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Estimation of saturated hydraulic conductivity of Korean weathered granite soils using a regression analysis

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Abstract. Saturated soil hydraulic conductivity is a very important soil parameter in numerous practical engineering applications, especially rainfall infiltration and slope stability problems. This parameter is difficult to measure since it is very highly sensitive to various soil conditions. There have been many analytical and empirical formulas to predict saturated soil hydraulic conductivity based on experimental data. However, there have been few studies to investigate in-situ hydraulic conductivity of weathered granite soils, which constitute the majority of soil slopes in Korea. This paper introduces an estimation method to derive saturated hydraulic conductivity of Korean weathered granite soils using in-situ experimental data which were obtained from a variety of slope areas of South Korea. A robust regression analysis was performed using different physical soil properties and an empirical solution with an R^2 value of 0.9193 was suggested. Besides that this research validated the proposed model by conducting in-situ saturated soil hydraulic conductivity tests in two slope areas.

Keywords: in-situ hydraulic conductivity; Guelph permeameter; regression analysis

1. Introduction

As soil and rock involves necessary uncertainty, it is difficult to evaluate accurately engineering properties, geological conditions, and design parameters. It is also not easy to ensure a representative value that is to be used for stability analysis or design from scattered data. However, when slope stability is evaluated, one representative value is selected from a deterministic method before the calculation and the stability analysis. This approach causes severe individual deviation and is likely to cause overestimation and underestimation in the ground parameter evaluation, consequently leading to a decreased reliability in stability decision. To address this, a probabilistic analysis approach is being used. The probabilistic analysis approach assumes input variables that are used for geo-engineering as probability variables to analyze probability properties identified in the variables and uses probability theory for analysis. The probabilistic analysis can be generally categorized into two stages: one analyzes the probability properties of a ground parameter that determines the probability distribution function based on understanding of the mean value,

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standard deviation, and dispersion while considering the data distribution characteristics, and the other is to make a probabilistic analysis of the limit state function based on the first one. This probabilistic approach is actively being used.

In order to analyze the probability properties of the ground parameter, Jeon *et al*. (2011) intended to create a joint probability distribution function for unsaturated soil properties, such as the soil water characteristic curve (SWCC), unsaturated soil hydraulic conductivity and unsaturated soil shear strength. Kim and Lee (2010) investigated the correlation between the SWCC and the hydraulic conductivity of unsaturated soil. Phoon *et al*. (2010) conducted a probabilistic analysis of the SWCC based on that of van Genuchten. In addition, Oka and Wu (1990) examined the statistical characteristics of physical properties such as soil properties, and concluded that most probability distributions have normal or lognormal distributions.

For probabilistic analysis, there have been many reasonable stability evaluations through the probabilistic analysis of the slope that considers the uncertainty of the soil physical properties (Cornell 1971, Li and Lumb 1987, Wolff and Wang 1992, Christian *et al*. 1994, Kim *et al*. 2013, Lee *et al*. 2013, Shin *et al*. 2013). Among these soil parameters, saturated hydraulic conductivity is one of the most important variables representing water flow within the ground. In particular, saturated hydraulic conductivity is considerably affected by rainfall infiltration in the slope. Fig. 1 shows the variation in the safety factor according to saturated hydraulic conductivity of Korean weathered granite soils (Ministry of Science, ICT and Future Planning of Korea 2013). The safety factor dramatically decreases with higher saturated soil hydraulic conductivity because the saturated wetting depth appears fast because of rainfall infiltration when saturated soil hydraulic conductivity is high.

Given that the saturated hydraulic conductivity is sensitive to many variables, including compactness, macropores, sample size, temperature, and air trapped in a gap, it is important to estimate an accurate saturated hydraulic conductivity. The experiment to evaluate the saturated hydraulic conductivity has two types of indoor and in-situ experiments. The indoor test results in quite inaccurate values due to sample disturbance. Day and Daniel (1985) carried out in-situ saturated hydraulic conductivity tests and indoor experiments over the undisturbed samples and reproducible samples taken from two test construction areas, respectively. It was indicated that the indoor hydraulic conductivity can be expressed up to 1000 times smaller than that of the site and the significance of the in-situ saturated hydraulic conductivity test was emphasized. However, due to the convenience and simplicity of the indoor test, it has been used for most parts of the saturated hydraulic conductivity. In particular, there has been no accurate site experiment on the saturated hydraulic conductivity for weathered granite soil, which constitutes the majority of the soil slope.

This paper analyzed in-situ saturated hydraulic conductivity of Korean weathered granite soil for 44 soil slope areas in South Korea and performed a robust regression analysis based on the measured data using different physical soil properties. This study also proposed an empirical formula by which the saturated hydraulic conductivity can be estimated using basic physical soil properties. This research additionally conducted in-situ saturated hydraulic conductivity tests in two slope areas to validate the suggest empirical formula.

2. Saturated hydraulic conductivity models

Various models of saturated hydraulic conductivity have been introduced considering the empirical relation of capillary effect and the hydraulic radius. Many empirical models are based

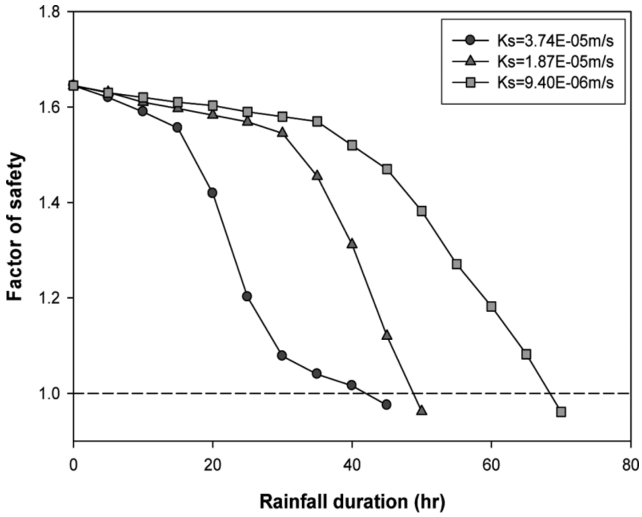


Fig. 1 FS (Factor of safety) of slope versus soil hydraulic conductivity (Ministry of Science, ICT and Future Planning of Korea 2013)

on the particle size distribution of soils. Hazen (1982) suggested an estimation model as Eq. (1) using the effective size (D10) and a constant (c) varying from 1.0 to 1.5.

$$k = cD_{10}^2 \tag{1}$$

Eq. (1) is based on loose, clean, filter sands with a D_{10} between 0.1 mm and 3 mm (Ahuja *et al*. 1989). Kozeny (1927) and Carman (1956) also suggested another form of the equation as Eq. (2) which is suitable for sandy soils. It is known that this equation can be used for most soils, but it is not adequate for clays (Ahuja *et al*. 1989).

$$k = \frac{1}{C_S S_S^2 T^2} \frac{\gamma_W}{\eta} \frac{e^3}{1+e} \tag{2}$$

where, C_s is the shape factor that is a function of the shape of flow channels, S_s is the specific surface area per unit volume of particles, T is the tortuosity of the flow channels, γ_w is the unit weight of water, η is the viscosity of the water and e represents the void ratio of the soil. Ahuja *et al*. (1989) and Jeon *et al*. (2011) demonstrated a strong relationship between saturated hydraulic conductivity and effective porosity (Φ_e) which can be defined as the total porosity minus the volumetric soil water content at 33 kPa tension. Eq. (3) is called the generalized Kozeny-Carman equation.

$$k = B\phi_e^n \tag{3}$$

where, B and n are constants. Later, Timlin *et al*. (1999) improved Eq. (3) by applying for Brooks-Corey pore-size distribution index (λ) into the Kozeny-Carman equation like Eq. (4).

$$k = C_3 10^{C_4 \lambda} \phi_e^n \tag{4}$$

Here, C3 and C4 are coefficient. Using Eq. (4) improved the fit for a large value of k (2.5 × 10-5 m/s), especially for coarse-textured soils (Timlin *et al*. 1999). However, soil water characteristic curve (SWCC) experimental results are needed to get a Φ_e and λ to use in Eq. (3) and Eq. (4). Jeon *et al*. (2011) found inaccuracies between the experimental data and the empirical models above for the estimation of saturated soil hydraulic conductivity with the Korean weathered granite soils in slope areas. Furthermore, many statistical analyses (Lee and Kim 2009, Jeon *et al*. 2011) have been conducted to estimate the saturated soil hydraulic conductivity of the weathered granite soils with lab test results, not in-situ data.

3. Experimental setup

Permeability is the measurement of the ability of the soil to pass through the water The in-situ saturated hydraulic conductivity means the saturated permeability coefficient considering the trapped air contained by soil. This value is thought to be more appropriate in an actual unsaturated zone than the fully saturated permeability coefficient because the uplift pressure does not remain full as more and more of the trapped air gets melted in water under unsaturated conditions (Kim 2009).

3.1 Guelph permeater

The Guelph permeameter is an instrument that applies a constant level of head working based on the Mariotte siphon principle, which provides a rapid and easy method to determine the in-situ permeability coefficient. The measurable range is between 10^{-4} and 10^{-8} m/s (Kim 2009). Fig. 2 shows the experimental process of Guelph permeameter.

Reynolds and Elrick (1987) presented a formula by analyzing the normal flow leaving a circular well. Eq. (5) describes all the forces that induce a three-dimensional flow to ensure that water enters into the soil. In other words, they include the water pressure-using force to push water into soil, the pulling force supported by the gravity of liquid flowing out through the bottom of a well, and the pulling force by capillarity, which causes water to travel from a well to the neighboring ground.

(a) Making a hole (b) Installation of equipment (c) Measurement of water level

Fig. 2 Process of Guelph permeameter experiment

$$Q_S = \frac{2\pi H^2}{C} K_{in-situ} + \pi a^2 K_{in-situ} + \frac{2\pi H}{C}\phi_m \tag{5}$$

where, Q_s is the steady rate of water outflowing from the well, H is the steady head in the well, a is the radius of the well, Φ_m is the matric flux potential, C is the shape factor according to the well radius, and H is the head of the water in the well. However, Eq. (6) can be used to apply for the Guelph permeameter experimentally.

$$K_{in-situ} = 0.041YR_2 - 0.054YR_1 \tag{6}$$

Here, Y represents reservoir constant used when the inner reservoir is selected. Also, R_1 and R_2 means the steady state rate of fall of water in the reservoir when the first and second head of water are established, respectively.

Table 1 Summary of descriptive statistics quantity

Basic soil properties	Minimum	Maximum	Average	Standard deviation	Variance
Percentage of gravel, gravel (%)	0.00	57.23	17.971	18.646	347.677
Percentage of sand, sand (%)	5.94	99.10	64.595	21.617	467.301
Percentage of clay, clay (%)	0.21	94.06	17.469	23.080	532.701
Dry unit weight, r_d (t/m^3)	1.020	1.720	1.463	0.156	0.024
Void ratio, e	0.540	1.490	0.826	0.211	0.044
Water content, w (%)	2.660	46.8	15.741	8.081	65.302
Saturated hydraulic conductivity, K_s (m/s)	1.050E-06	9.480E-05	2.095E-05	2.211E-05	0.000

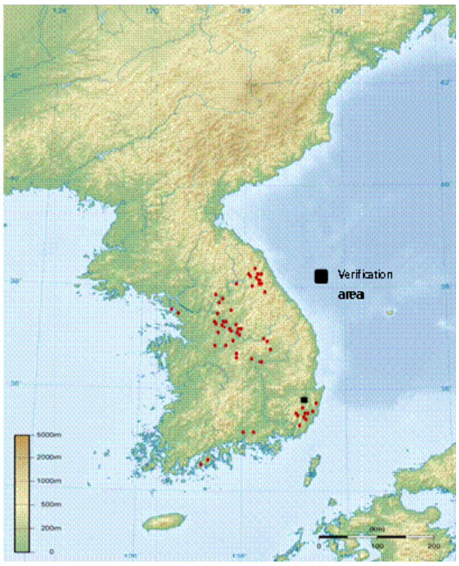


Fig. 3 Location map of the in-situ hydraulic conductivity test, South Korea

3.2 Experimental database

There were previous studies on conducting an in-situ hydraulic conductivity test using the Guelph permeameter. Among 44 sets of experiment data, 28 cases were conducted from this research and the rest of the 16 cases were conducted from previous studies (Kim 2009). The depth for the in-situ hydraulic conductivity test was about 1~2 m from the surface. Basic indoor tests, such as sieve analysis, water content, dry unit weight and specific gravity, were also conducted with 44 undisturbed samples. Table 1 shows the descriptive statistics quantity for 44 sets of data. Fig. 3 shows the location in South Korea of the previous 44 test sites plotted as red circles and newly conducted areas by this research as black rectangle.

4. Results of regression analysis

This research focused on estimating saturated soil hydraulic conductivity using six independent variables shown in Table 1. First, correlation analysis was conducted to find out which variables affect dependent variable, saturated soil hydraulic conductivity. Table 2 shows the results of the Pearson correlation analysis of each variable (Cohen 1988). The percentage of sand, dry density and the void ratio can affect the saturated soil hydraulic conductivity because the significant probability is less than 0.05 from the Pearson correlation coefficient. However, most researches (Lee and Kim 2009, Jun *et al.* 2010) have shown that clay content can significantly affect the saturated hydraulic conductivity. Pearson correlation coefficient between clay content and saturated hydraulic conductivity is -0.229, and it can also affect the saturated hydraulic conductivity to some extent. Therefore, multiple regression analyses were performed with four independent variables to estimate saturated soil hydraulic conductivity.

Table 2 Results of correlation analysis

		Gravel	Sand	Clay	r_d	e	w	K_s
Gravel	Correlation coefficient	1	-.348*	-.483**	-.077	-.043	-.209	-.083
	P-value (two sided)		.018	.001	.613	.777	.164	.583
Sand	Correlation coefficient	-.348*	1	-.653**	.043	-.139	-.237	.316*
	P-value (two sided)	.018		.000	.775	.357	.113	.032
Clay	Correlation coefficient	-.483*	-.653**	1	.021	.164	.392**	-.229
	P-value (two sided)	.001	.000		.889	.275	.007	.125
r_d	Correlation coefficient	-.077	.043	.021	1	-.919**	-.456**	-.402**
	P-value (two sided)	.613	.775	.889		.000	.001	.006
e	Correlation coefficient	-.043	-.139	.164	-.919**	1	.616**	.359*
	P-value (two sided)	.777	.357	.275	.000		.000	.014
w	Correlation coefficient	-.209	-.237	.392**	-.456**	.616**	1	.061
	P-value (two sided)	.164	.113	.007	.001	.000		.687
K_s	Correlation coefficient	-.083	.316*	-.229	-.402**	.359*	.061	1
	P-value (two sided)	.583	.032	.125	.006	.014	.687	

* Correlation coefficient is significant at two sides ($P < 0.05$)
** Correlation coefficient is significant at two sides ($P < 0.01$)

4.1 Regression analysis

By combining the independent variables and the transformation of variables, the optimal empirical equation from a robust regression analysis was suggested as in Eq. (7). The units of soil properties in Eq. (7) are same shown in Table 1. A 3-D curved surface model (CSM) was developed and taken by the polynomial robust regression analysis from the surface fitting tool box in MATLAB program (Fig. 4). This tool box in MATLAB has a function for deriving the optimum equation that yields the highest coefficient of the determination value (Go *et al*. 2014). *X* means sand (%) × clay (%), *y* is ln (γ_d / e) and *z* means saturated hydraulic conductivity in Fig. 4.

$$K_{in-situ} = 0.00004473 - 0.0000000046\,46(\text{sand}(\%)\times\text{clay}(\%)) - 0.00004056\ln(\gamma_d / e) \quad (7)$$

In the multiple variable regressions, the adjusted coefficient of determination (${}_{adj}R^2$) is used instead of the coefficient of determination (R^2) because just adding even meaningless variables to a model can increase the coefficient of determination (Anthony 2012, Phoon *et al*. 2010). The adjusted coefficient of determination can be expressed by Eq. (8), and it compensates for the number of variables in the model.

$${}_{adj}R^2 = 1-(1-R^2)\frac{k-1}{n-k-1} \quad (8)$$

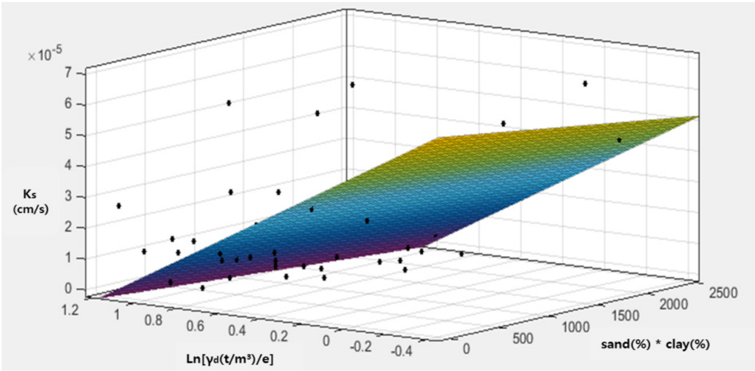
where, *n* indicates the number in the data set and *k* is the number of independent variables. The value of *n* is 44, and *k* is 2. The adjusted coefficient of determination from suggested model in this research was 0.9153. Table 3 shows the results of the regression analysis. From the *t* statistical analysis, *p*-value of coefficient in the all the independent variables were lower than 0.05, which means that every independent variable can be used significantly to estimate dependent variables. The variance inflation factor (VIF) of the independent variables was lower than 10 indicating that there was no multicollinearity between independent variables, which implies that there is no correlation between independent variables (Hocking and Pendleton 1983). If multicollinearity exists between independent variables, it can result in inaccuracies in the regression model (Yoon *et al*. 2014, Anthony 2012, Gunst and Mason 1980, Hocking and Pendleton 1983).

4.2 ANOVA analysis

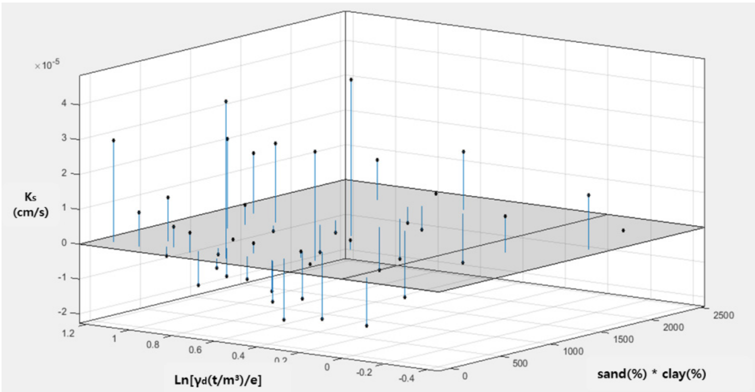
The analysis of variance that is called ANOVA can be also constructed for a regression analysis. For the ANOVA, sum of squares (*SS*) and degree of freedom (DF) are calculated. SS measures the variability of the dependent variable. The total sum of squares (SST) is a measure of the total variability in the data set, and partitioned into a sum of squares for regression (SSR) and a sum of squares for error (SSE) as Eq. (9) (Anthony 2012).

$$SST = \sum_{i=1}^{n}(y_i - y)^2,\quad SSR = \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2,\quad SSE = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (9)$$

where, y_i indicates measured test data, $\bar{y}$ is the average value of measured test data, and $\hat{y}_i$ is the value from the regression analysis model. With SS and DF values, mean square (MS) can be defined into as the SS divided by DF. *F* value from the ANOVAN analysis can be defined as Eq. (10).



(a) 3-D curved surface model



(b) Fitting residuals

Fig. 4 Regression analysis model

Table 3 Results of multiple regression analysis

	B	Standard error	*t*	*P*-value	VIF
Constant	.00004473	.00000569	15.722		
X_1 (sand (%)*clay (%))	-.00000000569	.00000000216	-3.247	<.01	1.001
X_2 (ln r_d/e)	-.00004056	.000004935	-16.438	<.01	1.001
R^2	.9193				
$_{adj}R^2$	.9153				
SSE	1.248E-06				

*B: non-standardized coefficient, t: B/standard error, VIF: variance inflation

$$F = \frac{SSR / DF}{SSE / DF} \tag{10}$$

Table 4 shows the results of the ANOVA. Since the p value was less than 0.01, the significance between an independent and dependent variable is very high, which means that the empirical equation from the regression analysis can be used.

Table 4 Results of ANOVA analysis

	DF	*SS*	*MS*	*F*	*P*-value
Regression	2	8.5702E-09	4.2851E-09	15.929	< .001
Residual	41	1.1030E-08	2.6902E-10		
Total	43	1.9600E-08			

4.3 Residual analysis

The residual analysis is very important in regression analysis. The residuals are the difference between the observed values of the dependent variable and the corresponding fitted values (Anthony 2007). In particular, there should not be auto-correlation among the residuals in the regression analysis. In evaluating the auto-correlation criteria, the most frequently used index is the Durbin-Watson (DW) index (Durbin and Watson 1971, Hibbs 1974). However, it is known that DW index in the experimental results doesn't have to be considered.

In addition, a normal probability plot of the residuals should be checked to determine if the residuals appear to be normally distributed. The evaluation of normal distribution can be checked with the values of kurtosis and skewness, Q-Q plot and *P*-value of the Shapiro-Wilk verification (Anthony 2012, Hair *et al*. 2009). Since the values of kurtosis and skewness were less than 2, we can consider that the residuals follow normal distribution. The values of kurtosis and skewness were 0.768 and 1.007, respectively. The Shapiro-Wilk verification can be used to evaluate the normal distribution with small sample size of which number is less than 50 (Royston 1992, Shapiro and Wilk 1965). If the *P*-value from the Shapiro-Wilk verification for the standardized residuals is larger than 0.1, the residuals also follow normal distribution (Shapiro and Wilk 1965). The *P*-value of the Shapiro-Wilk verification was 0.440.

Furthermore, Fig. 5 shows the Q-Q plot of residuals from the statistical package for the social sciences (SPSS) program. As most data are close within the linear line, it can be said that residuals follow normal distribution.

Finally, residuals must satisfy the homoscedasticity condition in the regression analysis. Standardized residuals should be distributed without any trend or fixed rule within the value of $\pm$ 3 (Hair *et al*. 2009). Fig. 6 shows the homoscedasticity plot of the residuals. It can be also considered that residuals can follow the homoscedasticity condition because they do not have any specific trend or pattern in the graph.

4.4 Verification of regression model

In order to validate the empirical model suggested by this research, in-situ soil saturated hydraulic conductivity tests were conducted in two slope areas using a Guelph permeameter (Fig. 2). The undisturbed soil samples were collected from the sites and basic properties of the soils were also obtained as shown in Table 5. The basic properties of the soils showed similar ranges as given in Table 1. Table 6 summarizes the comparative results between in-situ test data and values obtained by the empirical formula using Eq. (7). The relative error showed 30.9% and 24.9%, respectively. It can be concluded that the empirical model suggested by this research can appropriately predict in-situ soil saturated hydraulic conductivity.

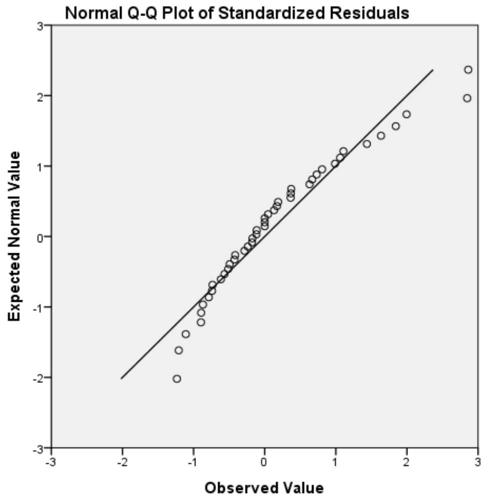


Fig. 5 Q-Q plot of the standardized residuals

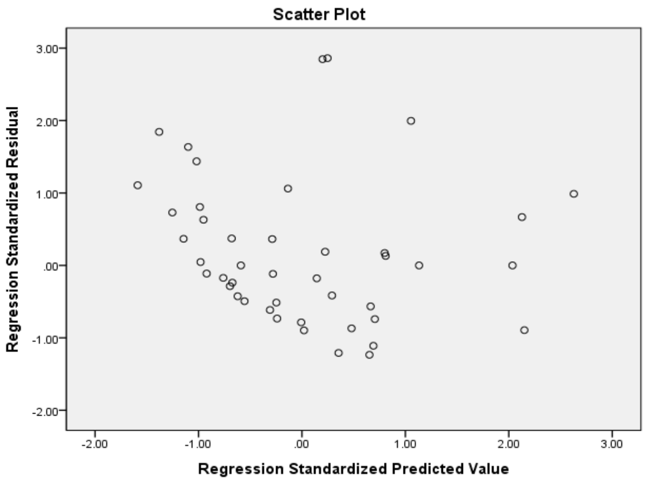


Fig. 6 Homoscedasticity plot of residuals

Table 5 Descriptive statistics quantity in four areas

Basic soil properties	No. 1	No. 2
Percentage of gravel, gravel (%)	11.79	37.45
Percentage of sand, sand (%)	77.53	59.87
Percentage of clay, clay (%)	10.68	2.68
Dry unit weight, r_d (t/m^3)	1.51	1.52
Void ratio, e	0.78	0.70
Water content, w (%)	13.6	7.91
Saturated hydraulic conductivity, K_s (m/s)	2.04E-05	1.67E-05

Table 6 Validation of regression model

	In-situ test data	Regression model	Relative error (%)
No. 1	2.040E-05	1.409E-05	30.9
No. 2	1.670E-05	1.254E-05	24.9

5. Conclusions

Among soil parameters, saturated hydraulic conductivity is one of the most important variables representing water flow within the ground, especially in the analysis of slope safety considering the infiltration effect. Therefore, it is very important to measure in-situ saturated soil hydraulic conductivity exactly. However, there has been no accurate in-situ experimental data on saturated soil hydraulic conductivity, especially for the Korean weathered granite soils constituting the majority portion of soil slope. This study analyzed the in-situ saturated hydraulic conductivity for 44 soil slope areas in South Korea and performed a robust regression analysis based on the measured data using different physical soil properties. The following conclusions can be drawn.

(1) First, a correlation analysis was conducted to determine which variables affect dependent variables and saturated soil hydraulic conductivity. The percentage of sand, dry density and void ratio can affect the saturated soil hydraulic conductivity because the significant probability is less than 0.05 according to the Pearson correlation coefficient. Even though the significant probability of the percentage of clay is around 0.1, it is known that the percentage of clay can affect the saturated hydraulic conductivity.

(2) A robust regression analysis was performed with four independent variables to estimate saturated soil hydraulic conductivity. By combining independent variables and the transformation of variables, the optimal empirical equation from the robust regression analysis was suggested using a curved surface model. The adjusted coefficient of determination from the suggested model in this research was 0.9153.

(3) The ANOVA and residual analysis were also conducted to check the significance of the regression model. The *p*-value was less than 0.01 for the ANOVA, and the significance between an independent and dependent variable was very high, which means that the empirical equation from the regression analysis can be used successfully. In terms of residual analysis, the values of kurtosis and skewness of the residuals were 0.768, 1.007, respectively, and demonstrated the significant results of the Q-Q plot and Shapiro-Wilk verification. Additionally, the residuals satisfied the homoscedasticity condition because they showed distribution without any trend or fixed rule.

(4) In-situ soil saturated hydraulic conductivity tests were conducted in two slope areas using a Guelph permeameter to validate the proposed empirical model. The comparative results showed that the empirical model proposed in this research can predict in-situ saturated hydraulic conductivity of Korean weathered granite soil.

Acknowledgments

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