right)^{-1.1625} \text{ (MPa)}, R^2 = 0.76 \quad (4)$$

$$P_L = -9.0592 + 0.0001(N_{60})^{1.8969} + 18.4856\left(\frac{VR}{\sigma'_v/P_a}\right)^{-0.3767} \text{ (MPa)}, R^2 = 0.46 \quad (5)$$

For evaluation, the results obtained by the empirical Equations (4) and (5) derived in this study were compared with the results of equations derived in relevant previous studies presented in Table 2, as shown in Figure 11. The types of soils for the equation presented in Table 2 are different from that used in this study. However, unfortunately, there are very few studies for estimating the relationship between the results of PMT and SPT on weathering granite. Therefore, in this study, the most similar studies performed on sandy material among the existing studies were compared with the Equations (4) and (5). The equations in the previous studies used a single variable, $SPT-N_{60}$, and can thus be only used to estimate E_m or P_L for a certain $SPT-N_{60}$. However, the equations derived in this study use an additional variable, VR , which is a measure of the degree of weathering and can thus be used to estimate E_m and P_L from $SPT-N_{60}$. Furthermore, the present empirical equations derived by nonlinear multiple regression can more accurately reproduce the PMT results for South Korean granite compared with the equations suggested by the other studies that are presented in Table 2.

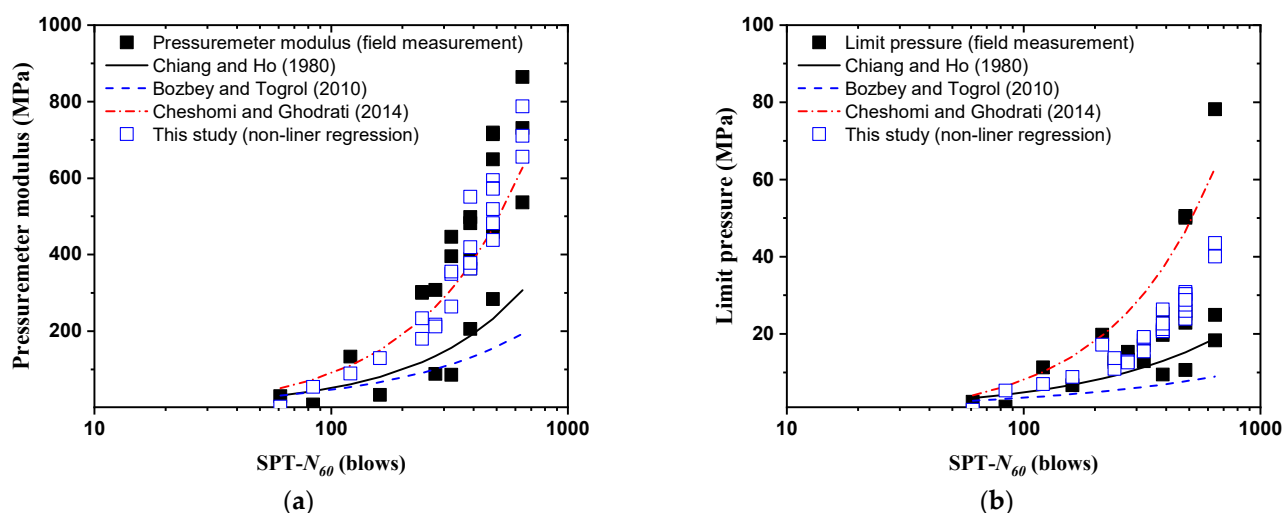


Figure 11. Comparison of the measured and predicted values of (a) E_m and (b) P_L .

Although the equation proposed by Chiang and Ho [6] was based on the analysis of weathered granite in Hong Kong, which is similar to the target stratum of this study, it underestimates E_m and P_L for the weathered granite of the present study. This is because Chiang and Ho [6] derived the equations using data that contained SPT- N_{60} values of ≤ 130 , as opposed to those with SPT- N_{60} values of 61–644 that were used in the present study. The equations proposed by Bozbey and Togrol [8] were based on the results of SPTs and PMTs conducted on the medium to very dense sandy soils with SPT- $N_{60} \leq 100$ and also underestimate the PMT results for the weathered granite examined in the present study. However, Cheshomi and Ghodrati [9] obtained their empirical equations based on data for dense to very dense silty sands (SPT- $N_{60} < 50$), with the predictions of E_m for weathered granite comparable to those of the present corresponding equation; however, their predicted P_L are higher than those obtained in the presented study. Regarding the similarity for E_m , the E_m values for the specific samples used by Cheshomi and Ghodrati [9], where SPT- $N_{60} \geq 35$, were approximately 30% larger than those for the samples used by Bozbey and Togrol [8]. Therefore, a local correlation based on the local rock characteristics is important for predicting the engineering properties of geo-materials. The proposed equations of E_m and P_L are intended for use in the geotechnical survey of weathered granite in South Korea.

5. Conclusions

In this study, the modulus of deformation E_m (pressuremeter modulus) and limit pressure P_L of weathered granite in South Korea were assessed based on the SPT- N_{60} value and chemical weathering index VR . Nonlinear multiple regression analysis was conducted using SPT- N_{60} and VR as the independent variables, specifically for the values measured at three sites in South Korea. The analysis was used to derive empirical equations for E_m and P_L , and the predictions of the equations were compared with the equations suggested in the previous relevant studies. The study and its findings can be summarized as follows:

- (1) The relationships between the PMT and SPT- N_{60} results were derived by simple regression analyses, which revealed that E_m tended to increase with increasing SPT- N_{60} . Relatively high correlations were observed when both an allometric model and linear model were utilized, as represented by R^2 of 0.71. The correlations were lower for P_L , as represented by the R^2 values of 0.44 and 0.43 for the two models, respectively, revealing no significant difference.
- (2) The chemical weathering index that has been rarely considered in previous studies was used to evaluate the PMT results. The *normalized VR* with vertical effective stress revealed a relatively good correlation with E_m ($R^2 = 0.67$). Therefore, it is useful

as a simple method for the estimation of E_m of weathered granite in preliminary site characterization.

- (3) Nonlinear multiple regression analyses were conducted by combining the allometric models that produced improved correlations between E_m , P_L , SPT- N_{60} , and *normalized VR*. The obtained equations of E_m and P_L had better R^2 values (0.76 and 0.46, respectively) than the equations obtained by simple regression in other studies. Even though the obtained slight increase in the coefficient of determination was lower than expected, this study is meaningful in that it is possible to obtain improved prediction of the E_m and P_L values of weathered granite by additionally considering VR, which is a chemical weathering index that represents the physical properties of weathered granite.
- (4) Empirical equations suggested in other studies were based on a single variable (i.e., SPT- N_{60}) and can thus be only used to estimate either E_m or P_L for a particular SPT- N_{60} . However, the empirical equations proposed in this paper utilize an additional variable VR can thus predict the E_m and P_L by considering both the degree of weathering and SPT- N_{60} . To determine the engineering properties of geo-materials, this study proposes the E_m and P_L equations for use in geotechnical surveys of weathered granite in South Korea.

Author Contributions: Conceptualization, S.-H.L. and K.-H.P.; methodology, S.-H.L.; software, S.-H.L.; validation, S.-H.L., T.-Y.K. and K.-H.P.; formal analysis, S.-H.L.; investigation, T.-Y.K.; resources, S.-H.L.; data curation, S.-H.L.; writing—original draft preparation, S.-H.L.; writing—review and editing, T.-Y.K. and K.-H.P.; visualization, T.-Y.K.; supervision, K.-H.P.; funding acquisition, K.-H.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Construction Technologies Program funded by the Ministry of Land, Infrastructure and Transport of the Korean government, grant number 21SCIP-C151438-03. The authors are grateful for the support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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