

# Characteristics of S-wave and P-wave velocities in Gyeongju - Pohang regions of South Korea: Correlation analysis with strength and modulus of rocks and N values of soils

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**Abstract.** With increasing demand for nuclear power generation, nuclear structures are being planned and constructed worldwide. A grave safety concern is that these structures are sensitive to large-magnitude shaking, e.g., during earthquakes. Seismic response analysis, which requires P- and S-wave velocities, is a key element in nuclear structure design. Accordingly, it is important to determine the P- and S-wave velocities in the Gyeongju and Pohang regions of South Korea, which are home to nuclear power plants and have a history of seismic activity. P- and S-wave velocities can be obtained indirectly through a correlation with physical properties (e.g., N values, Young's modulus, and uniaxial compressive strength), and researchers worldwide have proposed regression equations. However, the Gyeongju and Pohang regions of Korea have not been considered in previous studies. Therefore, a database was constructed for these regions. The database includes physical properties such as N values and P- and S-wave velocities of the soil layer, as well as the uniaxial compressive strength, Young's modulus, and P- and S-wave velocities of the bedrock layer. Using the constructed database, the geological characteristics and distribution of physical properties of the study region were analyzed. Furthermore, models for predicting P- and S-wave velocities were developed for soil and bedrock layers in the Gyeongju and Pohang regions. In particular, the model for predicting the S-wave velocity for the soil layers was compared with models from previous studies, and the results indicated its effectiveness in predicting the S-wave velocity for the soil layers in the Gyeongju and Pohang regions using the N values. The proposed models for predicting P- and S-wave velocities will contribute to predicting the damage caused by earthquakes.

**Keywords:** correlation; Gyeongju and Pohang regions; N value; S-wave velocity; site characterization

## 1. Introduction

More than 20% of the world's electricity is derived from nuclear power (Mazen *et al.* 2009), which is regarded as a practical energy source because of rising oil prices and the environmental issues caused by carbon dioxide emissions. With increasing demand for nuclear power generation, nuclear structures are being planned and constructed worldwide. The nuclear power plants (NPPs) in the Gyeongju and Pohang regions of South Korea have been in operation since 1978. However, a major safety concern regarding nuclear structures is that they are sensitive to large-magnitude shaking, for example, during earthquakes (Chapman and Hooper 2012). In the 2011 Fukushima disaster, substantial environmental damage, including radiation contamination, occurred owing to the destruction

of nuclear structures caused by earthquakes (Zulfikar *et al.* 2023). In 2016 and 2017, earthquakes with magnitudes (ML) ranging from 3.4 to 5.8 occurred in the Gyeongju and Pohang regions of South Korea.

The dotted symbols in Fig. 1 represent the locations of the epicenter, foreshock, and aftershocks. The color of these dots varies depending on the depth of the hypocenter, and the major aftershocks occur along the monoclines. Fortunately, there have been no significant issues regarding the safety of nuclear facilities in these two regions (Fig. 1). Many researchers have studied the impact of ground motion on nuclear structures because earthquakes significantly endanger their safety.

Bao *et al.* (2019) evaluated the effects of near- and far-fault seismic sequences on the fragility of the containment structures. Choi *et al.* (2008) performed a nonlinear seismic analysis of a CANDU (Canada Deuterium Uranium) containment structure. Nguyen *et al.* (2018) and Jin *et al.* (2020) analyzed the effects of near-fault ground motions on the seismic capacity and fragility of NPP structures. In the aforementioned studies, the physical properties of the site, including its dynamic properties, were used to analyze the ground behavior during an earthquake (i.e., site characterization). Site characterization using dynamic properties (e.g., Young's modulus, P-wave velocity, and S-

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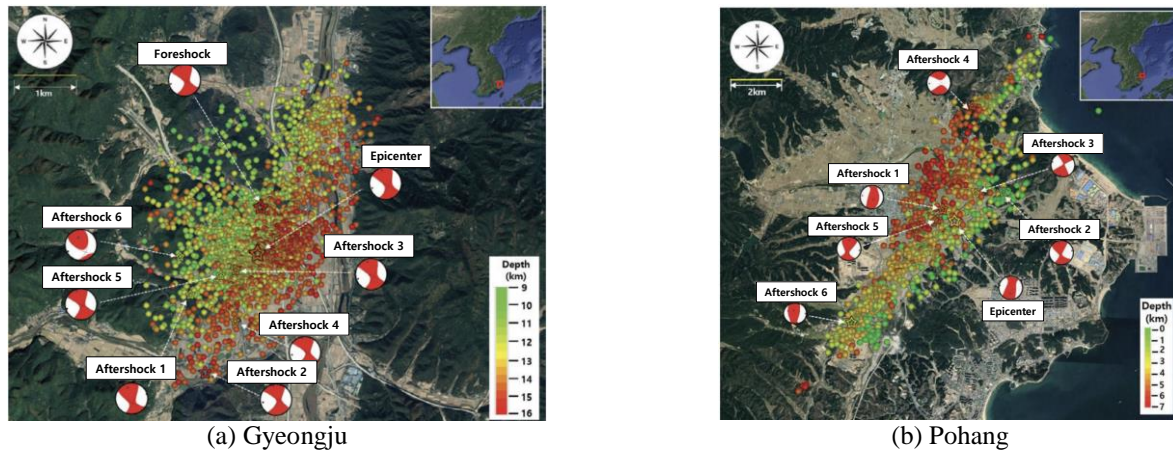


Fig. 1 Earthquakes in the Gyeongju and Pohang regions of South Korea (KIGAM 2018)

Table 1 Relationship between S-wave velocity and N values from previous studies

No.	Target area	Author	Model	R <sup>2</sup>
1	India	Sil and Sitharam (2014)	$V_s = 123N^{0.22}$	-
2	Japan	Ohta and Goto (1978)	$V_s = 85.34N^{0.348}$	-
4	Tiwan	Lee (1990)	$V_s = 57.4N^{0.49}$	-
5	India	Kirar <i>et al.</i> (2016)	$V_s = 99.5N^{0.345}$	0.80
6	Caspian Sea	Esfehanizadeh <i>et al.</i> (2015)	$V_s = 107.2N^{0.63}$	0.63
7	United States of America (USA)	Fatehnia <i>et al.</i> (2015)	$V_s = 77.1N^{0.355}$	0.89
8	Nationwide (Korea)	Sun <i>et al.</i> (2008)	$V_s = 65.64N^{0.407}$	0.56
9	Nationwide (Korea)	Heo and Kwak (2022)	$V_s = 140.3N^{0.2529}$	0.72
10	Seoul Gyeonggi Province and Gyeongsang Province (Korea)	Jeong (2008)	$V_s = 144.7N^{0.380}$	0.67
11	Seoul Gyeonggi Province (Korea)	Chae (2009)	$V_s = 141.484N^{0.223}$	0.50
12	Gyeongsang Province (Korea)	Chae (2009)	$V_s = 115.775N^{0.298}$	0.68
13	Chungcheong Province (Korea)	Do <i>et al.</i> (2011)	$V_s = 125.3N^{0.26}$	0.70
14	Chungcheong Province (Korea)	Chae (2009)	$V_s = 136.939N^{0.279}$	0.45

wave velocity) is a basic requirement for the seismic design of a site because the extent of damage caused by earthquakes can depend on the characteristics of the site (Yoo *et al.* 2022, Huynh *et al.* 2021). Thus, it is necessary to establish a database of dynamic properties, with particular emphasis on obtaining the P- and S-wave velocities corresponding to the target area.

The P- and S-wave velocities in the soil and rock layers are determined by the characteristics of the soil and rock, such as the density, effective stress, soil type, and rock type (Santamarina *et al.* 2001). S-wave velocity, which is a representative dynamic property, has been emphasized as a seismic design parameter (Sun *et al.* 2008, Cui *et al.* 2023).

The S-wave velocities in soil layers can be directly measured through various experimental techniques, such as suspension P-S logging (SPS) and downhole tests (DHTs); however, these techniques are expensive and time-consuming. In comparison, the standard penetration test (SPT) for obtaining N values is easier to implement, and the N values from the SPT can be correlated with S-wave velocities. Therefore, researchers worldwide have suggested regression equations for S-wave velocities using the N values.

Studies on the relationship between S-wave velocity and the N value have been conducted in many countries and regions, including Japan, Taiwan, India, the Caspian Sea, and the USA (Table 1). Ohta and Goto (1978) determined the correlation between the N value and the S-wave velocity of alluvial plains in Japan. Sil and Sitharam (2014) performed dynamic site characterization and analyzed the correlation between the S-wave velocity and N values for Agartala City, the capital of Tripura state in northeast India. Kirar *et al.* (2016) determined the relationship between the N values and S-wave velocities for the Roorkee region in India. Lee (1990) studied the S-wave velocity and N value with respect to depth in the Taipei Basin. Esfahanizadeh *et al.* (2015) determined the correlation between N value and S-wave velocity in young sand deposits in the coastal areas of the Caspian Sea. Fatehnia *et al.* (2015) suggested a new empirical formula that can correlate the N values and S-wave velocities for typical soil materials in North Florida, USA. These studies clearly indicate that the regression equations between S-wave velocities and N values vary between countries and regions.

In addition, since 2008, the correlation between the S-wave velocity and N value has been studied at many sites in

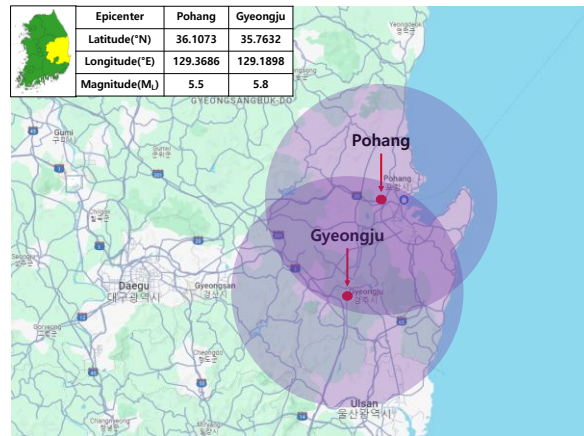


Fig. 2 The target area in the Gyeongju and Pohang regions of South Korea

South Korea, including in Seoul, Gyeonggi Province, Gyeongsang Province, and Chungcheong Province (Sun *et al.* 2008, Jeong 2008, Chae 2009, Do *et al.* 2011, Heo and Kwak 2022). However, these studies did not consider the Gyeongju and Pohang regions of South Korea. These regions are home to NPPs and have a history of seismic activity. Thus, it is critical to predict the S-wave velocity in these regions and conduct site interpretations accordingly. Furthermore, owing to the variations in ground characteristics among different countries, the S-wave velocities determined from the N values exhibited differences. Therefore, the results obtained from Gyeongsang Province may not be applicable to the Gyeongju and Pohang regions.

In the present study, a database was constructed by collecting data from 690 boreholes in Gyeongju and Pohang. This database includes the physical properties of these regions. Using the constructed database, the geological characteristics of the Gyeongju and Pohang regions and the correlations between the physical properties and P- and S-wave velocities in the soil and bedrock layers were analyzed. Additionally, a model for predicting the S-wave velocity using N values was developed, and a comparative analysis was performed against previously proposed models. The model proposed in this study for predicting S-wave velocity, which is a key factor in site interpretation in the Gyeongju and Pohang regions, is expected to allow the prediction of the damage caused by earthquakes through stability assessments and seismic vulnerability analyses of NPPs. If integrated with three-dimensional ground visualization and monitoring systems with various types of input and output information, the constructed database is expected to be of substantial practical value.

## 2. Geological characteristics and physical properties of soil and bedrock layers in Gyeongju and Pohang regions

The target area for data collection in this study corresponded to regions within a radius of 30 km from the

epicenters of the mainshocks that occurred in the Gyeongju and Pohang regions of Korea (Fig. 2). To establish the database, 690 borehole samples were collected from geotechnical investigation reports. The borehole logs of each borehole were referenced to classify the geological layers (e.g., fill, sand, and clay layers), and the physical properties corresponding to each geological layer were entered into the database with averages and standard deviations.

The physical properties of each layer include the basic characteristics of the soil or bedrock (unit weight, specific gravity, liquid limit, and plastic limit), physical characteristics (N value and uniaxial compressive strength), and dynamic characteristics (Young's modulus, P-wave velocity, and S-wave velocity). Then, the geological characteristics and physical properties of the Gyeongju and Pohang regions were analyzed using the constructed database, as described below.

### 2.1 Geological characteristics

In South Korea, the terrain typically consists of mature landscapes that exhibit gentle slopes due to ongoing erosion and weathering. In particular, the terrains of Gyeongsang Province and the southern part of Gangwon Province in southeastern South Korea are dominated by sedimentary rocks (Sun *et al.* 2005). According to a geological survey conducted by the Korea Institute of Geoscience and Mineral Resources (KIGAM), Gyeongsang Province in South Korea was formed during the Cambrian–Quaternary period. This region is composed of sedimentary and relatively hard rocks, such as metamorphic and igneous rocks. In particular, according to the database, sedimentary rocks, such as gneiss and shale, dominate the target area of this study, that is, the Gyeongju and Pohang regions, which are part of Gyeongsang Province. The bedrock depth ranges from 6 to 12 m, and the bedrock is saturated with groundwater. Furthermore, alluvial deposits from the Quaternary period are distributed atop the bedrock and consist of a mixture of sand, silt, clay, and gravel. Therefore, it is challenging to obtain a representative cross-section of the soil layers in the Gyeongju and Pohang regions.

Table 2 Basic characteristics of soil layers

Parameters	$r_t$ (kN/m <sup>3</sup> )	$G_s$ (-)	$W$ (%)	$LL$ (%)	$Pl$ (%)
Max. value	19.61	2.76	84.6	99.8	69
Min. value	16.30	2.46	2.6	1.5	0.5
Average	17.62	2.65	24.32	44.5	21.5
Standard deviation	1.08	0.03	14.68	15.6	12.2

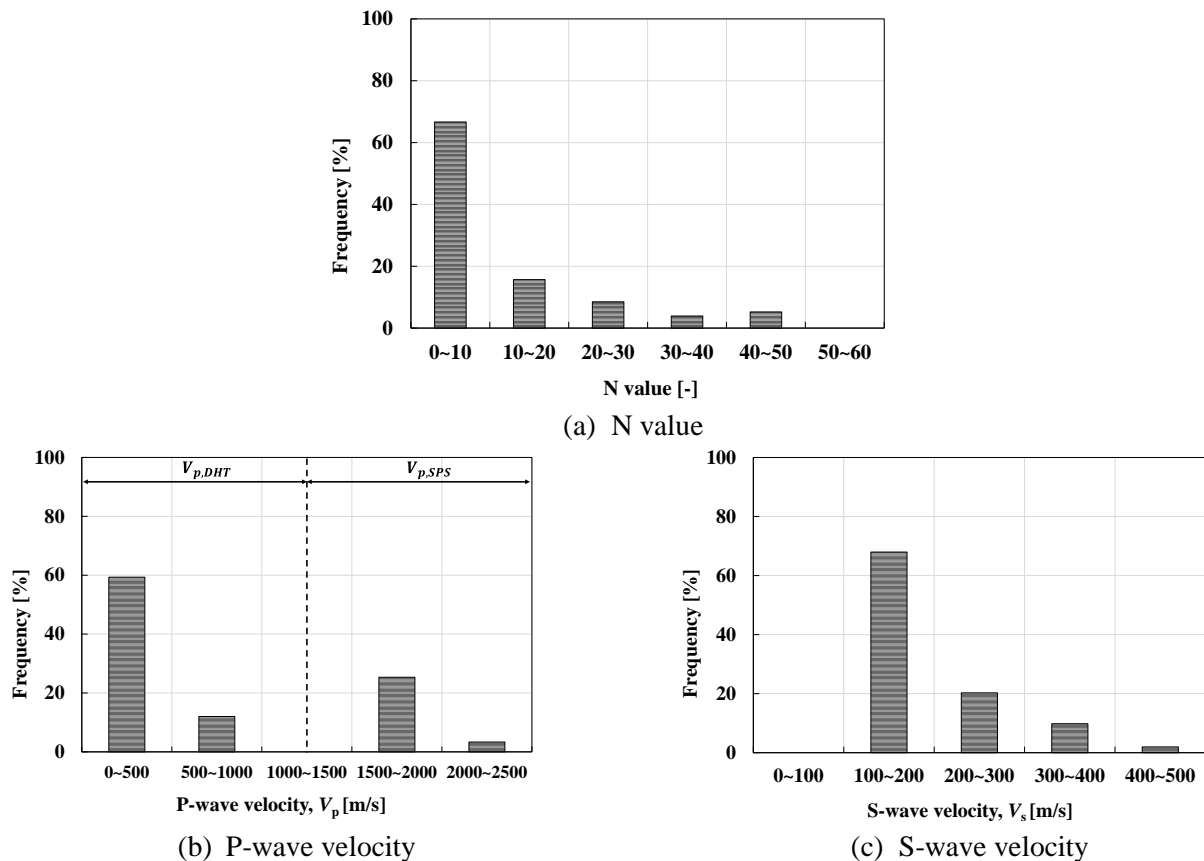


Fig. 3 Distribution of N value and wave velocities in the Gyeongju and Pohang regions of South Korea (soil layers)

## 2.2 Physical properties of soil layers

Table 2 presents the statistics for each physical property related to the basic characteristics of the soil layers, including unit weight ( $r_t$ ), specific gravity ( $G_s$ ), water content ( $W$ ), liquid limit ( $LL$ ), and plastic limit ( $Pl$ ). The average unit weight was 17.62 kN/m<sup>3</sup>, with a standard deviation of 1.08 kN/m<sup>3</sup>. The average specific gravity was 2.65, with a standard deviation of 0.03. The average water content of the clay layers was 24.32%, with a standard deviation of 14.68%. The average liquid limit was 44.5%, with a standard deviation of 15.6%. The average plastic limit was 21.5%, with a standard deviation of 12.2%. The N value and the P- and S-wave velocities are properties related to the physical and dynamic characteristics of the soil layers. The N values were determined in the field using the SPTs. The P- and S-wave velocities were measured in the field using the SPS and DHT. The average N value was 11, with a standard deviation of 10. As shown in Fig. 3(a),

the N values were found at the highest frequency in the range of 0–10 (64%).

Fig. 3(b) shows the frequency of the P-wave velocity. The P-wave velocities from the DHTs ( $V_{p,DHT}$ ) ranged from 302 m/s to 685 m/s. The average and standard deviations of these values were 395 and 112 m/s, respectively. The P-wave velocity values from the SPS ( $V_{p,SPS}$ ) ranged from 1508 to 2128 m/s. The average and standard deviation of the values were 1683 and 218 m/s, respectively. The P-wave velocity values from the DHTs were approximately 1000 m/s lower than those from the SPS, which was also observed by Jeong (2008). The SPS generated seismic waves at each measurement point, whereas the seismic source of the DHT was located on the surface. As the depth increased, the waves generated by the DHTs propagated downward and were attenuated, thereby reducing the P-wave velocity.

No significant differences were observed between the S-

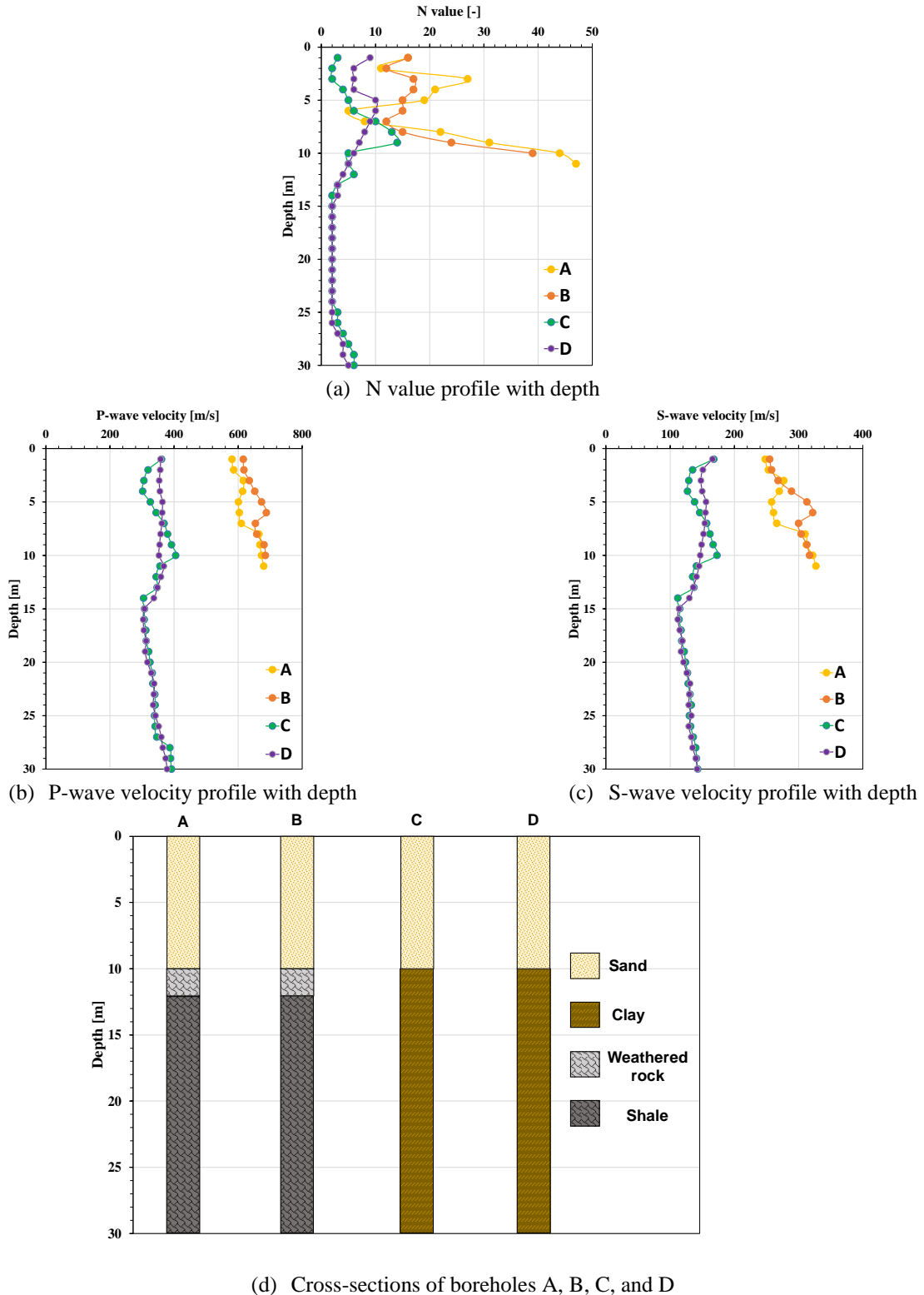


Fig. 4 Examples of P-wave velocity, S-wave velocity, and N value profiles for soil layers in the Gyeongju and Pohang regions of South Korea

wave velocities obtained using the different test methods. Therefore, the S-wave velocity values cannot be distinguished using these methods. Fig. 3(c) shows the frequency of the S-wave velocity. The S-wave velocities ranged from 112 to 420 m/s and occurred at the highest

frequency (67%) in the range of 100–200 m/s. The average and standard deviation of these values were 187 and 75 m/s, respectively. Furthermore, examples of P- and S-wave velocities and N value profiles for the soil layers were obtained from boreholes A, B, C, and D, where downhole

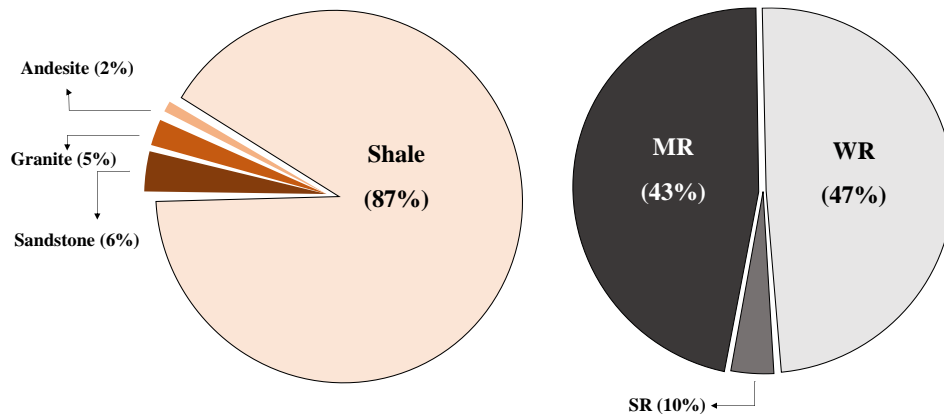


Fig. 5 Distribution in bedrocks according to rock type and uniaxial compressive strength in the Gyeongju and Pohang regions of South Korea

Table 3 Statistics of basic characteristics of bedrock layers

Parameters	$\gamma_t$ (kN/m <sup>3</sup> )	$G_s$ (-)	$n$ (%)	$\nu$ (-)
Max. value	30.52	2.81	9.77	0.40
Min. value	10.98	1.69	0.17	0.12
Average	24.87	2.62	2.22	0.26
Standard deviation	4.11	0.17	2.48	0.06

tests were conducted (Figs. 4(a)-4(c)). The boreholes are divided into two groups based on the depth of the bedrock, which for boreholes A and B is 12 m and for boreholes C and D is 40 m (the P- and S-wave velocities were only measured to a depth of 30 m in boreholes C and D). Fig. 4(d) shows the cross sections of the four boreholes, displaying only up to a depth of 30 m. Boreholes A and B (and C and D) were located in close proximity to each other and shared identical cross-sections. In boreholes A and B, the P- and S-wave velocities at the surface are approximately 600 and 250 m/s, respectively. The P- and S-wave velocities increase at a rate of approximately 7 m/s per 1 m with increasing depth. In boreholes C and D, the P- and S-wave velocities at the surface are approximately 360 m/s and 166 m/s, respectively. At a depth of 15 m from the surface, the P- and S-wave velocities increase at a rate of approximately 2 m/s per 1 m with increasing depth.

### 2.3 Physical properties of bedrock layers

The characteristics of the bedrock layer are determined by the rock type. Therefore, the frequency of rock types in the target area was analyzed, and the rock layers were classified according to their strength. The bedrock in the target area includes shale, sandstone, granite, and andesite. Shale occurs with the highest frequency (87%), and the frequencies of occurrence of sandstone, granite, and andesite are 6%, 5%, and 2%, respectively. The International Society for Rock Mechanics (ISRM) proposed that, when the uniaxial compressive strength ranges from 0 to 25 MPa, 25 to 100 MPa, and exceeds 100 MPa, the rock should be classified as weak rock (WR), moderate rock (MR), or strong rock (SR), respectively. According to the

rock classification proposed by the ISRM, the bedrock in the target area is mainly composed of 90% weak and moderate rocks (Fig. 5). The bedrock depth ranges from 6 to 12 m, and the bedrock is oversaturated with groundwater.

Table 3 presents the statistics of the basic characteristics of the bedrock layers: unit weight ( $\gamma_t$ ), specific gravity ( $G_s$ ), porosity ( $n$ ), and Poisson's ratio ( $\nu$ ). The average unit weight was 24.87 kN/m<sup>3</sup>, with a standard deviation of 4.11 kN/m<sup>3</sup>. The average specific gravity was 2.62, with a standard deviation of 0.17. The average porosity of the clay layers was 2.22%, with a standard deviation of 2.48%. The average Poisson's ratio was 0.26, with a standard deviation of 0.06.

The properties related to the physical and dynamic characteristics obtained from the bedrock layers were uniaxial compressive strength (UCS), Young's modulus ( $E$ ), and P- and S-wave velocities. In addition, the database established in this study mostly includes borehole data with shale as the bedrock, with limited borehole data for other bedrock types. Therefore, this study was conducted using borehole data for shale as the bedrock.

The uniaxial compressive strength and Young's moduli of the bedrock layers were determined through uniaxial compressive tests. The uniaxial compressive strength values ranged from 4.1 to 235.2 MPa, with an average and standard deviation of 48 and 42 MPa, respectively. Fig. 6(a) shows the distribution of the uniaxial compressive strength into five groups at 50 MPa intervals. Most values were in the <150 MPa range, and the least (2%) were in the > 150 MPa range. Fig. 6(b) shows the frequency distribution of the Young's modulus values into five groups of 20 GPa intervals. Young's modulus values of < 20 GPa occurred at a significantly higher frequency (51%) than those > 40 GPa

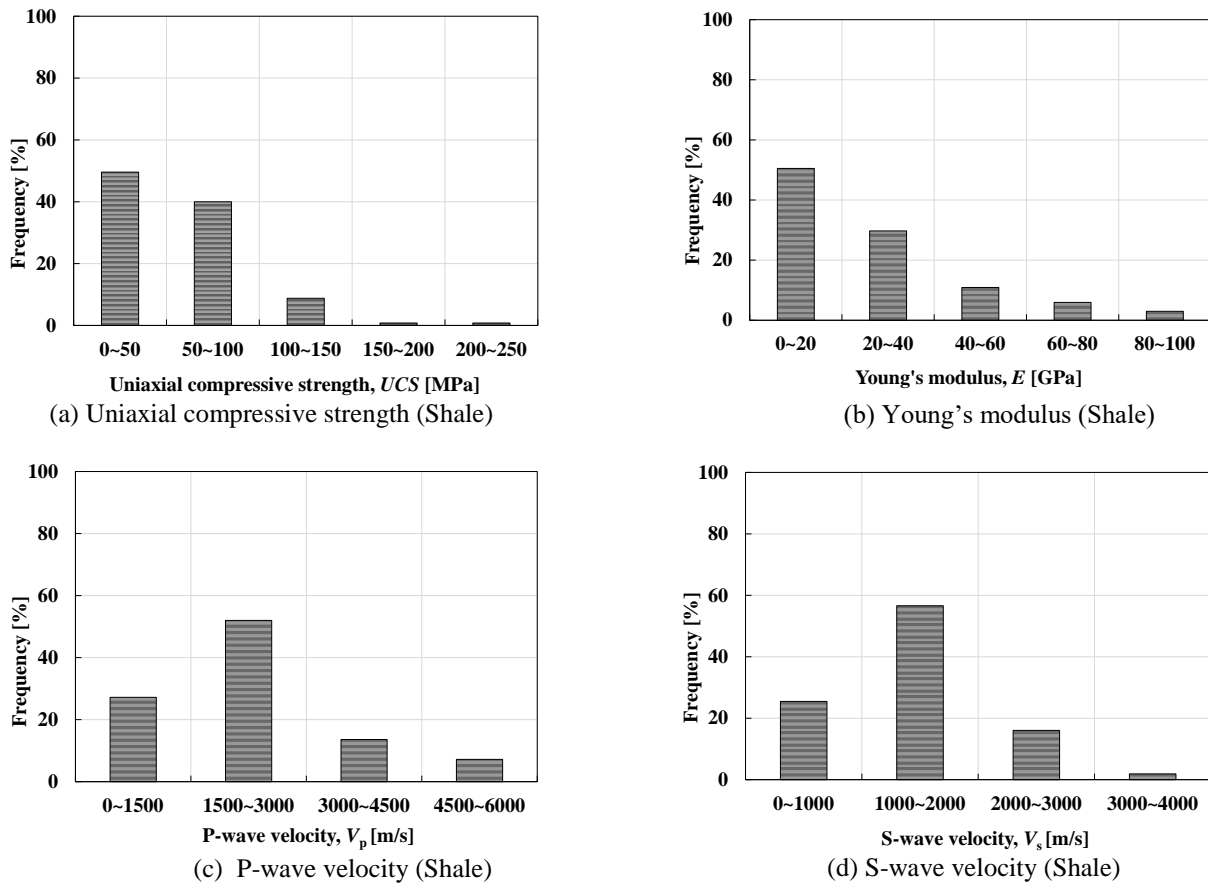


Fig. 6 Distribution of physical properties and wave velocities in the Gyeongju and Pohang regions of South Korea (shale layers)

(20%). The maximum Young's modulus value was 83 GPa, with an average value of 23 GPa and a standard deviation of 22 GPa (Fig. 6(b)).

The P- and S-wave velocities in the bedrock layers were determined using core-based sonic logging. The P-wave velocity values ranged from 800 to 5882 m/s, with an average and standard deviation of 2280 and 1138 m/s, respectively. Fig. 6(c) shows the frequency distribution of the P-wave velocity into four groups at intervals of 1500 m/s. P-wave velocities in the range of 1500–3000 m/s occurred at the highest frequency (52%), whereas P-wave velocities >3000 m/s occurred at a lower frequency (21%). The S-wave velocities ranged from 462 to 3839 m/s, with an average and standard deviation of 1308 and 634 m/s, respectively. S-wave velocities in the range of 1000–2000 m/s occurred at a significantly higher frequency (57%) than those in the range of 3000–4000 m/s (2%) (Fig. 6(d)).

### 3. Correlations between physical properties and wave velocities

The correlations between the physical and dynamic properties of bedrock layers obtained from the established database were analyzed to develop regression equations for these properties. The equations formulated in this study are based on a power function for comparison with previous

studies in which correlations based on this function were developed (Table 1). Correlations were analyzed for each layer: soil and bedrock. The error index between the actual value and the predicted value from the regression equation is denoted by the residual standard deviation ( $\sigma$ ) (refer to Eq. (1)).

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{y}_i - y_i)^2} \quad (1)$$

where  $\sigma$  is the standard deviation of the model,  $n$  is the number of data points,  $\hat{y}_i$  denote the predicted values of the model, and  $y_i$  are the actual values.

#### 3.1 Soil layers

Correlations were determined via regression analysis of the  $N-V_p$  and  $N-V_s$  datasets of the soil layer properties (148 pairs of  $N-V_p$  datapoints and 153 pairs of  $N-V_s$  datapoints, respectively). The regression equations developed using these datasets are presented in Table 4. As mentioned in Section 2, considering the difference of approximately 1000 m/s in the P-wave velocity values depending on the testing method, the correlation between the P-wave velocity and  $N$  value was analyzed separately for each testing method. As shown in Fig. 7(a), a linear relationship was hypothesized between the  $N$  value and P-wave velocity from the SPS, and

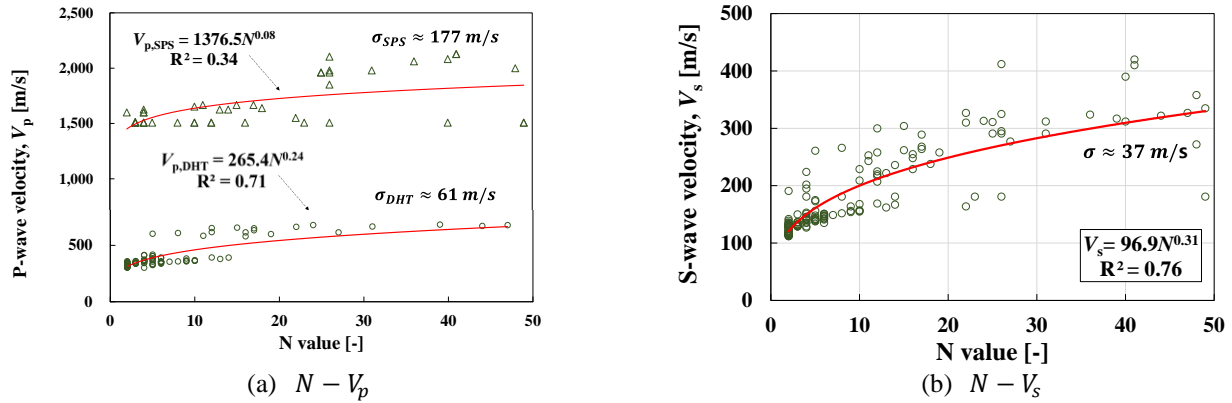


Fig. 7 Correlation between N values and P- and S-wave velocities in the Gyeongju and Pohang regions of South Korea (soil layers)

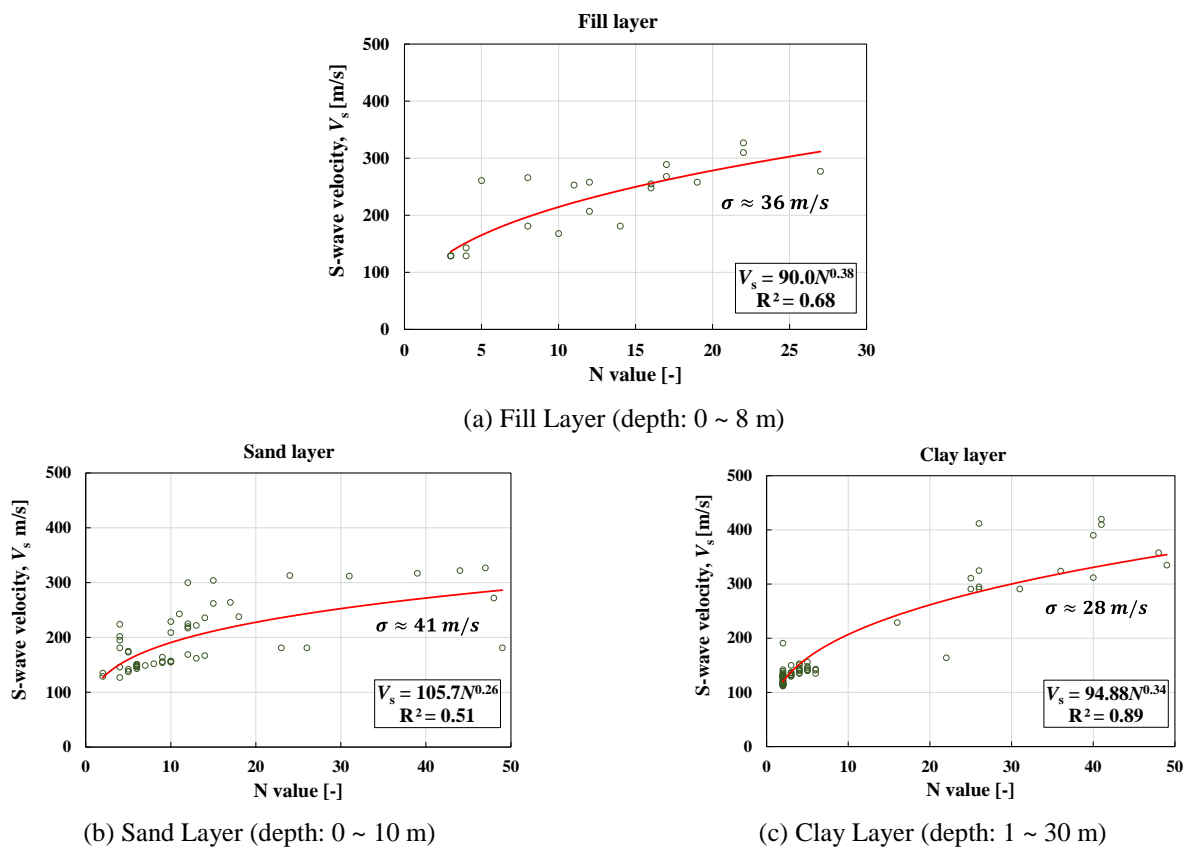


Fig. 8 Correlation between N values and S-wave velocities according to soil type in the Gyeongju and Pohang regions of South Korea

Table 4 Correlation between physical properties and P- and S-wave velocities in the soil layers in the Gyeongju and Pohang regions of South Korea

Layer	Model	R <sup>2</sup>
Soil (all)	$V_{p,SPS} = 1376.5N^{0.08}$	0.34
	$V_{p,DHT} = 265.4N^{0.24}$	0.71
	$V_s = 96.9N^{0.31}$	0.76
Soil (fill)	$V_s = 90.0N^{0.38}$	0.68
Soil (sand)	$V_s = 105.7N^{0.26}$	0.51
Soil (clay)	$V_s = 94.88N^{0.34}$	0.89

the correlation coefficient was evaluated to be 0.34. The same procedure was applied to the N values and P-wave velocities from the DHTs, and the correlation coefficient had a larger value of 0.71. The correlation coefficient was the largest (0.76) for the N values and S-wave velocities (Fig. 7(b)). This is because the S-wave velocity has a dominant influence on the effective stress, making the sensitivity of the S-wave velocity to the N values far higher than that to the other physical properties. The proposed equation for calculating the S-wave velocity using the N values in Fig. 7(b) is expected to accurately predict the S-wave velocities in the soil layers of the Gyeongju and Pohang regions.

Table 5 Correlations between physical properties and P- and S- velocities for bedrock layers in the Gyeongju and Pohang regions of South Korea

Layer	Model	R <sup>2</sup>
Rock (shale)	$V_p = 1167E^{0.25}$	0.52
	$V_p = 655.1UCS^{0.33}$	0.39
	$V_s = 697.5E^{0.23}$	0.35
	$V_s = 65.64G^{0.23}$	0.35
	$V_s = 429.8UCS^{0.28}$	0.24

Furthermore, regression analysis of  $N-V_s$  datasets was conducted for different soil types: fill, sand, and clay layers. The  $N-V_{p,SPS}$  and  $N-V_{p,DHT}$  datasets for the various soil types were limited; thus, it was impossible to conduct a regression analysis of  $N-V_p$  for each soil type. Fig. 8 shows the regression equations of the  $N$  values and S-wave velocities for different soil types. As  $N$  increased, the difference in the predicted S-wave velocities for each soil type increased, with a maximum difference of 80 m/s. The correlation coefficients for the fill, sand, and clay layers are 0.68, 0.51, and 0.89, respectively. Thus, the regression equations shown in Fig. 8 are applicable for predicting the S-wave velocity in specific soil types in the Gyeongju and Pohang regions, particularly in the clay layer, for which a highly accurate equation with a correlation coefficient of 0.89 was obtained.

### 3.2 Bedrock layers

The uniaxial compressive strength and Young's modulus of the shale layer were utilized for a correlation analysis to predict the P- and S-wave velocities. A correlation analysis was conducted using 107 pairs of Young's modulus and P-wave velocity data, 104 pairs of Young's modulus and S-wave velocity data, 123 pairs of uniaxial compressive strength and P-wave velocity data, and 114 pairs of uniaxial compressive strength and P-wave velocity data corresponding to the shale layer. The regression equations developed using these datasets are presented in Table 5.

The coefficient of determination for the relationship between Young's modulus and P-wave velocity was 0.52, whereas that for the equation involving Young's modulus and S-wave velocity was 0.35 (Fig. 9). The Young's modulus had a weaker correlation with the S-wave velocity than with the P-wave velocity. Therefore, Young's modulus was converted into shear modulus using Poisson's ratio; however, analysis of the correlation between the shear modulus and S-wave velocity revealed a coefficient of determination of 0.26, indicating no significant difference (Eq. (2); Santamarina *et al.*, 2021). This is attributed to the almost constant Poisson's ratio of 0.26 obtained for the shale layer (Fig. 10).

$$G = \frac{E}{2(1 + \nu)} \quad (2)$$

The coefficient of determination for the equation involving uniaxial compressive strength and P-wave velocity was 0.39, and that for the equation involving

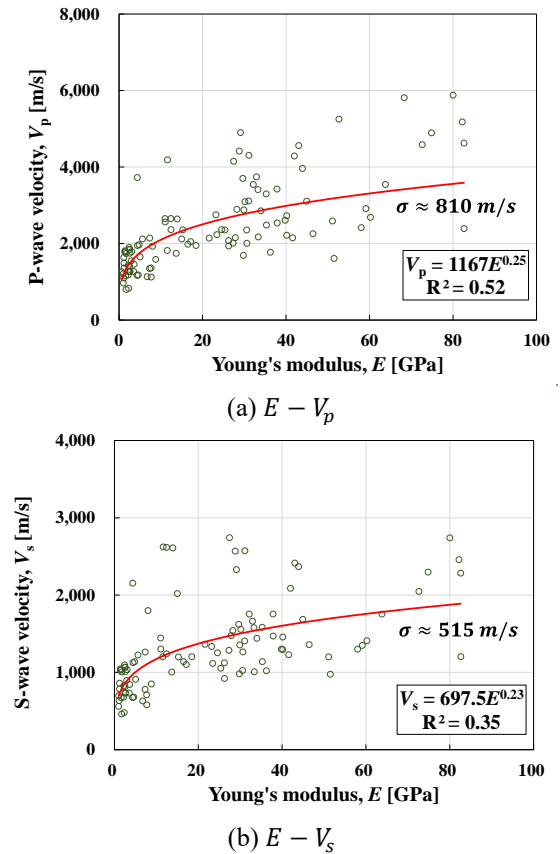


Fig. 9 Correlation between Young's modulus and P- and S-wave velocities in the Gyeongju and Pohang regions of South Korea

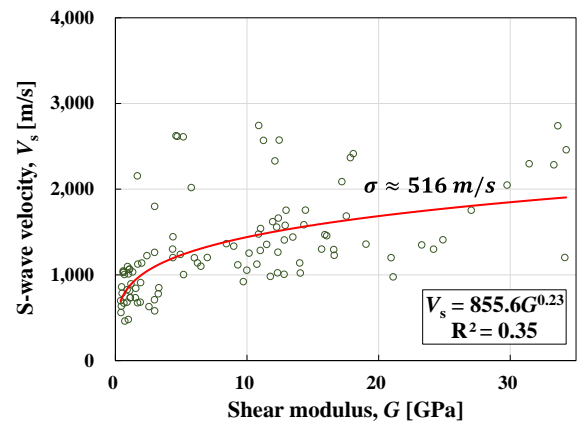


Fig. 10 Correlation between shear modulus and S-wave velocity in the Gyeongju and Pohang regions of South Korea

uniaxial compressive strength and S-wave velocity was 0.24 (Fig. 11). Overall, the correlations between the physical properties and P- and S-wave velocities in the bedrock layer were weaker than those in the soil layer. This is because soil and rock samples can have slightly different physical and chemical properties, even if they are collected from the same location. In particular, rock samples, even if they are of the same rock type and from the same area, can exhibit significant differences owing to considerable variations in

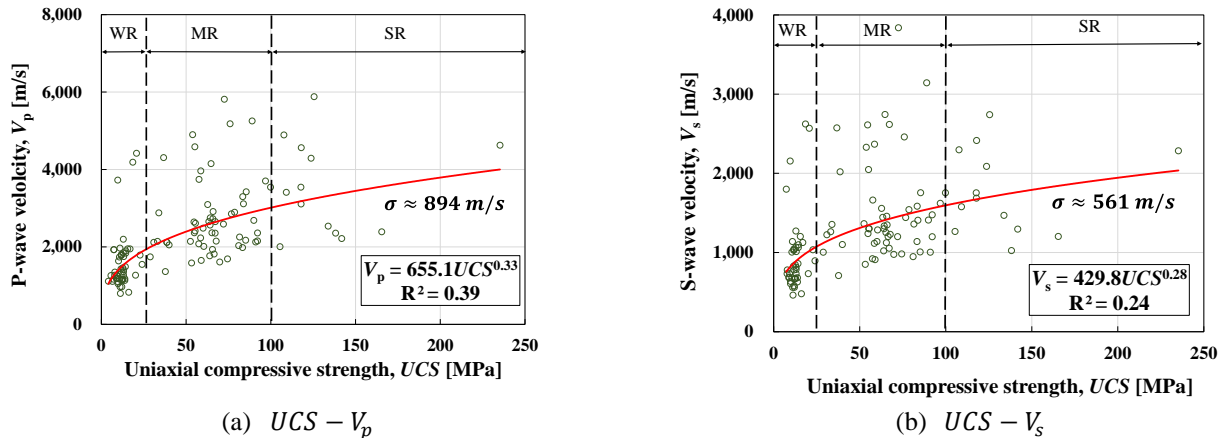


Fig. 11 Correlation between uniaxial compressive strength and P- and S-wave velocities in the Gyeongju and Pohang regions of South Korea

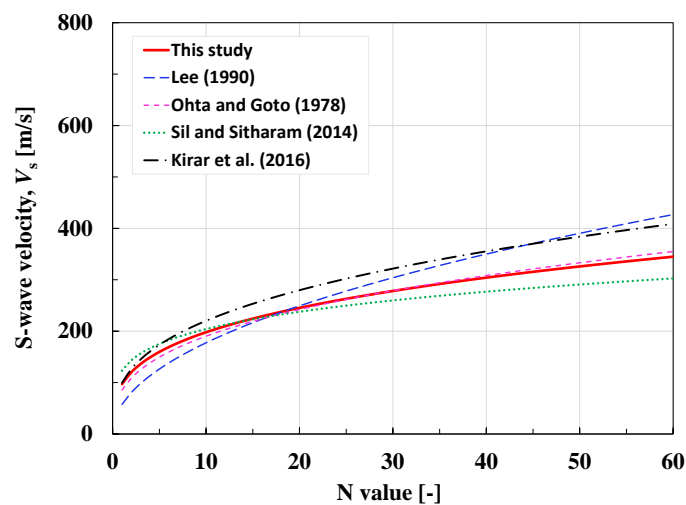


Fig. 12 Model comparison by world region (all soil layers)

the physical and mineralogical characteristics of the rock masses, such as the mineral composition, rock texture and structure, grain size and shape, interstitial size, and weathering (Budetta *et al.* 2001).

#### 4. Comparison with models from previous studies

In Section 3, N values are analyzed as potential indicators for predicting the S-wave velocity in the soil layer. In this section, the developed model for predicting the S-wave velocity using the N values from the soil layers is analyzed and compared with previously proposed models by country and region. To compare the results of this study with those of previous studies by country and region, the models mentioned in this section are based on databases of all soil layers rather than specific layers.

##### 4.1 Comparison with models from international studies

Four cited models for predicting S-wave velocity using N values were selected from previous studies conducted in

different countries and regions and compared with the model developed in this study. Ohta and Goto (1978) collected 300 datasets comprising N values and S-wave velocities and determined the correlation between the N values and S-wave velocities in alluvial plains in Japan. This study, which is a representative study of the correlation between the N value and S-wave velocity, has been cited by numerous researchers. Sil and Sitharam (2014) and Lee (1990) investigated the correlation between the N values and S-wave velocities by collecting 381 datasets in India and 88 pairs of data in Taiwan. Kirar *et al.* (2016) collected 74 data pairs by conducting SPT and a multichannel analysis of surface waves (MASW) at ten sites in India and employed a simple regression analysis.

A comparison of the model used in this study with the models developed in four previous studies conducted in Japan, India, and Taiwan is shown in Fig. 12. The four models from the previous studies conducted in Japan, India, and Taiwan considered soil layers, whereas the two models from the studies by Esfahanizadeh *et al.* (2015) and Fatehnia *et al.* (2015) considered specific layers (sand or clay). Therefore, these two models were not compared to the model proposed in this study. When the N value

increased, the difference between the S-wave velocity predicted by the proposed model and that predicted by the models of Sil and Sitharam, Lee, and Kirar increased. The differences ranged from 40 to 120 m/s. However, the difference between the S-wave velocities predicted by the proposed model and those predicted by Ohta and Goto was negligible (<10 m/s).

The proposed model for predicting the S-wave velocity using N values provided different results from the results of models developed for foreign soils, with a maximum difference of 120 m/s in the S-wave velocity prediction. Therefore, it is anticipated that applying models based on foreign soils to predict the S-wave velocities in the Gyeongju and Pohang regions would yield inaccurate values.

#### 4.2 Comparison with models from domestic studies

The models developed in previous studies for domestic soils were categorized into regional and Korean models for comparison with the proposed models (Table 1).

##### 4.2.1 Regional comparison with domestic models

The proposed model was compared with models developed in previous studies conducted in Seoul and Gyeonggi, Gyeongsang, and Chungcheong provinces in South Korea. In two previous studies conducted in Seoul and Gyeonggi Province, Jeong (2008) and Chae (2009) proposed models for predicting the S-wave velocity according to the N value using SPTs and SPS. A comparison of the results of our model with those of two previous studies is shown in Fig. 13(a). The S-wave velocity predicted by the Chae model exhibited a trend similar to that predicted by the proposed model. The S-wave velocity predicted by Chae's model was 2% higher than that predicted by the proposed model, and the difference decreased as N increased. Therefore, the model proposed by Chae can be used for predicting the S-wave velocity in the Gyeongju and Pohang regions when the N value is  $\geq 40$ . However, the S-wave velocity predicted by the Jeong model was approximately twice that predicted by the proposed and Chae models (Table 1 and Eq. (3)). This was attributed to the higher S-wave velocity values of the weathered soil in the study by Jeong compared with those in the study by Chae, which resulted in higher predicted S-wave velocity values for the entire soil basis.

$$V_s = 96.9 N^{0.31} \text{ (All soil layers)} \quad (3)$$

Two previous studies were conducted in Chungcheong Province. Do *et al.* (2011) and Chae (2009) developed models for predicting the S-wave velocity using the N value by conducting SPTs and SPS. Chae developed three separate models for Seoul, Gyeonggi Province, Chungcheong Province, and Gyeongsang Province, separating the data by region. A comparison of the proposed model with the models developed in two previous studies conducted in Chungcheong Province is shown in Fig. 13(b). The S-wave velocities predicted by the models of Do *et al.* and Chae were approximately 5% and 24% higher, respectively, than those predicted by the proposed model.

The prediction of S-wave velocity in the Gyeongju and Pohang regions when applying the models of previous studies to data from Chungcheong Province may be higher than that of our model.

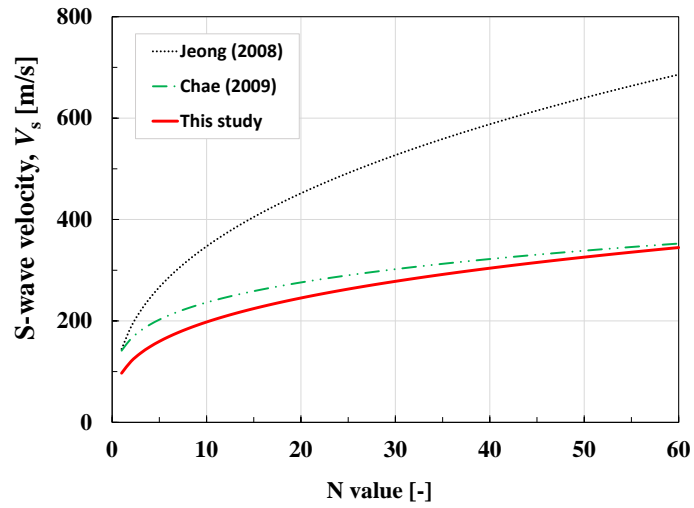
Chae (2009) proposed a model for predicting the S-wave velocity using the N value by conducting SPTs and SPS in Gyeongsang Province, South Korea. The S-wave velocity predicted by this model is 50 m/s higher than that predicted by the proposed model (Fig. 13(c)). When applying a model developed using Gyeongsang Province data to predict S-wave velocities in the Gyeongju and Pohang regions, it should be considered that the predicted values may be approximately 50 m/s higher than those of our model.

##### 4.2.2 Model comparison considering the entire Korea

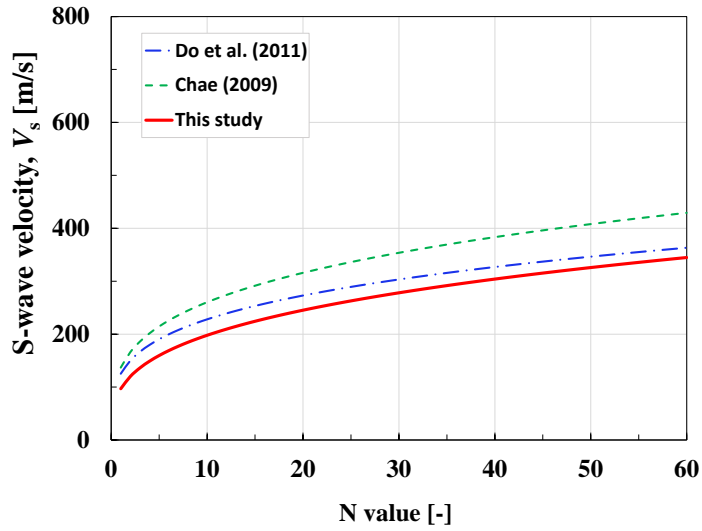
A comparison was conducted between the models developed in previous studies, including those developed for all of Korea, and the model developed in this study. Two models from previous studies have been developed for all of Korea: Sun *et al.* (2008) developed a model for predicting S-wave velocities using N values by collecting 377 pairs of data from SPTs, cross-hole tests, DHTs, and up-hole tests, and Heo and Kwak (2022) developed a model by collecting 2507 pairs of data from a geotechnical information DB system. As shown in Fig. 14, as the N value increased, the difference between the S-wave velocities predicted by the proposed model and those predicted by the model of Sun *et al.* decreased. The results indicate that when the N value is  $\geq 40$ , the model of Sun *et al.* can be applied to predict S-wave velocities in the Gyeongju and Pohang regions. Furthermore, compared with the S-wave velocity predicted by the Heo and Kwak models, the velocity predicted by the proposed model was approximately 50 m/s lower. If the Heo and Kwak model is used to predict the S-wave velocity in the Gyeongju and Pohang regions, the predicted velocity may be approximately 50 m/s higher than that predicted by our model.

## 5. Conclusions

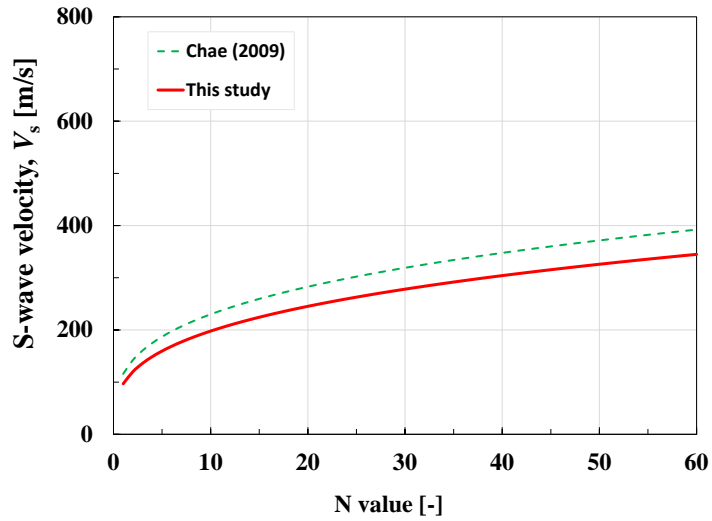
A database was constructed by collecting data from 690 boreholes within a 30-km radius of the epicenters of the Gyeongju (2016) and Pohang (2017) earthquakes in South Korea. The database includes physical properties such as the N values and P- and S-wave velocities of the soil layer, as well as the uniaxial compressive strength, Young's modulus, and P- and S-wave velocities of the rock layer. Using the constructed database, an analysis was conducted to examine the ground characteristics and correlations between the physical properties and P- and S-wave velocities in the Gyeongju and Pohang regions. Furthermore, a model for predicting S-wave velocities using N values was developed for all the soil layers in the Gyeongju and Pohang regions. The proposed model was compared with the models from previous studies. The conclusions of this study and recommendations for the use of various models are as follows:



(a) Seoul and Gyeonggi Province



(b) Chungcheong Province



(c) Gyeongsang Province

Fig. 13 Model comparison according to region in Korea (all soil layers)

- The soil layers in Gyeongju and Pohang consist of a mixture of sand, silt, clay, and gravel. The representative basic and physical properties of the soil layers are as follows: The unit weight is 17.62 kN/m<sup>3</sup>, the specific gravity is 2.65, the water content is 24.32%, the liquid limit is 44.5%, and the plasticity index is 21.5%. The N value is 11. The P-wave velocities from the DHTs, SPS, and S-waves were 395, 1683, and 187 m/s, respectively.
- The bedrock layers in the Gyeongju and Pohang regions include shale, sandstone, granite, and andesite, with shale being the predominant layer. These rock layers are mostly saturated with groundwater, and the bedrock depth is typically 6–12 m. The basic and physical properties of the bedrock layers are as follows: The unit weight is 24.87 kN/m<sup>3</sup>, the specific gravity is 2.62, the porosity is 2%, and the Poisson's ratio is 0.26. The uniaxial compressive strength, Young's modulus, P-wave velocity, and S-wave velocity are 48 MPa, 23 GPa, 2280 m/s, and 1308 m/s, respectively.
- The correlations between the physical properties and the P- and S-wave velocities obtained from the soil and bedrock layers were analyzed. In the soil layers, the N values exhibited a strong correlation with the S-wave velocity, particularly in the clay layers. In the rock layers, the Young's modulus exhibited a strong correlation with the P-wave velocity. The strongest correlation was observed between the N values and S-wave velocities in the soil layers. Accordingly, a model was developed for the Gyeongju and Pohang regions to accurately predict the S-wave velocities in the soil layer.
- This study focused on the construction of a database and the analysis of ground characteristics in the Gyeongju and Pohang regions, where NPPs are located and earthquakes have occurred. The S-wave velocities estimated from the proposed model according to the N value ranged from 96 to 341 m/s. The error between the estimated values from the model and the actual values is 38 m/s in the residual standard deviation ( $\sigma$ ). The proposed model, targeting the Gyeongju and Pohang regions, will contribute to seismic design hazard analysis. Furthermore, integrating an established database with a three-dimensional ground visualization system and monitoring systems with various types of input and output information has substantial practical value.

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