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Development of Revegetated Slope Stability Assessment System in South Korea

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This research was conducted to develop the revegetated slope stability assess (RSSA) system for revegetated cut–slopes in South Korea. A field survey was conducted on potential risk slopes and stable slopes using the twenty three variables. Through a non–parametric test and a correlation analysis of the field survey results, nine variables were identified as primary determinants of slope failures. Of these variables, six variables were from the soil category, (soil porosity, soil water content, soil depth, soil tensile strength, salt concentration, and soil organic matter) and three variables were from the vegetation category, (vegetation coverage, number of trees, and vegetation community). None of the physical characteristic variables were selected as determinants.

Discriminant analysis was conducted to develop evaluation indicators from nine variables. As a result, the discriminant function included four variables: soil porosity, soil tensile strength, soil organic matter, and vegetation coverage as the indicators of the discriminant function. The data of vegetation community was excluded from the discriminant analysis as it was a nominal scale but used for the final screening of stability using the relationship between the discriminant score and vegetation community. RSSA system was developed by combining these two processes. Although RSSA system is not a complete system for slope stability assessment, it is very practical for revegetated slope stability assessment because it requires relatively few indicators which can be easily measured. Therefore, it should be useful for the initial assessment or supplemental assessment with the integrated slope stability assessment system to be developed in the future.

Key words: discriminant analysis, ecological restoration, environmental engineering, revegetation slope stability

INTRODUCTION

Slope stabilization of biotechnical engineering using vegetation and soil entails ecological restoration. Biotechnical engineering refers to techniques where vegetation is integrated with inert structures such as concrete blocks (Morgan and Rickson, 1995). Biotechnical stabilization employs comprehensive mechanics of soil and plants to prevent slope erosion and failure (Gray and Sotir, 1996).

Slope revegetation measures as a representative method of biotechnical stabilization include hydro seeding, seeding with thick layer vegetation media, vegetation mat, lined sodding work, planting, and vegetation mesh bag in South Korea (MOLIT, 2009). They have positive effects on slope stability and facilitates successful restoration when accompanied with a proper understanding of environmental limitations (Urbanska, 1997; Morgan and Rickson, 1995). However, since the slope revegetation works have been conducted with a lack of ecological consideration in South Korea, slope failures have been continuously occurred. Korean Ministry of Land, Infrastructure and Transport (MOLIT) reported that the slope failures including revegetated slope failures occurred approximately 150 times each year from 2008 to 2012 in South Korea (MOLIT, 2013).

To prevent slope failure, the related Korean national research institutions have tried to develop assessment tools for slope stabilization employing slope stability analysis mostly from the field of civil engineering. For example, Korea Institute of Civil Engineering (KICT), Korea Expressway Corporation Research Institute (KECRI), and National Disaster Management Institute (NDMI) developed the indicators for the slope stability analysis and conducted the risk assessments through field surveys on failure slopes, which focused on topographical and geological aspects but of little botanical aspect (Jeong, 2009; Kim *et al.*, 2012; NEMA, 2011). In other countries, these kind of assessment also focused on civil engineering aspects using the indicators for the method of scoring and a stochastic analysis (Peng *et al.*, 2011; Wang *et al.*, 2010; Cheng *et al.*, 2007; Jeong, 2009;

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Park, 2006). These studies evaluated slope stability related to the use of concrete structures to make steady–state in damaged slopes by numerical and statistical analyses.

MOLIT (2009) suggested an assessment of slope revegetation including an ecological consideration. The assessment, however, was aimed at the selection of a revegetation method through trial construction rather than the evaluation of slope stability with specific variables or tools. Previous studies on the slope stability were also indirectly relevant to the issue of revegetated slopes stability. For example, the studies were conducted by discrimination analysis of slope stability of a natural cut–slope without revegetation (Jeon *et al*., 2003; Lee, 1987), interpretation of vegetation distribution of revegetated slopes (Woo and Jeon, 2005; Woo *et al*., 1996), and interpretation and standardization of partial properties of soil and vegetation (Mola *et al*., 2011; Karim and Mallik, 2008; David *et al*., 2007; Jeon, 2002; Kil *et al*., 2012). Therefore, it is necessary to evaluate sustainable stability of revegetated slopes based on the environmental understanding.

This study aims to develop the revegetated slope stability assessment (RSSA) system for revegetated cut–slopes in South Korea. First, we analyzed specific indicators to develop the system through a correlation analysis and a non–parametric test using the measured data of physical, vegetation and soil characteristics in ten sites in Kangwon province in South Korea. Then discriminant analysis was introduced in RSSA system with the final screening of slope stability using nominal indicator. The developed RSSA system was found to be practical for revegetated slope stability assessment because it requires relatively few indicators which can be easily measured.

MATERIALS AND METHODS

Study sites

Study sites were located in Gangwon Province where 81.7 percent of the land is covered by mountainous terrain consist mostly of granite rock layer (Website of Gangwon Provincial Office). Most of the disasters related to steep slopes in South Korea from 1999 to 2011 were occurred in Gangwon Province (NDMI, 2011).

The field surveys were conducted in ten revegetated slopes located next to the roadside in 2012. The study sites were five test sites and five control sites (Fig. 1, Table 1). The five test sites were the potential risk slopes having a high possibility of slope failure in the near future, which were detected with unaided eye. The five control sites were the stable slopes, which passed the warranty period of two years after the slope revegetation work having no failures up to the time of the field survey in 2012.

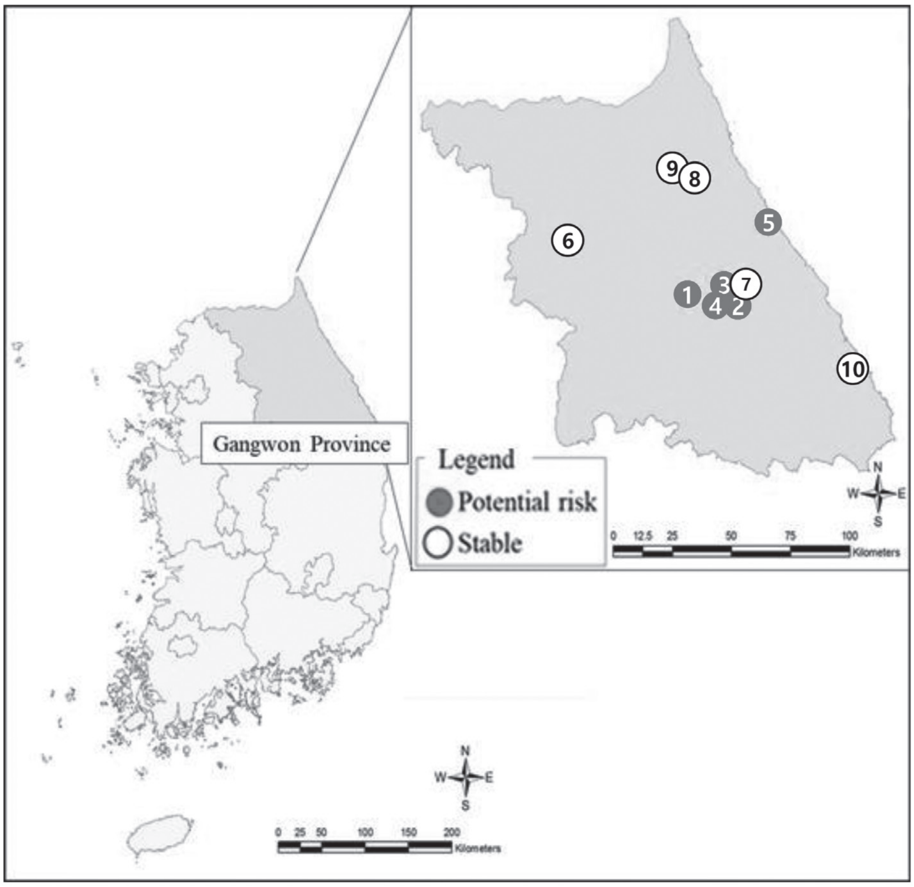

Fig. 1. Location of study sites.

Table 1. General information of study sites

No. (in Fig.1)	Address	Survey date	Revegetation completed year	Revegetation type	Altitude (m)	Failure or not
1	Pyungchang–gun Bongpyung–myeon Mui–ri San 56	2012.09.26	2009	grass–oriented	657	○
2	Pyungchang–gun Jinbu–myeon Songjung–ri San 266	2012.09.26	2010 (estimation)	grass–oriented	308	○
3	Pyungchang–gun Jinbu–myeon Hajinbu–ri San 16	2012.09.16	2007	grass–oriented	596	○
4	Pyungchang–gun Jinbu–myeon Hajinbu–ri San 474	2012.09.16	2011	herbaceous	517	○
5	Yangyang–gun Hyunnam–myeon Juk–ri San 7–1	2012.10.19	2009	bush and herbaceous	51	○
6	Chuncheon–si Onui–dong San 38	2012.10.19	2006	woody, bush, and herbaceous	102	×
7	Pyungchang–gun Jinbu–myeon Homyeong–ri San 64	2012.09.15	2008	herbaceous	682	×
8	Yangyang–gun Seo–myeon Osaek–ri San 1–27	2012.10.19	2007	herbaceous	925	×
9	Injae–gun Buk–myeon Hangae–ri San 1–59	2012.10.19	2006	woody, bush, and herbaceous	510	×
10	Samchuck-si Geunduk-myeon Sangmaegbang-ri San 30–16	2012.10.19	2003	woody, bush, and herbaceous	61	×

Selecting Variables

It is not effective to analyze all the variables used in previous studies because explaining too many variables for evaluating slope stabilization would be too costly and resource–intensive. Therefore, we used the variables selected by Kil *et al.* (2015) for the slope failure, soil erosion, slope revegetation, and landslide analyses (Table 2). The data were measured roughly three times per slope and the mean values were applied for the analysis.

Data analysis

The field survey data (Kil *et al.*, 2015) were analyzed statistically to select the variables that significantly affected occurrence of slope erosion or failure. The data were compared whether the variables had positive or negative correlations with one another using Spearman's correlation analysis. The data measured in a nominal scale were converted to a ratio scale. Correlation analysis and non–parametric testing were conducted. The correlation analysis examined the correlations between variables, and non–parametric testing compared and analyzed the field survey results. Nine variables were selected through correlation analysis and non–parametric testing at significant levels for the discriminant analysis. In the nine variables, six variables were from soil category (soil porosity, soil water content, soil depth, soil tensile strength, soil salt concentration, and soil organic matter) and three variables were from vegetation category (vegetation coverage, the number of trees, and vegetation community) (Table 3). The vegetation community was surveyed as a nominal scale. Therefore, the indicator of vegetation community was excluded in the discriminant analysis. The selection method of variable in the discriminant analysis was step–wise.

The discriminant analysis can be effectively used to evaluate the growth of vegetation and the slope stabilization. The previous studies using probabilistic methods focused on many physical characteristics such as inclination, direction, and length of slope but a few parameters of soil and vegetation such as soil texture, soil depth and vegetation coverage (Rice and McCasion, 1985; Yoshimura *et al.*, 1996; Ma, 1994; Lee, 1987). On the other hands, this study was focused on soil and vegetation variables and six soil variables and two vegetable variables were applied for the discriminant analysis for the revegetated slope stability assessment (RSSA). Although the variables of vegetable community was

Table 2. First candidate explanatory variables in this study

Category	Candidate explanatory variables
Physical	Slope angle, Slope height, Slope type, Slope width, Aspect, Drainage system, Time since revegetation (years), Ground layer, Seepage water
Vegetation	Number of tree species by nomenclature, Number of herb species by nomenclature, Vegetation coverage, Vegetation community*
Soil	Depth, Porosity, Acidity, Hardness, Water content, Texture, Permeability coefficient, Tensile strength, Organic matter, Salt concentration

* Vegetation community: heterogeneous single layer, homogeneous single layer, heterogeneous multiple layer, homogeneous multiple layer

Table 3. Summaries of second candidate explanatory variables for each study site

Site category	No. (in Fig.1)	Region	Soil category						Vegetation category		
			Porosity* (m^3/m^3)	Water content* (m^3/m^3)	Depth* (cm)	Tensile strength* (kPa)	Salt concentration* (%)	Organic matter* (%)	Coverage* (%)	No. of trees*	Community
Potential risk	1	Pyungchang	0.50±0.05	0.16±0.002	4.30±1.65	1.72±0.07	0.005±0.0004	1.08±0.26	15.00±10.00	0.33±0.58	Heterogeneous simple layer
	2		0.55±0.05	0.09±0.006	4.33±1.78	1.47±0.08	0.005±0.0016	1.10±0.02	28.67±5.03	2.00±1.00	Heterogeneous simple layer
	3		0.42±0.03	0.11±0.055	1.33±1.88	1.47±0.09	0.039±0.0083	7.00±1.08	90.67±5.13	3.00±1.00	Heterogeneous multiple layer
	4		0.48±0.06	0.10±0.025	3.57±2.00	1.43±0.03	0.007±0.0010	1.89±0.42	92.67±4.16	0.33±0.58	Heterogeneous simple layer
	5	Yangyang	0.53±0.03	0.12±0.007	4.37±0.91	1.50±0.06	0.006±0.0010	0.55±0.36	39.33±5.13	0.33±0.58	Heterogeneous simple layer
Stable	6	Chuncheon	0.58±0.08	0.06±0.004	7.67±0.84	1.62±0.23	0.012±0.0021	5.00±2.32	99.00±1.00	3.00±1.00	Homogeneous multiple layer
	7	Pyungchang	0.55±0.00	0.13±0.004	1.03±0.97	1.54±0.05	0.011±0.0010	2.99±0.09	93.67±5.13	5.00±1.00	Homogeneous multiple layer
	8	Yangyang	0.63±0.03	0.67±0.058	13.17±2.95	1.97±0.12	0.070±0.0220	13.19±0.11	99.67±0.58	1.00±0.00	Heterogeneous multiple layer
	9	Injae	0.65±0.05	0.62±0.050	7.57±3.23	2.04±0.06	0.031±0.0018	14.47±2.52	99.33±1.15	3.00±1.00	Heterogeneous multiple layer
	10	Samchuck	0.62±0.03	0.15±0.020	13.80±2.03	1.89±0.07	0.048±0.0041	16.40±1.48	99.33±1.15	8.67±1.15	Homogeneous multiple layer

* Mean ±standard deviation

excluded in the discriminant analysis because it was measured in nominal scale, it was compared with the discriminant score extracted by the discriminant analysis and used for the final decision of RSSA system.

The computer programs used for the data collection were Hangul 2010, Microsoft Excel 2010, and Microsoft Power Point 2010, and the one for the statistical analysis was SPSS 21.0.

RESULTS AND DISCUSSION

Analysis of discriminant score for slope stability

Four variables, soil porosity, soil tensile strength, soil organic matter, and vegetation coverage, were selected as the indicators from the eight variables by the discriminant analysis. The discriminant function to evaluate the revegetated slope stability was as follows:

$$Z = -18.758 + 14.981X_1 + 4.558X_2 - 0.143X_3 + 0.050X_4 \qquad (1)$$

where Z is the discriminant score for slope stability, X_1 is the soil porosity (m^3/m^3), X_2 is the soil tensile strength (kPa), X_3 is the soil organic matter (%), and X_4 is the vegetation coverage (%). The discriminant score Z higher than zero evaluate the slope as stable, and Z zero or less evaluate the slope as potential risk.

The canonical correlation coefficient of the discriminant function was 0.906 in Table 4, which was higher than the value of previous studies (Lee, 1987; Jeon *et al.*, 2003). The value of Wilks' lambda (λ) was 0.179, and the significant level was $p < 0.01$ in Table 5. The R–square for the discriminant function satisfied the significant level ($p < 0.01$).

The result of the discriminant analysis indicates that the revegetated soil and plant growth characteristics were more important than the physical characteristics for slope stabilization. The physical characteristics have indirect effects on slope stability by controlling the plant growth.

Standardized canonical discriminant function coefficients of Eq. (1) were summarized in Table 6. The vegetation coverage was the most important indicator according to the standardized coefficient. It was also selected as an important indicator in other studies (Rice and McCasion, 1985; Lee, 1987). The soil porosity and the soil organic matter are closely related with the growth of plants (Brady and Weil, 2009). The soil tensile strength represents the physical energy, which resists against the failure and supports elongation of roots (Ibarra *et al.*, 2005). Eventually, the discriminant analysis of this study implies that the environmental condition

Table 4. Eigenvalues of discriminant function

Function	Eigenvalue	% of variance	Cumulative %	Canonical Correlation
1	4.575	100.0	100.0	0.906

Table 5. Wilks' Lambda of discriminant function

Test of function	Wilks' Lambda	Chi–square	df	Sig.
1	0.179	44.675	4	0.000

Table 6. Standardized canonical discriminant function coefficients

Indicator	Coefficient
Soil porosity	0.865
Soil tensile strength	0.837
Soil organic matter	–0.633
Vegetation coverage	1.202

for healthy growth of plants can determine the revegetated slope stability.

The scatter diagrams of the discriminant score and each indicator are shown in Fig. 2. To evaluate a slope as potential risk, the value of each indicator should be less than 0.5 m^3/m^3 for soil porosity (Fig. 2A), less than 1.4 kPa for soil tensile strength (Fig. 2B), less than 3% for soil organic matter (Fig. 2C), and less than 60% for vegetation coverage (Fig. 2D). On the other hand, to evaluate a slope as stable, the value of each indicator should be more than 0.6 m^3/m^3 for soil porosity (Fig. 2A), more than 1.8 kPa for soil tensile strength (Fig. 2B), more than 8% for soil organic matter (Fig. 2C), and more than 96% for vegetation coverage (Fig. 2D). However, single indicator cannot wholly determine potential risk or stable because there were overlapped ranges of indicators both in potential risk and stable slopes. The overlapped range of indicator is shown in Table 7.

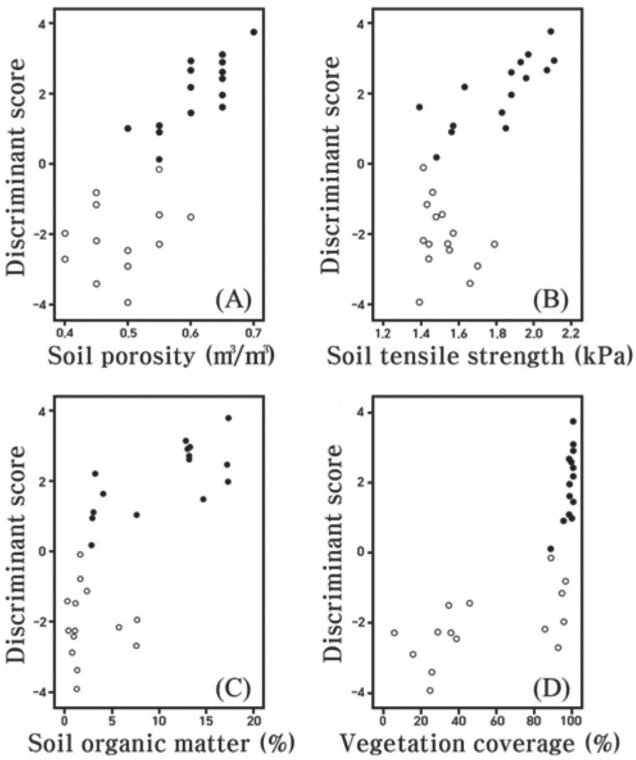

Fig. 2. Scatter diagrams of discriminant score and each indicator: (A) soil porosity; (B) soil tensile strength; (C) soil organic matter; and (D) vegetation cover. White circles denote potential risk slopes while black circles denote stable slopes.

Table 7. Overlapped range of indicator between potential risk and stable slopes

Indicator	Unit	Overlapped range between potential risk and stable
Soil porosity	m^3/m^3	0.5–0.6
Soil tensile strength	kPa	1.4–1.8
Soil organic matter	%	3–8
Vegetation coverage	%	88–96

The discriminant scores of four types of vegetation community is shown in Fig. 3. Almost all discriminant scores of heterogeneous single layer (hetero–single–layer) were below zero ranged from –3.92 to 0.07 with an average of –2.12. All discriminant scores of homogeneous multiple layer (homo–multi–layer) were above zero ranged from 0.20 to 2.91 with an average of 1.59. The discriminant scores of heterogeneous multiple layer (hetero–multi–layer) and homogeneous single layer (homo–single–layer) widely ranged below and above zero approximately –3 to 4: hetero–multi–layer (–2.69 ~ 2.95 with an average of –0.25), homo–single– layer (–2.88 ~ 3.77 with an average of 0.74). Therefore, the hetero–single–layer represented potential risk slope whereas the homo–multi–layer represented a stable slope. On the other hand, it was hard to judge the stability of slope from both hetero–multi–layer and homo–single–layer since they showed broad range of discriminant scores.

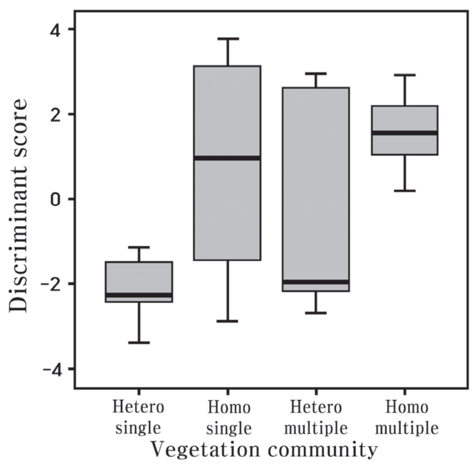

Fig. 3. Comparative boxplots for discriminant scores among the four categories of vegetation community: hetero–single–layer, homo–single–layer, hetero–multi–layer, and homo–multi–layer.

Revegetated slope stability assessment system

Combining the above-mentioned results of the discriminant score, we constructed the revegetated slope stability assessment (RSSA) system to evaluate slope stability whether the slope is stable or potential risk. The target slope to evaluate was the slope underwent a soil–based slope revegetation construction at least two years prior to the time of application. The review for structural stability must have been completed in advance.

The algorithm of the RSSA system is shown in Fig. 4. The RSSA system involved the three soil indicators (soil porosity, soil tensile strength, and soil organic matter) and the two vegetation indicators (vegetation coverage and vegetation community). The slopes should be thoroughly investigated even if the discriminant score (Z) is higher than zero. If slope failure occurs even if the discriminant score is higher than zero, the cause might be a structural problem or an unexpected drainage system

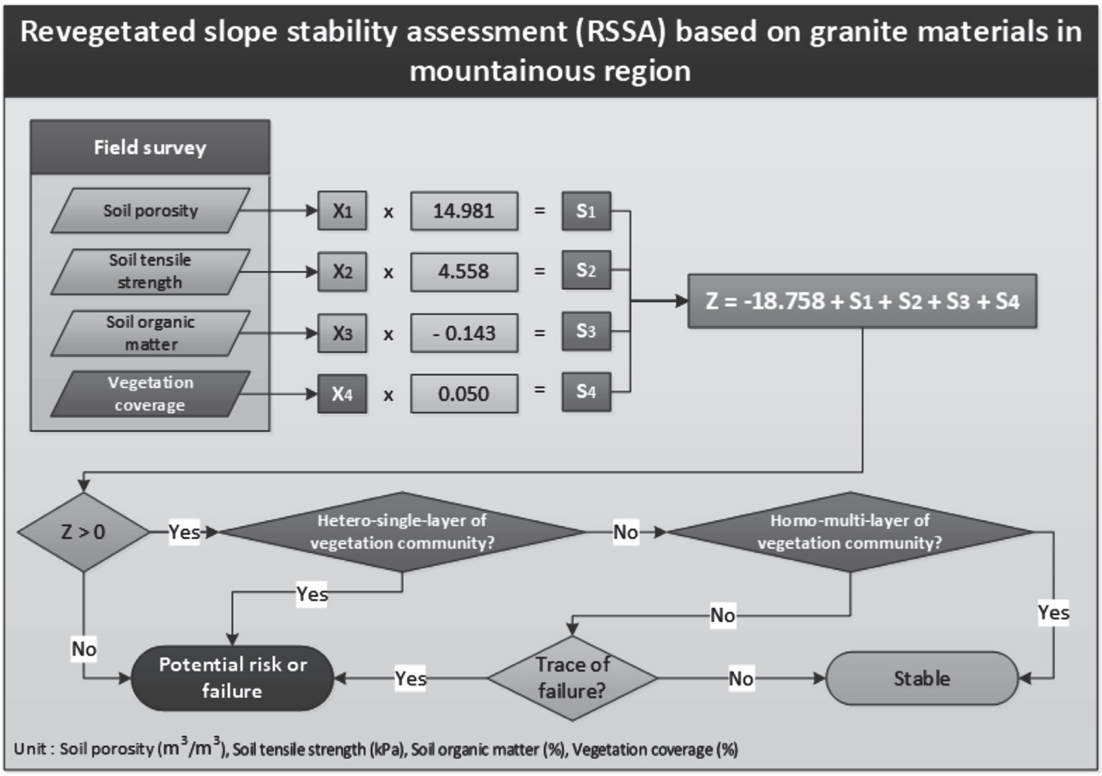

Fig. 4. Revegetated Slope Stability Assessment (RSSA) System.

problem.

The application range of indicators for RSSA system was shown in Table 8. The range of soil porosity and soil organic matter are within normal for forest soil in South Korea (Park *et al*., 2010; Jeong *et al*., 2002). The range of vegetation coverage and vegetation community could be also applied to all target slopes in South Korea. The range of soil tensile strength is relatively narrow. The range of tensile strength in soil containing a higher ratio of sand was approximately 0.5 to 1.6 kPa (Kim *et al*., 2004). Since the sand ratio in the soil used for the slope revegetation works was consistently high, the range of soil tensile strength of the revegetated slopes should be narrow such as the applicable range of soil tensile strength for RSSA system. If the value of each indicator exceeds the range on Table 8, further studies are required.

Table 8. Application range for RSSA

Indicator	Range
Soil porosity	0.4–0.7 m^3/m^3
Soil tensile strength	1.4–2.1 kPa
Soil organic matter	0.3–17.4%
Vegetation coverage	10–100%
Vegetation community	Vegetated

When the ground surface is weathered or blasted rock, slope revegetation work is generally performed with physically based devices installation such as wire mesh and fiber mesh. However, when the ground surface is soil, slope revegetation work is often performed without the physically based devices installation ignoring the soil properties, which could make the slopes unstable. The soil properties are crucial for vegetation development and erosion control. Therefore, if the ground surface is soil, the ground soil properties should be closely investigated.

Indicators for structural slope stability assessment used in previous researches were mostly focused on geological and topographical features such as joint condition, tension crack, rock type, soil texture, soil cohesion, soil friction angle, slope angle, and slope height with a tenuous approach of vegetation (Peng *et al*., 2011; Cheng *et al*., 2007; Lawrence and Robert, 1993). These indicators were widely used in numerical analysis such as limit equilibrium analysis (Duncan and Wright, 2005), empirical model such as Universal Soil Loss Equation (Wischmeier and Smith, 1978), and spatial analysis such as GIS techniques (Youssef *et al*., 2009; Poudyal *et al*., 2010). However, these analyses are complicated and inconvenient because numerous indicators should be considered simultaneously in specific range. The RSSA system developed in this study enables simple evaluation of stability of the revegetated slope using only five indicators selected among numerous variables.

The previous evaluation method of revegetation slope stability used to depend on the naked eye observation of vegetation coverage for judging the possibility of failure. However, the RSSA system can enable a scientific verification on failure of revegetated slopes through the discriminant analysis.

The previous discriminant analysis has applied nominal scale indicators as the independent variables (Rice and McCasion, 1985; Lee, 1987). However, in the RSSA system, the nominal–scale indicator was excluded and the only ratio–scale indicators were applied as the independent variables for discriminant analysis. Then, the nominal scale indicator, which is the vegetation community, is compared to finally determine stable or potential risk. As a result, original data were not skewed in the RSSA system.

CONCLUSIONS

This research was conducted to develop the revegetated slope stability assessment (RSSA) system for revegetated cut–slopes. Discriminant analysis was conducted as a part of process to develop evaluation indicators from nine variables. Five indicators of soil porosity, soil tensile strength, soil organic matter, vegetation coverage, and vegetation community were selected as stability evaluation indicators on revegetated cut–slopes. However, each indicator did not represent a discriminant standard between a stable slope and a potential unstable slope because the measured data of each indicator was overlapped in both stable and potential risk slope. Therefore, a comprehensive interpretation of the five indicators was required to evaluate revegetated slope stability.

As the result of analysis, the discriminant function included four variables: soil porosity, soil tensile strength, soil organic matter, and vegetation coverage. The data of vegetation community was excluded from the discriminant analysis as it was a nominal scale but used for the final screening of stability using the relationship between the discriminant score and vegetation community. RSSA system was developed by combining these two processes. If the revegetated slope have discriminant score zero or less, the slope is evaluated as potential risk slope. Even if the revegetated slope have discriminant score above zero, if the slope is covered by hetero–single–layer of vegetation, the slope is also evaluated as potential risk slope. However, if the revegetated slope having discriminant score above zero is covered by homo–multi–layer of vegetation, the slope is evaluated as stable slope. Only in the other cases of revegetated slopes having discriminant score above zero but the surface is covered by homo–single/hetero–multi-layers of vegetation, the trace of slope failure of the slopes should be additionally investigated and determine the slope stability. Although RSSA system is not a complete system for slope stability assessment, it is very practical for revegetated slope stability assessment because it requires relatively few indicators which can be easily measured. Therefore, it should be useful for the initial assessment or supplemental assessment with the integrated slope stability assessment system to be developed in the future by conducting long–term monitoring and additional studies on the effects of rainfall, vegetation variables such as species richness, dominant vegetation species, germination rate and geographical variables such as tensile root strength and shear strength.

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AUTHOR CONTRIBUTIONS

Sung–Ho Kil designed the research, analyzed data, and wrote this manuscript; Suk–Woo Kim reconstructed and revised the manuscript; Dong–Kun Lee provided suggestions and comments on the manuscript; Nam–Choon Kim, Sangjun Im, and Gwan–Soo Park contributed to improving the discussion about the manuscript; Kyoichi Otsuki revised and commented the manuscript. All authors read and approved the final manuscript.

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