

Geotechnical comparison of weathering degree and shear wave velocity in the decomposed granite layer in Hongseong, South Korea

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Abstract As part of a fundamental characterization of a subsurface layer in South Korea, the weathering degree and shear wave velocity (V_S) were evaluated in a decomposed granite in Hongseong, using X-ray fluorescence analyses and site investigations, including borehole drilling with standard penetration test (SPT) and in situ seismic tests. The subsurface layer was composed of a weathered layer 10–40 m thick at most sites. Weathering degree analyses indicated that three chemical weathering indices, the modified weathering potential index (MWPI), Vogt ratio (VR), and weathering index of Parker (WIP), generally increased with decreasing depth. In situ seismic tests revealed that V_S ranged between 200 and 500 m/s in the weathered layer. Using the V_S and N values from the SPT at borehole seismic testing sites, correlations between V_S and N values were established for the weathered layer. Furthermore, examination of the relationships of the V_S and

N values with the MWPI, WIP, and 100/VR indices showed that the index values increased linearly with increasing V_S and exponentially with increasing N values.

Keywords Weathering degree · Shear wave velocity · Decomposed granite · Weathering index · N value · Weathered layer

Introduction

Granite in a fresh bedrock state is broken and changed by external physical, chemical, and biological weathering actions to become weathered rock and weathered soil (Ceryan et al. 2008; Molina Ballesteros et al. 2011; Sousa and Gonçalves 2013). These weathered rocks and soils are collectively called a decomposed granite layer (or stratum). The weathered soil is also called residual soil (GSL 1995; Rahardjo et al. 2004) because, compared with lower layers of weathered rock, it exists near the ground surface. In South Korea, weathered granite layers are found not only at the ground surface of ancient mountains and hills, but also underlying artificial fill layers or alluvial layers on plains (Sun et al. 2005). The decomposed granite layer, as one of the representative geotechnical layers (geo-layers) of the Korean Peninsula (Sun et al. 2006), has been studied by geotechnical engineers seeking to quantify the engineering characteristics and apply them to geotechnical design (Antonie et al. 1995; Kang et al. 2013; Ozcan et al. 2013).

The weathering degree is a fundamental characteristic of the formation and development of a decomposed granite layer and can serve as a basic index of strength and deformation characteristics (Lee and Chang 2003; Gürer et al. 2008; Dipova 2011). Several studies have proposed quantitative indices of the weathering degree and examined

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its correlations with engineering characteristics (Tugrul and Gurbinar 1997; Guan et al. 2001; Duzgoren-Aydin et al. 2002; Son et al. 2010; Regmi et al. 2014). Of the various engineering characteristics of the decomposed granite layer, shear wave velocity (V_S) is determined through in situ seismic tests. As a real index signifying geotechnical stiffness, V_S can help to reveal the subsurface structure of a target site (Kim et al. 2002; Islam and Chik 2011). In addition, this important geotechnical parameter is directly used to evaluate seismic response characteristics for purposes of both earthquake-resistant design and understanding static soil behavior (Över et al. 2011; Sun 2012; Sun et al. 2013). Therefore, the weathering degree and spatial distribution of V_S in a decomposed granite layer are important basic factors for understanding the characteristics of this representative layer in the Korean Peninsula.

To quantitatively evaluate the weathering degree and V_S of the decomposed granite layer in the Korean Peninsula, this study chose Hongseong as a representative area having a developed decomposed granite layer (Sun et al. 2005, 2006). To evaluate the subsurface layer distribution, weathering degree, and V_S of several locations in the area of interest, borehole drilling investigations and in situ seismic tests were conducted. Samples were also collected and subjected to various tests to evaluate their characteristics, including analyses of the weathering degree and resonant column tests. Through these analyses, the distribution characteristics of the quantitative weathering degree and V_S of the local decomposed granite layer were revealed.

This study presents the results of chemical analysis in the laboratory and geotechnical field site investigation conducted on the decomposed granite of the Hongseong area. Geotechnical characteristics in the area of interest are discussed by examining and correlating V_S and N values obtained from a standard penetration test (SPT). Chemical weathering indices are then correlated with the V_S and N values and their suitability to quantify the weathering degree is discussed, in particular for the decomposed granite layer.

Geotechnical characteristics of Hongseong

Geological setting

The Korean Peninsula includes ancient landforms whose slopes have become gentle through a long period of erosion and weathering (Kim and Park 2003; Sun et al. 2005). Such ancient landform characteristics are particularly remarkable in the western part of the Korean Peninsula (Lee and Jo 2000), where millennia of weathering have produced a

weathered layer on top of the bedrock. The bedrock of Korea is mostly composed of granite or granitic gneiss except for the sedimentary rock distributed in southeastern areas. In particular, granitic rocks are evenly distributed throughout the major structural landmass of the southern part of Korea, namely the Gyeonggi massif, Okcheon belt, and Yeongnam massif, in which granites formed and intruded in the Jurassic period of the Mesozoic age, as shown in Fig. 1.

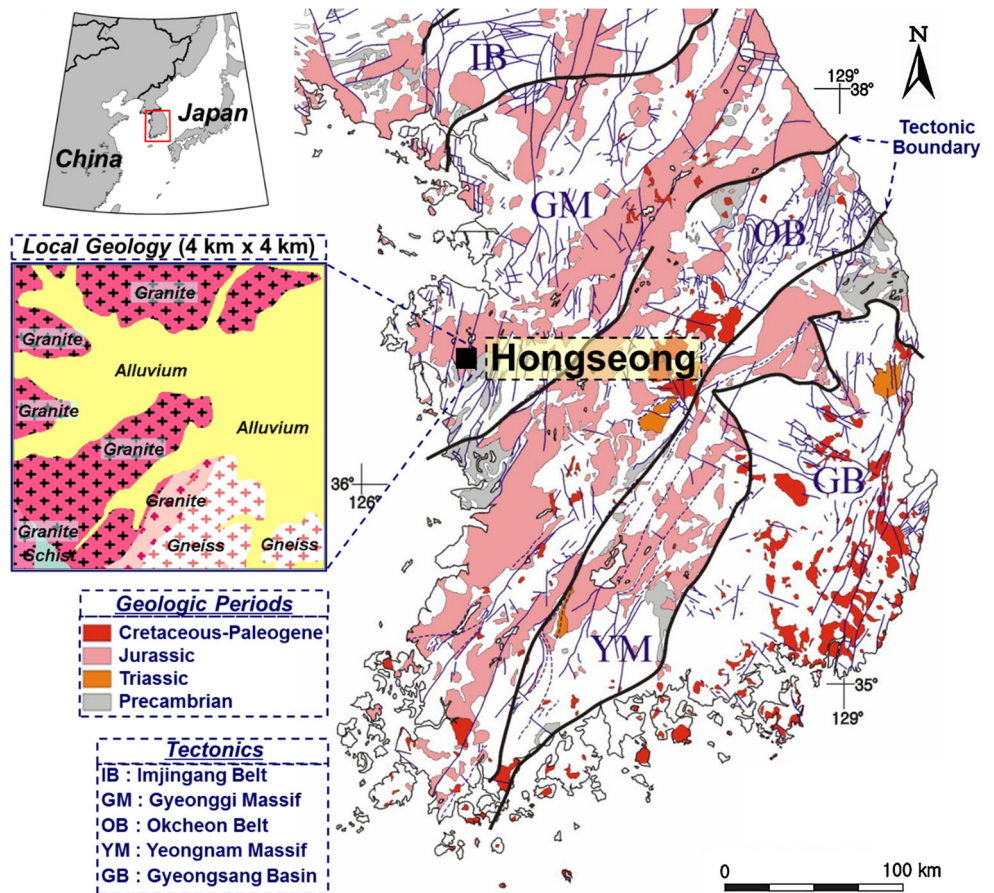
The bedrock in these ancient landform areas is similar to that in the western part of the Korean Peninsula and is represented by granite with a nearly developed weathered layer, mostly having granite as its parent rock. The western part of South Korea is considered to be a representative area of such decomposed granite layers (Fig. 1). This study selected Hongseong, which has a thick weathered layer, as its investigation target. Figure 1 also shows the geographic location and local geologic setting of Hongseong. Hongseong is located in the Gyeonggi massif, with Jurassic granite as the parent rock. A 4 km × 4 km geologic map of the target area shows that most of the ground surface in the area is composed of granite and alluvium, except for some gneiss in the southeast. Therefore, from the granite parent material, the weathered rock and soil layer in Hongseong developed on top of the bedrock and are located near the ground surface. Alluvium of shallow depth is distributed in some areas near streams.

Spatial geotechnical variation from in situ investigation

To evaluate geotechnical and weathering characteristics in Hongseong, 16 sites were selected on the basis of geologic and geographic information: three mountain sites, six hill sites, and seven sites on the plains. At six of these sites, borehole drilling investigations, SPTs, and borehole seismic tests were performed, as displayed in Fig. 2. In addition, spectral analysis of surface waves (SASW) was conducted at all sites except one (Gwangkyeong Bridge). Of the borehole seismic tests, downhole tests were conducted at all six sites and crosshole tests were conducted at three sites (Chungoon University, Hongju M.S., and County Hall). For quantitative analysis of the weathering degree, samples obtained during SPTs were collected from four sites (Chungoon University, a small creek, County Hall, and Gwangkyeong Bridge). Figure 2 shows the locations of the sites and describes which tests were conducted at each site.

Geotechnical layers were classified by the N value (blow counts for penetrating 30 cm down borehole) from the SPT, which was 50/15 in the case of weathered residual soil and weathered rock, as well as by drilling capability and visual examination in the case of weathered rock and

Fig. 1 Distribution of granite in South Korea and geological setting of Hongseong



soft rock (Sun et al. 2005; Anbazhagan and Sitharam 2009). For the sites where SASW was conducted, geotechnical layers were classified on the basis of V_s distribution by layer, which was determined through a borehole seismic test, according to the V_s of SASW. The in situ tests indicated that the weathered layer is distributed thickly under a quite shallow reclaimed fill layer and alluvial soil deposits in Hongseong. The V_s profiles showed the following ranges by layer: about 120–410 m/s for soil-like fill, alluvial soil, and weathered soil; about 360–540 m/s for weathered rock; 680 m/s for the bedrock layer of soft rock and higher in cases with large fractures; and over 1,200 m/s in areas with good rock quality.

The depth to soft rock in Hongseong was roughly 15–45 m, mostly near the city; in some sites, no soft rock was found even at depths over 45 m. This suggests that the weathered layer of 10–40 m or more thickness overlays bedrock including soft and harder rocks. Weathered soil is approximately 5–30 m thick in the weathered layer. Figure 3 shows the geotechnical layer distribution of a south–north section in Hongseong (Fig. 2). Figure 2 shows that the weathered layer composed of weathered soil and weathered rock is developed quite thickly compared with alluvial soil. This weathered layer in Hongseong is

expected to have developed not only by erosion and weathering prior to alluvial layer formation, but also under a stable weathering environment after the alluvial layer was formed.

Minerals and soil characteristics revealed by laboratory tests

To understand the mineral compositions of the weathered material, X-ray diffraction (XRD) analysis was conducted (Duzgoren-Aydin et al. 2002; Heinrichs and Fitzner 2011) using samples collected from the three crosshole testing sites. The samples showed the major structural minerals of the granite parent rock, including quartz, mica, and orthoclase, and of kaolinite, which is a secondary clay mineral. In some samples, sericite mineral was also found.

In addition, an index property test of the soil and a direct shear test were conducted to determine strength parameters and representative mechanical characteristics. According to the test results, the weathered soil was classified as soil having much sand, such as SW, SP, and SM of the Unified Soil Classification System (USCS) (ASTM 2004). The soil had a specific gravity of 2.62–2.66, friction angles of 39°–45°, and cohesion of 0.0–0.4 kg/cm². Weathered soil

Fig. 2 Geotechnical investigation sites and tests conducted for this study in Hongseong. *Solid circle* and *solid triangle* represent locations of testing site and pre-existing boring site, respectively. *C, D, and S* in parentheses indicate crosshole, downhole, and SASW tests, respectively. Four sites with boxed name were selected to analyze weathering degree. *Thick dashed line* of north–south is for a section of geotechnical layers in Hongseong

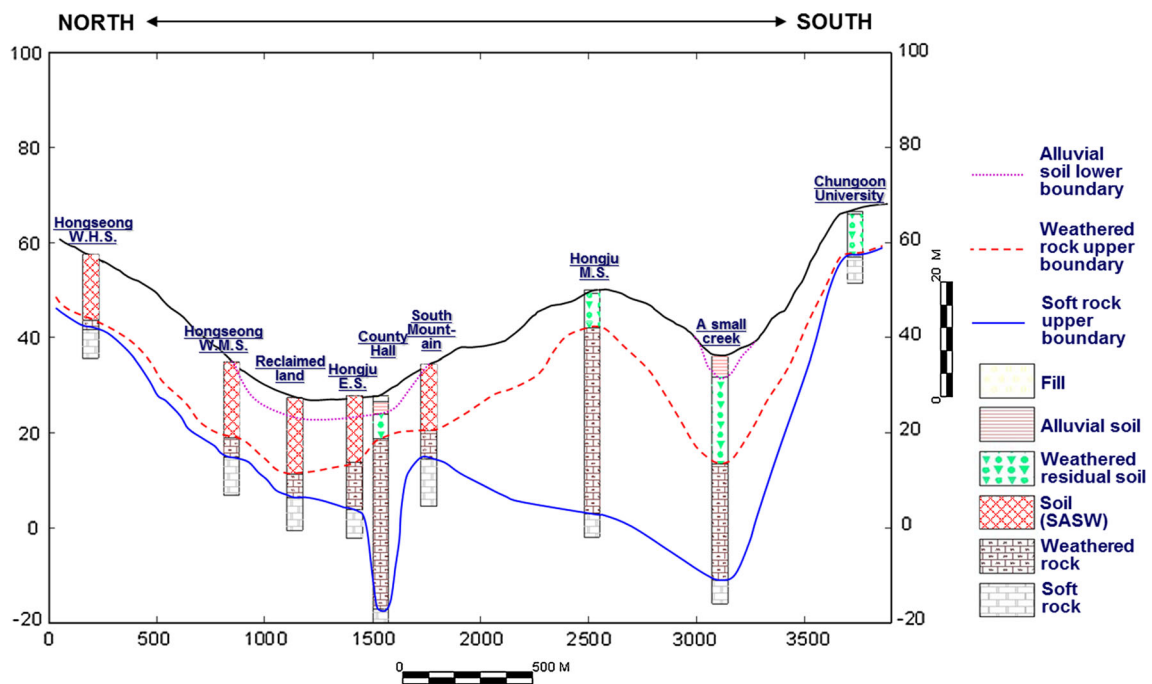
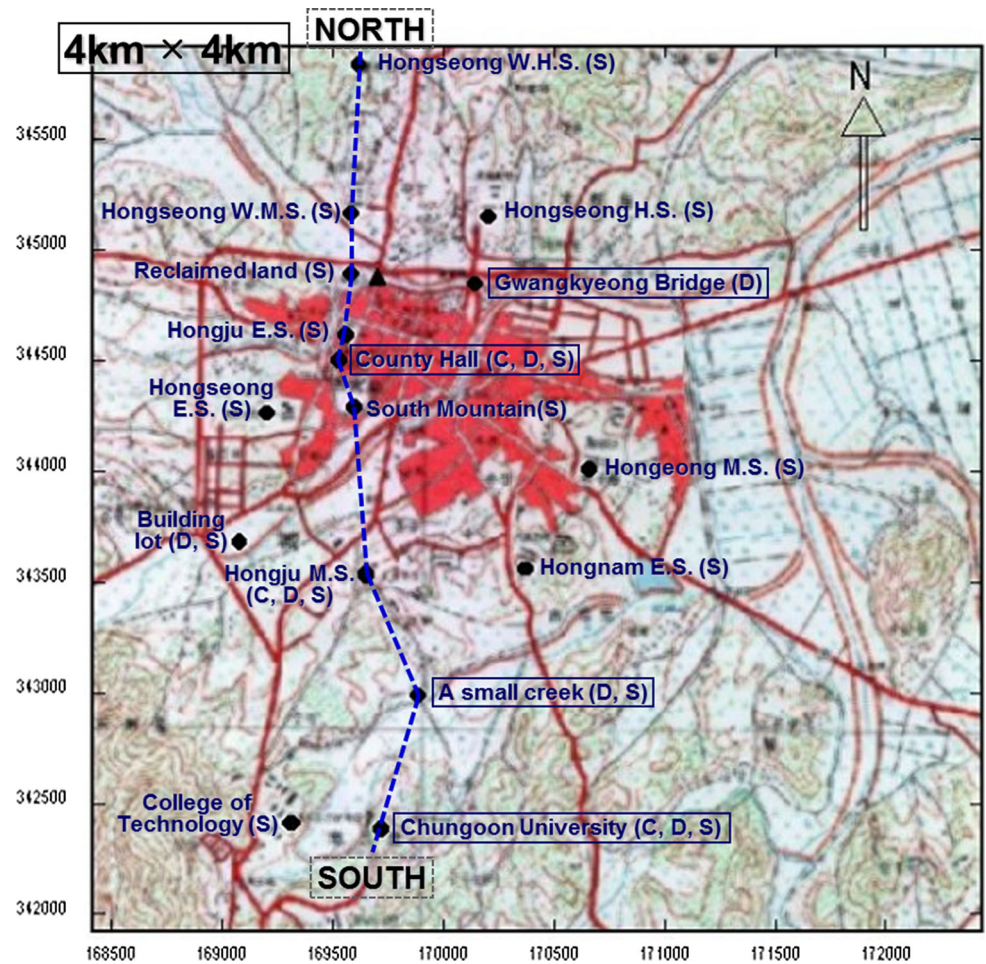


Fig. 3 Section of geotechnical layers along north–south line presented in Fig. 2 in Hongseong

collected from two sites (a small creek and Hongju M.S.) was also reconstituted to the same state as it was at the sites; resonant column tests to determine strain-dependent stiffness and damping variation were then conducted and V_S was evaluated.

Weathering degree in Hongseong

Weathering refers to the crushing and alteration of coarse minerals in the ground surface, eventually creating stable minerals under new physical and chemical environments (Antonie et al. 1995; Park and Lee 1999; Khanlari et al. 2012). Depending on the developmental processes and causes, weathering can be divided into physical, chemical, and biological weathering (Sun et al. 2006; Jiang and Esaki 2002). From an engineering viewpoint, physical and chemical weathering are considered more major actions than biological weathering which occurs under restricted circumstances such as surface organic soil (Son and Chang 2009; Ferrier et al. 2010; Koralay et al. 2011).

Weathering mechanism of granite

Weathering is the process of alteration and breakdown mainly of rock material by chemical decomposition and physical disintegration (GSL 1995; Regmi et al. 2014), and has recently become a research target in geotechnical engineering (Son et al. 2010). In the case of granite weathering, physical and chemical weathering are the primary focus (Guan et al. 2001; Ceryan et al. 2008). Physical and chemical weathering mostly act together: the progress of chemical weathering usually relying on fractures opened or formed partly as a result of physical weathering (Irfan 1996). The form of weathering and nature of the weathering products are influenced mainly by lithology and climate.

Physical weathering refers to the process by which rock is broken into pieces without chemical changes. Cracks and joints in rocks including granite further develop under collapse-promoting phenomena such as ice formation in bedrock, internal temperature gradient changes, anisotropic thermal expansion of crystals, and repetition of dry and wet conditions. This process promotes physical weathering; in turn, chemical weathering occurs and diffuses through cracks created by physical weathering (Akin 2010).

Chemical weathering refers to the process by which chemical actions influenced by external circumstances change structural minerals into secondary clay minerals. The main processes of chemical weathering depend on the presence of water. The susceptibility of rocks to chemical action is a function of mineralogical composition and texture as well as the presence of fractures (GSL 1995). In more detail, the chemical weathering changes the

mineralogical, textural, and chemical composition of rocks. This occurs mainly through oxidation and hydrolysis processes. During chemical weathering dissolution, leaching, precipitation, enrichment, and formation of secondary minerals occur at diverse scales, thereby reducing the rock strength and density (Che et al. 2012).

Once granite has weathered, its existing chemical components change, depending on the degree of weathering (Irfan 1996). This weathering process can be classified into three stages. In the first stage of weathering, alkali or alkali earth metals such as CaO, Na₂O, MgO, and MnO are eluviated. In the second stage, SiO₂ is slowly eluviated. In the third stage, Al₂O₃, Fe₂O₃, and TiO₂ accumulate and at the same time, loss on ignition (LOI) rapidly increases. Chemical weathering indices evaluated in this study, which use the changes in these oxides (chemical elements), are summarized in Table 1; of these indices, VR, CIA, CWI, and LOI increase, but RR, WIP, and MWPI decrease as weathering becomes severe (Sun et al. 2006; Khanlari et al. 2012).

In general, LOI is preferred not only in aspects of geology because of its importance as a chemical element, but also in discrimination of the degree of chemical weathering. In addition, because of its ease of use, this index is often used as a representative weathering index (Park and Lee 1999; Rahardjo et al. 2004). In general, under the weathering conditions in the same subsurface layer, the weathering degree decreases as the depth increases. We can thus expect that the shallower the depth, the larger the external influences will be (e.g., changes in external temperature and ground water level and uplift and erosion), and therefore the more severe the weathering degree will be. Weathering index values will reflect these influences by depth.

Weathering indices of target sites

For the sites of interest in Hongseong, X-ray fluorescence (XRF) analyses were conducted by a X-ray fluorescence spectrometer to determine the variation in relative abundance of the major elements throughout the weathering sequence. Specimens were prepared first by grinding into a fine powder. Subsequently, the powders were well mixed with borate glass powders, melted at 950–1200 °C for 10–20 min and formed circular plates. A standard specimen was used for calibrating the spectrometer before testing each group of samples. Quantitative analysis was conducted by comparing with a standard of the same elemental makeup. Both peak and background intensities near the peak were counted to permit estimation of peak heights (Chiu and Ng 2014).

The determined relative mobility of elements in each weathering grade shows the stability or differential movement of cations with respect to cations present in the parent

material (Shafiei et al. 2007). Table 2 shows the results of XRF analysis of samples from the four target sites: Chungoon University, a small creek, County Hall, and Gwangkyeong Bridge, and also describes the geotechnical layers at each site. On the basis of XRF analyses, Fig. 4 shows the changes with depth of chemical oxides eluviated and

accumulated in the three weathering stages for two representative sites in Hongseong: Chungoon University and a small creek. In the bottom left of each graph in Fig. 4, an arrow of general trend in elemental components by stage with decreasing depth (i.e., generally more weathering at shallower depth) is shown for comparison with actual results.

Table 1 Summary of chemical weathering indices for this study

Weathering index	Formula	Trend of index by weathering degree ^a	Index name and reference
RR	$RR = \frac{SiO_2}{Al_2O_3}$	Negative (↘)	Ruxton ratio (Ruxton 1968)
WIP	$WIP = \frac{2Na_2O}{0.35} + \frac{MgO}{0.90} + \frac{2K_2O}{0.25} + \frac{CaO}{0.70}$	Negative (↘)	Weathering index of (Parker 1970)
VR	$VR = \frac{Al_2O_3 + K_2O}{MgO + CaO + Na_2O}$	Positive (↗)	Vogt ratio (Vogt 1927; Roaldset 1972)
MWPI	$MWPI = \frac{Na_2O + K_2O + CaO + MgO}{Na_2O + K_2O + CaO + MgO + SiO_2 + Al_2O_3 + Fe_2O_3} \times 100 (\%)$	Negative (↘)	Modified weathering potential index (Vogel 1973)
CIA	$CIA = \frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O + K_2O} \times 100 (\%)$	Positive (↗)	Chemical index of alteration (Nesbitt and Young 1982)
CWI	$CWI = \frac{Al_2O_3 + Fe_2O_3 + TiO_2 + H_2O(\pm)}{\text{All chemical components}} \times 100 (\%)$	Positive (↗)	Chemical weathering index (Sueoka 1988)
LOI	$LOI = \frac{\text{Loss by ignition}}{\text{Mass}} \times 100 (\%)$	Positive (↗)	Loss on ignition

^a The arrow in parenthesis indicates the general trend with decreasing depth (up to ground surface) correspondent to increasing weathering degree

Table 2 Elemental compositions from XRF of the samples at the four sites in Hongseong

Site name	Geo-layer	Depth (m)	Compositions (%)										
			SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	MnO	P ₂ O ₃	LOI
Chungoon University	Weathered rock	3.0	70.99	15.57	0.28	2.38	0.47	0.31	1.41	4.29	0.05	0.03	3.95
		6.0	70.96	14.95	0.26	2.46	0.44	0.99	2.77	4.05	0.05	0.03	2.36
		8.0	69.91	15.60	0.24	2.16	0.39	0.72	2.90	5.18	0.05	0.03	2.05
		10.0	73.90	13.47	0.28	2.32	0.53	0.82	2.87	3.98	0.06	0.06	1.64
	Soft rock	12.5	72.11	15.01	0.26	2.04	0.50	1.27	3.75	4.09	0.05	0.10	1.25
		14.0	72.72	13.72	0.26	2.46	0.54	1.69	3.04	4.14	0.07	0.11	1.26
		19.5	73.33	13.70	0.24	1.86	0.43	0.67	3.45	4.62	0.05	0.07	1.02
A small creek	Weathered soil	9.0	74.00	14.12	0.24	2.11	0.34	0.31	1.12	4.09	0.06	0.03	3.37
		12.5	72.97	15.17	0.19	1.77	0.36	0.70	1.93	4.56	0.06	0.05	2.73
		13.5	75.65	13.89	0.19	1.60	0.36	0.74	2.08	4.60	0.05	0.05	1.86
		15.0	72.10	15.35	0.20	1.78	0.32	0.84	2.45	3.91	0.05	0.02	2.23
		16.5	72.76	14.52	0.22	1.95	0.32	0.80	2.60	4.25	0.06	0.02	1.99
		18.0	70.40	15.29	0.22	2.21	0.32	0.89	2.54	4.91	0.06	0.02	2.16
		20.0	70.50	15.94	0.23	2.13	0.44	1.24	3.26	3.78	0.06	0.05	2.11
County Hall	Weathered soil	4.5	70.16	15.74	0.23	1.41	0.34	0.84	2.37	5.10	0.02	0.04	2.39
		6.0	73.03	13.58	0.23	2.41	0.35	0.60	2.59	4.14	0.02	0.05	2.13
		8.0	72.07	14.15	0.21	2.15	0.32	0.76	2.50	4.70	0.02	0.05	1.80
Gwangkyeong Bridge	Weathered rock	10.0	69.21	15.89	0.19	2.14	0.26	1.09	3.36	4.83	0.03	0.04	1.58
		7.5	71.12	14.50	0.20	2.98	0.30	0.78	2.54	4.82	0.03	0.07	2.20
		9.0	68.69	15.26	0.30	3.46	0.47	1.29	3.46	4.07	0.05	0.06	2.03

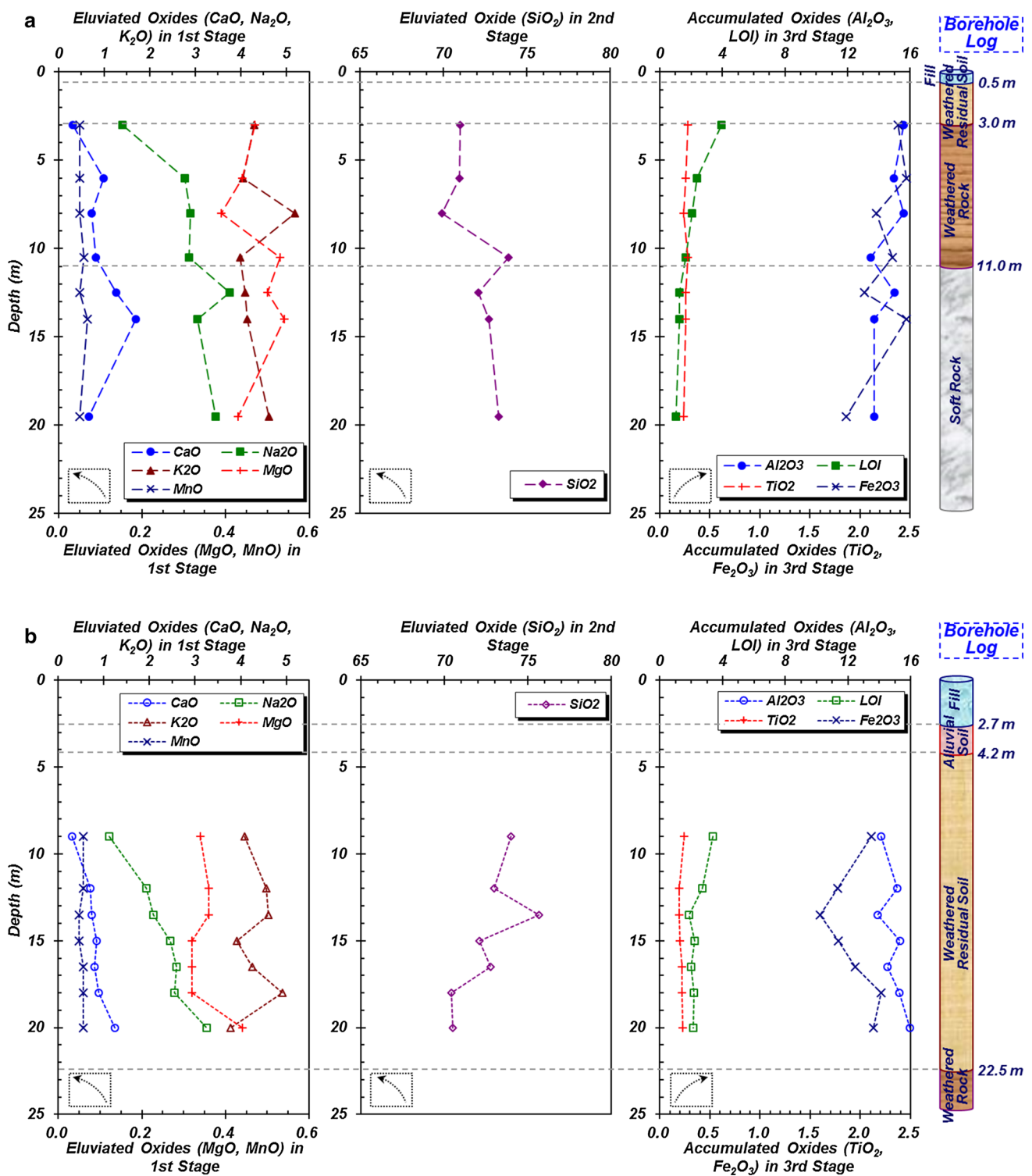


Fig. 4 Variation of elemental compositions with depth at two representative sites of **a** Chungoon University and **b** a small creek in Hongseong. Profile of geotechnical layers investigated from

borehole drilling is presented in *right part* of figure. Arrow in dotted box in lower left part of graph indicates the general trend of each oxide with decreasing depth

The results in Fig. 4 show the typical increase or decrease trend by depth, even though only a limited depth was examined. At the Chungoon University site, located on

a hill, the depth from the ground surface to the soft rock was relatively shallow at a depth of 11.0 m, and the weathered rock and soft rock layer at 3.0–19.5 m depth

was analyzed. On the other hand, the small creek was located on flat land and determined to have been under stable weathering circumstances for a long time. Therefore, the layer of 9.0–20.0 m depth, which was targeted for the analysis of weathering degree, was an old weathered layer. Changes in SiO_2 and Al_2O_3 with depth at the small creek site were opposite to the general trend and changes in Fe_2O were irregular. These features may influence the results of chemical weathering indices.

The chemical elements with depth found at each testing site (Table 2) and the results calculated by the chemical indices (refer to Table 1) are shown in Table 3. In addition, Fig. 5 shows the weathering index distribution by depth at the Chungoon University and small creek sites. The arrows in the legend of each graph describe the general increase or decrease trend in each weathering index with depth reduction.

At the Chungoon University site (Fig. 5a), most of the chemical weathering indices reflect the changes in weathering degree by depth (soft rock in the lower part and weathered rock in the upper part). This finding agrees with the finding that changes in chemical elements with depth at Chungoon University (Fig. 4a) are usually consistent with the universal trend by depth. There were no significant changes in the chemical weathering indices in the case of

the lower soft rock, but eluviation of fluidal chemical components and accumulation of TiO_2 occurred frequently in the upper weathered rock, creating changes in the weathering indices.

In particular, the uppermost depth (the target for analysis of weathering degree) and interface depth (3.0 m) with weathered soil showed substantial weathering, and some weathering indices differed largely from the distribution trend with depth. On bedrock such as soft rock, physical weathering was more dominant than chemical weathering, and the latter had similar values. However, in the weathered layer of rock or soil, chemical weathering was active and values changed remarkably with depth. These results indicate that on weathered rock as opposed to bedrock, the discriminating capacity of the chemical weathering degree is large, making chemical weathering indices highly useful.

The weathered layer at the small creek site was highly weathered (Fig. 5b), and some of the indices had difficulty showing the weathering degree by depth. In particular, RR showed little change or even a slight increase, in contrast to the expected general trend in which the degree of weathering increases and index values decrease near the surface. This result is attributable to the changes in SiO_2 and Al_2O_3 with depth, which were opposite to the general trend (refer to Table 2), as described above (Fig. 4b).

Table 3 Chemical weathering indices in weathered layers at four sites in Hongseong

Site name	Geo-layer	Depth (m)	Indices						
			RR	WIP	VR	MWPI	CIA	CWI	LOI
Chungoon University	Weathered rock	3.0	4.56	43.28	9.10	6.78	72.18	22.25	3.95
		6.0	4.75	50.16	4.52	8.54	65.67	20.17	2.36
		8.0	4.48	59.50	5.18	9.49	63.92	20.20	2.05
		10.0	5.49	50.03	4.13	8.38	63.71	17.72	1.64
	Soft rock	12.5	4.80	56.52	3.46	9.73	62.23	18.49	1.25
		14.0	5.30	53.55	3.39	9.58	60.73	17.70	1.26
		19.5	5.35	58.14	4.03	9.35	61.04	16.91	1.02
A small creek	Weathered soil	9.0	4.91	54.49	5.35	8.69	64.07	19.96	3.37
		12.5	4.50	54.72	3.71	9.61	63.36	21.23	2.73
		13.5	5.24	39.99	10.31	6.10	71.88	19.88	1.86
		15.0	4.81	48.90	6.62	7.74	67.85	19.77	2.23
		16.5	5.45	50.14	5.84	7.86	65.20	17.35	1.99
		18.0	4.70	46.87	5.33	7.78	68.04	19.70	2.16
		20.0	5.01	50.40	5.04	8.21	65.48	18.78	2.11
County Hall	Weathered soil	4.5	4.61	55.41	5.40	8.96	64.71	20.07	2.39
		6.0	4.42	51.10	3.99	8.96	65.82	20.46	2.13
		8.0	4.46	55.92	5.88	9.01	65.46	20.04	1.80
		10.0	5.38	49.19	5.00	7.95	64.92	18.50	1.58
Gwangkyeong Bridge	Weathered rock	7.5	5.09	53.29	5.27	8.56	64.01	18.55	2.20
		9.0	4.36	59.68	4.40	9.85	63.14	20.08	2.03

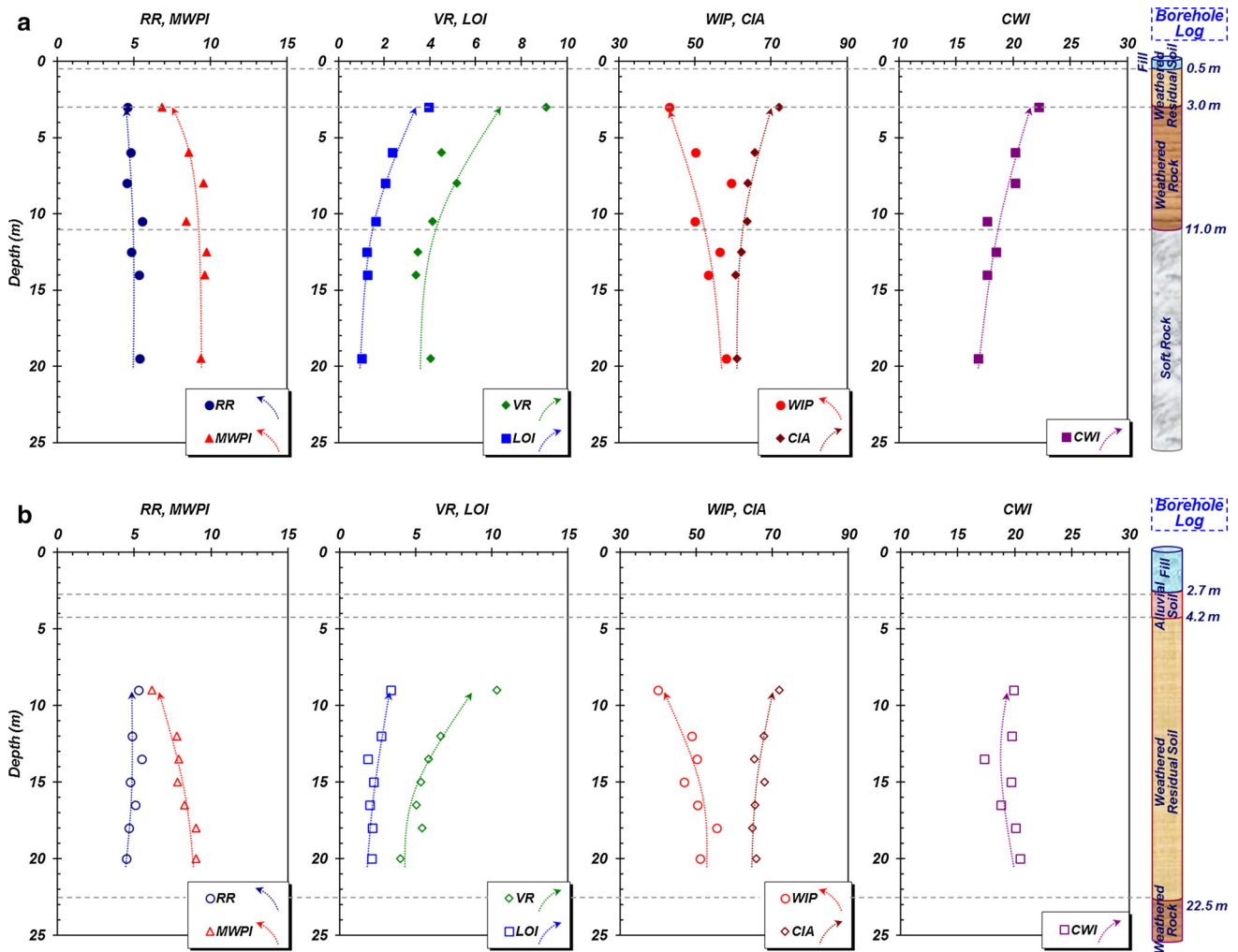


Fig. 5 Variation of weathering indices with depth at two representative sites of **a** Chungoon University and **b** a small creek in Hongseong. Profile of geotechnical layers investigated from borehole drilling is presented in *right part* of figure. *Trend line* along markers

for each index is also plotted with *dotted arrow*. *Arrow* within legend in graph indicates the general trend of each index with decreasing depth

The Ruxton ratio (RR) is defined as the ratio of the two chemical elements contributing the largest shares (Table 1). The chemical weathering index (CWI) from Sueoka (1988) also showed no change near the ground surface, probably because Fe₂O₃ in the weathered soil layer at the small creek site was irregularly distributed and the changes in TiO₂ by depth were very small. In contrast, the modified weathering potential index (MWPI), Vogt ratio (VR), chemical index of alteration (CIA), and weathering index of Parker (WIP) usually showed the general trend of reduced weathering degree with increased depth, even in the single layer of weathered soil. The elements composing these weathering indices, especially CaO and Na₂O eluviation elements, showed the general decrease trend toward the surface. In addition, loss on ignition (LOI) was consistent with the trend in weathering degree with depth.

All the weathering indices for the small creek and Chungoon University shown in Fig. 5 indicate changes in weathering degree in relation to the weathered rock layer. For the weathered soil layer, MWPI, VR, CIA, WIP, and LOI were determined to be the most accurate, and MWPI, VR, and WIP were used as references for evaluation. Table 4 presents weathering degree results for four target sites in Hongseong, giving the ranges and mean values of MWPI, VR, and WIP for soft rock, weathered rock, and weathered soil; the increase or decrease trend of the weathering indices with depth is consistent with the expected general trend. Although these values were derived from limited data, they can serve as preliminary references with which to estimate the weathering degree in Hongseong in places where quantitative evaluations have not yet been conducted.

Table 4 Statistical values of three weathering indices with geotechnical layers in Hongseong

Geo-layer	Indices											
	MWPI				VR				WIP			
	Mean	SD	Max.	Min.	Mean	SD	Max.	Min.	Mean	SD	Max.	Min.
Weathered soil	8.11	0.87	9.01	6.10	5.87	1.70	10.31	3.99	50.12	4.57	55.92	39.99
Weathered rock	8.76	1.05	9.85	6.78	5.20	1.81	9.10	3.71	53.12	5.82	59.68	43.28
Soft rock	9.55	0.19	9.73	9.35	3.63	0.35	4.03	3.39	56.07	2.33	58.14	53.55

SD standard deviation

Shear wave velocity in Hongseong

Shear wave velocity profiles at borehole drilling sites

To investigate geotechnical dynamic characteristics in Hongseong, shear wave velocity (V_S) profiles were determined in the field using borehole seismic tests such as crosshole and downhole tests, and the SASW test for six sites. In addition, the resonant column test was carried out in the laboratory to determine the V_S and nonlinear behavior curves of a soil sample obtained during the SPT. Figure 6 gives the V_S profiles with a representative V_S profile (Sun et al. 2005), and N values from SPTs conducted during a borehole drilling.

Depending on the testing method, V_S changed even in the same depth layer at a single site. However, most sites showed a trend of V_S increase with increasing depth. That is, higher V_S was found in the lower weathered layer composed of weathered soil and weathered rock than in the upper fill or alluvial soil distributed near the surface. The larger V_S at deeper depth is explained by the decrease in the void ratio and increase in confining pressure as depth increases. In the weathered soil layer, the growth rate of V_S was much larger than that in other layers; this finding is attributable to the decrease in the weathering degree with depth. As depth increases in the weathered layer, the weathering degree decreases and the void ratio becomes small so that V_S becomes faster.

In addition to in situ seismic tests, this study reconstituted samples of weathered soil obtained from the small creek and Hongju M.S. to the same conditions as found in the field. Resonant column tests were then conducted and V_S was evaluated, with the results shown in Fig. 6b and e. The V_S results from the resonant column tests were similar to those obtained by the borehole seismic tests. Therefore, if in situ seismic testing cannot be conducted, laboratory resonant column tests, with soil conditions similar to those in the field, can be used to estimate V_S .

To show V_S profiles in the weathered layer, which is the major stratum in Hongseong, representative values of V_S of the target sites and the average V_S distribution by

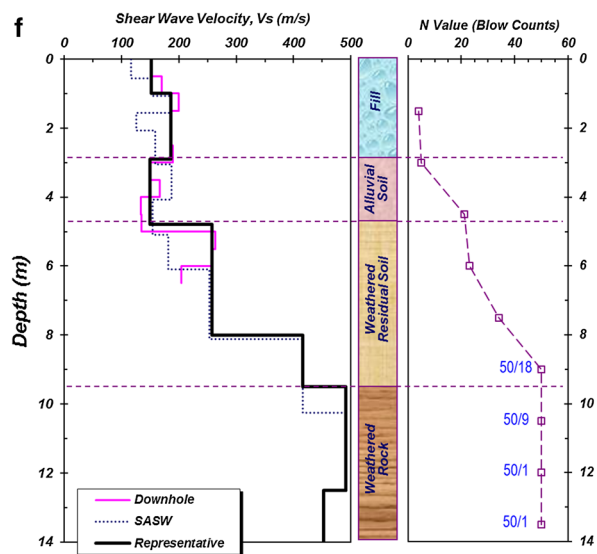
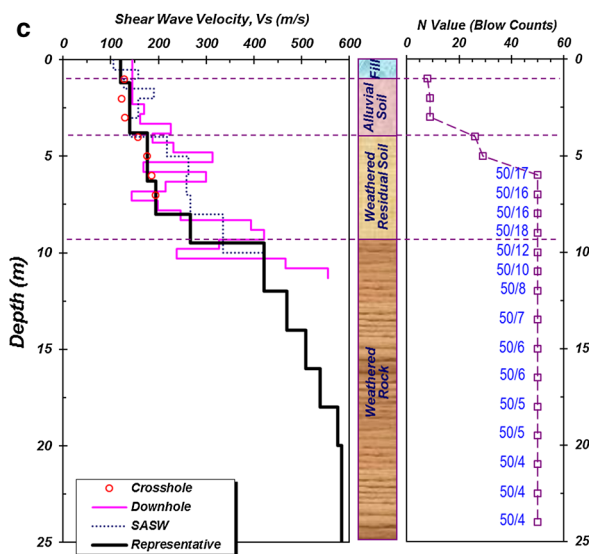
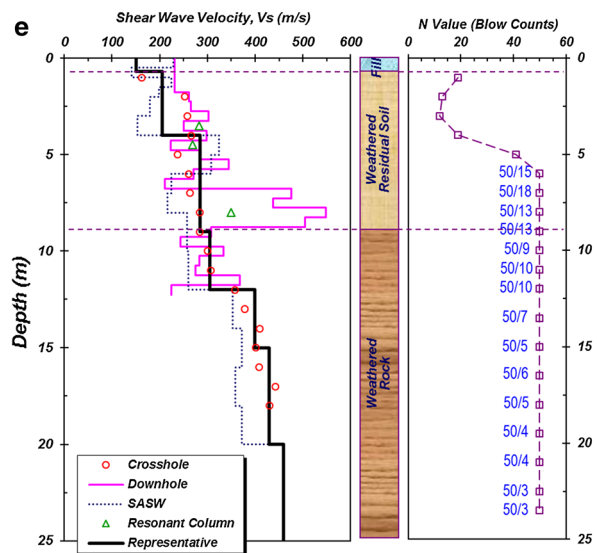
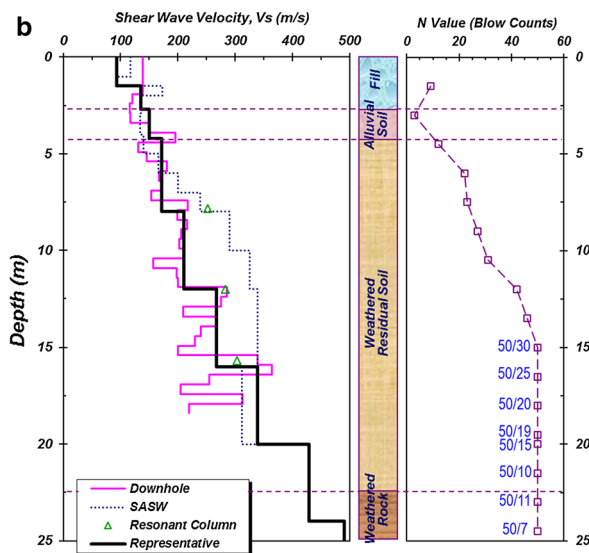
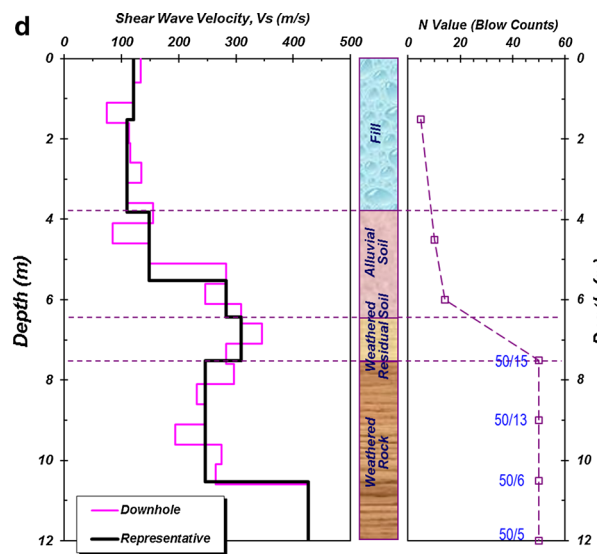
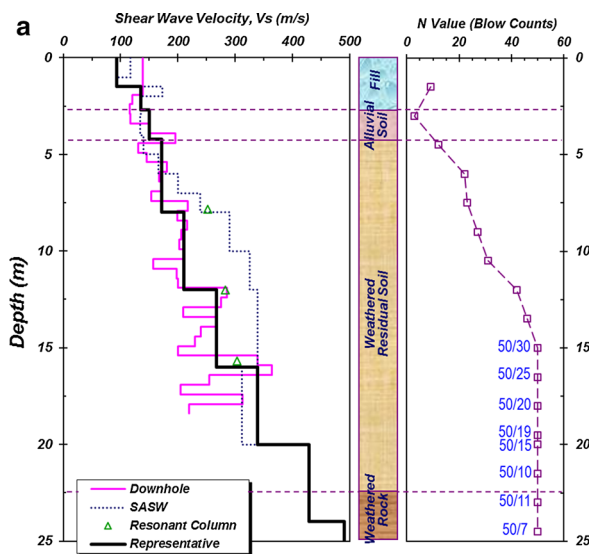
weathered layer depth are given in Fig. 7. Figure 7a also presents the average V_S and standard deviation (SD), which indicate the trend of increasing V_S with increasing depth. Figure 7b separately illustrates the weathered soil and the weathered rock, which make up the weathered layer. The weathered soil has a V_S range of 200–400 m/s and the weathered rock has a V_S range of 300–500 m/s. In other words, the overall weathered layer has a V_S range of 200–500 m/s. These results were obtained from a limited number of sites; to confirm the findings and obtain more detailed V_S profiles of the weathered layer in Hongseong, further study is needed.

Relationship between shear wave velocity and N value in the weathered layer

Shear wave velocity (V_S) profiles with depth can be determined through in situ seismic tests. Such tests are rare in site investigations for conventional geotechnical structures, such as general foundations and excavation, and are often only conducted if earthquake engineering research is necessary (Dikmen 2009; Sun et al. 2013). In cases in which geotechnical site investigations are conducted, SPT is typically performed, together with borehole drilling, so that the N value with depth can be obtained (Fig. 6). The N value is closely related to the mechanical characteristics of the ground, especially stiffness, and can be correlated with V_S . Therefore, by establishing an empirical relationship between the N value and V_S , we can estimate V_S by depth from previously existing site investigation data.

For determining V_S , the crosshole seismic test is most reliable, followed by a downhole seismic test, and then the SASW test. In other words, seismic tests in boreholes are more reliable than the non-destructive surface wave tests (Sun et al. 2005; Turesson 2007). A downhole test

Fig. 6 Shear wave velocity profiles and N values with depth at borehole seismic testing sites of **a** Chungoon University, **b** a small creek, **c** County Hall, **d** Gwangkyeong Bridge, **e** Hongju M.S., and **f** building lot in Hongseong. Profile of geotechnical layers investigated from borehole drilling is presented in central part of figure



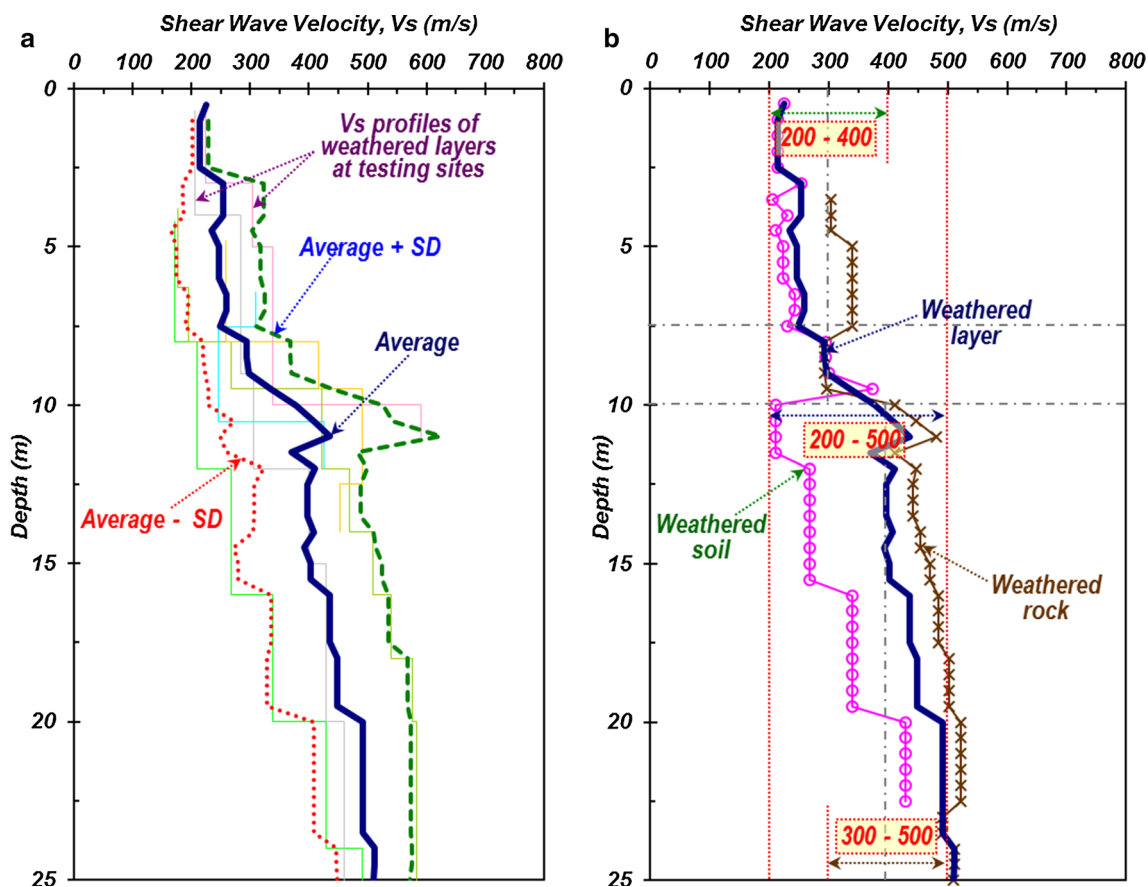


Fig. 7 Average shear wave velocity profile of weathered layer together with shear wave velocity profiles of **a** borehole seismic testing sites and \pm standard deviation (SD) and **b** weathered soil and

rock. The main ranges of shear wave velocities of weathered soil, weathered rock, and weathered layer are inserted in (b)

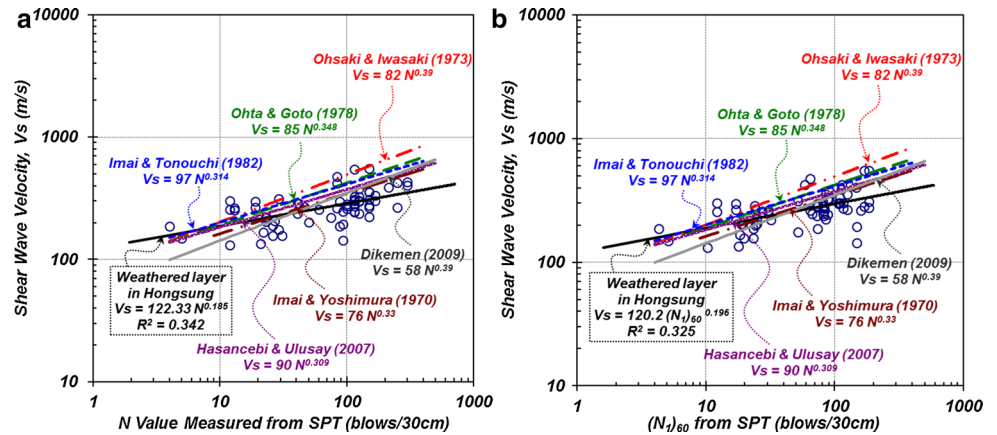
generates waves on the ground surface and receives waves under the ground surface, while a crosshole test using triggering and receiving waves in the ground results in more reliable V_S estimation. Therefore, this study used only V_S determined by crosshole and downhole tests of the weathered layer in Hongseong to determine the correlations between V_S and N values.

For blow counts above 50 (e.g., 50/25 or 50/6) in the layers of weathered soil and weathered rock, N values were extrapolated linearly to a penetration depth of 30 cm to analyze the regression between V_S and N values (Oh and Sun 2008; Sun et al. 2013). The absolute meaning of N values measured in the field may differ between tests owing to differences such as the type of hammer, the method of using the hammer, borehole diameter, ground conditions, rod length, difference in working capability, and effective overburden pressure (Aggour and Radding 2001). This study derived correlations with V_S for the actual measured N values and the corrected N , which indicate $(N_1)_{60}$ considering 60 % hammer energy efficiency, borehole diameter, sample collection method, rod

length, and effective overburden pressure. Figure 8 presents the relationships with V_S , derived in the form of power functions of the N value. Although the correlations, as quantified by the coefficient of determination (R^2), are all low, the correlations for the uncorrected N value measured in the field (Fig. 8a) seem to be more useful than those for the corrected N value (Fig. 8b). Furthermore, the measured N value has the practical advantage of not requiring a correction procedure.

As shown in Fig. 8, the correlations between V_S and N (both the field-measured and corrected N values) in the weathered granite layer at Hongseong differed from those in previous studies in other countries (Imai and Yoshimura 1970; Imai and Tonouchi 1982; Ohsaki and Iwasaki 1973; Ohta and Goto 1978; Hasancebi and Ulusay 2007; Dikmen 2009). In particular, the correlations in the present study produced smaller exponents and correspondingly milder slopes compared with other correlations. The correlations between V_S and N in this and previous studies are summarized in Table 5. Reasons for the difference may be that previous studies did not focus only on

Fig. 8 Correlations between shear wave velocity and N values in the weathered layer in Hongseong. **a** Measured N value and **b** corrected N value



conditions in the weathered layer. The correlations between V_S and N reflect the inter-relationship between deformation and strength for the geotechnical layer of interest. Thus, the correlations in this study might be more meaningful especially in the decomposed granite, than those in former studies mostly considering all soils and strata.

However, the exponent (about 0.2) of the correlations of the decomposed granite layer in Hongseong was very small compared with previously reported correlations (about 0.3–0.4), as presented in Fig. 8. The V_S (about 120 m/s: V_S axis-intercept of the graph) for the N value of 1 at Hongseong was larger than in previous studies (about 65–97 m/s). These results suggest that the V_S of the weathered layer in Hongseong becomes relatively larger than that in general subsurface conditions when the N value is small (usually shallow depth) and becomes relatively smaller when the N value is large (usually deep depth). Therefore, the V_S of the decomposed granite layer in Hongseong was determined to have a region-specific pattern that gradually increases in the range of 200–500 m/s with depth increase, rather than increasing rapidly.

Table 5 Summary of correlations between shear wave velocity and N value from the present and previous studies

Reference	Correlation
Measured N value in weathered layer in Hongseong	$V_S = 122.33 N^{0.185}$
Corrected N value, $(N_1)_{60}$, in weathered layer in Hongseong	$V_S = 120.20 (N_1)_{60}^{0.196}$
Imai and Yoshimura (1970)	$V_S = 76 N^{0.33}$
Imai and Tonouchi (1982)	$V_S = 97 N^{0.314}$
Ohsaki and Iwasaki (1973)	$V_S = 82 N^{0.39}$
Ohta and Goto (1978)	$V_S = 85 N^{0.348}$
Hasancebi and Ulusay (2007)	$V_S = 90 N^{0.309}$
Dikmen (2009)	$V_S = 58 N^{0.39}$

Relationship between weathering degree and geotechnical parameters in Hongseong

To examine the influence of the weathering degree on V_S in the weathered layer in Hongseong, this study compared the representative V_S with chemical weathering indices. The representative V_S was determined through in situ seismic tests conducted at four sites (Chungoon University, Gwangkyeong Bridge, a small creek, and County Hall), which were selected to evaluate the weathering degree. Of the various weathering indices, three indices, MWPI, VR, and WIP, were adopted for comparison with V_S in Hongseong. The relationships between the weathering indices and V_S are presented in Fig. 9. Here, VR, which decreases as depth increases, is converted into $100/\text{VR}$, and correspondingly the value is proportionate to V_S .

The 3.0-m-depth region at Chungoon University and the 9.0-m-depth region at the small creek, which constitute the upper interface of weathered layer in each site, differ from the general correlation pattern and the R^2 is rather low (about 0.11–0.17) owing to the relatively small amount of data; however, the representative V_S of the sites generally increases linearly with increases in MWPI, WIP, and $100/\text{VR}$. The correlations in Fig. 9 were obtained after excluding the two irregular data values for the layer interface. Because these correlations were obtained from a small number of data in Hongseong, they cannot be considered representative quantitative relationships between the V_S and chemical weathering indices of the decomposed granite layer. More data and analyses are needed to expand on the current results.

To analyze relationships with V_S for the decomposed granite layer in Hongseong, this study quantitatively compared uncorrected N values measured in the field, whose correlation was derived in the form of a power function, with three representative weathering indices, MWPI, VR, and WIP. Many N data are available from practical SPT studies carried out over a long time period

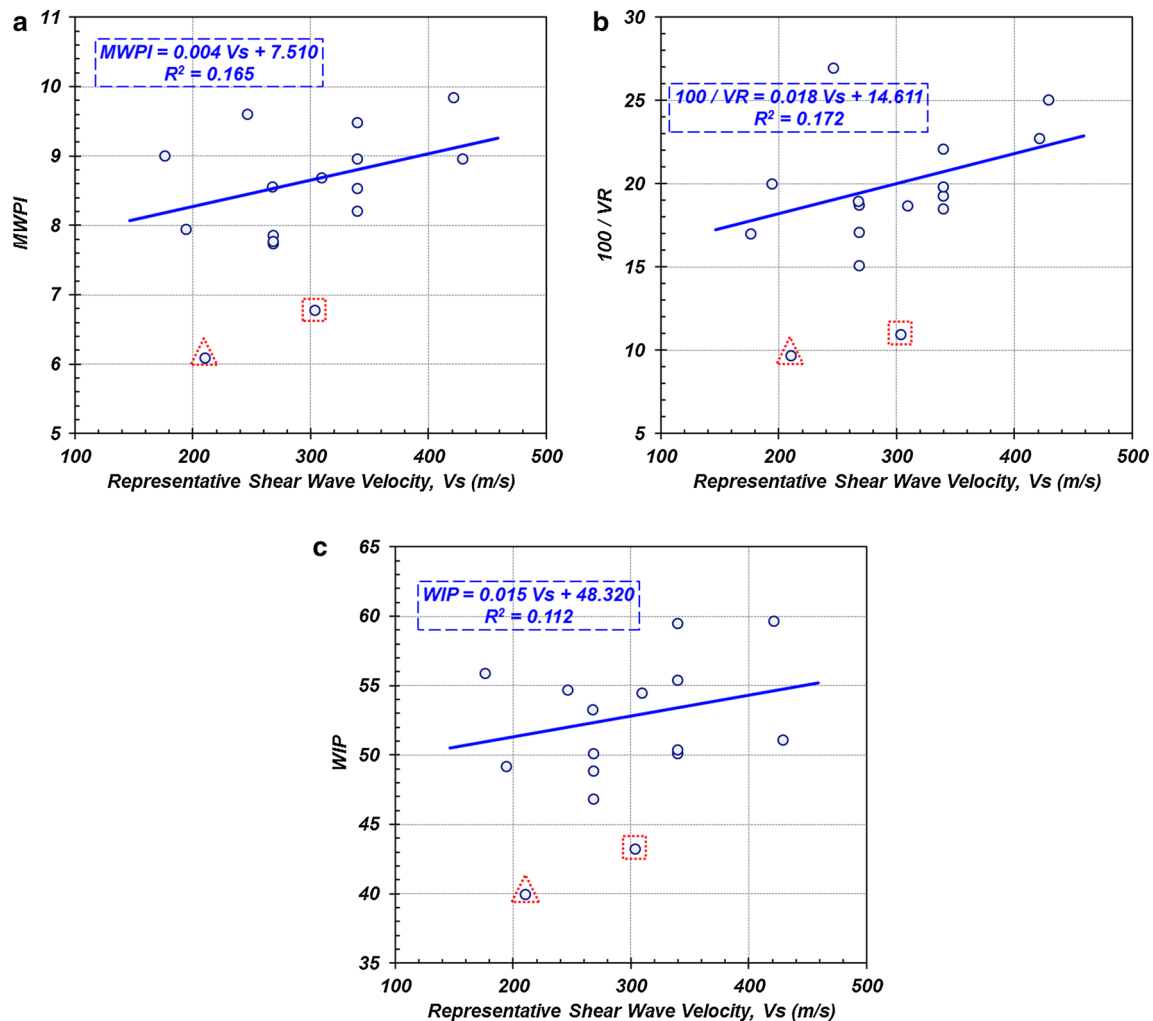


Fig. 9 Correlations between weathering indices and shear wave velocity in the weathered layer in Hongseong. **a** MWPI, **b** VR, and **c** WIP. Markers in dotted quadrangle and triangle indicate the data of

3.0 m depth at Chungoon University site and 9.0 m depth at the small creek, respectively

(Hasancebi and Ulusay 2007; Sun et al. 2013); thus, if the N value can be used to predict the degree of weathering with depth in the decomposed granite layer, then empirical weathering degree analysis can be conducted in many parts of South Korea using conventional site investigation data. Figure 10 shows the relationships among the MWPI, WIP, and 100/VR, and the N value from the SPT.

Like the correlations between weathering indices and V_S , the data for the 3.0-m-depth region at Chungoon University and 9.0-m-depth region at the small creek also differed from the general trend. They lacked a general trend and were thus excluded from the regression analyses. As shown in Fig. 10, the weathering indices and N value showed R^2 values of 0.17–0.50; this range is higher than that between the weathering indices and V_S (Fig. 9). The correlations between the weathering indices and V_S in the weathered layer (Fig. 9) in Hongseong and between

weathering indices and N values (Fig. 10) are summarized in Table 6.

The V_S , which is a deformation characteristic of a very small strain level, can be considered a quantitative index directly related to ground deformation characteristics, unlike N values obtained through dynamic penetration in the field. However, in this study, regardless of the quantitative characteristics, N values had higher correlation with the weathering degree than did V_S . This trend cannot be clarified by only partial examination of the ground deformation characteristics based on limited data. Multifaceted research, such as mineralogical analysis using extensive data and analysis of geotechnical strength characteristics, should be systematically conducted to clarify the causes.

As estimated from the relationship between N value and V_S (power function; see Fig. 8) and the relationship between V_S and weathering indices (linear function; see Fig. 9),

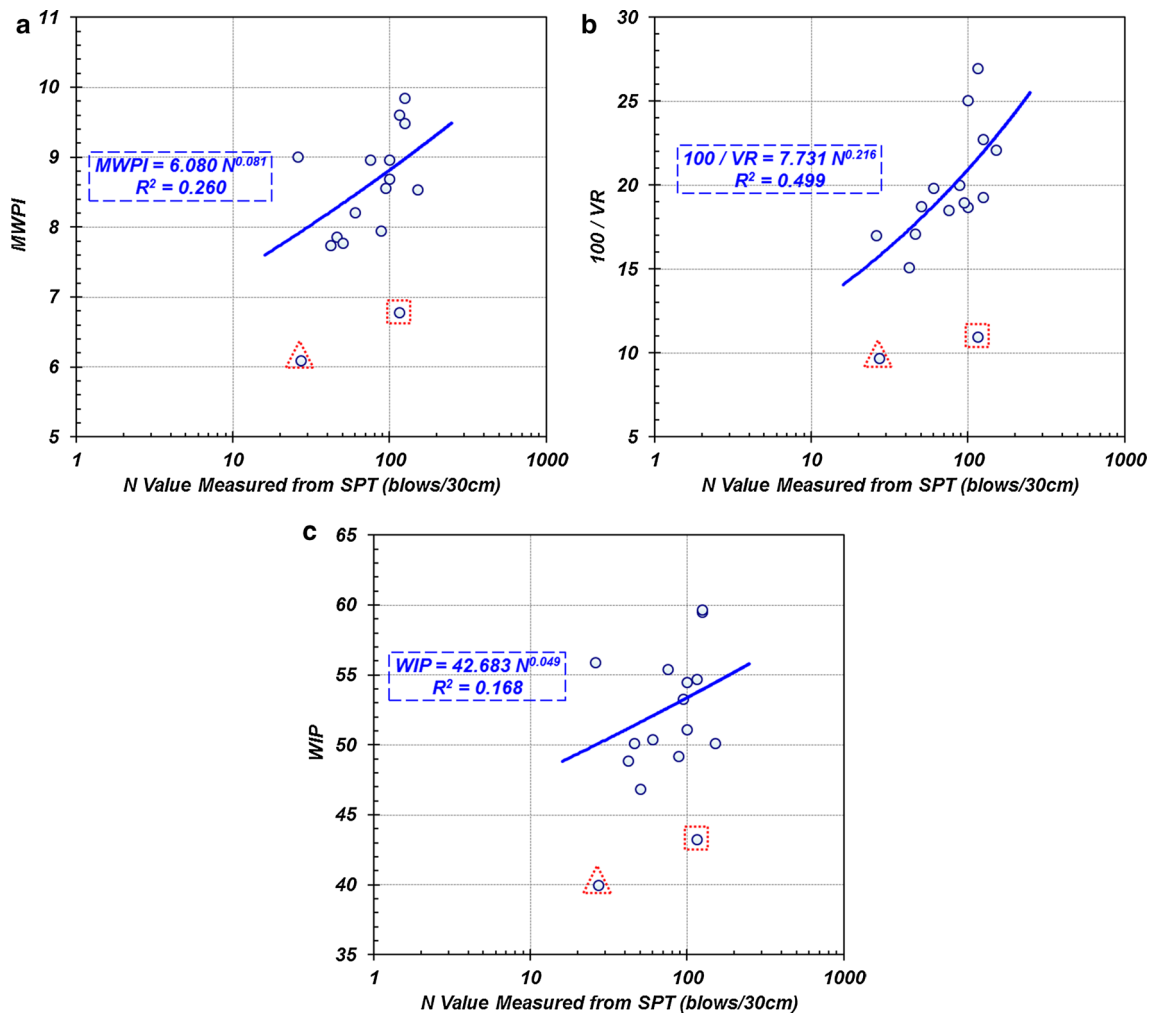


Fig. 10 Correlations between weathering indices and *N* values in the weathered layer in Hongseong. **a** MWPI, **b** VR, and **c** WIP. Markers in dotted quadrangle and triangle indicate the data of 3.0 m depth at Chungoon University site and 9.0 m depth at the small creek, respectively

Table 6 Summary of correlations between the weathering indices and the shear wave velocity and *N* value for the weathered layer in Hongseong

Geotechnical parameter	Weathering index	Correlation	R^2
Shear wave velocity	MWPI	$MWPI = 0.004 V_s + 7.510$	0.165
	VR	$100/VR = 0.018 V_s + 14.611$	0.172
	WIP	$WIP = 0.015 V_s + 48.320$	0.112
Measured <i>N</i> value	MWPI	$MWPI = 6.080 N^{0.081}$	0.260
	VR	$100/VR = 7.731 N^{0.216}$	0.499
	WIP	$WIP = 43.683 N^{0.049}$	0.168

weathering indices tended to increase as a power function of the *N* value. In particular, the correlation between VR and *N* value ($R^2 = 0.50$) was higher than that between V_s and *N* value ($R^2 = 0.33$ – 0.34). Although data and sites were limited in this study, the relationship between the weathering indices and *N* value can be considered a preliminary approach for estimating weathering degree based on many *N* values in the decomposed granite layer in Hongseong.

Therefore, if more data for the weathering degree in the decomposed granite layer can be obtained in various areas, their correlations with the *N* value could be analyzed, enabling empirical evaluation of the weathering degree using the *N* value. In Hongseong, VR was found to be particularly useful in terms of engineering and can serve as a representative chemical weathering index, using its distribution by depth or its correlation with V_s or *N* value.

Conclusions

This study evaluated the weathering degree and a representative dynamic characteristic, V_S , at Hongseong, where a thick layer of decomposed granite has developed. In situ and laboratory investigations revealed the following:

1. Geotechnical investigations, including borehole drilling and in situ seismic tests conducted at 16 sites in Hongseong, showed that the weathered layer composed of weathered soil and weathered rock was developed to a maximum thickness of 40 m. Weathered soil and weathered rock were formed by long-term weathering of granite bedrock at hill and plains sites, including a city location.
2. From analysis of XRF with depth conducted at four sites (Chungoon University, a small creek, County Hall, and Gwangkyeong Bridge), chemical weathering indices were determined. Distribution of the weathering indices with depth at Chungoon University and the small creek indicated that the weathering degree decreases as depth increases in most of the decomposed granite layer at Hongseong. This result was shown by most of the weathering indices, except for RR and CWI at the small creek site. Considering the overall trends shown by the weathering indices, MWPI, VR, and WIP are suggested as reasonable and representative chemical weathering indices that can discriminate the weathering degree by depth in the decomposed granite layer of Hongseong.
3. The V_S of the weathered layer was determined by borehole seismic tests at six sites (Chungoon University, a small creek, County Hall, Gwangkyeong Bridge, Hongju M.S., and building lot); V_S increased as the depth increased, which was similar to V_S findings in a laboratory resonant column test. The weathered soil layer and weathered rock layer that composed the weathered layer showed V_S ranges of 200–400 and 300–500 m/s, respectively.
4. This study also calculated correlations between V_S (obtained from borehole seismic tests in the Hongseong decomposed granite layer), in situ measured N values, and corrected $(N_1)_{60}$ in the form of a power function. The V_S of the decomposed granite layer gradually increased as depth increased in the V_S range of 200–500 m/s. Compared with previously determined local and overseas correlations, the V_S axis-intercept of the power function with the N value was quite large, while the exponent was very small.
5. Analysis of the relationships between three representative weathering indices, MWPI, VR (100/VR), and WIP, with V_S and N values showed that some depth data of the upper interface of the weathered layer fell

significantly outside the general trend and the correlations were very low, although it was possible to confirm the linear increase relationship with V_S . The fairly good correlations of weathering indices with the N value suggested the possibility of empirically evaluating the weathering degree by use of the N value, which showed an increase trend in the form of a power function. In particular, VR was judged to have high engineering usefulness as a representative weathering index for the decomposed granite layer in Hongseong.

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References

- Aggour MS, Radding WR (2001) Standard penetration test (SPT) correction. Report no. MD02-007B48. Maryland State Highway Administration, Baltimore
- Akin M (2010) A quantitative weathering classification system for yellow travertines. *Environ Earth Sci* 61(1):47–61
- Anbazhagan P, Sitharam TG (2009) Spatial variability of the depth of weathered and engineering bedrock using multichannel analysis of surface wave method. *Pure appl Geophys* 166(3):409–428
- Antonie P, Giraud A, Meunier M, Van Asch T (1995) Geological and geotechnical properties of the Terres Noires in southeastern France: weathering, erosion, solid transport and instability. *Eng Geol* 40(3–4):223–234
- ASTM (2004) Standard practice for classification of soils for engineering purposes (unified soil classification system): annual book of ASTM standards. D 2487-00. American Society for Testing and Materials, Philadelphia, pp 249–260
- Ceryan S, Zorlu K, Gokceoglu C, Temel A (2008) The use of cation packing index for characterizing the weathering degree of granitic rocks. *Eng Geol* 98(1–2):60–74
- Che VB, Fontijn K, Ernst GGJ, Kervyn M, Elburg M, Ranst EV, Suh CE (2012) Evaluating the degree of weathering in landslide-prone soils in the humid tropics: the case of Limbe, SW Cameroon. *Geoderma* 170:378–389
- Chiu CF, Ng CWW (2014) Relationships between chemical weathering indices and physical and mechanical properties of decomposed granite. *Eng Geol* 179:76–89
- Dikmen Ü (2009) Statistical correlations of shear wave velocity and penetration resistance for soils. *J Geophys Eng* 6(1):61–72
- Dipova N (2011) Geotechnical characterization and facies change detection of the Bogacay coastal plain (Antalya, Turkey) soils. *Environ Earth Sci* 62(4):883–896
- Duzgoren-Aydin NS, Aydin A, Malpas J (2002) Re-assessment of chemical weathering indices: case study on pyroclastic rocks of Hong Kong. *Eng Geol* 63(1–2):99–119
- Ferrier KL, Kirchner JW, Riebe CS, Finkel RC (2010) Mineral-specific chemical weathering rates over millennial timescales: measurements at Rio Icacos, Puerto Rico. *Chem Geol* 277(1–2):101–114

- GSL (1995) The description and classification of weathered rocks for engineering purposes. Geological society engineering group working party report. *Q J Eng Geol Hydroge* 28(3):207–242
- Guan P, Ng CWW, Sun M, Tang W (2001) Weathering indices for rhyolitic tuff and granite in Hong Kong. *Eng Geol* 59(1–2):147–159
- Gürer A, Bayrak M, Gürer ÖF, Şahin SY (2008) Delineation of weathering in the Çatalca granite quarry with the very low frequency (VLF) electromagnetic method. *Pure appl Geophys* 165(2):429–441
- Hasançebi N, Ulusay R (2007) Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments. *Bull Eng Geol Environ* 66(2):203–213
- Heinrichs K, Fitzner B (2011) Assessment of weathering damage on the Petroglyphs of Cheonjeon-ri, Ulsan, Republic of Korea. *Environ Earth Sci* 63(6–7):1741–1761
- Imai T, Tonouchi K (1982) Correlation of *N*-value with *s*-wave velocity and shear modulus. In: Proceedings of the second European symposium on penetration testing. Amsterdam, pp 57–72
- Imai T, Yoshimura Y (1970) Elastic wave velocity and soil properties in soft soil. *Tsuchi-to-Kiso* 18(1):17–22 (in Japanese)
- Irfan TY (1996) Mineralogy, fabric properties and classification of weathered granites in Hong Kong. *Q J Eng Geol Hydroge* 29(1):5–35
- Islam T, Chik Z (2011) Advanced performance in geotechnical engineering using tomography analysis. *Environ Earth Sci* 63(2):291–296
- Jiang K, Esaki T (2002) Quantitative evaluation of stability changes in historical stone bridges in Kagoshima, Japan, by weathering. *Eng Geol* 63(1–2):83–91
- Kang SS, Kim HY, Jang BA (2013) Correlation of in situ modulus of deformation with degree of weathering, RMR and Q-system. *Environ Earth Sci* 69(8):2671–2678
- Khanlari GR, Heidari M, Momeni AA (2012) Assessment of weathering processes effect on engineering properties of Alvand granitic rocks (west of Iran), based on weathering indices. *Environ Earth Sci* 67(3):713–725
- Kim S, Park HD (2003) The relationship between physical and chemical weathering indices of granites around Seoul, Korea. *B Eng Geol Environ* 62(3):207–212
- Kim DS, Chung CK, Sun CG, Bang ES (2002) Site assessment and evaluation of spatial earthquake ground motion of Kyeongju. *Soil Dyn Earthq Eng* 22(5):371–387
- Koralay T, Özkul M, Kumsar H, Çelik SB, Pektaş K (2011) The effect of welding degree on geotechnical properties of an ignimbrite flow unit: the Bitlis castle case (eastern Turkey). *Environ Earth Sci* 64(3):869–881
- Lee CK, Chang SM (2003) Evaluation of weathering intensity and strength parameter for weathered granite masses (I). *J Korean Geotech Soc* 19(2):227–236 (in Korean)
- Lee KS, Jo WR (2000) The gradient analysis of the Korean peninsula by using DEM. *J Korean Assoc Geogr Inf Stud* 3(1):35–43 (in Korean)
- Molina Ballesteros E, García Talegón J, Iñigo AC, González Sánchez M, Herrero Fernández H (2011) Importance of porosity and transfer of matter in the rock weathering processes: two examples in central Spain. *Environ Earth Sci* 64(7):1741–1754
- Nesbitt HW, Young GM (1982) Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. *Nature* 299:715–717
- Oh S, Sun CG (2008) Combined analysis of electrical resistivity and geotechnical SPT blow counts for the safety assessment of fill dam. *Environ Geol* 54(1):31–42
- Ohsaki Y, Iwasaki R (1973) On dynamic shear moduli and Poisson's ratio of soil deposits. *Soils Found* 13(4):61–73
- Ohta Y, Goto N (1978) Empirical shear wave velocity equations in terms of characteristic soil indexes. *Earthq Eng Struct Dyn* 6(2):167–187
- Över S, Büyüksaraç A, Bekta Ö, Filazi A (2011) Assessment of potential seismic hazard and site effect in Antakya (Hatay Province), SE Turkey. *Environ Earth Sci* 62(2):313–326
- Ozcan NT, Ulusay R, Isik NS (2013) A study on geotechnical characterization and stability of downstream slope of a tailings dam to improve its storage capacity (Turkey). *Environ Earth Sci* 69(6):1871–1890
- Park BK, Lee KC (1999) Evaluation methods of weathering degree for Korean decomposed granite soils. *J Korean Geotech Soc* 15(1):127–140 (in Korean)
- Parker A (1970) An index of weathering for silicate rocks. *Geol Mag* 107:501–504
- Rahardjo H, Aung KK, Leong EC, Rezaur RB (2004) Characteristics of residual soils in Singapore as formed by weathering. *Eng Geol* 73(1–2):157–169
- Regmi AD, Yoshida K, Dhital MR, Pradhan B (2014) Weathering and mineralogical variation in gneissic rocks and their effect in Sangrumba Landslide, East Nepal. *Environ Earth Sci* 71(6):2711–2727
- Roadset E (1972) Mineralogy and geochemistry of Quaternary clays in the Numendal area, southern Norway. *Nor Geol Tidsskr* 52(4):335–369
- Ruxton BP (1968) Measures of the degree of chemical weathering of rocks. *J Geol* 76(5):518–527
- Shafiei A, Heidari M, Dusseault MB (2007) Weathering and geomechanical properties of Alvand granitic rocks, western Iran. In: Proceedings of the first Canada-US rock mechanics symposium. Vancouver, pp 27–31
- Son YH, Chang PW (2009) Breakage index of weathering soil reflecting breakage level and weathering degree. *KSCE J Civ Eng* 13(5):325–332
- Son Y, Oh M, Lee S (2010) Estimation of soil weathering degree using electrical resistivity. *Environ Earth Sci* 59(6):1319–1326
- Sousa LMO, Gonçalves BMM (2013) Differences in the quality of polishing between sound and weathered granites. *Environ Earth Sci* 69(4):1347–1359
- Sueoka T (1988) Identification and classification of granitic residual soils using chemical weathering index. In: Proceedings of the second international conference on geomechanics in tropical soils, vol 1. Singapore, pp 55–61
- Sun CG (2012) Applications of a GIS-based geotechnical tool to assess spatial earthquake hazards in an urban area. *Environ Earth Sci* 65(7):1987–2001
- Sun CG, Kim DS, Chung CK (2005) Geologic site conditions and site coefficients for estimating earthquake ground motions in the inland areas of Korea. *Eng Geol* 81(4):446–469
- Sun CG, Kim BH, Chung CK (2006) Investigation on weathering degree and shear wave velocity of decomposed granite layer in Hongseong. *J Korean Soc Civil Engrs* 26(6C):431–443 (in Korean)
- Sun CG, Cho CS, Son M, Shin JS (2013) Correlations between shear wave velocity and in situ penetration test results for Korean soil deposits. *Pure appl Geophys* 170(3):271–281
- Tugrul A, Gürpınar O (1997) The effects of chemical weathering on the engineering properties of Eocene basalts in northeastern Turkey. *Environ Eng Geosci* 3(2):225–234
- Turesson A (2007) A comparison of methods for the analysis of compressional, shear, and surface wave seismic data, and determination of the shear modulus. *J Appl Geophys* 61(2):83–91
- Vogel DE (1973) Precambrian weathering in acid metavolcanic rocks from the superior province, Villebon Township, southcentral Quebec. *Can J Earth Sci* 12:2080–2085
- Vogt T (1927) Sulitjelmefeltets geologi og petrografi. *Nor Geol Unders* 121:1–560 (in Norwegian)