Ph.D Dissertation

# Development of Stability Evaluation Indicators on Revegetated Cut-slopes of Mountainous Terrain of Korea

산악 지형의 절토 비탈면 녹화 이후 안정성 평가를 위한 지표 개발

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# Development of Stability Evaluation Indicators on Revegetated Cut-slopes of Mountainous Terrain of Korea

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# Abstract

## Development of Stability Evaluation Indicators on Revegetated Cut-slopes of Mountainous Terrain of Korea

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Slope stabilization of biotechnical engineering, which is one of the fields of ecological restoration, entails the use of vegetation. Biotechnical stabilization employs reciprocal mechanics of soil and biological elements, mostly plants, to prevent slope erosion and failure.

Slope revegetation, a representative method of biotechnical stabilization, has positive effects on slope stability and facilitates successful restoration when accompanied with a proper understanding of environmental limitations. However, slope revegetation works has been conducted with a lack of ecological consideration, and therefore, a continual collapse has occurred in Korea.

This research was conducted to develop stability evaluation indicators on revegetated cut-slopes. A total of 69 initial variables were selected through literature review and then 23 variables were selected through an expert survey. Among those, nine variables were categorized

under ″physical characteristics″, which are aspect, slope angle, slope type, slope width, slope height, ground layer, seepage water, elapsed year, and drainage system. Ten variables were categorized under ″soil″, which are porosity, soil hardness, water content, soil texture, tensile strength, permeability coefficient, soil depth, soil acidity, salt concentration, and soil organic matter. Finally, four variables were categorized under ″vegetation″, which are vegetation community, vegetation coverage, number of trees, and number of herbs.

A field survey was conducted on failure sites, potential risk sites and stable sites using the 23 variables. Through a non-parametric test and a correlation analysis of the field survey results, nine variables were identified as primary determinants of failures. Of these variables, six variables were from the soil category, including porosity, water content, soil depth, tensile strength, salt concentration, and soil organic matter; and three variables were from the vegetation category, including vegetation community, vegetation coverage, and number of trees. None of the physical characteristic variables were selected as prime determinants.

Discriminant analysis was conducted as a part of process to develop evaluation indicators from nine variables. As a result, the discriminant function included four variables: porosity, tensile strength, soil organic matter, and vegetation coverage, which were major indicators. The data of vegetation community was excluded from the discriminant analysis as it was a nominal scale. The box-plot of discriminant score and vegetation community classification was conducted. A revegetated site that had both heterogeneous simple layer and discriminant score below zero could collapse. In contrast, a revegetated site that had both homogeneous layer and discriminant score above zero could become stable.

Five indicators of porosity, 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 and potential risk site because the survey data of each indicator was overlapped in both stable and potential risk site. Therefore, a comprehensive interpretation of the five indicators was required to determine slope stabilization.

Most of the failure sites had soil slopes. A soil slope at a construction site was generally attached to a shallow layer of hydroseeding without a physical secondary device, such as fiber or wire mesh. However, this treatment could result in failure as it disregards the properties of the soil surface of the slope.

The failure soil, which was exposed during failure or erosion, and the potential risk soil, which was attached to the failure location were compared. The porosity, water content, permeability coefficient, salt concentration, and soil organic matter were significantly different in the non-parametric analysis. The failure risk level occurred when it had three to five of the following indicators: porosity of below 0.5$m^3/m^3$, water content of below 0.1$m^3/m^3$, permeability coefficient of above 6.00 × 10-3 cm/s, salt concentration of below 0.005%, and soil organic matter of below 1%. Also, the sand ratio of the failure soil was higher than the potential risk soil. The permeability coefficient was high and the soil organic matter was low in the failure soil. A soil that had high ratio of sand increased the water load during rainfall. It

was substantially different from the soil used in the revegetation work. Therefore, material segregation could have occurred between the ground-layer soil and the revegetation soil. A physical secondary device was required to moisturize and prevent this situation.

According to the results of this study, the slope revegetation evaluation analysis (SRSEA) system was developed. the target of evaluation was an area that underwent a soil-based slope revegetation construction at least two years prior to the time of study. The review for structural stability must have been completed in advance through stability analysis of slope. The evaluation items were three indicators of soil and two indicators of vegetation. The soil indicators were porosity, tensile strength, and soil organic matter. The vegetation indicators were vegetation community and the vegetation coverage.

▣ Keywords : Biotechnical Engineering, Slope Stabilization, Ecological Restoration, Slope Restoration, Mann-Whitney U test, Spearman Correlation, Discriminant Analysis, Slope Revegetation

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# Table of Contents

# List of Tables

# List of Figures

# 1. Introduction

## 1.1 Research Background

Slope stabilization of biotechnical engineering[1], which is one of the fields of ecological restoration, entails the use of vegetation. Biotechnical stabilization employs reciprocal mechanics of soil and biological elements, mostly plants, to prevent slope erosion and failure (Gray and Sotir, 1996).

Slope revegetation, a representative method of biotechnical stabilization, has positive effects on slope stability and facilitates successful restoration when accompanied with a proper understanding of environmental limitations (Urbanska, 1997; Golley, 1999; Morgan and Rickson, 1995). However, slope revegetation[2] works has been conducted with a lack of ecological consideration, and therefore, a continual collapse has occurred in Korea. MOLIT[3] announced in a September 2013 press release that the whole slope failure has occurred approximately 150 times annually, including slope revegetation failure, from year 2008 to 2012.

To handle persistent slope failure, institutions have tried to develop assessment tools for slope stabilization; however, so far they have focused on employing slope stability analysis from the field of civil engineering. For example, KICT[4], KEC[5], and NDMI[6] developed

1) Biotechnical engineering refers to techniques where vegetation is integrated with inert structures such as concrete blocks (Morgan and Rickson, 1995).
2) Slope revegetation measures include hydro seeding, seeding with thick layer vegetation media, vegetation mat, lined sodding work, planting, and vegetation mesh bag.
3) Ministry of Land, Infrastructure and Transport
4) Korea Institute of Construction Technology
5) Korea Expressway Corporation

indicators for the slope stability analysis and conducted risk assessments through a field survey on failure sites, 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 were also conducted including a method of scoring and a stochastic analysis of indicators focused on civil engineering (Peng et al., 2011; Wang et al., 2010; Cheng et al., 2007; Jeong, 2009; Park, 2006). Consequently, more consideration should be given to the method of slope revegetation in the assessment in order to improve the current approach and overcome the persistent slope failure.

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 at the evaluation of slope stability with specific variables or tools. Previous studies were also indirectly relevant to the issue of stabilization of revegetated slopes. For example, the studies were conducted on discrimination analysis of slope stability of a natural cut-slope, a slope without revegetation (Jeon et al., 2003; Lee, 1987), interpretation of vegetation distribution of revegetated slopes (Woo and Jeon, 2005; Woo et al., 1996b), 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 develop and interpret comprehensive indicators for evaluation of sustainable stability of revegetated slopes based on the environmental understanding.

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6) National Disaster Management Institute

## 1.2 Research Objective

The purpose of this research was to develop stability evaluation indicators on revegetated cut-slopes as follows:

1) Selection of practical variables relevant to the failure of revegetated slopes

There are numbers of variables that explain the condition of slope, including the slope stability analysis, landslide induction, and slope revegetation. However, there is no research on variable relevant to the failure after the slope revegetation. Therefore, this study considered failure variables scattered throughout other fields and extracted variables relevant to failure of revegetated slopes.

2) Verification of the selected variables as indicators for stabilization by statistical means of correlation analysis, non-parametric test and discriminant analysis on field survey data of potential risk, failure and stable sites

Final indicators were resulted from the selected variables through two correlation analysis, a comparison between potential risk[7] and stable site; and potential risk and failure site[8], in order to verify the difference of the data of variables that might have triggered the erosion or failure. Non-parametric test affirmed the specific variables

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7) Most of the slope failures after the revegetation works take on a partial and sporadic aspect rather than as a whole. Therefore, a revegetated spot located right next to the plainly visible failure spot, which will be called as ‘potential risk’, has high possibility of failure in near future. It is worthwhile to compare the properties of its variables with the stable site since it retains the soil and vegetation condition comparable to the stable site unlike the plainly visible failure spot which has only exposed soil left from the ground layer.

8) Potential risk and failure site: The soil of the ground layer, which is exposed in failure, could have heterogeneous characteristics in comparison to the soil used in the slope revegetation. Therefore, both soils are compared and analyzed in this study to seek improvements.

that showed significant difference in the site comparisons as a major failure inducing variables. A discriminant function analyzed by selected variables can establish evaluation standards to judge potential risk of failure. Variables included in the discriminant function can be regarded as major indicators of the evaluation standard.

3) Development of Slope Revegetation Stability Evaluation Analysis (SRSEA)

A stability evaluation system was developed through the process of indicator and equation development for stabilization analysis of revegetated slopes.

## 1.3 Scope of study

### 1.3.1 Content scope

The scope of this study was to develop stabilization indicators for revegetated slopes constructed with revegetation method of artificial soil utilization[9]. Characteristics of the artificial soil used in the slope revegetation differ from natural soil formed from parent material such as granite, gneiss, and sedimentary rock. The failure of revegetated slope, therefore, differs in cause and aspect from spontaneous landslides. The scope of variable selection was limited to the variables directly related to the establishment of revegetation stability. The variables related to structural stability were excluded since the slope revegetation is constructed after slope stability analysis.

9) Artificial soil utilization: The method of artificial soil using soil amendments is used for slope revegetation which represents hydro-seeding, vegetation mat, lined sodding work, and planting. It is one of the methods widely used in Korea.

### 1.3.2 Spatiotemporal scope

The province of Gangwon-do was chosen for the purpose of this study with several reasons. Gangwon-do has 81.7 percent of mountainous terrain with most of granite rock layer (Website of Gangwon-do Provincial Office). In addition, most of disastrous events related to steep slopes that were investigated in Korea from 1999 to 2011 occurred in Gangwon-do (NDMI[10], 2011). Furthermore, these events are expected to increase with the demands for development in Gangwon-do in accordance with hosting the 2018 Olympic Winter Games.

The study sites were all chosen from the area of revegetated slopes and were classified into test sites and control sites. The test sites were the five failure sites detected with unaided eye while searching through Gangwon-do in year 2012. The control sites were the five stable sites with a known construction method and date of slope revegetation in Gangwon-do in year 2012. The elapsed time of the study sites ranged from three to nine years after the slope revegetation work, which all passed the warranty period of two years.

10) National Disaster Management Institute

# 2. Literature review

## 2.1 Definition of terms

### 2.1.1 Slope revegetation

As an ecological restoration technology, slope revegetation includes all behaviors that restore the damaged area into a natural state as much as possible. Generally, ecological restoration is “the process of assisting the recovery of an ecosystem that has been damaged and destroyed” (SER, 2002; Hobbs and Cramer, 2008). However, there are many terms related to restoration, as shown in Table 1 is the list of different terms used as the restoration in previous studies.

Table 1. Arrangement of restoration and analogous terms.

| Category | Definition | Note |
|---|---|---|
| Restoration | · Attempt to restore natural or near-natural conditions of a landscape unit damaged by man, e.g. worked bog, piped stream, gravel dredging pit, by implementing active or passive measures of habitat management | 1) |
| | · The process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed | 2) |
| | · Both the implication of returning to an original state and to a state that is perfect and healthy | 5) |
| | · This is the recreation of the structure and function of the plant community identical to that which existed before disturbance. Restoration’s goal is conservation, with the intention of maximizing biodiversity and functioning | 6) |
| Reclamation | · To rescue it from an undesirable state | 3) |
| | · Aim to convert land damaged through resource extraction or poor management to productive use | |
| | · This is the recreation of a site that is designed to be habitable for the same or similar species that existed prior to disturbance. Reclamation differs from restoration in that species diversity is lower and projects do not recreate identical structure and function to that before disturbance. However, a goal of long term stability with minimum input is implied. | 6) |

(Continued).

| Category | Definition | Note |
|---|---|---|
| Rehabilitation | · Act or process of making possible a compatible use for a property through repair, alterations, and additions while preserving those portions or features that convey its historical, cultural, or architectural values | 1) |
| | · The reparation of ecosystem processes and services, whereas restoration includes the reestablishment of biotic integrity | 2) |
| | · Almost synonym with restoration and a more flexible term | 3) |
| | · To build again or bring back to a previous condition | |
| | · An alternative ecosystem following a disturbance, different from the original and having utilitarian rather than conservation values | 4) |
| | · The action of restoring a thing to a previous condition or status | 5) |
| | · Something that is rehabilitated is not expected to be in as original or healthy a state as if it had been restored. | |
| | · This process creates alternative ecosystems that have a different structure and function from the pre-disturbance community, such as a park, pasture, or silvicultural planting. | 6) |
| Recovery | · Recovery assumes that autonomous processes produce an integral ecosystem | 3) |
| | · It does not assume that the recovered land is necessarily restored in the sense of historical fidelity | |
| Remediation | · The process of remedying ecological insults | 3) |
| | · Typically the lack of focus on historical conditions and recovery of ecological integrity makes the differences between restoration and remediation easy to spot | |
| | · To rectify, to make good | 5) |
| | · On the process rather than on the endpoint reached | |
| Revegetation | · Reestablishment of vegetation in an area without plant growth for a long period of time | 1) |
| | · The goal is to reestablish vegetation on a disturbed site. This is a general term that may refer to restoration, reclamation, and rehabilitation. | 6) |
| Replacement | · To provide or procure a substitute or equivalent in place of(although an alternative meaning is to restore) | 5) |
| Revitalization | · Aim and result of measures which restore the vitality of an abandoned landscape, a neglected park, a run-down street, etc. and increase their attractiveness; industrial revitalization /redevelopment of industrial areas | 1) |

Note: 1) Evert (2010), 2) Bullock et al. (2011), 3) Higgs (2003), 4) Allen et al. (2000), 5) Bradshaw (1996), 6) Allen et al. (1997)

The dictionary definition of restoration means restoring the damaged condition into the original state. Not all behaviors and processes of restoration is regarded as the ecological restoration. Technological restoration is a “restoration in which efficiency and uniformity are transcendent, and leads both to the projects themselves and to the process of developing those projects being rendered as commodities” (Higgs, 2003). Thus, the slope vegetation, as an attempt of rehabilitation, is included in the branch of the ecological restoration.

### 2.1.2 Slope stabilization

Slope stabilization may be defined as erosion control of slopes using biotechnical construction techniques[11]. It prevents avalanches and safeguards against the erosion of banks and beds of watercourses. Slope stabilization may also use conventional engineering methods, such as building walls, dams, and bank revetments (Evert, 2010). In addition, slope stability may be defined as the resistance of any inclined surface such as an open pit to failure by sliding or collapsing (Kliche, 1999).

An appropriate term for the purpose of this study is the slope stabilization rather than the slope stability. The term “stabilization” and “stability” is different in a sense that the stabilization refers to a process to make stable or steadfast, whereas the stability refers to a state or quality of being stable (Joseph et al., 2007). The term of slope stability will be appropriate in a study of cause-and-effect

11) Biotechnical construction techniques is method of landscape construction which primarily use living or dead plant material. It mainly use slope revegetation method based on hydroseeding in South Korea.

relationship on slope failure using mathematical equations or engineering approach such as modeling and simulation.

### 2.1.3 Slope failure

A stabilized slope decreases the possibility of failure. Thus, the slope failure is a contrary concept to slope stability. Representative terms of failure include landslide[12], slope failure, and soil erosion. The type of slope failure depends on form, velocity, direction, size, object, and location. The failure sweeps the artificial soil used in revegetation to the bottom of a slope on a small scale on soil erosion caused by freeze-thaw cycles and heavy rains. The slope revegetation is applied on the slope after civil engineers and soil conservation engineers evaluate the slope stability in order to protect failures in early stages.

Landslide is a natural disaster that has different features from the failure after the slope revegetation. The type of most landslides in Korea is debris-flow which mostly occurs in period of local torrential rain, from June to August (Kim et al., 2000). Varnes (1978) classified slope movements relevant to the landslide by type and material of movement according to the following standard (Table 2).

12) Regarding the landslide, the United States Geological Survey (USGS) provided many illustrations and much information. It categorized the landslide into rotational slides, translational slides, block slides, rockfalls, topples, debris flows, debris avalanches, earth flows, creeps, and lateral spreads (see Appendix A).

Table 2. Types of landslides. Abbreviated version of Varnes' classification of slope movements (Varnes, 1978).

| Type of Movement | | Type of Material | | |
|---|---|---|---|---|
| | | Bedrock | Engineering Soils | |
| | | | Predominantly coarse | Predominantly fine |
| Falls | | Rock fall | Debris fall | Earth fall |
| Topples | | Rock topple | Debris topple | Earth topple |
| Slides | Rotational | Rock slide | Debris slide | Earth slide |
| | Translational | | | |
| Lateral Spreads | | Rock spread | Debris spread | Earth spread |
| Flows | | Rock flow | Debris flow | Earth flow |
| | | (deep creep) | (soil creep) | |
| Complex | | Combination of two or more principal types of movement | | |

### 2.1.4 Artificial slope and natural slope

An artificial slope[13] is an inclined plane having an angle of repose formed by an artificial landform, such as roadway construction. A natural slope is an inclined plane caused by naturally geomorphological processes without slipping. Therefore, a failure of an artificial slope indicates a collapse of slope constructed through earthwork. A failure of a natural slope indicates a collapse by natural causes such as erosion or earthquakes.

13) Artificial slope and natural slope are legal terms that appear in an Act of Korea, however, they have not been legally defined. The definition of those terms could be inferred from other fields of literature (Evert, 2010; Grasso et al., 1991; Mueller-Dombois, 1963).

### 2.1.5 Indicator and variable

An indicator is a qualitative or quantitative variable that offers a simple and trustworthy means to perceive changes linked to an intervention (Church and Rogers, 2006). It is a measurement that shows the situation of an social, economic or environmental system for years (Redefining Progress et al., 1997). Therefore, an indicator reflects the status of environmental system through representative variables.

## 2.2 Stability of slope revegetation

### 2.2.1 Objective of slope revegetation

Most of slope revegetation measures seek to enhance self-sustaining native vegetation communities with a process of natural succession (Clewell et al., 2005; Brown and Amacher, 1999). This objective reflects enhancing an ecological structure and function by establishing vegetation on barren slopes. When the work of slope revegetation is sustainable, it could protect soil, enhance visual amenity, and develope environmental health. Thus, the slope revegetation plays a major role in environmental enhancement and control. The following Table 3 classified these objectives in five fields: erosion control, visual enhancement, weed control, wildlife protection, and cost management (David et al. 2007).

Table 3. Objectives of road revegetation (David et al., 2007).

| Revegetation Objectives | Function of Native Plants |
|---|---|
| Erosion Control | · Controlling surface erosion and thereby protecting soil and water quality is a high priority on road construction projects.<br>· Native grasses, forbs, and other herbaceous plants can help meet this challenge, particularly when they are accompanied by appropriate mulching treatments.<br>· Deep-rooted native trees and shrubs can also enhance stability of cut and fill slopes. |
| Visual Enhancement | · Vegetation is often used to enhance the aesthetic experience of the traveler. Wild flowers add beauty in spring; deciduous trees change color in fall; and evergreen species stay green all year.<br>· Vegetation can also be used to hide structures such as gabion walls or slopes covered by riprap. |

(Continued).

| Revegetation Objectives | Function of Native Plants |
|---|---|
| Weed Control | · Roadsides can be corridors for the transport and establishment of noxious or invasive weed species. Once established, weeds are hard to eradicate and become seed sources for further encroachment.<br>· Revegetating with desirable native species minimizes opportunities for problem species to establish. |
| Wildlife Protection | · Many roads intercept animal corridors.<br>· Techniques to make roads more permeable to wildlife (often via under- or over-passes) are being developed. The revegetation specialist can help by minimizing dangerous interactions between vehicles and wildlife. The presence of birds and small animals can be enhanced when appropriate plant species are reestablished. |
| Cost Management | · Advanced planning, an integrated approach, and the use of appropriate stocktypes and equipment all facilitate successful and cost-effective revegetation. |

### 2.2.2 Erosion control of slope revegetation

The interaction between soil erosion and vegetation controls the self-sustainability and successional progress of successful ecosystems (Moreno de las Heras et al., 2011; Bochet and Garcia-Fayos, 2010; Nicolau, 2003). The soil erosion can influence plant growth through different mechanisms, such as removal of nutrients and seeds from regolith, direct vegetation removal, and the damage of water resources through surface runoff (Pimentel et al., 1995). The vegetation reduces and prevents frozen erosions, such as frostbite, freeze-thaw, and wind erosion on the ground. Complete vegetation coverage prevents rain splash erosion and surface erosion through an umbrella effect (Toy et al., 2002; Park, 2002; Jeon et al., 2003). Thus, the soil used in the revegetation work requires an interim process to control erosion and establish vegetation. And if the soil overcomes the arduous processes to establish vegetation without erosion, it will be stabilized.

### 2.2.3 Vegetation establishment of slope revegetation

Abundant plants embody multidimensional structure of a plant community. A representative form of the plant community shows multiple layers that combine trees, shrubs, and groundcovers. The combined layer provides erosion control as it minimizes the impact of raindrops on soil (Zheng, 2006). The plant community of revegetated slope has a pioneer vegetation, which first colonizes a nonvegetated site before the permanent community[14] reaches self-sustaining form by steady-state succession. Until now, the method of revegetation has mainly utilized species of introduced plants, which are mostly non-native such as cold-season grasses that have quick-growing properties after seed germination (Kim et al., 2007). The use of excessive non-native species lead to heterogeneous landscapes and soil erosions (Kim et al., 1998).

The factors influencing vegetation coverage included numbers of appeared species, numbers of individual herbs, thickness of soil, soil moisture, slope width, slope height, slope angle, aspect, and elapsed year (Jeon, 2002; Woo et al., 1993). The number of appeared species had a strong positive effect on the vegetation coverage, whereas the thickness and the moisture of soil had a negative effect (Kil et al., 2011). Kil et al. (2012) summarized the variables influencing the vegetation coverage that showed significant value in the data from previous studies as following Table 4.

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14) Permanent community is a form of plant community which has not yet reached the climax from whatever cause, remains unchanged for a long time and maintains its community relationships (Evert, 2010).

Table 4. Variables influencing vegetation coverage.

| Category | Condition of vegetation coverage | | |
|---|---|---|---|
| | Bad <------------------------------------------------------------------> Good | | |
| Slope angle | below 1:0.7<br>(over about 60°) | | over 1:1<br>(below about 45°) |
| Length (horizontal) | Extensive | <---------------------------------> | Narrow |
| Height (Vertical) | 20m or more | | 7m or less |
| Moisture | Low | | High |
| Aspect | South-------------------------------->West-------------------->North----------->East | | |

## 2.3 Slope stability evaluation method

### 2.3.1 Slope Stability Analysis

Slope stability analysis is performed to evaluate safe and economic design of slopes and critical equilibrium parameters. It uses numerical and statistical analysis to perform risk assessment on failures such as steep slope failure and rainfall-induced slope failure (Peng et al., 2011; Cheng et al., 2007; Jeong, 2009; Park, 2006; Wang et al., 2010; El-Ramly et al., 2005; Wu and Kraft, 1970).

Many domestic and foreign researches on slope stability including variable development for stability evaluation have focused on structural stability with categories of topography, geology, environment, and meteorology[15] (Lawrence and Robert, 1993; Juang et al., 1992; Lee and Min, 2001; Lee et al., 2012). The research was limited to the civil engineering approach with physical structures such as geological structures and topographical patterns (Jeong, 2009; Park, 2006). Those categories were reclassified as conventional variables were unsuitable for the purpose of this study.

An evaluation on slope stability generally consists of the structural stability and the stability after the revegetation. The examination on the structural stability precedes the revegetation of a slope. The revegetation aims to build up the slope stability through erosion control and ecological improvement. The slope stability has not been secured yet and failure or soil erosion occurred persistently. Therefore,

15) Meteorology was excluded in this study due to the temporal and physical constraints since data collection and geographical information systems (GIS) analysis through long-term monitoring were required for driving forces, such as rainfall or freeze-thaw cycles.

a new evaluation method that supplements and improves conventional method was required for revegetated slope.

### 2.3.2 Landslide assessment

Landslides occur when a steady-state slope becomes unstable. Researches were conducted with variables to figure out the cause of landslides (Piacentini et al., 2012; Kim, 2006). Many studies have investigated the start-up mechanisms of rock or soil movement using field monitoring systems (May and Gresswell, 2004; Tecca et al., 2003; Mikos et al., 2004). They have also conducted field surveys and soil testing in a laboratory (Godt and Coe, 2007; Coe et al., 2008; Pelfini and Santilli, 2008; Wen and Aydin, 2005), analytical methods (Iverson and Reid, 1992; Reid and Iverson, 1992) and physical-based models for rainfall-induced shallow landslide such as SIMMAP (Pack et al., 1998), dSLAM (Wu and Sidle, 1995), SHETRAN-landslide (Burton and Bathurst, 1998), and TRIGRS (Baum et al., 2002). The studies generally showed numerical analysis modeling.

In addition, other studies have carried out landslide analysis using probabilistic models through mapping inventory techniques with remote sensing and GIS techniques (Lee et al., 2012; Pradhan and Youssef, 2009; Poudyal et al., 2010; Nandi and Shakoor, 2010). These studies were applicable to the natural slope and might not be directly applicable to the case of failure of revegetated slope as it is an artificial.

### 2.3.3 Slope revegetation evaluation

Slope revegetation is generally performed to protect from unexpected failures after slope stability analysis. The method of evaluation for the slope revegetation has mainly focused on establishing vegetation (Garcia-Palacios et al., 2010; Mola et al., 2009; Lee and Park, 2006) and numerical models for interactive relationship between erosion and vegetation (Moreno de las Heras et al., 2011; Kirkby et al., 1997; Thornes, 1985). These studies required long-term monitoring and numerical analysis.

A representative evaluation method of slope revegetation referred in this study is the “Design and Construction Guidelines for Road-slope Vegetation” published by MOLIT (2009) in South Korea. The guideline includes revegetation methods selected by procedural process to revegetate and evaluate trial revegetation to reflect soil and vegetation characteristics.

## 2.4 Variables related to slope stabilization

The variables relevant to slope stabilization could be found in fields such as slope stability analysis, landslide assessment, and slope revegetation. Refer to Appendix B for the characteristics of each variable.

### 2.4.1 Slope Stability Analysis

A representative method of slope stability analysis uses a standard scoring table with selected variables as the standard for failure varies from country to country. Table 5 summarizes the variables of domestic and foreign evaluation methods for slope stability analysis.

Table 5. Major variables for slope stability analysis.

| Major category[16)] | Main variables[17)] |
|---|---|
| Topography | Slope height, Slope angle, Slope type, Catchment basin |
| Geology | Rock type (granite, diorite, gneiss), Weathered Characteristics, Weathered condition, Joint condition, Joint orientation, Water condition (dampness, seeps, ground water), Tension crack, Soil texture |
| Environment | Forest stand, Collapse history, Scale of failure, Checking existence of road, Drainage system, Existence of slope protection, Reinforcement condition |
| Meteorology | Rain intensity |

16) The major category followed the classification organized by Juang, et al. (1992). p. 482.
17) The main variables appeared more than three times from variables organized by Jeong (2009) p. 100-108.

### 2.4.2 Landslide

Thirty three domestic and foreign studies[18] were analyzed to extract variables. The selected variables are summarized in Table 6.

Table 6. Major variables of landslide assessment.

| Major category | Main variables[19] |
|---|---|
| Topography | Slope angle, Aspect, Altitude, Landslide length, Curvature, Landslide width, Location, Slope type, Landslide depth, Landslide type, SPI(Stream Power Index), TWI(Topographic Wet Index), Slope length, Drainage system |
| Geology | Parent rock, Rock floor, Effective soil depth, Soil depth, Permeability coefficient, Air-void ratio, Soil texture, Water content, Porosity, Specific gravity, Grain size, Tensile strength, Shear strength |
| Environment | Forest stand, Timber diameter class, Timber age class, Vegetation density, Land use |
| Meteorology | Accumulated rainfall, Amount of rainfall, Rain intensity |

18) Kang and Kim (2009); Quan et al. (2008), Kim (2006); Kim et al. (2006); Kim (2007); Kim et al. (2007); Kim et al. (2008); Kim et al. (2008); Kim et al. (2011); Kim et al. (2012); Kim and Chae (2009); Ma and Jeong (2007); Ma et al.(2008); Park et al. (2012); Park et al.(2010); Bae et al. (2009); Yeon (2011); Oh et al.(2009); Oh (2010); Yun (2009); Yun et al. (2010); Lee et al. (2009); Lee et al.(2012); Lee et al.(2006); Jun et al. (2010); Jung et al. (2008); Cho et al. (2006); Jo and Jo (2009), Cho and Chang (2006); Choi et al. (2011); Piacentini, et al. (2012); Lee et al. (2012); Lee and Min (2001)

19) The main indicators appeared more than three times from preceding researches

### 2.4.3 Slope revegetation

Forty one domestic and foreign studies[20] and standards were analyzed to extract variables relevant to slope restoration. The variables were extracted from studies of soil erosion, revegetation stability by experimentation, and improved methods of revegetation construction as summarized in Table 7.

Table 7. Major variables for slope revegetation.

| Major category | Main variables[21] |
|---|---|
| Topography | Slope angle, Aspect, Slope length, Altitude, Slope location, Slope type, Slope width, Reinforced facility |
| Geology | Parent rock, Soil acidity, Soil hardness, Soil organic matter, Soil texture, Total nitrogen, Water contents, C.E.C(Cation Exchange Capacity), Available phosphate, Soil moisture, C/N, Grain size, Exchangeable potassium, Exchangeable calcium, Salt concentration, Exchangeable magnesium, Bulk density, Gravel contents, EC(Electronic Conductivity), Exchangeable sodium |
| Environment | Vegetation coverage, Individual number, Tree height, Dominance value, Germination percentage, Species diversity, Plant community, Maximum species diversity, Number of trees, Number of herbs, Surrounding vegetation, Crown width, Grass width, Elapsed year |
| Meteorology | - |

20) Woo et al. (1993); Woo et al. (1996a); Woo et al. (1993b); Kim et al. (1998); Kim and Woo (1999); Kim et al. (1999); Nam et al. (1999); Kim and Kang (1999); Kim et al. (2001); Kang et al. (2001); Jung (2001); Kim et al. (2002); Jeon (2002); Park (2002); Jeon (2003); Lee et al. (2003a); Lee et al. (2003b); Song et al. (2003); Ahn et al. (2004); Jeon (2004); Kim et al. (2004); Jeon and Ma (2004); Woo and Jeon (2005); Yeo et al. (2005); Kim et al. (2006); Kim et al. (2007); Kim et al. (2008); Koh et al. (2010); Kil et al. (2011); Kil et al. (2012); Park et al. (2006); Lee et al. (2012); Fehmi and Kong (2012); Karim and Mallik (2008); Bochet et al. (2007); Hosogi et al. (2006); Mola et al. (2011); Tinsley et al. (2006); Hooke and Sandercock (2012); García-Fayos et al. (2010); Cortina et al. (2011)

21) The main variables appeared more than three times from preceding researches

# 3. Data and Methods

## 3.1 Study site

All study sites were located next to the roadside. Four failure sites were located in Pyeongchang-gun and other failure sites were located in Yangyang-gun. The stable sites had no failures occurred up to the time of this study. Table 8 summarizes the major features of each site.

Table 8. General information in survey sites.

| No. | Address | Survey date | Year completed | 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 | × |

Figure 1. Study sites of Gangwon-do (failure sites and non-failure sites).

Figure 2. Site 1.

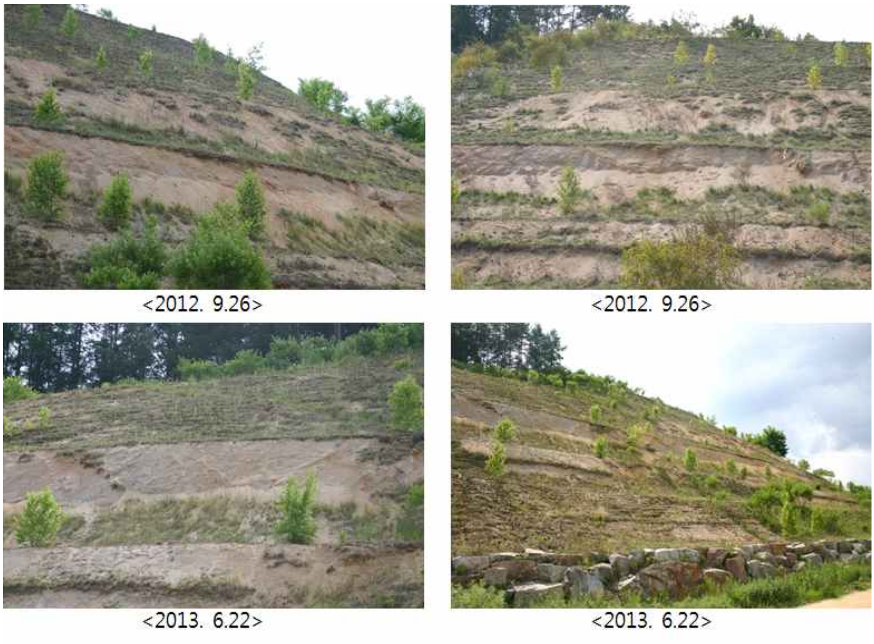


Figure 3. Site 2.


Figure 4. Site 3.


Figure 5. Site 4.


Figure 6. Site 5.


Figure 7. Site 6.


Figure 8. Site 7.


Figure 9. Site 8.


Figure 10. Site 9.

<2012. 10.19>

<2012. 10.19>

<2013. 6.22>

<2013. 6.22>

Figure 11. Site 10.

## 3.2 Methodology of study

The research method consisted of five steps: 1) a variable selection, 2) a field survey, 3) major variable section through statistical analysis 4) comparison of soil properties within failure sites, and 5) a discriminant analysis.

1) To select variables relevant to the failure of revegetated slope, variables were collected from several fields of study such as stability analysis, landslides, and slope revegetation. The variables were then extracted via two steps. First, variables that were reviewed at least three times were extracted. Then, major variables were selected from those extracted by experts through an questionnaire survey with a multiple response method[22] (see Appendix C).

2) The field survey was conducted on failure sites, potential risk sites and stable sites to collect data for variables selected in the first step.

3) Correlation analysis and non-parametric testing[23] were conducted. The correlation analysis examined the correlations between variables, and non-parametric testing compared and analyzed the field survey results.

4) The properties of the soil of failure sites and potential risk sites were compared through non-parametric testing. The results were interpreted in comparison with previous studies.

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22) Multiple response method allows a respondent to choose two or more answers on a question.

23) Non-parametric test is a test method to generally use mark or grade of measured value, not estimating the distribution of population (Park et al. 2004).

5) Discriminant analysis used major variables selected by correlation analysis and non-parametric testing. A nominal-scale indicator of surveyed data was excluded in the discriminant analysis. However, the nominal-scale indicator was compared with discriminant score extracted by the discriminant analysis. Finally, slope revegetation stability evaluation analysis (SRSEA) using the final indicators was suggested.

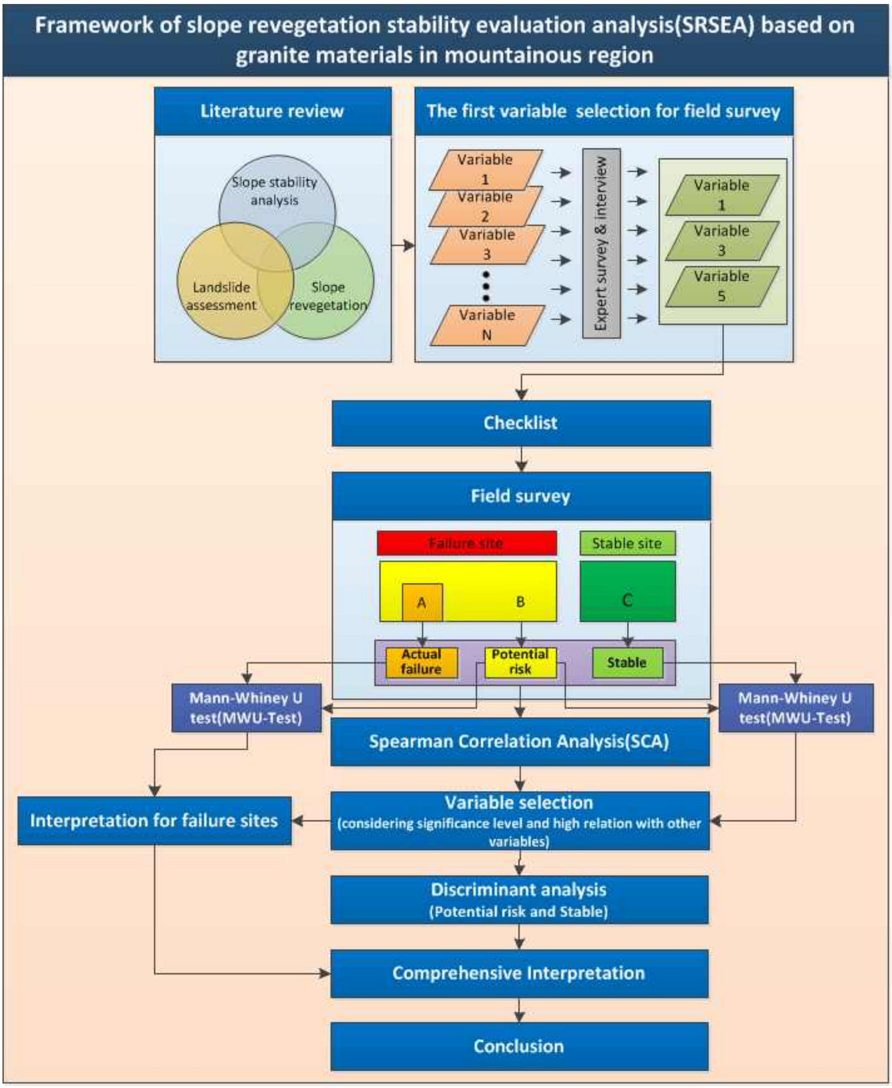


Figure 12. Framework of this study.

### 3.2.1 Variable selection

Consideration of all the variables collected from previous studies was not effective because certain variables were inadequate to explain slope failure or had a minor effect on other variables. Consideration of representative variables that were highly relevant to the slope stabilization could be rather more effective. In addition, explanation of each and every variable required too much time and money. For variable extraction, domestic and foreign research papers, legislations, and principles were comprehensively reviewed.

The variables relevant to failure were able to collect from the fields of civil engineering, soil erosion control engineering, and slope restoration. Then the variables were organized in one table. The first major category followed the classification organized by Juang et al. (1992, p. 482). The main variables appeared more than three times in preceding research were selected. Variables with overlapped meanings or repetitive appearances were integrated into a single term. For example, slope inclination, inclination, and slope angle have the same meaning. Thus, “slope angle” was chosen for variable selection. In addition, the variables dealing with structural stability before slope revegetation were excluded or integrated. Through the process, the final variables for a questionnaire survey were selected.

The questionnaire survey used a multiple response method based on an expert survey. The expert survey was conducted with 37 experts to simplify the variables through interview and e-mail from April 1st to April 13th, 2013. The experts consist of twenty landscape architects, four environmental engineers, nine civil engineers, and four forest specialists. Most of them had more than 10 years of experience in their respective fields. The demographic analysis of the survey is shown on Table 9. The variables selected from the expert survey were those offered by more than half of respondents, from which the final variables for slope revegetation were selected.

Table 9. Demographic Profile of Respondents to extract variables.

| Expert survey (1st) | | Frequency |
|---|---|---|
| Field | Landscape Architecture | 20 |
| | Environmental Engineering | 4 |
| | Civil Engineering | 9 |
| | Forestry | 4 |
| Institution | Private company | 24 |
| | Educational Institution | 3 |
| | Public Institution | 10 |
| Career | below one year | 0 |
| | 1 to 3 years | 0 |
| | 3 to 5 years | 2 |
| | 5 to 10 years | 10 |
| | over 10 years | 25 |
| Total | | 37 |

### 3.2.2 Data Collection

The field survey was conducted twice, the first survey was from September 15 to October 19, 2012, and the second survey was from June 21 to 23, 2013. The second survey was conducted to collect supplementary data for the width and length of slopes. The field survey was conducted on both failure sites and stable sites. The survey methods of each variable are summarized in the following Table 10.

Table 10. Method of measurement each variable.

| Variables | Method | Reference |
|---|---|---|
| Slope angle | · Clinometer of Digital PRO 365M for 3 times in each site | Woo et al. (1996) |
| Aspect | · Compass of SILVA RANGER | Jeon et al. (2003) |
| | · Classification of north-northeast (N-NE), northeast-east (NE-E), east-southeast (E-SE), southeast-south (SE-S), south-southwest (S-SW), southwest-west (SW-W), west-northwest (W-NW), north-northwest (N-NW) | |
| Slope width | · Equipment of KMC-1800 tapeline | Woo et al. (1996) |
| | · Straight-line distance of lower section in a slope | |
| Slope height | · Equipment of KMC-1800 tapeline | Woo et al. (1996) |
| | · Straight-line distance from the center of bottom of a slope to the top of adjacent forests | |
| Slope type | · Convex(凸), concave(凹), Straight(□), compound(凹凸) | Jeon et al. (2003) |
| Ground layer | · Classification of soil, weathered rock and blasted rock | KCPA[24] (2012) |
| Seepage water | · Examination for whether it was occurred or not | NEMA[25] (2010) |
| Elapsed year | · Report with officers' interview since after construction of revegetation was completed | Jeon et al. (2003), Im and Ma (1999) |
| Drainage system | · Report about facility and smooth progress of a drain | NEMA (2010), MOLIT (2009) |

24) KCPA: Korea Construction Promotion Association
25) NEMA: National Emergency Management Agency

(Continued).

| Variables | Method | Reference |
|---|---|---|
| Porosity | · Calculation by values of bulk density[26] and particle density[27]<br>$P = 100 \times \left(1 - \frac{Bd}{Pd}\right)$<br>where, P : Porosity(%)<br>Bd : Bulk density<br>Pd : Particle density | Brady and Weil (2007) |
| Soil hardness | · Pocket penetrometer (SHM-1) for 3 times | Woo et al. (1996) |
| Water content | · Gravimetric method<br>· Calculation by comparing weights of soil samples collected from the sites before and after drying | Gardner (1968) |
| Soil texture | · Measurement of ratio of sand, silt and clay by the standard of USDA[28]<br>· Hydrometer method | Shirazi and Boersma (1984) |
| Tensile strength | · Technique by Nearing et al. (1988) | Nearing et al. (1988) |
| Permeability coefficient | · Calculation by constant head method using the flux per hour, length of soil column, and hydraulic head with applied in the Darcy law | Hillel (1972) |
| Soil depth | · Measurement with a tapeline after soil removed up to ground layer for the 3 times in each site | MOLIT (2009) |
| Soil acidity (pH) | · Measurement by a method using a 1:5 dilution of soil:water through sample soils | Rayment and Higginson (1992) |
| Salt concentration | · Conversion by electronic conductivity(EC) measured by a method using a 1:5 dilution of soil:water<br>· Electronic conductivity(EC) units (ds/m) using formula: 1 ds/m = 1ms/cm = 1mmho/cm = 640ppm = 640 mg/L = 0.64g/L = 0.064% | Rayment and Higginson (1992) |
| Soil organic matter | · Wakely-Black wet oxidation method | Walkley and Black (1934) |
| Plant community | · Classification of heterogeneous simple layer, heterogeneous multiple layer, homogeneous simple layer and homogeneous multiple layer | Lee et al. (2012) |
| Vegetation coverage | · Quadrat method (1m×1m) in each site for 3 times | MOLIT (2009) |
| Number of trees | · Quadrat method (1m×1m) in each site for 3 times<br>· Number of tree species by plant nomenclature | MOLIT (2009) |
| Number of herbs | · Quadrat method (1m×1m) in each site for 3 times<br>· Number of tree species by plant nomenclature | MOLIT (2009) |

26) Bulk density: It is a variable of soil compaction. It is calculated as the dry weight of soil divided by its volume (USDA, 2008).

The soil samples were collected from the slope surface, with a stainless steel 100cc can and a trowel. The stainless steel can was used to examine the water content and porosity, and the trowel was used to collect 500g of each soil sample to examine the other variables. In addition, certain spots of slopes were classified for the soil sample collections. It was classified into three spots: failure, potential risk, and non-collapsed spots. The failure and the potential risk spots had same physical characteristics as they were classified within a single site. The potential risk spot was positioned next to the failure spot. The failure spot was differentiated from the potential risk spot in that the ground layer was obviously exposed and the artificial soil used in revegetation was removed by erosional forces. The non-collapsed spot was chosen from stable sites which were not collapsed after the slope revegetation.

The soil sampling was conducted thrice on each and every spot. The sealed samples were analyzed in two laboratories, the Research Institute of Forest Soils at Chungnam National University and KICT[29]. The Research Institute of Forest Soils was in charge of partial physical properties of soil such as water content, porosity, and texture; and whole chemical properties of pH, salt concentration, and soil organic matter. KICT examined the rest of the physical properties, tensile strength and permeability coefficient.

### 3.2.3 Data Analysis

The field survey data were analyzed by statistical means to select variables that significantly affected occurrence of erosion or failure. The data were compared with that of previous research to determine

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27) Particle density: It is the volume of solid particles in the volume of a unit (Brady and Weil, 2007).
28) USDA: United States Department of Agriculture
29) Korea Institute of Construction Technology

whether the variables had positive or negative correlations with one another using Spearman's correlation analysis30). The data measured in a nominal scale were converted to a ratio scale and were frequently used for the statistical analysis using quantification theory31). Each variable that satisfied a significant level and had a high coefficient was discussed in relation to previous studies.

The difference of value in each variable between failure and stable sites was also analyzed using Mann-Whitney U test32). A variable that satisfied a significant level of the Mann-Whitney U test could differentiated a failure site from a stable site and therefore could explain the classification between those groups. Each variable resulted from the Mann-Whitney U test was discussed in relation to previous studies. It was also analyzed the different value of each variable between soil from the potential risk spot and exposed soil from the failure spot using the Mann-Whitney U test to determine the reason of failure. The results of variables were also discussed in relation to previous studies.

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

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30) Spearman's correlation analysis is a non-parametric correlation analysis; it is not based on an assumption of normal distribution (Rho, 2006).

31) Quantification theory is a method that deal with quantification data measured by nominal scale and ordinal scale. It is close to an approach of dummy variable (Rho, 2006). It was applied to discriminate risk assessment using categorical data and figure out a risk level (Jade and Sarkar, 1993; Lee, 1987; Hayashi, 1951).

32) Mann-Whitney U test is a non-parametric test which is used to determine whether two independent groups came from same populations or not. The test shows the highest detecting ability among the non- parametric tests. It is most useful to replace the non-parametric t test when a researcher wants to avoid the limitation of t test or when the study scale is weaker than interval scale (Rho, H.J., 2006).

# 4. Results and Discussion

## 4.1 Evaluation Variables

The variables for slope stability evaluation were selected relevant to failure and soil erosion from the field of slope stability analysis, landslide, and slope revegetation.

Table 11. Major variables relevant to slope failure selected from previous studies.

| Category | Slope stability analysis | Landslide | Slope revegetation |
|---|---|---|---|
| Topography | Slope height, Slope angle, Slope type, Catchment basin | Slope angle, Aspect, Altitude, Landslide length, Curvature, Landslide width, Location, Slope type, Landslide depth, Landslide type, SPI (Stream Power Index), TWI (Topographic Wet Index), Slope length, Drainage system | Slope angle, Aspect, Slope length, Altitude, Slope location, Slope type, Slope width, Reinforced facility |
| Geology | Rock type (granite, diorite, gneiss), Weathered Characteristics, Weathered condition, Joint condition, Joint orientation, Water condition (dampness, seeps, groundwater), Tension crack, Soil texture | Parent rock, Rock floor, Effective soil depth, Soil depth, Permeability coefficient, Air-void ratio, Soil texture, Water content, Porosity, Specific gravity, Grain size, Tensile strength, Shear strength | Parent rock, Soil acidity, Soil hardness, Soil organic matter, Soil texture, Total nitrogen, Water contents, C.E.C (Cation Exchange Capacity), Available phosphate, Soil moisture, C/N, Grain size, Exchangeable potassium, Exchangeable calcium, Salt concentration, Exchangeable magnesium, Bulk density, Gravel contents, EC (Electronic Conductivity), Exchangeable sodium |
| Environment | Forest stand, Collapse history, Scale of failure, Checking existence of road, Drainage system, Existence of slope protection, Reinforcement condition | Forest stand, Timber diameter class, Timber age class, Vegetation density, Land use | Vegetation coverage, Individual number, Tree height, Dominance value, Germination percentage, Species diversity, Plant community, Maximum species diversity, Number of trees, Number of herbs, Surrounding vegetation, Crown width, Grass width, Elapsed year |
| Meteorology | Rain intensity | Accumulated rainfall, Amount of rainfall, Rain intensity | - |

Terms with duplicated meanings were then filtered and integrated into a single term (e.g., slope inclination or inclination → slope angle) in accordance with categories of topography, geology, environmental studies, and meteorology. A questionnaire survey were then conducted, targeting experts with total of sixty nine variables (Table 12).

Table 12. Sixty nine variables for expert survey.

| Category | Major variables |
|---|---|
| Topography (11) | Slope angle, Slope height, Slope location, Slope type, Slope width, Altitude, Aspect, Curvature, Catchment basin, SPI (Stream Power Index), TWI (Topographic Wet Index) |
| Geology (31) | Parent rock, Rock floor, Rock type, Joint condition, Joint orientation, Weathered Characteristics, Weathered condition, Soil depth, Porosity, Bulk density, Gravel contents, Grain size, Soil acidity, Soil hardness, Water content, Soil texture, Permeability coefficient, Tensile strength, Shear strength, Specific gravity, Tension crack, C.E.C, EC (Electronic Conductivity), Available phosphate, Soil organic matter, C/N, Salt concentration, T-N, Exchangeable calcium, Exchangeable magnesium, Exchangeable potassium, Exchangeable sodium |
| Environment (23) | Forest stand, Tree height, Plant length, Species diversity, Maximum species diversity, Dominance value, Number of trees, Number of herbs, Grass width, Crown width, Vegetation coverage, Vegetation density, Germination percentage, Plant community, Timber age class, Timber diameter class, Surrounding vegetation, Land use, Drainage system, Elapsed year, Scale of failure, Collapse history, Reinforced facility for slope protection |
| Meteorology (3) | Accumulated rainfall, Amount of rainfall, Rain intensity |

In the survey result, the sixty nine variables were narrowed down to the thirty two variables which were selected by more than half of respondents. In the process, tensile strength[33] was selected but shear strength[34] was not selected. The reason why the shear strength was

33) Tension strength: It is a strength to endure stretching forces; it is a resistance of a soil to separation from ever-increasing tension (Evert, 2010).

34) Shear strength: It is a strength to resist cutting forces; it is a maximum resistance of a soil to shearing stress (Evert, 2010).

not selected might be because most respondents of this survey majored in environmental fields. In addition, more than half of the experts from the survey referred to the variable “seepage water,” although no preceding research was found on it. As a result, total of 33 variables were selected (Table 13).

Table 13. Thirty three variables selected by expert survey.

| Category | Major variables |
|---|---|
| Topography (5) | Slope angle, Slope height, Slope type, Slope width, Aspect |
| Geology (14) | Rock floor, Joint orientation, Weathered Characteristics, Soil depth, Porosity, Soil acidity, Soil hardness, Water content, Soil texture, Permeability coefficient, Tensile strength, Soil organic matter, Salt concentration, Seepage water |
| Environment (11) | Species diversity, Number of trees, Number of herbs, Vegetation coverage, Vegetation density, Germination percentage, Plant community, Drainage system, Elapsed year, Collapse history, Reinforced facility for slope protection |
| Meteorology (3) | Accumulated rainfall, Amount of rainfall, Rain intensity |

Then, some of the 33 variables were integrated or replaced to omit variables that reflected the majority opinion among the surveyed experts but were irrelevant to slope revegetation. The variables of rock floor, joint orientation, weathered characteristics, and reinforced facility for slope protection all dealt with structural stability before the slope revegetation. Thus, they were integrated to become the variable “ground layer.” The variable of species diversity was excluded because it closely relates to other variables (the number of trees and the number of herbs) although it reflects a comprehensive interpretation of species richness and species equilibrium. The variables of vegetation density and germination percentage were excluded because they closely relate to the variable of vegetation coverage. Thus, they were integrated into the latter. The variable of collapse history refers to the record of naturally occurring events before slope revegetation. Thus, it was excluded. Meteorology was excluded from this study due to temporal and physical constraints, as data collection and GIS analysis through long-term monitoring was required for driving forces, such as rainfall or freeze-thaw cycles. Consequently, 23 final variables were selected (Table 14).

Table 14. Twenty three final variables related to slope revegetation.

| Category | Major variables |
|---|---|
| Topography (5) | Slope angle, Slope height, Slope type, Slope width, Aspect |
| Geology (10) | Soil depth, Porosity, Soil acidity, Soil hardness, Water content, Soil texture, Permeability coefficient, Tensile strength, Soil organic matter, Salt concentration |
| Environment (8) | Number of trees, Number of herbs, Vegetation coverage, Plant community, Drainage system, Elapsed year, ground layer, Seepage water |
| Meteorology (0) | - |

The classifications of topography, geology, environment, and meteorology were the outcome not focused on the slope revegetation but on the structural stability. Therefore, to meet the purpose of this study, the selected variables were reclassified into a new categories of physical characteristics, soil properties, and vegetation properties (Table 15).

Table 15. Twenty three final variables reclassified under new categories.

| Category | Major variables |
|---|---|
| Physical characteristics (9) | Slope angle, Slope height, Slope type, Slope width, Aspect, Drainage system, Elapsed year, ground layer, Seepage water |
| Soil (10) | Soil depth, Porosity, Soil acidity, Soil hardness, Water content, Soil texture, Permeability coefficient, Tensile strength, Soil organic matter, Salt concentration |
| Vegetation (4) | Number of trees, Number of herbs, Vegetation coverage, Plant community |

## 4.2 Interrelation between variables

Spearman's correlation analysis was used to analyze the field survey data. The analyzed variables were nine variables of physical characteristics, ten variables of soil properties, and four variables of vegetation properties. Refer to Appendix D for the whole analyzed results.

The result indicated that most of variables of physical characteristics were not related with other variables. However, the ground layer was somewhat correlated with permeability coefficient ($r=0.757$, $p<0.05$), soil depth ($r=0.650$, $p<0.05$), soil acidity ($r=0.650$, $p<0.05$), soil organic matter ($r=0.677$, $p<0.05$), and vegetation coverage ($r=0.667$, $p<0.05$).

The correlation coefficient between the ground layer and several variables of soil and vegetation properties showed significant differences. The value of several soil variables and vegetation coverage of revegetated slope on blasted rock surface was higher than that on soil surface. The type of ground layer therefore could have determined the quality of several soil variables and the vegetation coverage.

In summary, except for the variables of physical characteristics, the variables of soil and vegetation indicated high correlationship. The variables that had high correlations with other variables are summarized in Table 16 and Figure 13.

Table 16. Correlation coefficient for each variable,

| Variable | | Related variable (correlation coefficient) |
|---|---|---|
| Ground layer | | Permeability coefficient (r=0.757*), Soil depth (r=0.650*), Soil acidity (r=0.650*), Soil organic matter (r=0.677*), and Vegetation coverage (r=0.667*) |
| Porosity | | Tensile strength (r=0.787**), Soil depth (r=0.793**), Salt concentration (r=0.665*), Vegetation coverage (r=0.701*) |
| Soil hardness | | Vegetation community (r=-0.695*), Number of trees (r=-0.765**) |
| Water content | | Clay (r=0.685*), Tensile strength (r=0.733*), Salt concentration (r=0.636*), Soil organic matter (r=0.685*) |
| Soil texture | Sand | Silt (r=-0.976**), Tensile strength (r=-0.685*) |
| | Silt | Sand (r=-0.976**), Tensile strength (r=0.685*) |
| | Clay | Water content (r=0.685*) |
| Tensile strength | | Porosity (r=0.787**), Water content (r=0.733*), Sand (r=-0.685*), Silt (r=0.685*), Soil depth (r=0.685*), Salt concentration (r=0.721*) |
| Permeability coefficient | | Soil organic matter (r=0.661*), Number of herbs (r=0.717*) |
| Soil depth | | Porosity (r=0.793**), Tensile strength (r=0.685*), Soil acidity (r=0.842**), Salt concentration (r=0.685*) |
| Soil acidity | | Soil depth (r=0.842**) |
| Salt concentration | | Porosity (r=0.665*), Water content (r=0.636*), Tensile strength (r=0.721**), Soil depth (r=0.636*), Vegetation coverage (r=0.682*) |
| Soil organic matter | | Water content (r=0.685*), Permeability coefficient (r=0.661*), Vegetation coverage (0.813**) |
| Vegetation community | | Soil hardness (r=-0.695*), Vegetation coverage (r=0.769**), Number of trees (r=791**) |
| Vegetation coverage | | Porosity (r=0.701*), Salt concentration (r=0.682*), Soil organic matter (r=0.813**), vegetation community (r=0.769**), Number of trees (r=0.699*) |
| Number of herbs | | Permeability coefficient (r=0.717*) |
| Number of trees | | Soil hardness (r=-0.765**), Vegetation community (r=791**), Vegetation coverage (r=0.699*) |

[Note] *: p<0.05, **: p<0.01

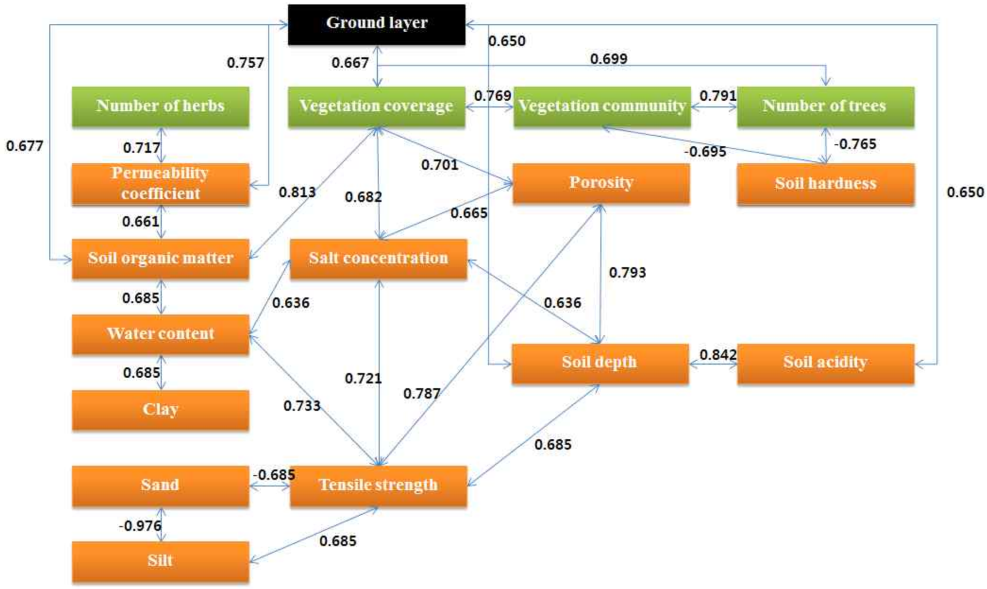


Figure 13. Correlation between variables.

The porosity positively correlated with tensile strength, soil depth, salt concentration, and vegetation coverage. All sites of this study had a salt concentration of less than 0.1%[35] and therefore had no negative effect on vegetation, although stable sites had a relatively higher salt concentration compared with failure sites.

The soil hardness negatively correlated with vegetation community and number of trees. A hard soil formed heterogeneous and simple layers of plant community and reduced the number of trees (Park et al., 2006; Kil et al., 2012). It also had a negative effect on leaf areas and root improvement (Passioura, 2002).

The water content positively correlated with clay, tensile strength, salt concentration, and soil organic matter; the high water content resulted in high proportion of clay in soil texture, high tensile

35) Plant can hardly live at the salt concentration of 0.256% (Brady and Weil, 2009; Kim et al., 2006).

strength, high salt concentration, and high soil organic matter.

The sand ratio of soil texture was negatively correlated with silt and tensile strength. Variables related to the silt ratio of soil texture were positively correlated with tensile strength and negatively correlated with the sand ratio. The clay ratio of soil texture positively correlated with water content.

The tensile strength positively correlated with porosity, silt, soil depth, and salt concentration while negatively correlated with sand ratio. That is, a soil with good viscosity indicated high porosity, silt ratio, soil depth, and salt concentration but low sand ratio. Tensile strength was a major variable of failure because it had six variables with high correlations, which was more than any other variable. The result originated from the complicated physicochemical relations of soil, and the viscosity of soil increased or decreased in correlations between the various soil variables.

The permeability coefficient positively correlated with soil organic matter and the number of herbs. High permeability coefficient means high soil organic matter and high number of herbs. A soil that contains sufficient soil organic matter forms a stable granular structure in which water conducts more rapidly than in an unstable structure, which is easily damaged by humidity (Lal, 1999; Brady and Weil, 2009). A larger number of herbs also appeared in the soil with stable granular structure.

The vegetation communities had high correlations with soil hardness, the number of trees, and the vegetation coverage. Particularly, as the soil hardness increased, the vegetation communities took the shape of heterogeneous simple layers. In addition, the vegetation coverage and the number of trees were high in the sites with homogeneous multiple layers. The vegetation communities of slopes that harmonized with the surrounding landscape and had a harmonious shape played positive roles for human visual preferences (Kim, 2003). Therefore, the vegetation communities with multiple layers that harmonized with the surrounding landscape provided visual stability and helped with structural stability.

The vegetation coverage showed high correlations with the variables of porosity, soil organic matter, salt concentration, vegetation community, and the number of trees. It had more variables with high correlations than other vegetation variables did. That is, the vegetation coverage significantly influenced slope stabilization.

The number of trees highly correlated with soil hardness, vegetation community, and the vegetation coverage. That is, the number of trees meant that the species would increase in low soil hardness, vegetation community with homogeneous multiple layers, and a high vegetation coverage.

The number of herbs highly correlated with permeability coefficient. That is, as the number of herbs increases, the permeability coefficient is high. The number of herbs did not simply increases by high permea bility coefficient, but a certain range of increased permeability coefficient was assumed to interconnect with the increased number of herbs.

A high correlation coefficient between variables belonging to soil and vegetation refers to the close connection between vegetation and soil used in slope revegetation. The correlation between the variables was mixed because it is limited to explain stability as merely one variable. When interpreting the correlation results in this study, the number of sites (10) needs to be considered. The correlation results of some variables were somewhat different from previous research. Soil organic matter is generally seen as inversely proportional to permeability coefficient (Nemes et al., 2005; Saxton and Rawls, 2006). This may be a consequence of a narrow range of survey data.

## 4.3 Comparison between potential risk site and stable site

### 4.3.1 Physical characteristics of a slope

#### (1) Slope angle

The slope angle was measured thrice with a gradiometer at each of the ten sites. Its average value was calculated and then the average value of both potential risk and stable sites were calculated. The results for potential risk sites ranged from 43.00° to 69.27°, with an average of 56.05°. The stable sites ranged from 21.37° to 62.83°, with an average of 44.61°. As the results show, the average slope angle of potential risk sites was higher than that at stable sites. Table 17 summarizes the result.

Table 17. Slope angle in each site.

| Category | | Slope angle | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Avg. |
| | Measured average value | 69.27° | 57.27° | 58.67° | 43.00° | 52.07° | 56.05° |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Avg. |
| | Measured average value | 40.50° | 21.37° | 58.67° | 40.70° | 62.83° | 44.61° |

To verify the distinction between potential risk and stable sites due to the slope angle variable, a non-parametric testing method was applied using the Mann-Whitney U test of Two-independent-samples tests. According to the Mann-Whitney U test, the value of significant probability (or p-value) was 0.040, below the 0.05[36], verifying the significant difference between both groups due to the slope angle.

36) The value of 0.05 means the significant level of 95% in statistical analysis.

However, it was difficult to spot a threshold value of the slope angle that would cause the failure since, as shown in the results, the value of both groups have an overlapping range.

Although all sites were steeply sloped in this study[37], the risk of failure was higher on the potential risk slope than on the stable slope since the inclination of potential risk slope was steeper. Actually, erosion or failure has occurred on other potential risk slopes. The steep inclination is one of the sufficient conditions to cause failure (Cano et al., 2002). When the inclination of the soil slope was higher than approximately 35°, a waterway could be installed or a secondary device could serve as a buffer (Gray and Leiser, 1989). In Korea, a physically based secondary device is typically used when the slope angle is higher than 45° (KCPA, 2012). However, even though the failure sites were steeply sloped, the physically based secondary device was nonexistent. Therefore, it was possible that there were insufficient considerations for the revegetation construction method in the failure site.

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37) Steep slope: ① an artificial slope having over 5 meter of height from the ground, over 34° of slope angle, and over 20 meters of length. ② a natural slope having over 50 meters of height from the ground and over 34° of slope angle. ③ other artificial slopes or natural slopes or forest areas determined to be managed in necessity by management agencies or general directors of the Civic/District/Borough Emergency Management Agency in the special self-governing province, established in accordance with the Article 16 Section 1 of 「Framework Act on the Management of Disasters and Safety」 (Enforcement Decree of the Prevention of Steep Slope Disasters Act)

### (2) Aspect

The aspect was measured with a compass at all ten sites. The potential risk sites included one oriented south-southwest, one east-northeast, one east-southeast, and two north-northeast. The stable sites included two oriented south-southwest, two east-northeast, and one south-southeast.

Table 18. Aspect in each site.

| Category | | Aspect | | | | |
|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 |
| | Measured value | 212.5° | 76.4° | 120° | 3° | 35° |
| | Compass | S-SW | NE-E | E-SE | N-NE | N-NE |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 |
| | Measured value | 206° | 148° | 53° | 213° | 87.5° |
| | Compass | S-SW | SE-S | NE-E | S-SW | NE-E |

In the Mann-Whitney U test, $p=0.310$, indicating an insignificant difference between the groups due to aspect. Thus, it was hardly considered as a major failure-inducing variable (Jeon, 2004; Woo and Jeon, 2005). However, the aspect could have a strong effect on plant growth, including survival of seeds and seedlings since the temperature of soil and atmosphere are different according to the aspect of the slope (David et al., 2007). For example, a southern slope has poorer herbaceous growth or withered vegetation than a northern slope does, due to lower humidity resulted from strong exposure to sunlight (Bochet and Garcia-Fayos, 2004; Helgerson et al., 1992; Jeon, 2004). In summary, the aspect could have a direct effect on a slope's vegetation growth and therefore could have an indirect effect on slope stabilization.

### (3) Slope width and height

The slope width of the potential risk sites ranged from 29.7 m to 138 m, with an average of 92.02 m, and the stable sites ranged from 55 m to 145.4 m, with an average of 96.78 m. In the Mann-Whitney U test, $p=0.917$, indicating an insignificant difference between the groups due to slope width.

Table 19. Slope width in each site.

| Category | | Slope width | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Avg. |
| | Measured value(m) | 93.4 | 138 | 29.7 | 88 | 111 | 92.02 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Avg. |
| | Measured value(m) | 142.3 | 55 | 145.4 | 65.5 | 75.7 | 96.78 |

The slope height of the potential risk sites ranged from 8.2 m to 54 m, with an average of 25.5 m, and the stable sites ranged from 1.1 m to 50.5 m, with an average of 31.54 m. In the Mann-Whitney U test, $p=0.602$, indicating an insignificant difference between the groups due to slope height.

Table 20. Slope height in each site.

| Category | | Slope height | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Avg. |
| | Measured value(m) | 13.3 | 54 | 8.2 | 42 | 10 | 25.5 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Avg. |
| | Measured value(m) | 31.1 | 1.1 | 50.5 | 20 | 55 | 31.54 |

Thus, the statistical results indicated no distinction between potential risk and stable sites due to slope width or height, and they were hardly considered as a major failure-inducing variable. However, slope width and height could have an indirect effect on slope stabilization. They have a negative association with vegetation coverage, which indicates that a wide and tall slope has a slow vegetative growth, leaving a slope in a state of incomplete vegetation coverage with a risk of failure (Jeon, 2004). Except for site 4 among the investigated sites, most failure sites occurred as the result of defective maintenance within the recommended two-year span; thus, the reasons for failure probably were something other than the height and width of the slopes.

### (4) Slope type

The slope type was classified as convex (凸), concave (凹), and straight (□). The potential risk sites consisted of three straight types and two convex types, and the stable sites consisted of three straight types, one convex type, and one concave type.

Table 21. Slope type in each site.

| Category | | Slope type | | | | |
|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 |
| | Type | straight (□) | convex (凸) | straight (□) | convex (凸) | straight (□) |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 |
| | Type | straight (□) | concave (凹) | convex (凸) | straight (□) | straight (□) |

Table 22. Cross tabulation of slope type.

| Category | Concave(凹) | Convex(凸) | Straight(□) | Total |
|---|---|---|---|---|
| Potential risk | 0 | 2 | 3 | 5 |
| Stable | 1 | 1 | 3 | 5 |
| Total | 1 | 3 | 6 | 10 |

In the Mann-Whitney U test, p=0.811, indicating an insignificant difference between the groups due to slope type. Thus, it was hardly considered as a major failure-inducing variable. However, the slope type might have an indirect effect on slope stabilization since the amount of soil loss from erosion and the vegetation coverage differs according to slope type (Jeon et al., 2003; Kikuchi and Yokohama, 1973). It is necessary to further examine the occurrence of soil erosion and the amount of soil loss according to the slope type to establish a correlation between slope type and stabilization.

### (5) Ground layer

The ground layer was classified as soil, weathered rock, and blasted rock. The potential risk sites consisted of four soils and one blasted rock, and the stable sites consisted of one soil, one weathered rock, and three blasted rocks. The ground layer of most collapsed sites was soil, while most stable sites were blasted rock.

Table 23. Ground layer in each site.

| Category | | Ground layer | | | | |
|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 |
| | Type | Soil | Soil | Soil | Blasted rock | Soil |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 |
| | Type | Weathered rock | Soil | Blasted rock | Blasted rock | Blasted rock |

Table 24. Cross tabulation of ground layer.

| Category | Soil | Weathered rock | Blasted rock | Total |
|---|---|---|---|---|
| Potential risk | 4 | 0 | 1 | 5 |
| Stable | 1 | 1 | 3 | 5 |
| Total | 5 | 1 | 4 | 10 |

In the Mann-Whitney U test, p=0.106, indicating an insignificant difference between the groups due to the ground layer. Therefore, it was hardly considered as a major failure-inducing variable. However, since most failure sites had a soil ground layer, much attention should be paid to slope restoration on soil sites.

### (6) Seepage water

Traces of seepage were investigated to determine the correlation between water condition and site failure; however, no traces were found. All sites were completely dry. Most potential risk sites were more than two years old but no seepage was traced, indicating that other variables led to failure.

In the Mann-Whitney U test, p=1.000, indicating an insignificant difference between the groups due to seepage water; thus, it was hardly considered as a major failure-inducing variable.

Table 25. Seepage water in each site.

| Category | | Seepage water | | | | |
|---|---|---|---|---|---|---|
| Potential risk | Site (no.) | 1 | 2 | 3 | 4 | 5 |
| | Seepage trace | n/a | n/a | n/a | n/a | n/a |
| Stable | Site (no.) | 6 | 7 | 8 | 9 | 10 |
| | Seepage trace | n/a | n/a | n/a | n/a | n/a |

### (7) Elapsed year

The elapsed time of the potential risk sites ranged from one to five years, and of the stable sites ranged from four to nine years. In the Mann-Whitney U test, $p=0.020$, indicating a significant difference between the groups due to elapsed time; therefore, it was considered as a major failure-inducing variable.

Table 26. Elapsed year in each site.

| Category | | Elapsed year | | | | |
|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 |
| | year(s) | 3 | 2 | 5 | 1 | 3 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 |
| | year(s) | 6 | 4 | 5 | 6 | 9 |

The average elapsed time of the stable sites was more than that of the potential risk sites, meaning that elapsed time satisfied several conditions of non-failure. Particularly, as the elapsed time increased, the rate of herbaceous species growth decreased and the rate of arboreal species growth increased (Lee et al., 2003b), as did the vegetation coverage increase (Woo et al., 1993). Thus, the survival of vegetation could help with slope restoration (Stokes et al., 2007). Consequently, sufficient elapsed time is needed to stabilize the slope after construction. After long years, the slope revegetation could be considered stabilized.

### (8) Drainage system

The drainage system is summarized in Table 27. In the Mann-Whitney U test, $p=0.072$, indicating an insignificant difference between the groups due to the installation of a drainage system. Therefore, it was hardly considered as a major failure-inducing variable.

In this study, failure did not occur in places where drainage facilities were well installed, since it played an important role in reducing the amount of water input to the slope. Whether the drainage system is good or not, failure can occur. Therefore, other environment variables could have an effect on failure.

Table 27. Drainage system on sites.

| No. | Trace of failure | Drainage system |
|---|---|---|
| 1 | ○ | · No drainage system<br>· Being able to see soil exposed by steep inclination from surroundings forest |
| 2 | ○ | · Multi-layered steps and no drainage system in and out<br>· Continuously scouring erosion around steps |
| 3 | ○ | · No drainage system<br>· Sporadic erosion in relatively long section |
| 4 | ○ | · No drainage system in the berm<br>· Erosion of flow-in water around the berm |
| 5 | ○ | · Well-drained condition in upper and lower drainage |
| 6 | × | · Well-drained condition in a drainage system |
| 7 | × | · Well-drained condition(established in a concave surface as a rehabilitated site after landsliding) |
| 8 | × | · Being able to see drainage tubes to prevent sporadic seepage erosion<br>· Drainage system in the intervals<br>· Normal drainage system |
| 9 | × | · No drainage system<br>· No seepage erosion and no collapse |
| 10 | × | · Revegetation on the blasted rock<br>· No trench on upper slope<br>· No seepage erosion and no collapse |

### (9) Comprehensive interpretation on physical characteristic variables

The variables differing between the two groups were the slope angle and the elapsed time. Since the other variables did not make a difference, they do not have a direct effect on slope revegetation failure in this study.

The slope angle of potential risk sites was steeper. Even though the threshold value of inclination in the failure sites could not be found, the revegetation in slopes having more than 45° of inclination should be more carefully performed. In addition, slope revegetation should be carefully performed when revegetating site with a lot of soil in the ground layer. Since the soil in damaged slopes was exposed, risk of failure also increased with a steep slope. In these cases, physically based secondary devices, such as wire mesh, fabric mesh, and gabion, were necessary. Moreover, when the physically based secondary devices were differently applied according to the type of ground layers, the vegetation coverage showed difference (Kil et al., 2011). When a steep slope is hard pan of blasted rock and installed as wire mesh on that, vegetation coverage was high in comparison with another hard pan such as weathered rock and soil and another device such as fiber mesh.

Some variables influenced the structure and coverage of vegetation rather than site failure. The aspect, slope width, and slope height affected slope restoration according to the speed of vegetation coverage. For example, regarding the aspect, the slope with a southern exposure was dried by sunlight, making vegetation growth difficult there. Thus, it took considerable times for those slopes to stabilize. In addition, regarding slope width and height, as these variables increased, vegetation growth decreased. Thus, it took considerable time for slope stabilization to occur under these circumstances. In other words, slope aspect, height, or width was not characteristics of failure sites, but they implicate the possibility of failure.

The slope type, ground layer, seepage water, and drainage system speak to the slope’s state. Although the difference between the two groups was not verified in terms of these variables, there were some matters to be carefully considered. For example, a slope should be examined in which seepage water occurs, a drainage system is not installed, the slope’s shape is not straight, and the ground layer is soil. The variables were not sufficient but necessary condition to decide failure in this study.

### 4.3.2 Soil property

#### (1) Porosity

The porosity of the potential risk sites ranged from 0.417 to 0.55 $m^3/m^3$, with an average of 0.497 $m^3/m^3$, and the stable sites ranged from 0.55 to 0.65 $m^3/m^3$, with an average of 0.610 $m^3/m^3$. Thus, the average porosity of the potential risk sites was lower than that of the stable sites.

In the Mann-Whitney U test, p=0.000, indicating a significant difference between the groups due to porosity. Therefore, it was considered as a major failure-inducing variable.

Table 28. Porosity in each site.

| Category | | Porosity($m^3/m^3$) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 0.500 | 0.550 | 0.417 | 0.483 | 0.533 | 0.497 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 0.583 | 0.550 | 0.633 | 0.650 | 0.633 | 0.610 |

The average porosity value of the potential risk sites did not meet existing standard of 0.5 $m^3/m^3$ or higher (MOLIT, 2009; KILA[38], 2007). However, potential risk sites 2 and 5, which had poor vegetation coverage, met the standard, indicating that the failure resulted from no single variable (e.g., the porosity) but in a combination thereof.

The standard of 0.5 $m^3/m^3$ or higher is required to prevent erosion or failure, as supported by Jeon's (2002) study of standards for slope

38) KILA: Korean Institute of Landscape Architecture

revegetation. In studies of landslides, the high porosity of soil also had a more positive effect on failure prevention than low porosity did. Soil with high porosity contains large volumes of soil organic matter, which helps healthy vegetation growth, supplementing the soil's bearing capacity, whereas soil with low porosity permeates slowly (Iverson et al., 2000; Brady and Weil, 2009).

#### (2) Soil hardness

The soil hardness of potential risk sites ranged from 5.867 to 16 mm, with an average of 12.667 mm, and the stable sites ranged from 0.833 to 14.6 mm, with an average of 6.933 mm. Thus, the average value of soil hardness in the potential risk sites was higher than that of the stable sites.

In the Mann-Whitney U test, p=0.033, indicating a significant difference between the groups due to soil hardness. Therefore, it is considered as a major failure-inducing variable.

Table 29. Soil hardness in each site.

| Category | | Soil hardness(mm) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 15.000 | 16.000 | 5.867 | 14.067 | 12.400 | 12.667 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 0.833 | 4.000 | 6.900 | 8.333 | 14.600 | 6.933 |

If soil hardness is over 24 mm, a plant could hardly survive (MOLIT, 2009; Kil et al., 2012; Kobashi et al., 1982). All the sites in this study had a value far below the 24 mm, and therefore, plant growth was not hampered, although the average value of the potential risk sites was higher than that of the stable sites. Nevertheless, failure still occurred at potential risk sites, indicating that it did not result from soil hardness alone, but from a combination of variables.

In addition, MOLIT's (2009) "quality and economic evaluation standard and method of revegetation" classifies soil as "defective" if the soil hardness is 11 mm or less; thus, all the stable sites in this study would classified as defective. The standard, however, seems to require reconsideration, since the stable sites in this study have not failed in over six years after construction.

### (3) Water content

The water content was measured more than three days after a rainfall; therefore, a value closer to field moisture capacity[39] was obtained. The maximum water content available for plants was also measured. The soil had the maximum amount of water available for plants, and the pore was filled with sufficient air to provide good air permeability for the survival of aerotropic microorganisms and plant growth (Brady and Weil, 2009).

The water content of the potential risk sites ranged of 0.093 to 0.156 $m^3/m^3$, with an average of 0.115 $m^3/m^3$, and the stable sites ranged of 0.061 to 0.689 $m^3/m^3$, with an average of 0.327 $m^3/m^3$. Thus, the average value of water content of the potential risk sites was

39) After interruption of rainfall or irrigation, the water having the biggest soil porosity was immediately drained down by gravity. As the remaining water flowed down for one to three days, the rapid downstream became ignorable. Here, the soil reached the 'field moisture capacity' (Brady and Weil, 2009).

lower than that of stable sites, and the low water content of the former indicates the possibility of plant growth prevention (KILA, 2007; JSPA[40], 2006).

Table 30. Soil hardness in each site.

| Category | | Water content($m^3/m^3$) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential failure | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 0.156 | 0.093 | 0.116 | 0.102 | 0.109 | 0.115 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 0.061 | 0.128 | 0.153 | 0.601 | 0.689 | 0.327 |

In the Mann-Whitney U test, p=0.041, indicating a significant difference between the groups due to water content. Therefore, it is considered as a major failure-inducing variable.

The site 6, although it is a stable site, had a substantially low value of water content while the highest percentage of sand among the stable sites. Although no statistical correlation between the water content and the sand was found, the result of site 6 indicates the negative causal relationship between them. The available water content of the soil decreases across from silt loamy soil to loamy soil, and to sandy soil (Brady and Weil, 2009).

Site 6, albeit stable, had a substantially low value of water content while having the highest percentage of sand among the stable sites. Although no statistical correlation between the water content and the sand ratio was found, site 6 indicates a negative causal relationship between them. The available water content in the soil decreases from

40) JSPA: Japan Slope Protection Association (全国特定法面保護協会)

silt loamy soil to loamy soil, and to sandy soil (Brady and Weil, 2009).

According to KILA (2007) and JILA[41] (1984) standards, the average water content value of potential risk sites is “Fair” (0.08–0.12 $m^3/m^3$), which means a decent water condition for plant growth. However, since the value is far below the standard, a specific range of values leading to failure should be further examined.

### (4) Soil texture

Soil texture was classified as sand, silt, or clay. The percentage of each type for the potential risk sites was as follows: sand ranged from 81 to 92.63%, with an average of 88.77%; silt ranged from 3 to 12.77%, with an average of 6.80%; and clay ranged from 3.1 to 6.23%, with an average of 4.42%. For the stable sites, sand ranged from 76.37 to 89.10%, with an average of 82.13%; silt ranged from 6.7 to 19.63%, with an average of 13.51%; and clay ranged from 2.6 to 6.07%, with an average of 4.35%.

41) JILA: Japanese Institute of Landscape Architecture

Table 31. Soil texture in each site.

| Category | | | Soil texture | | | | | |
|---|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | Sand | 81.00 | 90.10 | 92.63 | 91.43 | 88.70 | 88.77 |
| | | Silt | 12.77 | 5.47 | 3.00 | 4.57 | 8.20 | 6.80 |
| | | Clay | 6.23 | 4.43 | 4.33 | 4.00 | 3.10 | 4.42 |
| Stable | Site(no.) | | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | Sand | 89.10 | 87.17 | 78.23 | 76.37 | 79.80 | 82.13 |
| | | Silt | 8.30 | 6.70 | 16.97 | 19.63 | 15.97 | 13.51 |
| | | Clay | 2.60 | 6.07 | 4.83 | 4.00 | 4.23 | 4.35 |

In the Mann-Whitney U test, $p=0.001$ for sand and $p=0.001$ for silt, both of which indicating a significant difference between the groups due to sand and silt soil textures. For clay, $p=0.771$, indicating an insignificant difference between the groups due to it. The percentage of sand in the potential risk sites was higher than that of the stable sites, whereas the percentage of silt in the potential risk sites was lower than that of the stable sites.

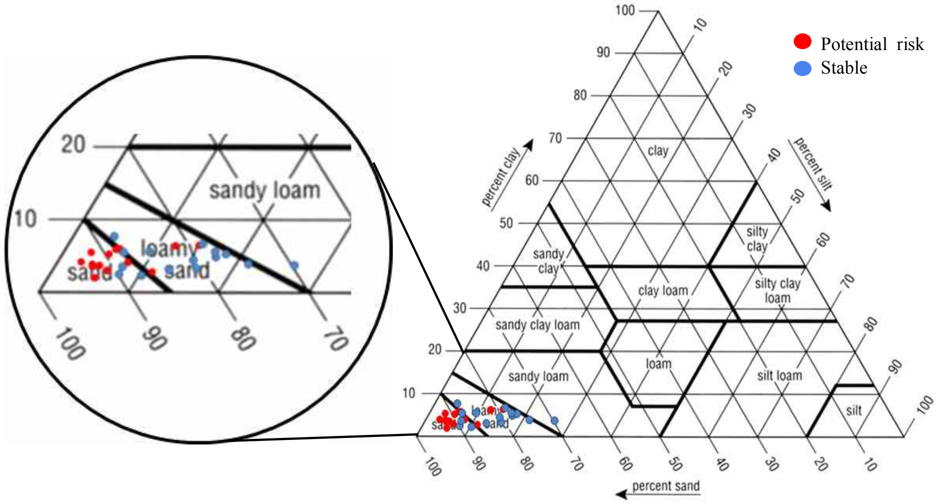


Figure 14. Soil texture triangle of potential risk and stable sites.

Soil texture can be determined by the USDA soil texture triangle. For example, the potential risk sites fell in the "sand" class (88.77% sand, 6.80% silt, and 4.42% clay). The stable sites fell in the "loamy sand" class (82.13% sand, 13.51% silt, and 4.35% clay). Thus, the soil texture of the potential risk sites had a highest percentage of sand while having the lowest percentage of silt than the stable sites had. The high percentage of sand means low soil organic matter as well as porosity in the soil (Brady and Weil, 2009).

The component ratio of the soil at the sites was similar those in Park et al. (2006) but significantly different from that of Korean forests: the topsoil layer was consisted of sand, ranging from 24 to 45%; silt, ranging from 39 to 51%; and clay, ranging from 15 to 23% (Jeong et al., 2003). The sand has negative correlation while the silt has positive correlation with the tensile strength in the correlation analysis. Thus, the lack of cohesion in the soil affected the failure in some areas. Higher percentages of sand increase the risk of failure and soil erosion (Park et al., 2006).

However, the soil of the stable sites also had a high percentage of sand (82.13% on average) when compared to the standard Korean forest soil. The non-failure, in spite of the high percentage of sand, is supposed to be due to prevention through physically based secondary devices at the time of slope revegetation.

### (5) Tensile strength

The tensile strength of the potential risk sites ranged from 1.433 to 1.717 kPa, with an average of 1.519 kPa, and the stable sites ranged from 1.537 to 2.043 kPa, with an average of 1.813 kPa. Thus, the average tensile strength of the potential risk sites was lower than that of the stable sites. In the Mann-Whitney U test, $p=0.001$, indicating a significant difference between the groups due to tensile strength.

Table 32. Tensile strength in each site.

| Category | Tensile strength(kPa) | | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 1.717 | 1.470 | 1.473 | 1.433 | 1.500 | 1.519 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 1.623 | 1.537 | 1.973 | 2.043 | 1.890 | 1.813 |

Although no correlation has been found in the statistical analysis of the water content in a soil with a high percentage of sand, the tensile strength increased in proportion to the water content (Kim et al., 2004; Kim and Hwang, 2003). The current study showed a similar result. However, the limit of artificial soil[42]'s tensile strength was not verified in this study, due to uncontrollable variables.

Tensile strength is a major variable to induce failure, as it has the highest correlation with other variables—six in total. This is due to the complicated physicochemical correlational characteristic of soil, which gives tensile strength the role of an adhesive controller among the variables.

### (6) Permeability coefficient

The permeability coefficient of the potential risk sites ranged from $2.38\times10^{-4}$ to $3.11\times10^{-3}$ cm/s, with an average of $1.34\times10^{-3}$ cm/s, and the stable sites ranged from $1.27\times10^{-3}$ to $8.23\times10^{-3}$ cm/s, with an average of $3.06\times10^{-3}$ cm/s. Thus, the average permeability coefficient of the stable site was higher than that of the potential risk site. In

42) The artificial soil calls soil used in the slope revegetation and generally mingle with soil ameliorant such as vermiculite, cocopeat and sawdust.

addition, the values of both groups were not in the failure inducing level. According to Chae et al. (2009), the standard range for a “Fair” condition is $2.5\times10^{-3}$ to $4.5\times10^{-3}$ cm/s. In the Mann-Whitney U test, p=0.007, indicating a significant difference between the groups due to permeability coefficient.

Table 33. Permeability coefficient in each site.

| Category | | Permeability coefficient(cm/s) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | $2.38\times10^{-4}$ | $2.53\times10^{-4}$ | $2.51\times10^{-3}$ | $3.11\times10^{-3}$ | $5.76\times10^{-4}$ | $1.34\times10^{-3}$ |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | $1.64\times10^{-3}$ | $1.27\times10^{-3}$ | $8.23\times10^{-3}$ | $1.55\times10^{-3}$ | $2.58\times10^{-3}$ | $3.06\times10^{-3}$ |

If permeability coefficient is over $1\times10^{-4}$ cm/s or under $1\times10^{-7}$ cm/s, it causes drainage problems and results in poor growth of plant roots (Brady and Weil, 2009; Marshall et al., 1996). Most sites in this study were within those limits; thus, plant growth was not constrained. However, the permeability coefficient of stable sites was higher than the potential risk sites because of sufficient porosity in the former to move plant root and water content.

### (7) Soil depth

The soil depth of the potential risk sites ranged from 0.2 to 6.2 cm, with an average of 3.58 cm, and the stable sites ranged from 0.2 to 16.1 cm, with an average of 9.21 cm. Thus, the average soil depth of the potential risk sites was lower than that of the stable sites. In the Mann-Whitney U test, p=0.002, indicating a significant difference between the groups due to soil depth.

Table 34. Soil depth in each site.

| Category | | Soil depth(cm) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 4.30 | 4.33 | 1.33 | 3.57 | 4.37 | 3.58 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 7.67 | 1.03 | 13.17 | 10.40 | 13.80 | 9.21 |

Except for in site 7, the soil of the stable sites was deeper than that of the potential risk sites. It was determined that the average slope of site 7 was very low (21.58°). Thus, the soil depth was slightly dependent on the artificial soil for revegetation. On steep slopes, a thick layer of soil is attached to prevent soil erosion or failure (KCPA, 2012). However, the thick layer of soil was not attached at the potential risk sites, even though all were steeply sloped. Therefore, a sufficiently thick layer of soil is needed for steep slopes.

### (8) Soil acidity (pH)

The soil acidity of the potential risk sites ranged from 4.58 to 7.41 pH, with an average of 6.07 pH, and the stable sites ranged from 5.01 to 7.77 pH, with an average of 6.89 pH. Thus, the average soil acidity in the potential risk sites was lower than that of the stable sites. In the Mann-Whitney U test, p=0.015, indicating a significant difference between the groups due to soil acidity.

Table 35. Soil acidity in each site.

| Category | | Soil acidity(pH) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 4.71 | 5.99 | 5.40 | 6.86 | 7.38 | 6.07 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 7.12 | 5.06 | 7.60 | 7.09 | 7.58 | 6.89 |

The soil acidity of all the study sites was not in the range that would hinder plant growth, although the value of stable sites was higher due to an organic acid inflow from a high content of soil organic matter (Brady and Weil, 2009). However, different plants have different tolerances to soil acidity; therefore, it is difficult to generalize the limiting conditions implied by soil acidity due to the physiological factors involved (Haigh, 2000).

### (9) Salt concentration

The salt concentration of the potential risk sites ranged from 0.005 to 0.039%, with an average of 0.012%, and the stable sites ranged from 0.011 to 0.070%, with an average of 0.034%. Thus, the average salt concentration in the potential risk sites was slightly lower, only 0.02%, than that of the stable sites. In the Mann-Whitney U test, $p=0.001$, indicating a significant difference between the groups due to salt concentration.

Table 36. Salt concentration in each site.

| Category | | Salt concentration(%) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 0.005 | 0.005 | 0.039 | 0.007 | 0.006 | 0.012 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 0.012 | 0.011 | 0.070 | 0.031 | 0.048 | 0.034 |

The salt concentration of all the study sites was not in the range that would hinder plant growth. Plants could hardly live in a salt concentration of 0.256% (Brady and Weil, 2009; Kim et al., 2006). All of the investigated data was less than 0.1%.

### (10) Soil organic matter

The soil organic matter of the potential risk sites ranged from 0.55 to 7.00%, with an average of 2.34%, and the stable sites ranged from 2.99 to 16.40%, with an average of 10.41%. This, the average amount of soil organic matter in the potential risk sites was lower than that in the stable sites. In the Mann-Whitney U test, p=0.000, indicating a significant difference between the groups due to soil organic matter. Therefore, it is considered as a major failure-inducing variable.

Table 37. Soil organic matter in each site.

| Category | | Soil organic matter(%) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential risk | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 1.08 | 1.17 | 7.00 | 1.89 | 0.55 | 2.34 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 5.00 | 2.99 | 13.19 | 14.47 | 16.40 | 10.41 |

Soil organic matter most significantly affects soil properties; it plays a dominant role in changing the physical properties of soil. It improves cation exchange capacity, provides the most nitrogen and 50 to 60% of available phosphate, and increases the water content to preserve the soil and availability for plant growth (Brady, 1990; Brady and Weil, 2009). According to the classification[43] of the horizon of the forest soil in Korea, the soil organic matter of layer A is at least more than 3% and of layer B is more than 1.5% (Jeong et al., 2003).

When the soil organic matter is higher, the slope becomes more stabilized. The soil organic matter of the stable sites were 2.99 – 16.40% (in site 7, it was close to 3%). Thus, it would not be probably detrimental. Even though the average soil organic matter in the forest area in Gangwon-do was as high as 4.93%, the minimum value was 2.49% (Jeong et al., 2002). However, it was very poor in all other potential risk sites (under 2%), except in site 3.

Thus, the low level of soil organic matter hindered plant growth and increased the probability of slope revegetation failure. As a results of research performed by Park et al. (2006) about the soil environment analysis of domestic cut slopes and surrounding natural vegetation, the soil organic matter ratios of slopes in adjacent expressways were 0.32 – 1.90%, and the soil organic matter ratios of the surrounding natural vegetation area were 1.88 – 5.43%. The results in this study were similar. However, in sites 8 – 10, it was more than twice the average soil organic matter of forest soils in Korea; it was similar with the soil organic matter of Jeju-do (Jeong et al., 2002) or of Japanese areas (Kawada, 1989).

43) The soil horizon is generally marked as O, A, B, C, and R; as it defines the correlations between the soil layers, it should have genetic meaning (Cho, B.H., 2002).

### (11) Comprehensive interpretation for soil properties

Significant differences occurred in the variables related to soil in the two groups. Among the soil variables, the most correlational variable was tensile strength. The tensile strength increased if the porosity and water content were high, the soil was deep, the sand content was low, and the silt content was high. Furthermore, tensile strength directly relations with slope revegetation failure. If the tensile strength is low, failure might occur. In addition, the porosity, water content, and soil organic matter were major variables having high correlations with more than three variables. That is, if the tensile strength among these variables were examined in the context of slope revegetation, the appropriate soil condition for slope restoration could be verified. Likewise, if these were examined, the structural safety of soil could be verified.

The minimum required tensile strength for slope stability is believed to be more than 1.5 kPa. The tensile strength of actual failure sites was mostly under 1.5 kPa. In addition, as the tensile strength of all stable sites was more than 1.5 kPa, this minimum requirement seems to be valid.

As the porosity of the potential risk sites was under 0.5 $m^3/m^3$ and over 0.5 $m^3/m^3$ in the stable sites, at least 0.5 $m^3/m^3$ seems to be the requirement for slope restoration.

As the water content of the potential risk sites was under 0.12 $m^3/m^3$ and was mostly over 0.12 $m^3/m^3$ in the stable sites, at least 0.12 $m^3/m^3$ seems to be the requirement for slope restoration.

As the soil organic matter of the potential risk sites was under

2.5% and was over 3% in the stable sites, at least 3% seems to be the requirement for slope restoration.

The other variables (soil hardness, soil texture, permeability coefficient, soil depth, soil acidity, and salt concentration) showed significant differences between the groups. Thus, they could be important variables. Soil hardness did not affect slope stability as much as it did plant growth in this study. However, the evaluation standard of “defective” soil hardness, less than 11 mm according to MOLIT (2009), should be improved because it was 6.933 mm on average in the stable sites for this study. In addition, the soil hardness of natural vegetation areas was approximately 5 ~ 11 mm (Park et al., 2006), so that standard also needs to be modified.

In the soil texture, the ratios of sand and silt were the important items for consideration. If the ratio of sand in the soil was more than 85% and that of silt was less than 10%, failure occurs. It is attributed to the low tensile strength of soil with a high ratio of sand.

The permeability coefficient of sites in this study was mostly in the range of $10^{-2}$ ~ $10^{-3}$ cm/s, which did not disturb the plant growth and thus limited the ability to find direct correlations with slope failure. However, it was evident that if the soil was deeper, it was more stable. Furthermore, as the soil acidity of the investigated data was 4.7 –7.60 pH on average, it did not interrupt plant growth. Nor did the salt concentration of all investigated data, which was less than 0.1%.

In summary, regarding the appropriate soil condition for slope stabilization, the tensile strength should be more than 1.5 kPa, the porosity should be more than 0.5 m3/m3, the water content should be more than 0.12 m3/m3, and the soil organic matter should be more than 3%. These results were applicable for the condition of “Fair” according to the standard of normal soil (KILA, 2007; JILA, 1984), except for the variable of tensile strength. Currently, MOLIT (2009) supports the representative soil standard for slope revegetation. Institutional supplements must add the standards of tensile strength, porosity, and water content to the existent standards for “Fair” conditions in the normal soil standards. Furthermore, some of the evaluation standards for soil hardness should be improved. The evaluation standards for soil with reduced sand content and increased silt content must also be improved. And the depth of soil is necessary for slope stabilization. Finally, in this study, the permeability coefficient, soil depth, soil acidity, and salt concentration did not hinder plant growth, but it should be continuously maintained. These various effects would contribute to the soil of healthy slope revegetation.

### 4.3.3 Vegetation property

#### (1) Vegetation community

All types of vegetation communities in the potential risk sites were heterogeneous. Most vegetative layers in the potential risk sites were simple. With the stable sites, homogeneous multiple layers were predominant.

In the Mann-Whitney U test, the difference between the groups were significantly different (p=0.000). Each classification of the vegetation communities are found on Tables 38 and 39.

Table 38. vegetation community in each site.

| No. | Potential failure slope | No. | Stable |
|---|---|---|---|
| 1 | Heterogeneous simple layer | 6 | Homogeneous multiple layer |
| 2 | Heterogeneous simple layer | 7 | Homogeneous multiple layer |
| 3 | Heterogeneous multiple layer | 8 | Homogeneous simple layer |
| 4 | Heterogeneous simple layer | 9 | Heterogeneous multiple layer |
| 5 | Heterogeneous simple layer | 10 | Homogeneous multiple layer |

Table 39. Classification of each site for vegetation community.

| Category | Simple | Multiple |
|---|---|---|
| Heterogeneous | 1, 2, 4, 5 | 3, 8, 9 |
| Homogeneous | - | 6, 7, 10 |

The variable of vegetation community was different between the potential risk and stable sites. Most stable sites showed a homogeneous landscape with adjacent environments and a vegetative form of multiple layers. Except for site 3, vegetation communities in the potential risk sites were heterogeneous and simple with very simple structures of vegetation. In sites 8 and 9, the community was heterogeneous and multiple, and even though there were various type of vegetation, mugwort mostly dominated the landscape.

### (2) Vegetation coverage

The vegetation coverage was 15 ~ 92.67% in the potential risk sites and 93.67 ~ 99.67% in the stable sites.

In the Mann-Whitney U test, the difference between the two groups was significant ($p=0.000$). Each rate of vegetation coverage is shown on Table 40.

Table 40. Vegetation coverage in each site.

| Category | | Vegetation coverage (%) | | | | | |
|---|---|---|---|---|---|---|---|
| Potential failure | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 15.00 | 28.67 | 90.67 | 92.67 | 39.33 | 53.27 |
| Stable | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 99.00 | 93.67 | 99.67 | 99.33 | 99.33 | 98.20 |

The variables of the vegetation coverage demonstrated a difference between the potential risk and stable sites. Except for sites 3 and 4, the vegetation coverage was less than 40% in the potential risk sites. Fewer arbor species existed in places with very low porosity, soil organic matter, and vegetation coverage. It was assumed to be the result of difficult soil conditions and ground layers for vegetation without physically based secondary devices.

### (3) Number of trees

Fifteen species of trees were observed in total. The potential risk sites had different number of species, ranging from 1 to 4 and the stable sites had different number of species, ranging from 2 to 10. Short-stalked bush clover (*Lespedeza cyrtobotrya*) appeared on seven sites. Indigo plants (*Indigofera pseudotinctoria*) appeared on five sites. False acacia plants (*Robinia pseudoacacia*), silk trees (*Albizzia julibrissin*), and Manchurian alder (*Alnus sibiroca*) appeared on four sites.

The dispersion of trees of the potential risk sites were mostly small-sized leguminous plants, whereas the stable sites were diverse including tall-sized *Quercus mongolica*, *Morus bombycis, Ailanthus altissima*. The diverse dispersion of tall-sized trees positively affected on rich organic matter accumulation due to their rotting leaves and root decomposition (Zhang and Chu, 2011; Brady and Weil, 1996; Berendse et al., 1998). Accordingly, the soil organic matter of the stable sites was higher than its potential risk sites.

In the Mann-Whitney U test, the difference between the two groups was significant (p=0.002). The number of trees on each site is summarized on Tables 41 and 42.

Table 41. State of trees on each site.

| Category | | Number of trees | Botanical name |
|---|---|---|---|
| 1 | Potential risk | 1 | *Lespedeza cyrtobotrya* |
| 2 | Potential risk | 3 | *Lespedeza cyrtobotrya, Rubus crataegifolius Bunge, Indigofera pseudotinctoria* |
| 3 | Potential risk | 4 | *Indigofera pseudotinctoria, Rubus crataegifolius Bunge, Robinia pseudoacacia, Lespedeza cyrtobotrya* |
| 4 | Potential risk | 1 | *Robinia pseudoacacia* |
| 5 | Potential risk | 1 | *Lespedeza cyrtobotrya* |
| 6 | Stable | 4 | *Clerodendrum trichotomum, Prunus sargentii, Lespedeza cyrtobotrya, Robinia pseudoacacia* |
| 7 | Stable | 6 | *Rhus chinensis, Albizzia julibrissin, Firmiana simplex, Salix koreensis Andersson, Indigofera pseudotinctoria, Alnus sibiroca* |
| 8 | Stable | 2 | *Albizzia julibrissin, Alnus sibiroca* |
| 9 | Stable | 4 | *Albizzia julibrissin, Quercus mongolica, Lespedeza cyrtobotrya, Indigofera pseudotinctoria* |
| 10 | Stable | 10 | *Albizzia julibrissin, Ailanthus altissima, Alnus sibiroca, Morus bombycis, Alnus sibiroca, Lespedeza cyrtobotrya, Indigofera pseudotinctoria, Zanthoxylum piperitum, Rubus crataegifolius Bunge, Robinia pseudoacacia* |

Table 42. Frequency of trees.

| Frequency | Botanical name |
|---|---|
| 7 | *Lespedeza cyrtobotrya* |
| 5 | *Indigofera pseudotinctoria* |
| 4 | *Albizzia julibrissin, Alnus sibiroca, Robinia pseudoacacia* |
| 3 | *Rubus crataegifolius Bunge* |
| 1 | *Ailanthus altissima, Clerodendrum trichotomum, Firmiana simplex, Morus bombycis, Prunus sargentii, Quercus mongolica, Rhus chinensis, Salix koreensis Andersson, Zanthoxylum piperitum* |

Except on site 3, trees rarely appeared. The most dominant species of trees were *Lespedeza cyrtobotrya*, followed by *Indigofera pseudotinctoria, Robinia pseudoacacia, Albizzia julibrissin, Alnus sibiroca* and *Rubus crataegifolius Bunge*. Altogether, leguminous and chrysanthemum plants dominated the sites.

### (4) Number of herbs

All the herbs observed were specimens of 59 species. There were 4 ~ 14 species in the potential risk sites and 6 ~ 22 species in the stable sites. The herbage, mugwort (*Artemisia princeps var. orientalis*), cool-season grasses (*Poa pratensis*), Japanese hops (*Humulus japonicus*), jewelweeds (*Impatiens textori*), yomena herbs (*Aster yomena*), wild chrysanthemum herbs (*Dendranthema boreale (Makino) Ling ex Kitam*) and daisy fleabanes (*Erigeron annuus*) appeared more than five sites.

In the Mann-Whitney U test, the difference between the two groups was insignificant ($p=0.394$). The number of herbs on each site is shown on Tables 43 and 44.

Table 43. State of herbs on each site.

| Category | | Number of herbs | Botanical name |
|---|---|---|---|
| 1 | Potential risk | 4 | *Poa pratensis, Humulus japonicus, Artemisia feddei Lev. et Van., Arundinella hirta* |
| 2 | Potential risk | 11 | *Aster yomena, Poa pratensis, Persicaria hydropiper, Miscanthus sinensis var. purpurascens, Crepidiastrum sonchifolium, Dendranthema boreale, Metaplexis japonica, Artemisia montana Pampan, Picris hieracioides var. glabrescens, Commelina communis, Solidago virga-aurea var. asiatica* |
| 3 | Potential risk | 11 | *Chelidonium majus var. asiaticum, Inula britannica var. chinensis, Poa pratensis, Clematis apiifolia, Commelina communis, Humulus japonicus, Impatiens textori, Erigeron annuus, Aster yomena, Dendranthema boreale* |
| 4 | Potential risk | 14 | *Artemisia princeps var. orientalis, Centaurea cyanus, Aster yomena, Coreopsis drummondii, Coreopsis tinctoria, Silene armeria, Crepidiastrum sonchifolium, Callistephus chinensis, Humulus japonicus, Medicago sativa, Cosmos bipinnatus, Dianthus superbus var. longicalycinus, Impatiens textori, Persicaria hydropiper* |
| 5 | Potential risk | 9 | *Cosmos bipinnatus, Trifolium repens, Artemisia princeps var. orientalis, Dendranthema boreale, Silene armeria, Dianthus superbus var. longicalycinus, Chenopodium album var. centrorubrum, Setaria viridis* |
| 6 | Stable | 19 | *Angelica decursiva, Aconitum pseudo-proliferum, Aster ageratoides Turcz. var. ageratoides, Peucedanum terebinthaceum, Crepidiastrum denticulatum, Artemisia princeps var. orientalis, Chenopodium album var. centrorubrum, Potentilla fragarioides var. major, Poa pratensis, Impatiens textori, Erigeron annuus, Persicaria hydropiper, Trifolium repens, Pteridium aquilinum var. latiusculum, Chenopodium ficifolium, Commelina communis, Humulus japonicus, Oenothera biennis, Pilea mongolica* |
| 7 | Stable | 13 | *Coreopsis drummondii, Lotus corniculatus var. japonicus, Poa pratensis, Echinacea angustifolia, Aster yomena, Dianthus superbus var. longicalycinus, Arundinella hirta, Rubia akane, Geranium sibiricum, Chelidonium majus var. asiaticum, Setaria viridis, Artemisia princeps var. orientalis, Erigeron annuus* |
| 8 | Stable | 15 | *Artemisia princeps var. orientalis, Lactuca indica var. laciniata, Dendranthema boreale, Impatiens textori, Taraxacum officinale, Prunella vulgaris Linne var. lilacina Nakai, Phragmites communis, Arundinella hirta, Rumex crispus L., Peucedanum terebinthaceum, Humulus japonicus, Coreopsis tinctoria, Silene armeria, Lotus corniculatus var. japonicus* |
| 9 | Stable | 6 | *Artemisia princeps var. orientalis, Miscanthus sinensis var. purpurascens, Lotus corniculatus var. japonicus, Erigeron annuus, Lespedeza cuneata, Arundinella hirta* |
| 10 | Stable | 22 | *Dendranthema boreale, Elsholtzia ciliata, Humulus japonicus , Rubia akane, Persicaria hydropiper, Poa pratensis, Stellaria media, Erigeron annuus, Setaria viridis, Boehmeria tricuspis , Aster yomena, Impatiens textori, Metaplexis japonica, Leonurus japonicus Houtt., Oenothera biennis, Oenanthe javanica, Lactuca indica var. laciniata, Artemisia princeps var. orientalis, Achillea millefolium, Aristolochia contorta Bunge , Imperata cylindrica var. koenigii,* |

Table 44. The frequency of herbs.

| Frequency | Botanical name |
|---|---|
| 7 | *Artemisia princeps var. orientalis* |
| 6 | *Poa pratensis, Humulus japonicus* |
| 5 | *Impatiens textori, Dendranthema boreale (Makino) Ling ex Kitam, Aster yomena, Erigeron annuus,* |
| 4 | *Persicaria hydropiper, Arundinella hirta* |
| 3 | *Setaria viridis, Silene armeria L., Commelina communis L., Commelina communis L., Dianthus superbus var. longicalycinus* |
| 2 | *Crepidiastrum sonchifolium, Coreopsis drummondii L., Peucedanum terebinthaceum, Rubia akane Nakai, Oenothera biennis, Chenopodium album var. centrorubrum, Metaplexis japonica, Chelidonium majus var. asiaticum, Miscanthus sinensis var. purpurascens, Lactuca indica var. laciniata, Coreopsis tinctoria, Cosmos bipinnatus, Trifolium repens L.* |
| 1 | *Phragmites communis, Aconitum pseudo-proliferum, Boehmeria tricuspis (Hance) Makino, Pteridium aquilinum var. latiusculum, Callistephus chinensis, Inula britannica, Aster ageratoides Turcz. var. ageratoides, Aster ageratoides Turcz. var. ageratoides, Imperata cylindrica var. koenigii, Rudbeckia hirta L, Pilea mongolica, Oenanthe javanica, Solidago virga-aurea var. asiatica, Angelica decursiva, Stellaria media, Artemisia feddei Lev. et Van., Clematis apiifolia DC., Artemisia montana Pampan, Artemisia montana Pampan, Achillea millefolium L., Rumex crispus L., Picris hieracioides var. glabrescens, Centaurea cyanus, Medicago sativa, Potentilla fragarioides var. major, Youngia denticulata, Leonurus sibiricus L, Chenopodium ficifolium, Aristolochia contorta Bunge, Geranium sibiricum L., Elsholtzia ciliata, Lespedeza cuneata* |

The most dominant species of herbs were *Artemisia princeps var. orientalis*, followed by *Poa pratensis* and *Humulus japonicus. Impatiens textori, Dendranthema boreale (Makino) Ling ex Kitam, Aster yomena*, and *Erigeron annuus* also appeared on five sites. As with the number of trees, poaceae and leguminous and chrysanthemum plants dominated the sites. Particularly, *Artemisia princeps var. orientalis, Poa pratensis* and *Humulus japonicus* were the plants of secession from the surroundings. If these plants dominated a site, the plants of surroundings environment would impossibly invade into. Even as time passed, it could not be led to natural landscape restoration or it would take a long time (Kim, 1998). Thus, the increased number of species was not always a good thing, and the domination rate of introduced species should be carefully monitored. As shown in site 8, even though five years had elapsed since construction, *Artemisia princeps var. orientalis* still dominated, slowing down the ecological succession. In addition, the increased number of herbs could not achieve slope restoration. If the number of herbs increases but vegetation coverage is low, the slope risks failure.

### (5) Comprehensive interpretation for vegetation properties

Except for the number of herbs, all of these variables made a difference between the potential risk and stable sites. Thus, the appearance of trees was assumed to be important for slope stabilization because the vegetation structure of the stable sites was mostly multiple layers with high vegetation coverage and large number of trees. The multiple layers instead of simple structures accompanied the appearance of trees. Thus, the increased number of trees is preferable for slope stabilization. The increased number of herbs, on the other hand, is not. There are many previous studies (Espigares et al., 2011; García-Fayos et al., 2010; Hosogi et al., 2006) regarding the use of herbs. However, trees should take precedent for sustainable stabilization.

Chrysanthemum and leguminous plants dominated the sites in the investigated area. Particularly, the leguminous plants were symbiotic for nitrogen fixation (Hopkins and Hüner, 2008). Since nitrogen is very important for plant growth, the nitrogen fixation of leguminous plants is beneficial for barren areas. Thus, the high ratio of leguminous plants indicates that sufficient nitrogen was supplied to the sites to the benefit of plant growth. Furthermore, nitrogen circulation helps to create soil organic matter.

### 4.3.4 Implication for potential risk site and stable sites

As shown in the previous results, the variables of physical characteristics had limitations as variables for slope stabilization. All the soil variables were related to slope failure. That is, rather than the environmental condition of the slope, the construction method of slope revegetation would cause failure. Thus, high soil quality would prevent the revegetation failure.

As shown in the results of the non-parametric testing and the correlation analysis, variables of physical characteristics that satisfied both analyses were not found. The variables of soil condition could be considered important. Particularly, regarding tensile strength, the standard of 1.5 kPa should be the new standard. However, if more future cases were researched, clearer standards would be established. Furthermore, the porosity should be more than 0.5 $m^3/m^3$, the water content should be more than 0.12 $m^3/m^3$, and the soil organic matter should be more than 3% to meet the standards for a “Fair” condition of normal soil evaluation. It was also confirmed that the evaluation standards of MOLIT (2009) should be extensively applied.

Soil hardness standards should be partly modified from the above evaluation standards, and other variables should be continuously maintained in relation to plant growth. In addition, except for the number of herbs, the vegetation community, vegetation coverage, and number of trees variables are necessary for slope stabilization. Particularly, the vegetation coverage highly correlates with other soil and vegetation variables, making it a major variable for slope stabilization. Moreover, failure did not occur in revegetation areas that matched with the surrounding landscape and have a large number of native trees. Therefore, the current, herb-oriented slope revegetation strategy should be reconsidered.

## 4.4 Comparison of Collapsed and Potential Risk Soil

The investigated data in this study indicates that slope erosion or failure occurs in the soil slope. Considering the phenomenon, the soil slope should be researched because it is based on the soil and the changes of physiochemical properties therein. Therefore, the properties of the soil in the ground layer and the conditions of slope revegetation should be compared. It was expected that the soil used in the soil slope and ground layer would be different. The parent material of the ground layer in all the failure sites was granite.

### (1) Porosity

The porosity in collapsed sites ranged from 0.467 to 0.533 $m^3/m^3$, with an average of 0.503 $m^3/m^3$, and it ranged from 0.417 to 0.533 $m^3/m^3$ in potential risk sites, with an average of 0.497 $m^3/m^3$.

In the Mann-Whitney U test, the difference between the groups was insignificant ($p=0.795$). Nevertheless, the average porosity of potential risk sites was lower than that of collapsed sites. Each average value of porosity is shown on Table 45.

Table 45. Porosity within each site.

| Category | | Porosity($m^3/m^3$) | | | | | |
|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 0.500 | 0.517 | 0.500 | 0.467 | 0.533 | 0.503 |
| Potential risk | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 0.500 | 0.550 | 0.417 | 0.483 | 0.533 | 0.497 |

### (2) Soil hardness

The soil hardness of collapsed sites ranged from 1.5 to 21.2 mm, with an average of 8.38 mm, and it ranged from 0.5 to 28 mm in potential risk sites, with an average of 12.667 mm.

In the Mann-Whitney U test, the difference between the groups was insignificant ($p=0.184$). Nevertheless, the average soil hardness of the collapsed sites was lower than that of the potential risk sites. Each average value of soil hardness is shown on Table 46.

Table 46. Soil hardness within each site.

| Category | | Soil hardness(mm) | | | | | |
|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 4.333 | 9.700 | 9.867 | 2.333 | 15.667 | 8.380 |
| Potential risk | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 15.000 | 16.000 | 5.867 | 14.067 | 12.400 | 12.667 |

### (3) Water content

The water content of the collapsed sites ranged from 0.041 to 0.090 $m^3/m^3$, with an average of 0.061 $m^3/m^3$, and it ranged from 0.045 to 0.158 $m^3/m^3$ in the potential risk sites, with an average of 0.115 $m^3/m^3$.

In the Mann-Whitney U test, the difference between the groups was significant ($p=0.000$). Thus, the average water content of the collapsed sites was lower than that of the potential risk sites. Each average value of water content is shown on Table 47.

Table 47. Water content within each site.

| Category | | Water content($m^3/m^3$) | | | | | |
|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 0.069 | 0.054 | 0.044 | 0.050 | 0.086 | 0.061 |
| Potential risk | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 0.156 | 0.093 | 0.116 | 0.102 | 0.109 | 0.115 |

### (4) Soil texture

The soil texture was classified as three types: sand, silt, or clay. Each ratio for the soil texture of the collapsed sites ranged from 84.4 to 94.5% for sand, with an average of 90.07%; it ranged from 2.2 to 9.9% for silt, with an average of 5.79%; and it ranged from 2.3 to 6.6% for clay, with an average of 4.15%. Likewise, at the potential risk sites, it ranged from 79.2 to 93.6% for sand, with an average of 82.13%; it ranged from 2.3 to 14.5% for silt, with an average of 6.80%; and it ranged from 1.8 to 6.3% for clay, with an average of 4.35%. Each averaged ratio of sand, silt, and clay is shown on Table 48 and Figure 16. According to the USDA soil texture triangle, most of the collapsed and potential risk sites had soil textures classified as “Sand.”

Table 48. Soil texture within each site.

| Category | | | Soil texture | | | | | |
|---|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | Sand | 86.33 | 93.30 | 93.03 | 88.83 | 88.87 | 90.07 |
| | | Silt | 7.53 | 3.00 | 3.57 | 6.17 | 8.70 | 5.79 |
| | | Clay | 6.17 | 3.73 | 3.43 | 5.00 | 2.43 | 4.15 |
| Potential risk | Site(no.) | | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | Sand | 81.00 | 90.10 | 92.63 | 91.43 | 88.70 | 88.77 |
| | | Silt | 12.77 | 5.47 | 3.00 | 4.57 | 8.20 | 6.80 |
| | | Clay | 6.23 | 4.43 | 4.33 | 4.00 | 3.10 | 4.42 |

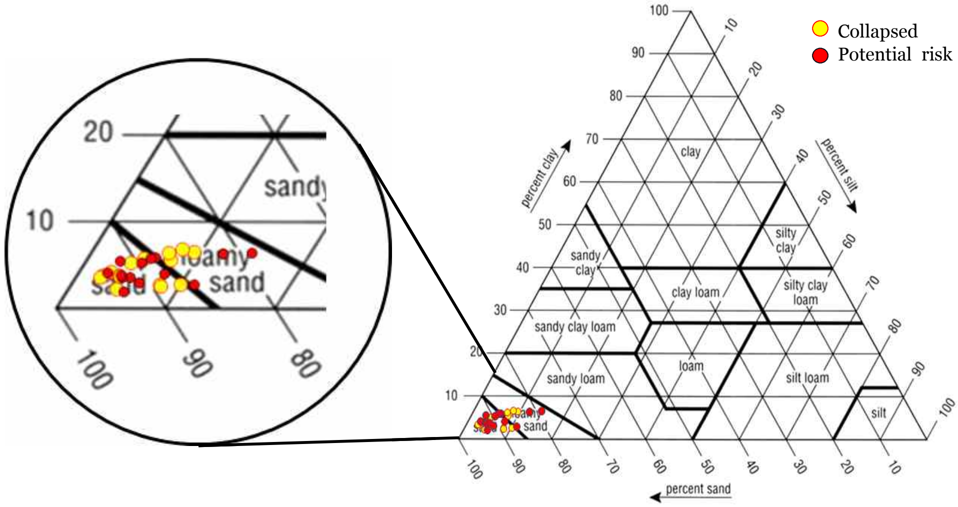


Figure 15. Soil texture triangle of collapsed and potential risk sites.

In the Mann-Whitney U test, the differences between the groups were insignificant (p=0.455 for sand; p=0.534 for silt; and p=0.575 for clay). Furthermore, the ratio of soil texture in the collapsed sites did not differ from that of the potential risk sites.

### (5) Tensile strength

The tensile strength of the collapsed sites ranged from 1.32 to 1.64 kPa, with an average of 1.49 kPa, and it ranged from 1.39 to 1.79 kPa for the potential risk sites, with an average of 1.52 kPa.

In the Mann-Whitney U test, the difference between the groups was insignificant (p=0.575). Nevertheless, the average tensile strength of the collapsed sites was lower than that of the potential risk sites. Each average value of tensile strength is shown on Table 49.

Table 49. Tensile strength within each site.

| Category | | Tensile strength(kPa) | | | | | |
|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 1.597 | 1.463 | 1.377 | 1.517 | 1.477 | 1.486 |
| Potential risk | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 1.717 | 1.470 | 1.473 | 1.433 | 1.500 | 1.519 |

### (6) Permeability coefficient

The permeability coefficient of the collapsed sites ranged from $2.89\times10^{-4}$to$4.21\times10^{-2}$cm/s, with an average of $6.39\times10^{-3}$cm/s, and it ranged from $1.42\times10^{-4}$ to $6.61\times10^{-3}$ cm/s for the potential risk sites, with an average of $1.34\times10^{-3}$cm/s.

In the Mann-Whitney U test, the difference between the groups was significant ($p=0.040$). Thus, the average permeability coefficient of the collapsed sites was lower than that of the potential risk sites. Each average value of permeability coefficient is shown on Table 50.

Table 50. Permeability coefficient within each site.

| Category | | Permeability coefficient(cm/s) | | | | | |
|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | $6.13\times10^{-4}$ | $5.31\times10^{-3}$ | $2.42\times10^{-2}$ | $6.92\times10^{-4}$ | $1.12\times10^{-3}$ | $6.39\times10^{-3}$ |
| Potential risk | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | $2.38\times10^{-4}$ | $2.53\times10^{-4}$ | $2.51\times10^{-3}$ | $3.11\times10^{-3}$ | $5.76\times10^{-4}$ | $1.34\times10^{-3}$ |

### (7) Soil depth

The comparison of soil depth between collapsed and potential risk sites is meaningless because actual failure site are washed down.

### (8) Soil acidity(pH)

Soil acidity at the collapsed sites ranged from 4.87 to 7.25 pH, with an average of 6.23 pH, and it ranged from 4.58 to 7.41 pH at the potential risk sites, with an average of 6.07 pH.

In the Mann-Whitney U test, the difference between the groups was insignificant ($p=0.624$). Nevertheless, the average soil acidity at the collapsed sites was lower than that at the potential risk sites. Each average value of soil acidity is shown on Table 51.

Table 51. Soil acidity within each site.

| Category | | Soil acidity(pH) | | | | | |
|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 4.96 | 6.25 | 6.21 | 6.54 | 7.19 | 6.23 |
| Potential risk | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 4.71 | 5.99 | 5.40 | 6.86 | 7.38 | 6.07 |

### (9) Salt concentration

The salt concentration of the collapsed sites ranged from 0.003 to 0.007%, with an average of 0.005%, and it ranged from 0.005 to 0.039% for the potential risk sites, with an average of 0.012%.

In the Mann-Whitney U test, the difference between the groups was significant (p=0.007). Thus, the average salt concentration of the collapsed sites was lower than that of the potential risk sites. Each average value of salt concentration is shown on Table 52.

Table 52. Salt concentration within each site.

| Category | | Salt concentration(%) | | | | | |
|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 0.004 | 0.003 | 0.007 | 0.005 | 0.004 | 0.005 |
| Potential risk | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 0.005 | 0.005 | 0.039 | 0.007 | 0.006 | 0.012 |

**(10) Soil organic matter**

The organic matter of the collapsed sites ranged 0.06 to 1.20%, with an average of 0.53%, and it ranged from 0.29 to 7.66% for the potential risk sites, with an average of 2.34%.

In the Mann-Whitney U test, the difference between the groups was significant (p=0.000). Thus, the average soil organic matter of the collapsed sites was lower than that of the potential risk sites. Each average value of soil organic matter is show on Table 53.

Table 53. Soil organic matter within each site.

| Category | | Soil organic matter(%) | | | | | |
|---|---|---|---|---|---|---|---|
| Collapsed | Site(no.) | 1 | 2 | 3 | 4 | 5 | Total Avg. |
| | Measured average value | 1.04 | 0.37 | 0.59 | 0.52 | 0.14 | 0.53 |
| Potential risk | Site(no.) | 6 | 7 | 8 | 9 | 10 | Total Avg. |
| | Measured average value | 1.08 | 1.17 | 7.00 | 1.89 | 0.55 | 2.34 |

### (11) Interpretation of soil slope failure

In the soil of collapsed sites, the permeability coefficient was very high in soils mostly containing a high ratio of sand. The porosity, soil hardness, soil acidity, and salt concentration did not hinder plant growth. However, the water content and soil organic matter (the water and nutrients for plant growth) were very low. The water content of the collapsed sites was “Poor” according to the KILA (2007) standards. In addition, the soil organic matter could not reach 1%, less than the B class (approximately 1.5%) of the soil horizon classification.

In the non-parametric testing for the soil in the collapsed sites and the potential risk soil in the surroundings, the water content, permeabi lity coefficient, salt concentration, and soil organic matter showed differences. The salt concentration of the groups was less than 0.1%, as it did not hinder plant growth. However, the water and soil organic matter were very low in both groups, which does hinder revegetation.

The permeability coefficient was higher in the collapsed sites than the potential risk sites, which increases the load at the slope bottom. It was assumed to be the result of the high ratio of sand. That is, as the sand ratio increased, the permeability coefficient might also increase. In addition, the possibility of reserving the soil organic matter would be rare at the collapsed sites, since the soil organic matter used in the revegetation came down to the bottom of the slope, decreasing the soil organic matter. Therefore, in the case of a ground layer with a high ratio of sand, physically based secondary devices are required for enough moisture to prevent material segregation. A fiber mesh of coconut dust or non-woven fabric would be an alternative method. However, in using a non-woven fabric, the dense fabric would interrupt the growth of plant roots; thus, biodegradable fabrics are recommended.

## 4.5 Evaluation of Discriminant Model

Discriminant analysis in this study used nine variables: porosity, water content, tensile strength, soil depth, salt concentration, soil organic matter, vegetation community, vegetation coverage, and the number of trees. The nine variables were chosen through correlation analysis and non-parametric testing at significant levels. Vegetation community of the nine variables was surveyed as a nominal scale. Therefore, the indicator of vegetation community was excluded in this discriminant analysis. However, it was compared and interpreted with the result of discriminant score derived from the analysis. The selection method of variable in the discriminant analysis was step-wise[44].

As the results show, there were four variables in the discriminant function: porosity, tensile strength, soil organic matter, and vegetation coverage. That is, these four variables were chosen as major indicators to evaluate the stability of slope revegetation. The discriminant function was as follows:

$$Z = -18.758+14.981X_1+4.558X_2 - 0.143X_3+0.050X_4 \qquad \text{(Equation 01)}$$

where Z is the discriminant score, $X_1$ is the porosity ($m^3/m^3$)), $X_2$ is the tensile strength (kPa), $X_3$ is the soil organic matter (%), and $X_4$ is the vegetation coverage (%).

44) The stepwise method extracted the major representative variables in prior, and then it was found the major variables influencing the following discriminant function. In this method, it was processed step by step, and the variable was not applied to the discriminant function any more if there were not a variable that influenced on the discriminant function.

Standardized canonical discriminant function coefficients[45] were summarized in the following Table 54. Vegetation coverage was the most important indicator according to the discriminant analysis. It was also selected as an important indicator in other studies (Rice and McCasion, 1985; Yim and Ma, 1999; Lee, 1987) while porosity, tensile strength, organic matter were not addressed at all. Among these indicators, the porosity and the organic matter are closely related with the growth of plants (Brady and Weil, 2009). The 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 focused on the environmental condition for healthy growth of plants.

Table 54. Standardized canonical discriminant function coefficients.

| Category | Function |
|---|---|
| Porosity | 0.865 |
| Tensile strength | 0.837 |
| Organic matter | -0.633 |
| Vegetation coverage | 1.202 |

The result of the discriminant analysis of this study indicates that revegetated soil and the plant structure were more important factors than the physical characteristics in slope stabilization. The physical characteristics take indirect effect against the failure by controlling the rate of plant growth. The fact that the failure occurred although the study sites were all more than two years old[46] also supports the result

45) Standardized canonical discriminant function coefficients indicate the relative importance of the independent variables (Rho, H.J., 2006).
46) The warranty period of slope revegetation is two years after the works, indicating

of the analysis, albeit the other possible cause of failure such as the quality of the soil used in the revegetation or the method of stabilization itself.

The discriminant analysis enabled the evaluation of 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; Yim and Ma, 1999; Yoshimura et al., 1996; Ma, 1994; Lee, 1987). The result of this study was focused on soil and vegetation variables rather than the physical characteristics as additional soil and vegetation variables were considered to the previous studies.

The canonical correlation coefficient[47] of the discriminant function was 0.906, which was higher than the value of previous studies (Lee, 1987; Jeon et al., 2003). The value of Wilks' lambda ($\lambda$) was 0.179, and the significant level was $p<0.01$. The R-square for the discriminant function satisfied the significant level ($p<0.01$). In evaluation of the stabilization, if the value (Z) according to the result of discriminant functions in application of each indicator was higher than zero, it was considered as stable. If not, it was categorized as potential risk.

that the period is enough for the full growth of plants.

47) Canonical correlation coefficient showed level of correlations between the discriminant function and the group, thus it could be considered as good if the value became higher. (Rho, H.J., 2006).

Table 55. Eigenvalues of discriminant function.

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

Table 56. Wilks' Lambda of discriminant function.

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

The scatter diagram between the discriminant scores according to the discriminant function and investigated data of each indicator is shown in Figures 16 ~ 19.

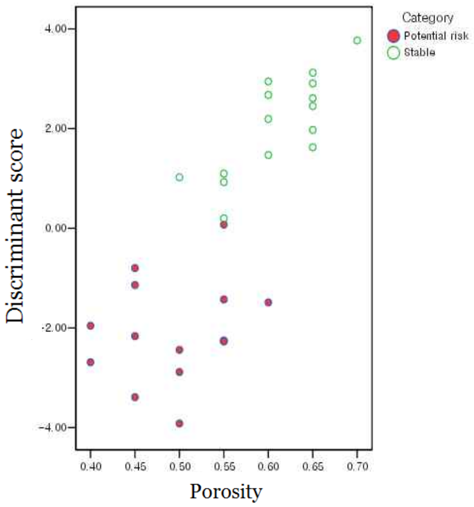


Figure 16. Scatter plot of discriminant score and porosity value.

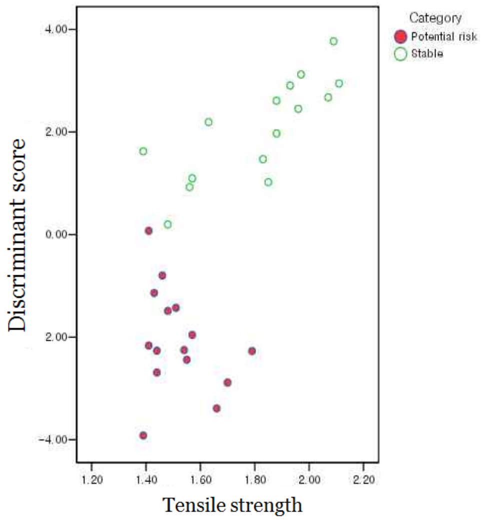


Figure 17. Scatter plot of discriminant score and tensile strength value.

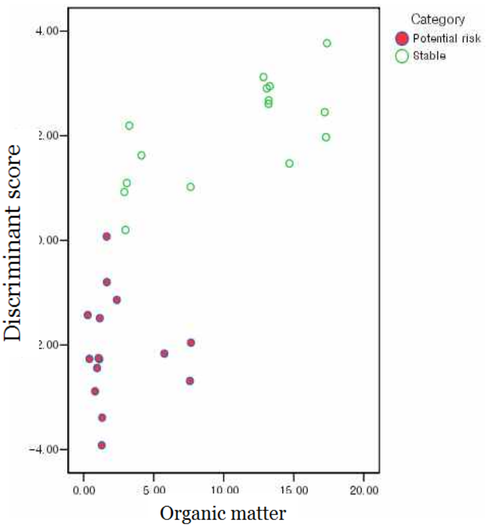


Figure 18. Scatter plot of discriminant score and soil organic matter value.

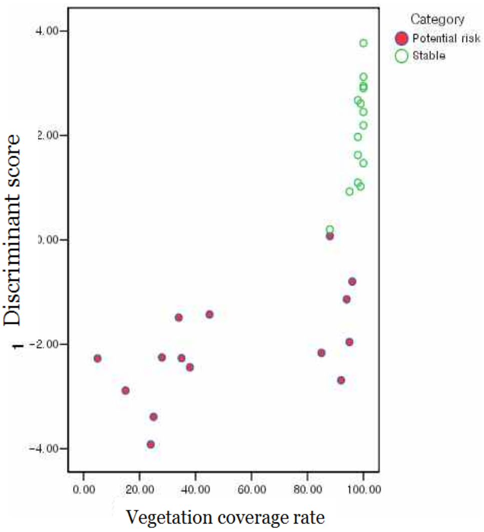


Figure 19. Scatter plot of discriminant score and vegetation coverage.

The scatter diagram of the discriminant score and each indicator can be interpreted as follows: To determine a certain area as potential risk site, the value of each indicator should be less than 0.5 $m^3/m^3$ of porosity, less than 1.4 kPa of tensile strength, less than 3% of soil organic matter, and less than 60% of vegetation coverage. On the other hand, to determine a certain area as stable site, the value of each indicator should be more than 0.6 $m^3/m^3$ of porosity, more than 1.8 kPa of tensile strength, more than 8% of soil organic matter, and more than 96% of vegetation coverage, and .

The scatter diagram of the discriminant score and each indicator can be interpreted as follows. To determine a certain area as a potential risk site, the value of each indicator should be less than 0.5 $m^3/m^3$ of porosity, 1.4 kPa of tensile strength, 3% of soil organic matter, a 60% of vegetation coverage, and heterogeneous simple layer in the vegetation community. On the other hand, to determine an area as a stable site, the value of each indicator should be more than 0.6$m^3/m^3$ of porosity, more than 1.8 kPa of tensile strength, more than 8% of soil organic matter, and more than a 96% of vegetation coverage.

As shown in the scatter diagram, the value of each indicator could not represent the discriminant score. In other words, the value of an indicator could not determine the risk of failure for the slope because the value of each indicator overlapped for the potential risk and stable sites. The overlapped range is shown on Table 57. If the investigated data showed significant difference for each indicator, without an overlapped range, the explanation of the discriminant function would be higher.

Table 57. Overlapped range of indicator between potential risk and stable.

| Indicator | Unit | Overlapped range between potential risk and stable |
|---|---|---|
| Porosity | $m^3/m^3$ | 0.5-0.6 |
| Tensile strength | kPa | 1.4-1.8 |
| Soil organic matter | % | 3-8 |
| Vegetation coverage | % | 88-96 |

The value of each indicator in the overlapped range could not determine if the slope was stabilized. Site 3 (potential risk site) and site 7 (stable site) clearly present this situation. In site 3, four of the five indicators (porosity excluded) were in the overlapped range. Likewise, in site 7, three of the four indicators (vegetation coverage excluded) were in the overlapped range. Nevertheless, the value of the indicators implicated the risk of failure. Consequently, the four indicators should be interpreted complexly to determine slope stability.

The box-plot diagram of the discriminant score and vegetation community can be interpreted as follows. All discriminant score of heterogeneous simple layer of vegetation community classification was below zero. All discriminant score of homogeneous simple layer was above zero. The discriminant score of heterogeneous multiple layer and homogeneous simple layer ranged from approximately -3 to 4. Therefore, the homogeneous simple layer of the vegetation community classification represented a stable slope whereas the heterogeneous simple layer represented a unstable slope. It was hard to judge the stability of both heterogeneous multiple layer and homogeneous simple layer since they showed broad range of discriminant score.

The discriminant score ranged from –3.92 to 0.07 for the heterogeneous simple layer, with an average of –2.12. It ranged from –2.69 to 2.95 for the heterogeneous multiple layer, with an average of –0.25. It ranged from –2.88 to 3.77 for the homogeneous simple layer, with an average of 0.74. It ranged from 0.20 to 2.91 for the homogeneous multiple layer, with an average of 1.59. In summary, a revegetated site that had both heterogeneous simple layer and discriminant score below zero could collapse whereas a revegetated site that had both homogeneous layer and discriminant score above zero could become stable.

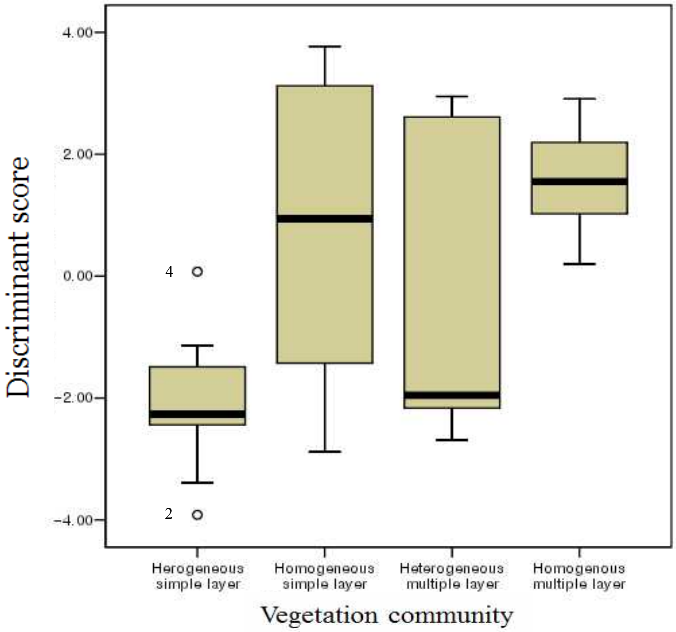


Figure 20. Box-plot of discriminant score and vegetation community.

Previous indicators for stability evaluation was focused on geological and topographical features such as joint condition, tension crack, rock type, and soil texture, cohesion, 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 variously 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[48] techniques (Youssef et al., 2009; Poudyal et al., 2010). However, these analyses are complicated and inconvenient in that numerous variables should be considered simultaneously in specific

48) GIS : Geographical Information System

range.

The discriminant analysis of this study enables simple evaluation of stability of the revegetated slope with just five indicators selected among numerous variables. It is also expected to enable a scientific verification on failure of revegetated slopes through the discriminant analysis. The previous evaluation method of stability used to depend on the naked eye to observe the condition of vegetation coverage in judging the possibility of failure.

The previous discriminant analysis[49] has applied nominal scale to the independent variables (Rice and McCasion, 1985; Lee, 1987). In this study, however, the nominal-scale was excluded and ratio-scale was applied to the independent variables. The discriminant score was then compared with vegetation community as a nominal scale variable. As a result, original data was not skewed in this method.

The further study could consider vegetation variables such as species richness, dominant species, germination rate and geographical variables such as tensile root strength and shear strength for development of additional discriminant analysis.

49) Discriminant analysis has a categorical dependent variable and continuous independent variables (Wetcher-Hendricks, 2011)

## 4.6 Slope Revegetation Stability Evaluation Analysis

According to the results of this study, the slope revegetation evaluation analysis (SRSEA) system was as follows: the target of evaluation was an area that underwent a soil-based slope revegetation construction at least two years prior to the time of study. The review for structural stability must have been completed in advance through stability analysis of slope.

The evaluation items were three indicators of soil and two indicators of vegetation. The soil indicators were porosity, tensile strength, and soil organic matter. The vegetation indicators were vegetation community and the vegetation coverage. The collecting method of each indicator is shown on Table 58.

Table 58. Data collection method for each indicator

| Indicator | Data collection method | Unit | Note |
|---|---|---|---|
| Porosity | $P = 100 \times \left(1 - \frac{Bd}{Pd}\right)$<br>where, P : porosity(%)<br>Bd : Bulk density<br>Pd : Particle density | $m^3/m^3$ | 1) |
| Tensile strength | Technique of Nearing et al. (1988) | kPa | 2) |
| Soil organic matter | Walkely-Black wet oxidation method | % | 3) |
| Vegetation community | 1m × 1m quadrat method<br>(1) Heterogeneous simple layer<br>(2) Homogeneous simple layer<br>(3) Heterogeneous multiple layer<br>(4) Homogeneous multiple layer | - | 4) |
| Vegetation coverage | 1m × 1m quadrat method<br>Rate of existing vegetation in a defined settlement area | % | 5) |

1) Brady and Weil (2007), 2) Nearing et al. (1988), 3) Walkley and Black (1934), 4) Lee et al. (2012), 5) MOLIT (2009)

The data was collected roughly three times per slope, and the mean value from the three collections was applied to each indicator. Through the algorithm shown in the following figure, it was determined if the area was safe from failure. The R-square of the discriminant function was not complete; thus, the sites should be thoroughly investigated, even if the discriminant score (Z) is higher than zero. If soil failure or erosion should occur, even if the discriminant score was higher than zero, the cause might be a structural problem or an unexpected drainage system problem.

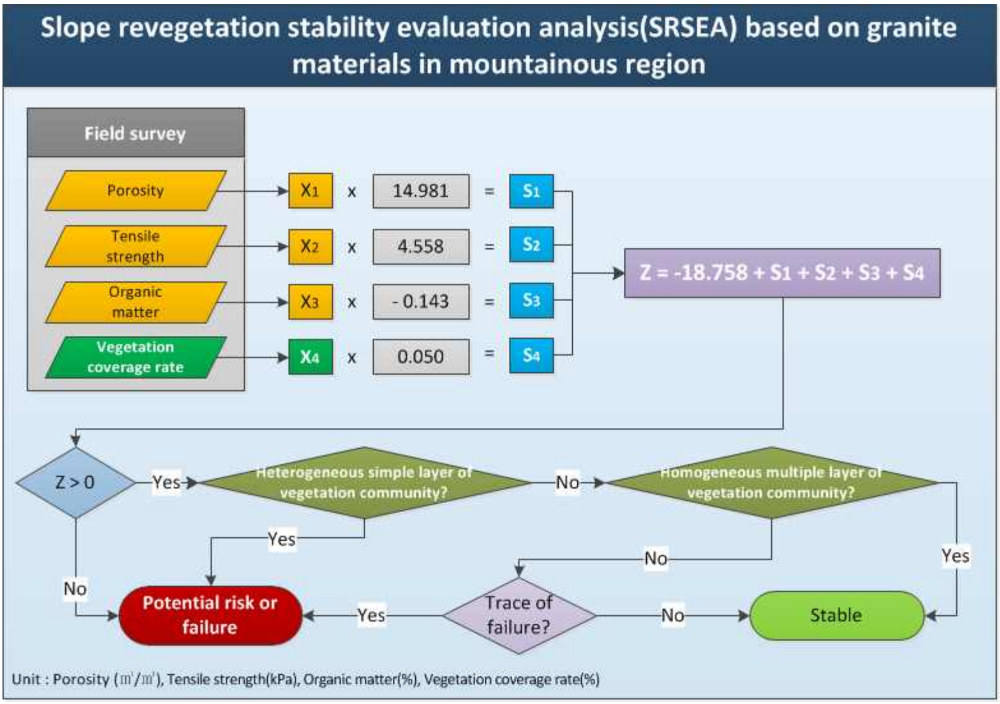


Figure 21. Slope Revegetation Stability Evaluation Analysis Model (SRSEA).

The application range of the discriminant function was as follows. The range of porosity and soil organic matter were within normal for forest soil in South Korea (Park et al., 2010; Jeong et al., 2002). The range of vegetation community and the vegetation coverage could also apply to all target areas. If the value of each indicator exceeds the range on Table 59, further studies are required.

In previous studies, the tensile strength was widely spread according to the percentage of water and soil organic matter (Blanco-Moure et al., 2012; Rahimi et al., 2000; Causarano, 1993). This was narrow in the present study because the ratio of sand was higher than in other studies. The range of tensile strength in soil containing a higher ratio of sand was approximately 0.5 ~ 1.6 kPa (Kim et al., 2004; Kim and Hwang, 2003). Thus, as the sand ratio in the soil used in the slope revegetation was consistently high, the range of tensile strength became narrower. The application range of SRSEA is shown on Table 59.

Table 59. Application range for SRSEA.

| Indicator | Range |
|---|---|
| Porosity | 0.4-0.7 $m^3/m^3$ |
| Tensile strength | 1.4-2.1kPa |
| Soil organic matter | 0.3-17.4% |
| Vegetation community | n/a |
| Vegetation coverage | 10-100% |

When the ground layer was weathered or blasted rock, physically based secondary devices[50] were generally installed. Thus, there was no erosion or failure in the results of this study. However, slope revegetation constructions were performed without the physically based

50) It is generally to prevent a revegetation measure from failure when a slope is steep (35° or more) and ground layer is weathered rock or blasted rock. The method are generally fiber mesh, wire mesh, gabion block and so forth.

secondary device, even in soil slope, ignoring the soil properties of ground layer. The soil properties are crucial for vegetation development and erosion control. Therefore, if the failure slope surface were soil, the soil in the failure site’s ground layer should be investigated.

If the soil in the ground layer had the following conditions, the method of revegetation should be improved. According to the data in this study, the soil properties in the ground layer of failure sites satisfied more than three of five indicators in the following conditions.

Table 60. Standard to contemplate characteristics of damaged soil in soil slope.

| Indicator | Standard |
|---|---|
| Water content | below 0.1 $m^3/m^3$ |
| Permeability coefficient | above 6.00 × 10-3 cm/s |
| Salt concentration | below 0.005% |
| Soil organic matter | below 1% |

## 4.7 Application Method of SRSEA

SRSEA could be used to evaluate the slope revegetation construction method for slope revegetations older than two years. SRSEA could not be applied for the slope revegetation construction method that uses coarse straw-mat mulching, vine plants, and concrete. However, SRSEA could be effectively used for the slope revegetation construction method in Korea, as that country's hydroseeding construction method is mainly used based on soil.

SRSEA could be applied to diagnose slope revegetation stability within the MOLIT (2009) standards. The MOLIT (2009) standards focus on determining the early slope revegetation construction. To increase the sustainability of revegetation and to stabilize it without erosion or failure, some of that system should be improved. The method for system improvement is to establish slope revegetation stability standards within the MOLIT (2009) standards or to use the referred discriminant functions to evaluate the substantiality of revegetation.

In addition, SRSEA might modify or supplement the NEMA (2011) standards. The NEMA (2011) standards score steep slope disaster hazards, using a method of slope stability analysis. SRSEA could be included in these standards to evaluate revegetation stability.

The slope revegetation stability evaluation model was developed as follows (Figure 23), modified from chosen procedures of the slope revegetation construction method presented in MOLIT (2009, p. 29).

According to that method, slope revegetation construction in mountainous regions depends on the properties of soil, weathered rock, and blasted rock. If the ground layer on the slope surface were weathered or blasted rock, the consideration of structural stability could have been already completed. However, the soil properties of the soil slope could not be correctly investigated with the naked eye. Therefore, an analysis should be performed for the properties of various types of soil. The results of this study were based on the analysis of porosity, water content, permeability coefficient, salt concentration, and soil organic matter selected by non-parametric testing and correlation analysis. If the soil properties of the slope in failure sites satisfied more than three standards (Table 60) among the above four indicators, appropriate measures should be taken in consultation with specialists in restoration or geological features.

Even though the elapsed time of slope revegetation sites using artificial soil is more than two years, soil quality and vegetation establishment could be poor. In that case, the discriminant function developed in this study could identify the quality of the artificial soil and vegetation conditions to determine if the site is stable or a potential risk of soil erosion or failure. The following algorithm (Figure 22) regarding the above results was schematized.

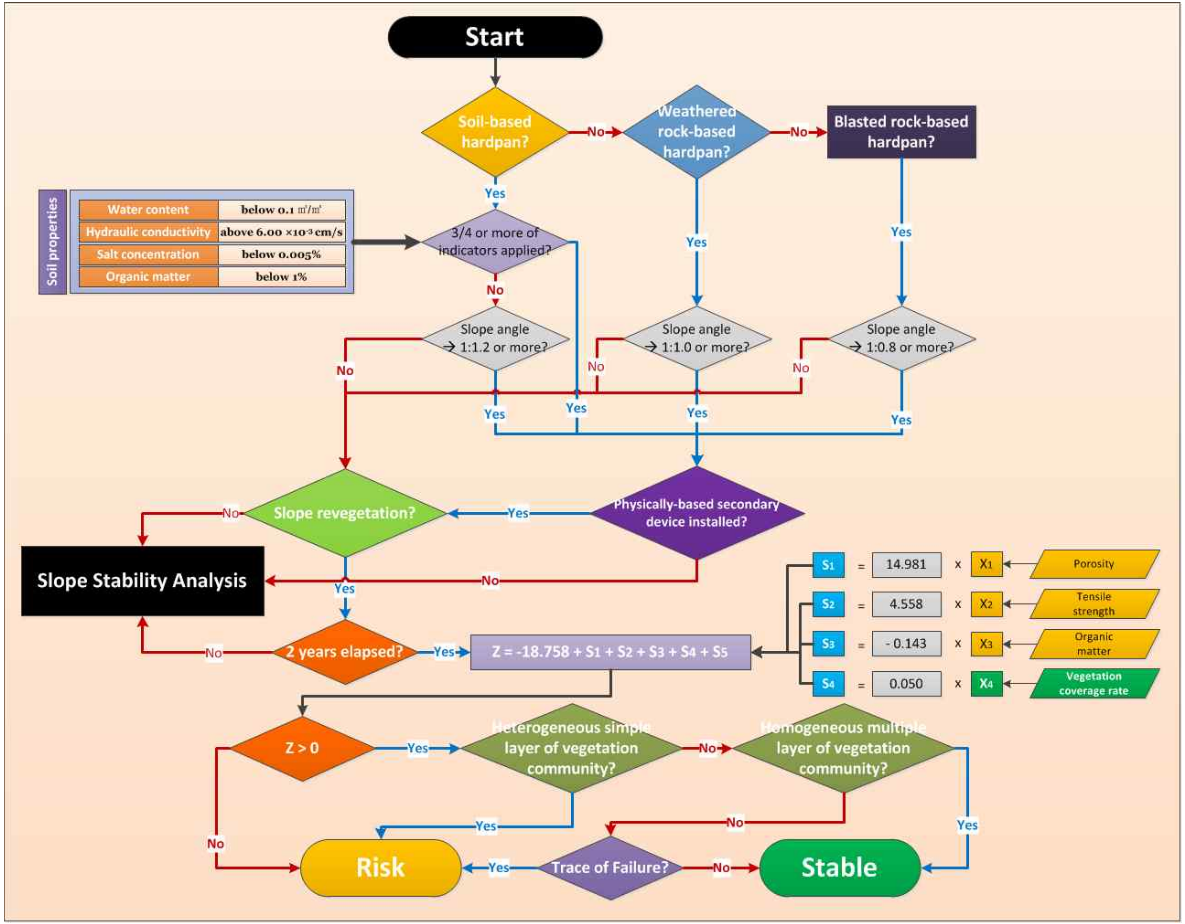


Figure 22. Application of SRSEA.

# 5. Conclusion

This research was conducted to develop stability evaluation indicators on revegetated cut-slopes. A total of 69 initial variables were selected through literature review and then 23 variables were selected through an expert survey. Among those, nine variables were categorized under ″physical characteristics″, which are aspect, slope angle, slope type, slope width, slope height, ground layer, seepage water, elapsed year, and drainage system. Ten variables were categorized under ″soi l″, which are porosity, soil hardness, water content, soil texture, tensile strength, permeability coefficient, soil depth, soil acidity, salt concentration, and soil organic matter. Finally, four variables were categorized under ″vegetation″, which are vegetation community, vegetation coverage, number of trees, and number of herbs.

A field survey was conducted on failure sites, potential risk sites and stable sites using the 23 variables. Through a non-parametric test and a correlation analysis of the field survey results, nine variables were identified as primary determinants of failures. Of these variables, six variables were from the soil category, including porosity, water content, soil depth, tensile strength, salt concentration, and soil organic matter; and three variables were from the vegetation category, including vegetation community, vegetation coverage, and number of trees. None of the physical characteristic variables were selected as prime determinants.

Discriminant analysis was conducted as a part of process to develop evaluation indicators from nine variables. As a result, the discriminant function included four variables: porosity, tensile strength, soil organic matter, and vegetation coverage, which were major indicators. The data of vegetation community was excluded from the discriminant analysis as it was a nominal scale. The box-plot of discriminant score and vegetation community classification was conducted. A revegetated site that had both heterogeneous simple layer and discriminant score below zero could collapse. In contrast, a revegetated site that had both homogeneous layer and discriminant score above zero could become stable.

Five indicators of porosity, 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 and potential risk site because the survey data of each indicator was overlapped in both stable and potential risk site. Therefore, a comprehensive interpretation of the five indicators was required to determine slope stabilization.

Most of the failure sites had soil slopes. A soil slope at a construction site was generally attached to a shallow layer of hydroseeding without a physical secondary device, such as fiber or wire mesh. However, this treatment could result in failure as it disregards the properties of the soil surface of the slope.

The failure soil, which was exposed during failure or erosion, and the potential risk soil, which was attached to the failure location were compared. The porosity, water content, permeability coefficient, salt concentration, and soil organic matter were significantly different in the non-parametric analysis. The failure risk level occurred when it had three to five of the following indicators: porosity of below 0.5$m^3/m^3$, water content of below 0.1$m^3/m^3$, permeability coefficient of above $6.00 \times 10^{-3}$ cm/s, salt concentration of below 0.005%, and soil organic matter of below 1%. Also, the sand ratio of the failure soil was higher than the potential risk soil. The permeability coefficient was high and the soil organic matter was low in the failure soil. A soil that had high ratio of sand increased the water load during rainfall. It was substantially different from the soil used in the revegetation work. Therefore, material segregation could have occurred between the ground-layer soil and the revegetation soil. A physical secondary device was required to moisturize and prevent this situation.

Slope revegetation is necessary for the rehabilitation on the basis of restoration. The structure and function of the slope revegetation are similar to ″replacement″ of restoration types. For a successful process of ecological restoration, evaluation criteria that provide a more complete ecological stabilization process must be developed. Therefore, additional studies on the effects of rainfall should be conducted. New researches may contain numerous cases, long-term monitoring, and systematic processes that create a detailed standard for selecting adequate measures, and experiments that compare ecological and structural stability.

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# Appendix

## Appendix A : Type of Slope Failure

Table 1. The type of slope failure(cited by previous researches).

| Category | Dictionary definition | Note |
|---|---|---|
| Landslide | · Type of shallow mass slippage of rock material, soil, artificial fill, or a combination of these, lubricated by rainwater down a slope, the result of a earthquake, or subsequent to inadequate road construction operations on slip planes<br>· Types of movement include falls, topples, slides, spreads or flows. If the slope failure in which the shear plane is largely parallel to the slope surface is shallow, the sliding will extend downward and outward along a broadly planar surface. | 1) |
| Rotational slide | · Downward movement, in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide; there is a downward intermittent movement of rock debris, caused by the gradual removal of material at the foot of the slope | 1) |
| | · A landslide on which the surface of rupture is curved upward (spoon-shaped) and the slide movement is more or less rotational about an axis that is parallel to the contour of the slope. The displaced mass may, under certain circumstances, move as a relatively coherent mass along the rupture surface with little internal deformation. The head of the displaced material may move almost vertically downward, and the upper surface of the displaced material may tilt backwards toward the scarp. If the slide is rotational and has several parallel curved planes of movement, it is called a slump. | 2) |
| Translational slide | · Which usually occurs along structural features, such as a bedding plane or between bedrock and weaker, overlying material | 1) |
| | · The mass in a translational landslide moves out, or down and outward, along a relatively planar surface with little rotational movement or backward tilting. This type of slide may progress over considerable distances if the surface of rupture is sufficiently inclined, in contrast to rotational slides, which tend to restore the slide equilibrium. The material in the slide may range from loose, unconsolidated soils to extensive slabs of rock, or both. Translational slides commonly fail along geologic discontinuities such as faults, joints, bedding surfaces, or the contact between rock and soil. In northern environments the slide may also move along the permafrost layer. | 2) |
| Block slide | · Overlying material moves as a single, little-deformed mass | 1) |
| Rockfall | · Relatively free falling of rock fragments such as newly detached segment of bedrock from a cliff, steep slope, cave or arch caused by rock slide | 1) |
| | · Falls are abrupt, downward movements of rock or earth, or both, that detach from steep slopes or cliffs. The falling material usually strikes the lower slope at angles less than the angle of fall, causing bouncing. The falling mass may break on impact, may begin rolling on steeper slopes, and may continue until the terrain flattens. | 2) |
| Topple | · A topple is recognized as the forward rotation out of a slope of a mass of soil or rock around a point or axis below the center of gravity of the displaced mass. Toppling is sometimes driven by gravity exerted by the weight of material upslope from the displaced mass. Sometimes toppling is due to water or ice in cracks in the mass. Topples can consist of rock, debris (coarse material), or earth materials (fine-grained material). Topples can be complex and composite. | 2) |
| Debris flow | · Form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope | 1) |
| | · A form of rapid mass movement in which loose soil, rock and sometimes organic matter combine with water to form a slurry that flows downslope. They have been informally and inappropriately called "mudslides" due to the large quantity of fine material that may be present in the flow. Occasionally, as a rotational or translational slide gains velocity and the internal mass loses cohesion or gains water, it may evolve into a debris flow. Dry flows can sometimes occur in cohesionless sand (sand flows). Debris flows can be deadly as they can be extremely rapid and may occur without any warning. | 2) |
| Debris avalanche | · Rapid flowage type of mass slippage<br>· Flowing slide of a big quantity of rock debris in narrow tracks down steep slopes | 1) |
| | · Debris avalanches are essentially large, extremely rapid, often open-slope flows formed when an unstable slope collapses and the resulting fragmented debris is rapidly transported away from the slope. In some cases, snow and ice will contribute to the movement if sufficient water is present, and the flow may become a debris flow and (or) a lahar. | 2) |
| Earth flow | · Relatively quick flowage movement of water-saturated clayey or silty earth material down low-angle terraces or hillsides, forming a circular cut, or shear plane and a bulging accumulation mound; however, dry flows of granular material are also possible | 1) |
| | · Earthflows can occur on gentle to moderate slopes, generally in fine-grained soil, commonly clay or silt, but also in very weathered, clay-bearing bedrock. The mass in an earthflow moves as a plastic or viscous flow with strong internal deformation. Susceptible marine clay (quick clay) when disturbed is very vulnerable and may lose all shear strength with a change in its natural moisture content and suddenly liquefy, potentially destroying large areas and flowing for several kilometers. Size commonly increases through headscarp retrogression. Slides or lateral spreads may also evolve downslope into earthflows. Earthflows can range from very slow (creep) to rapid and catastrophic. Very slow flows and specialized forms of earthflow restricted to northern permafrost environments are discussed elsewhere. | 2) |
| Creep | · Creep is the informal name for a slow earthflow and consists of the imperceptibly slow, steady downward movement of slope-forming soil or rock. Movement is caused by internal shear stress sufficient to cause deformation but insufficient to cause failure. Generally, the three types of creep are: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure for other types of mass movements. | 2) |
| Lateral spread | · Lateral spreads usually occur on very gentle slopes or essentially flat terrain, especially where a stronger upper layer of rock or soil undergoes extension and moves above an underlying softer, weaker layer. Such failures commonly are accompanied by some general subsidence into the weaker underlying unit. In rock spreads, solid ground extends and fractures, pulling away slowly from stable ground and moving over the weaker layer without necessarily forming a recognizable surface of rupture. The softer, weaker unit may, under certain conditions, squeeze upward into fractures that divide the extending layer into blocks. In earth spreads, the upper stable layer extends along a weaker underlying unit that has flowed following liquefaction or plastic deformation. If the weaker unit is relatively thick, the overriding fractured blocks may subside into it, translate, rotate, disintegrate, liquefy, or even flow. | 2) |

(continued).

| Category | Dictionary definition | Note |
|---|---|---|
| Slope failure | · Generic term for the collapse of an embankment or hillside through the development of a shear plane, resulting in mass downslope movement of material of which the slope is composed, mostly caused by incorrect earthwork construction | 1) |
| Shallow landslide | · A surficial mass movement in which the sliding plane is located within the soil or the weathered bedrock | 3) |
| Soil erosion | · Generic term covering all aspects of degradation of soil such as denudation, erosion, and accumulation resulting from the action of wind or water; usually understood to mean the soil erosion which results from human intervention above and beyond that resulting from natural processes alone. This man-made soil erosion may be normal wearing away of the land surface used by man, not greatly exceeding natural erosion, or may be "accelerated erosion", which is much more rapid than normal or natural erosion and may be caused by grazing animals on sloping ground, on bare surfaces exposed by fire or by large construction projects | 1) |
| Splash erosion | · Displacement of soil particles by the impact of large raindrops, particularly under intense convectional precipitation and bare earth conditions(syn. raindrop erosion) | 1) |
| Sheet erosion | · Removal of a fairly uniform layer of soil by runoff water | 1) |
| Flash erosion | · Severe wearing away of soil by sudden rainfall in gullies or ravines, which have been denuded of vegetation by human activities | 1) |
| Rill erosion | · Surface erosion process on sloping fields in which numerous and randomly occurring small channels of only several centimeters in depth are formed; occurs mainly on recently cultivated soils | 1) |
| Gully erosion | · Wearing of channels and small ravines by heavy rainfall and concentrated runoff, which, over short periods, removes the soil to considerable depths, typically ranging from 0.5 to as much as 25 to 30m | 1) |
| Stream-bank erosion | · Scouring of material and undercutting of channel banks by running water | 1) |
| Extensive erosion | · Wearing away of soil over broad areas which occurs mainly in arid and semiarid regions and which is caused by rare and heavy storms; those areas are characterized by lack of vegetation | 1) |

Source: 1) Evert (2010), Highland and Bobrowsky (2008), 3) Piacentini et al., (2012)

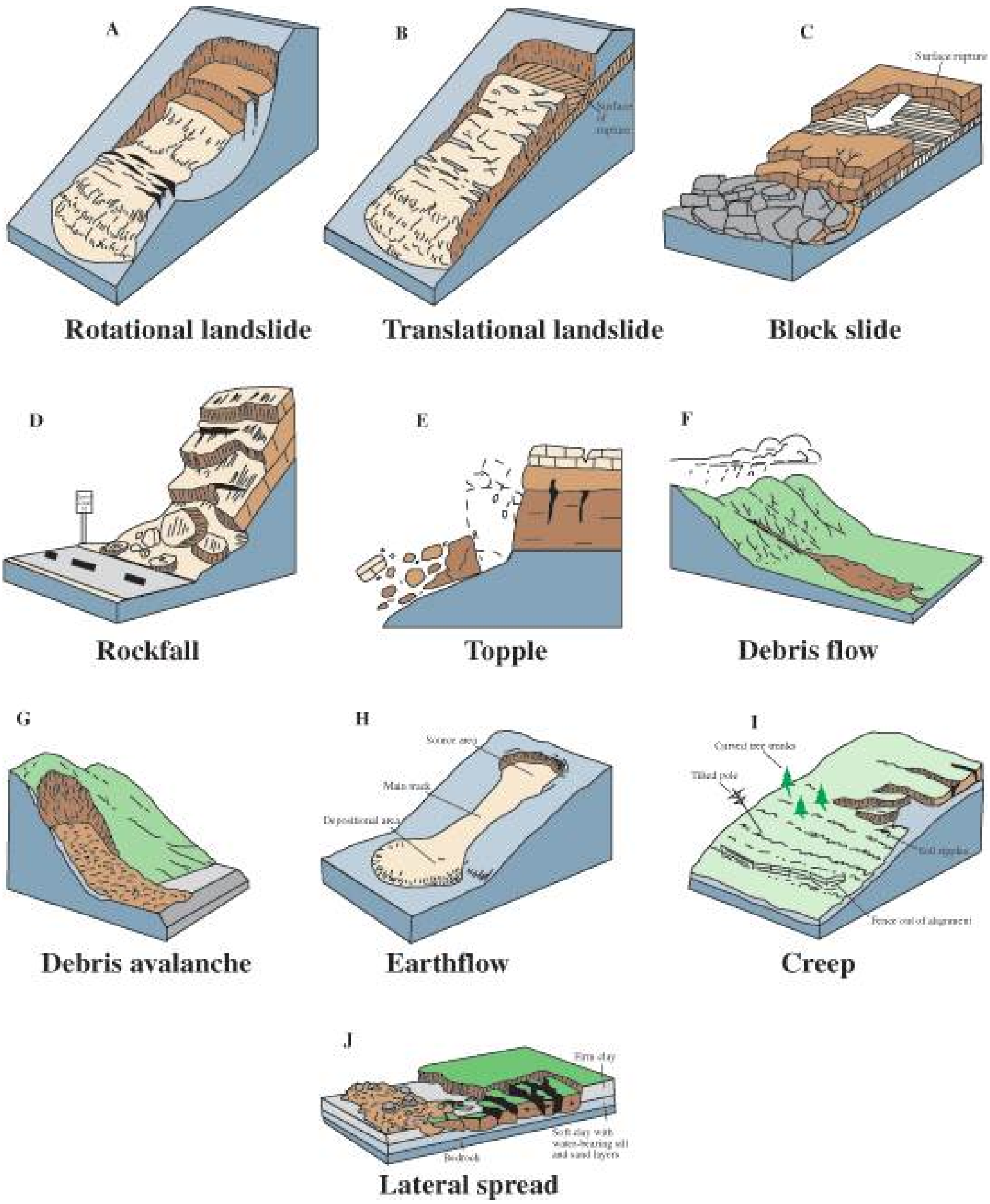


Figure 1. These schematics illustrate the major types of landslide movement(permitted by USGS, U.S. Geological Survey).

# Appendix B : Variable characteristics

## 1. Physical environments on cut-slope

Slope stabilization should consider physical environments of devastated slopes to determine slope revegetation works for how to apply for depending on it such as an angle of slope and aspect. The physical environments of slopes are usually considered in the beginning of slope revegetation with civil engineers and environmental engineers.

### 1.1 Slope Angle

The slope angle is one of major indicators in surface stability because it directly has an effect on how soil particles will respond to erosional strength (David, et al, 2007). The soil particles move downslope from direct gravity when a specific slope gradient exceed the angle of repose called the critical angle. In addition, the slope angle restricts vegetation cover and species diversity (Bochet and García-Fayos, 2004). Vegetation can protect the soil from the erosional strength (Morgan, 2007). The steep slope especially lead to water deficiency by low infiltration and high outflow from rainfall and torture of seed germination which doesn't have enough time to embed roots on it (David et al, 2007; Miyazaki et al., 1993). Therefore, Plant growth depends on slope angle. The vegetation growth suitability relying on slope angle is as shown in the Table 7 (KILA[51], 2007; JSPA[52], 2006).

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51) KILA : The Korean Institute of Landscape Architecture
52) JSPA : Japan Slope Protection Association, 全国特定法面保護協会

Table 3. Criterion of vegetation growth suitability by slope angle (JSPA, 2006).

| Slope angle | Response |
|---|---|
| 1:1.7 or gentle (below 30°) | · Importation of native species<br>· Restoration of tall tree-oriented colony<br>· Very good growth of vegetation<br>· Seldom erosion of surface when vegetation coverage is complete |
| 1:1.7~1:1.4 (30°~35°) | · Thriving community of native plants by succession |
| 1:1.4~1:1.0 (35°~45°) | · Good growth of vegetation<br>· Woody plants of low or medium height<br>· Desirable condition of herbs covering slope surface to make a plant community |
| 1:1.0~1:0.8 (45°~50°) | · Reduction of native species<br>· Poor growth of vegetation<br>· Plant community with partial shrubs and herbs |
| 1:0.8 or steep (over 50°) | · Very bad growth of vegetation<br>· Rapid decline of herbs<br>· Expectation of root elongation in a gap between rocks<br>· Possibility of low trees |

## 1.2 Aspect

Aspect refers to the direction that a slope faces with regard to solar radiation. The solar radiation is very important as a microclimate indicator in a cut slope (Cano et al., 2002). Aspect and slope determine an incidence angle of solar radiation in a cut-slope (Campbell and Norman, 1998; Evans and Winterhalder, 2000). Southern and western slopes receive more sunlight during a day than northern and eastern slopes(see Figure 2) (David et al, 2007). Thus, soil moisture of those slopes could be arid and germinating seeds could suffer from the long duration of sunlight. Moreover, those slopes bring about the reduction of water contents and the loss of fertilizer nutrients (Woo, B.M. et al., 1993). Germination of seeds and growth of vegetation on southern slope were difficult in comparison with those of northern slope (Nam, S.J. and Kim N.C., 1998). Vegetation density, plant biomass and vegetation coverage was low in southern, south-western and south-eastern slopes. And the order was S<SW<SE (Cano et al, 2002). In addition, The aspect affects on soil cohesiveness and stability since it triggers variation in moisture content of a soil and degree of a weathered soil (Cho, N.C. et al., 2006).

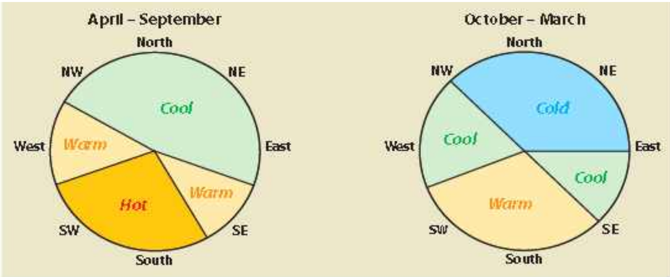



Figure 2. Site climate changes throughout the year depending on aspect(David et al., 2007. p. 67.).

### 1.3 Slope width and length

Long length of a downward slope enhances erosion force and long width at the bottom of a slope lags behind vegetative phase. The longer and higher the slope, the less vegetation coverage rate (Jeon, G.S., 2004; KHC[53], 1997). The long length of a slope requires slope catchments, which are structures like berms and terraces to seize water and sediment, in the middle of a slope (Im, B.J. and Ma, H.S., 1999). The slope catchments are related to drainage system. These phenomena could be vulnerable to soil erosion and failure because the vegetation cover doesn't have enough time to regenerate plants to prevent from the failure. Therefore, the width and length of a slope influence vegetative process and erosion control.

53) Korea Highway Corporation

## 1.4 Slope type

Slope type or shape has an effect on slope stability and soil erosion (Jeon, K.S. et al, 2003). There were two types of slope shape assessment through previous studies. First type is classified as convex (凸) shape, concave(凹) shape, compound(凹凸) shape and straight(□) shape (Jeon, K.S. and Ma, H.S., 2004; Jeon, K.S. et al, 2003; Jeong, W.O., 2001). Second type is classified into camber shape, in-slope shape, out-slope shape and flat shape (Park, M.S., 2002). Considering soil erosion and slope shape, convex slope(凸) has positive correlation while straight slope has negative interrelation (Jeon, K.S. et al, 2003).

## 1.5 Ground layer

Revegetation measures depend on composition of ground layer. The ground layer is classified into soil, solid sand, weathered soil, ripping rock, pelite mudstone, unique rock and blasted rock (MOLIT, 2009). However, other government authorities are generally divided into 3 groups: soil, weathered rock and blasted rock. The steep slope requires physically-based secondary device[54] regardless of soil, weathered rock and blasted rock. It is a necessary device when slope surface is weathered rock or blasted rock. Its method depends on technical specifications referring to revegetation measures.

Filled slopes have the good base of vegetation except for sinkage and failure caused by insufficient compactness at the beginning of construction. In comparison, cut slopes have lower erosion and collapse

54) It is generally to prevent a revegetation measure from failure when a slope is steep (45° or more) and ground layer is weathered rock or blasted rock. Its method are generally fiber mesh, wire mesh, gabion block and so forth.

than filled slopes. However, the cut slopes have higher soil hardness and lower soil fertility. Thus, the revegetation of the cut slopes are relatively more difficult (Kim, N.C. et al., 2001).

## 1.6 Seepage water

Seepage affects the stability of slope revegetation. Seepage flow often ensues when the pores between soils or the hole of a crack in a bedrock become saturated with water and intersect a restrictive laye r[55].

The presence of seeps in a slope could be concerned about construction faults of slope revegetation in the expert interview. The construction faults were caused by the outflow of water according to the level of underground water frequently occur. The Figure 3 below expresses well. This situation doesn't usually happen. However, arid and minute layer in ground water become saturated in rainfall and then abruptly flows water out. It makes streamlet erosion.

Figure 3. Seepage erosion(located at the side of road construction in Geo Je Island, taken by me(Aug. 12. 2010)).

55) A restrictive layer is any soil stratum or layer, including unfractured bedrock, which restricts the vertical movement of water. It has low permeability (Rawls, et al., 1993; David, et al, 2007).

## 1.7 Elapsed Year

When the elapsed year without failure after revegetation is long, the slope could become stabilized with healthy quality of soils and various communities of plants. Jeon, K.S. and Ma, H.S. (2004), based on the investigation of vegetation in the forest road slope, claimed that 27 herb species were growing after 1 year, 30 species after 2 years, 32 species after 4 years, 36 species after 5 years, and 39 species after 6 years. Lee, M.J. et al. (2003b) reported that 6 species appeared on average after 1-3 years of the construction, 8 species appeared on average after 4-5 years, 17 species appeared on average after 6-7 years, 25 species appeared on average after 8-10 years, and 22 species appeared on average after 11-14 years. Therefore, the elapsed year determines the enhancement of plant species and various plants entail slope stabilization with healthy soil.

## 1.8 Drainage system

The well-managed drainage could assist the stability of a slope through prevention of water runoff. The ditches packed into sediments disturb the flow of water. The plugged flow of water could incur soil erosion or slope failure. In addition, the absence of the drainage system could make unstable slopes resulted in uncontrollable erosion of natural runoff. South Korea has standards to maintain the stability of a slope. The standards encourage generally construction supervisors to equip the drainage facilities such as ridge drain and banquette drain. NEMA[56] (2009) refers to the method of a standard scoring to evaluate the drainage system on a slope. Also, MOLIT (2011a) refers to

56) NEMA : National Emergency Management Agency

requirements so as to install a ditch when slope height is over 5m. Therefore, the drainage system plays a major role in controlling flow of water and protecting surface of a slope covered by vegetation and soil.

## 2. Soil properties

Soil should sufficiently include much of humus layer in topsoil to make sound biotope (Kim, G.G. and Jo, D.G., 2004). Supplementary topsoil in soil is a source of nutrition supply and a method to preserve it from physical stimulation (Bradshaw and Chadwick, 1980). However, the removal of topsoil has very adverse conditions which appear on insufficient supply of nutrition and waster, easily freezing in winter and poor striking root of plants on the growth of vegetation resulted in shallow depth of soil and steep slope (Park, G.S., 2006; Pritchett and Fischer, 1985). The artificial soil for slope revegetation has large influence on plant growth (Kim, K.H. et al, 1999). Therefore, the artificial soil plays an important role in regeneration of plants in a slope. Soil physiochemical properties are very important whether the soil quality has good condition or not.

### 2.1 Soil depth

The removal of topsoil happens to drastic change of topography, barren soil and complete removal of plants and seeds (Meira-Neto et al., 2011). Surface drainage and physicochemical erosion in that case deteriorate sufficient nutrition and moisture (Clemente et al., 2004). The topsoil in the process of construction projects is generally damaged and the artificial soil as close substitute of it is used to recover the damaged surface of a slope with scarce nutrients. The amount of the artificial soil could determine fundamental status for viable plant growth. Therefore, soil depth plays an important role in the plant growth and further helps steady-state stability of the slope.

Regarding the spraying measures in standard estimation frequently used in constructions, the maximum soil depth is required as 15cm in general in Table 4 (KCPA[57], 2012). As the slope is steeper, the soil depth is increased; and as the ground layer is composed of more rocks, the soil depth is also increased (MOLIT, 2009). However, David et al., (2007) suggested that determining soil application depths could apply mathematic equations using 3 indicators: total soil nitrogen, soil bulk density and rock fragment content. Its method is based on the minimum amount of nitrogen for viable plant communities.

Table 4. Standard of soil depth(KCPA, 2012).

| Soil depth | Appication sites | Note |
|---|---|---|
| T=5cm | Hard soil or gravel mixed soil site in gentle slope gradient of 1:1 or less | Unnecessary net installation[58] in case of gentler gradient of slopes |
| T=7cm | Coarse sandy soil or dornick and gravel mixed site in slope gradient of around 1:1 | |
| T=10cm | Weathered rock, soft rock or blasted rock slightly mixed site in slope gradient around 1:0.7 | |
| T=15cm | Hard rock or soft rock in slope gradient around 1:0.5 | Poor plant growth in case of steeper gradient than 1:0.3 |

57) Korea Construction Promotion Association
58) Net installation is one of physically-based secondary device which is generally to prevent a revegetation measure from failure when a slope is steep (45° or more) and ground layer is weathered rock or blasted rock. Its method are generally fiber mesh, wire mesh, gabion block and so forth.

## 2.2 Soil physical properties

No matter how good the soil nutrients are, plant growth is harmful in case of hard soil or excessively saturated soil. The major indicator that has effect on plant growth is controlled by soil physical property (Kim, C.Y. et al, 2010). There are various indicators to evaluate soil physical condition: soil texture, bulk density, soil hardness, water contents and so forth. These indicators are widely used in the field of agriculture, dendrology and eco-engineering.

Soil hardness is a very important indicator to deal with whether root elongation and seed germination can be improved well (Kil, S.H. et al, 2012). Hard soil or compacted soil reduces root length and leaf area (Montagu, et al., 2001; Passioura, 2002). Kim, G.G. and Jo D.G. (2004) showed that soil improvement is necessary in case of over 20mm and plant growth would be difficult in case of over 30mm. Ryu S.H.(2002) claimed that if the soil hardness is over 25mm, permeability is not good and the root growth is harmed; below 10mm, it is classified as soft soil. Oh, K.K. and Kim, D.G.(2007) said that if it is under 23mm, the germination and growth of plant is satisfactory. Hasegawa (2006)[59] said that if it is over 27mm, root permeability in various ways is difficult; if it is 24~27mm, the root development is badly impacted; if it is 20~24mm, the plant may be a kind of the impeded root development; if it is 11~20mm, the root development is not disturbed; and if it is under 11mm, the root development does not have any problems with reduced or dried bearing capacity. MOLIT (2009) said that if it is 11~23mm, the standard, which evaluates an

59) Written by Japanese language

artificial soil required to revegetate a damaged slope, is satisfied; if it is below 11mm or over 27mm, the standard is not satisfied; if it is 23~27mm, the standard is general.

Pore space in the soil is formed according to the arrangement of soil particle, having significance in prospect of plant growth and environmental pollution (Kim, J.H. et al., 2006). The pore space exists between the solid particles of organic and inorganic matters in the soil, containing full of water and air; thus, the soil is composed of 3 phase system with solid, liquid and gas (Jin, H.O. et al, 1994). The 3 phases of soil play key role in the plant growth for breath of the root and supply of water (Jeong, J.H. et al., 2002); the physical, chemical, and biological relations between the 3 phases are affected by mutual characteristics or extrinsic indicators such as temperature, pressure, and light (KFS[60]), 2000). Furthermore, since air and water can flow into the pore space, the volume of water and air contained in the soil depends on the size of the pore space; even if it has same volume of pore space, the velocity of water flow and dryness is altered depending on the size of the pore space. Since water, soluble material, and air exist in the space, it needs to obtain appropriate size of pore space for the soil to absorb sufficient oxygen, water, and nutrition through the root of plant for healthy growth. Moreover, even though the soil contains same volume of pore space, the size of pore space is altered depending on the arrangement of soil particles, influencing on the plant growth and as well as on the migration of environmental pollutants (Kim, K.H. et al, 2006).

Water content refers to the amount of water in a soil to help plant

60) KFS : Korea Forest Service

growth and microbial activity. Since the water content in a soil directly influences on the plant growth, it is very important and it affects the characteristics of soil for air permeability, temperature, and consistency. Regarding the consistency of the characteristics, the available water content was generally increased across from sandy soil and loamy soil to silt loamy soil (Brady and Weil, 2009). High ratio of sand in a soil leads to low water content.

The soil texture is the fundamental property of the soil physical properties (Kim, K.H. et al., 2006). The soil texture indicates the relative size of soil particles, considering the size or roughness of the soil particles. That is, it identifies the relative ratio of sand, silt, and clay, determining characteristics of the various chemical properties, which are significant in the plant growth (Jin, H.O. et al, 1994). The soil texture is an important indicator and influences on the permeability, water holding capacity, air permeability, nutrition holding capacity, and facilitation of tillage works (Kim, K.H. et al., 2006).

In perspective of plant growth, the soil texture has a very significant meaning; the sand, silt, and clay content of the soil gives lots of information of the soil physical properties. For example, the soil containing large volume of sand has high level of permeability, but the nutrition holding capacity is low. The soil containing large volume of silt has medium level of infiltration and nutrition holding capacity; the soil containing large volume of clay has high level of nutrition and water holding capacity, but low level of infiltration.

The soil physical property evaluation generally used in landscape architecture, forestry, and agriculture can be summarized as followings Table 5.

Table 5. Collection of soil physical evaluation.

| Category | Unit | Good | Fair | Poor | Very poor | Note |
|---|---|---|---|---|---|---|
| Soil hardness | ㎜ | below 21 | 21~24 | 24~27 | over 27 | 1) |
| Porosity | $m^3/m^3$ | over 0.6 | 0.6-0.5 | 0.5-0.4 | below 0.4 | 1) |
| Solidity | % | over 20 | 20-30 | 30-40 | below 40 | 2) |
| Gravel contents | % | - | 20-40 | 40-60 | over 60 | 2) |
| Water holding capacity | % | 40-80% of dried weight(Topsoil suitability) -> the same as bulk density | | | | 3) |
| Water content | $m^3/m^3$ | over 0.12 | 0.12-0.08 | 0.08-0.04 | below 0.04 | 1) |
| | $\ell/m^3$ | over 120 | 120-80 | 80-40 | below 40 | 2) |
| Permeability coefficient | cm/s | over 10-3 | 10-3-10-4 | 10-4-10-5 | below 10-5 | 1) |
| | | - | - | 10-4-10-5 (Topsoil suitability) | - | 3) |
| Soil Texture | - | L, SL | SCL, SC, CL | S, SiL, SiC, SicL, LiC, SiC, HC | HC | 4) |
| | | Sandy loam - Clay loam(Topsoil suitability) | | | | 3) |
| Soil Color | - | Dark-brown to black(Topsoil suitability) | | | | 3) |
| Soil Structure | - | Granularity(Topsoil suitability) | | | | 3) |
| Rocks, gravels, etc. | - | No existence(Topsoil suitability) | | | | 3) |

Source : 1) KILA[61] (2007), 2) JILA[62] (1984) recited by Oh, K.K. et al. (2008), 3) MOLIT (2004), 4) Kobashi(小橋澄治)[63]. et al., 1983.

Kirkby and Morgan(1981) have suggested the degree of soil erosion in accordance with increase of organic matter in the soil texture; as the organic matter is increased, soil erosion is decreased; and the difference is shown in the difference of the soil texture summarized as below Table 6.

61) KILA : The Korean Institute of Landscape Architecture
62) JILA : Japanese Institute of Landscape Architecture, 日本造園学会土壌分科會
63) Written by Japanese language

Table 6. Relation with soil texture and soil erosion for the difference of organic matter(Kirkby and Morgan, 1981).

| Texture class | Organic matter content | | | Mean K |
|---|---|---|---|---|
| | <0.5 percent | 2 percent | 4 percent | |
| | K | K | K | |
| Sand | 0.05 | 0.03 | 0.02 | 0.033 |
| loamy sand | 0.12 | 0.10 | 0.08 | 0.100 |
| loamy fine sand | 0.24 | 0.20 | 0.16 | 0.200 |
| sandy loam | 0.27 | 0.24 | 0.19 | 0.233 |
| loam | 0.38 | 0.36 | 0.29 | 0.343 |
| silt loam | 0.48 | 0.42 | 0.33 | 0.410 |
| silt | 0.60 | 0.52 | 0.42 | 0.513 |
| sandy clay loam | 0.27 | 0.25 | 0.21 | 0.243 |
| clay loam | 0.28 | 0.25 | 0.21 | 0.247 |
| silty clay loam | 0.37 | 0.32 | 0.26 | 0.317 |
| sandy clay | 0.14 | 0.13 | 0.12 | 0.130 |
| silty clay | 0.25 | 0.23 | 0.19 | 0.223 |
| clay | 0.13~0.29 | | | 0.210 |

Note : Mean K was performed to classify the relations of organic matter and soil texture.

Furthermore, Chae, B.G. et al.(2009) have performed soil evaluation in relation with landslide in accordance with the standard summarized as below Table 7:

Table 7. Criterion of landslide occurrence(partially extracted from Choi, B.K et al., 2009).

| Category | unit | Small | Slightly small | Medium | Slightly | Large |
|---|---|---|---|---|---|---|
| Porosity | % | ≤46 | 46-67 | 67-75 | 75-80 | ≥80 |
| Water Contents | % | ≤10 | 10-20 | 20-30 | 30-40 | ≥40 |
| Permeability | ㎝/s | $\leq 1.0\times10^{-3}$ | $1.0\times10^{-3}$ ~ $2.5\times10^{-3}$ | $2.5\times10^{-3}$ ~ $4.5\times10^{-3}$ | $4.5\times10^{-3}$ ~ $6.0\times10^{-3}$ | $\geq 6.0\times10^{-3}$ ~ $1.0\times10^{-2}$ |

The representative standards for the soil physical properties in relation with the slope restoration in our country are MOLIT (2009) standard and a standard suggested by Jeon, G.S. (2002); Kil, S.H. et al(2012) have examined the slope vegetation in accordance with the soil hardness as summarized in the following Table 8:

Table 8. Soil physical criterion for slope revegetation.

| Category | Unit | Good | Normal | Bad | Very bad | note |
|---|---|---|---|---|---|---|
| Soil hardness | ㎜ | 11-23 | 23-27 | below 11 or over 27 | - | 1) |
| | | 11-20 | below 11 23-27 | 23-27 | over 27 | 3) |
| | | 15-20 | 21-23 14-8 | 24-26 7 | over 27 | 4) |
| | | below 24(Target value for improvement) | | | | 2) |
| Soil moisture | % | 0.5-5 | 5 - 8 | below 0.5 over 8 | - | 1) |
| Available moisture | g/100g | over 20 | 20-10 | below 10 | - | 4) |
| | $m^3/m^3$ | over 0.08 | | | | 2) |
| Porosity | $m^3/m^3$ | over 0.5 | | | | 2) |
| Permeability coefficient | ㎝/s | 10-1-10-2 | 10-2-10-4 | 10-4-10-6 | below 10-4 | 4) |
| | | over 10-4 | | | | 2) |

Source : 1) MOLIT, 2009, 2) Jeon, G.S., 2002, 3) Kil, S.H. et al., 2012, 4) Kobashi(小橋澄治)[64]. et al., 1983.

## 2.3 Soil chemical properties

Contrary to the physical properties having structural functions in the soil, the soil chemical properties measure the nutrient condition that is necessary for growth. The investigated items for the soil chemical properties are acidity (pH), electrical conductivity (EC), organic matter, nitrogen, phosphoric acid, exchangeable potassium, exchangeable magnesium, exchangeable kalium and natrium, available silicate, cation exchange capacity(CEC) and available phosphate (Kim, G.G. and Jo D.G., 2004).

As the soil acidity (pH) is one of the characteristics that can be easily observed among the soil chemical properties, pH 7.0 is called

64) Written by Japanese language

neutrality, over pH 7.0 is called alkaline soil, and under pH 7.0 is called acidic soil. The soil acidity (pH) can be altered by variation of vegetation communities, eluviation of nutrition, fertilization, decomposition of organic matter, and occurrence of fire. Particularly, decomposition of replaceable cation from the soil reduces the soil acidity (pH) (KFS, 2000; Kim, K.H. et al., 2006).

The soil acidification may be chiefly derived from acidic rocks such as granites and granite geniss being composed of parent material in South Korea; but rather it is more acidified by the alkaline eluviation (Kim, K.H. et al., 2006). In general, the fact for grave soil, which is that the ideal acidity of coniferous tree grave soil is pH 5.2-5.6, of broadleaf trees grave soil is pH 5.6-6.0, and of most forest tress is pH 4.5-6.5 for growth, is well known (KFS, 2000).

Generally, the organic matter is called as corrosion, including organic carbon or organic nitrogen for the nutrient source of soil microorganism and playing a key role in determination of the soil physical properties, air permeability, and water holding capacity (KFS, 2000). The organic matter increases the cation exchange capacity (CEC), water holding capacity and soil aggregation. Furthermore, it supplies the necessary nutrition for the growth of microorganism and plant, playing a key role in improving the quality of the soil (Kim, K.H. et al., 2006). Corrosion in the soil is decomposed by the microorganism; organic carbon is absorbed as the energy source and the organic nitrogen is absorbed as the source of nutrition in the decomposition of the microorganism to be used in the cell composition; and it is continuously changed with forming new microorganism. The velocity of the corrosion decomposition is influenced and altered by the indicators of denitrification, climate, air, topography, volume and characteristics of organic matter, and time; and the impact of the climate is very large. The decomposition of the organic matters is chiefly performed by aerobic bacteria; when the temperature is high and air is sufficiently supplied, the degree of the corrosion is low in the site; but when the temperature is low and the air is insufficiently supplied, the volume of the corrosion is high (KFS, 2000). The soil acidity (pH) also has a strong impact on the decomposition of the organic matters; for the most of the microorganism likes the neutral state, the decomposition of the organic matters get much slower when the soil is seriously acidified or alkalified (Kim, K.H. et al., 2006).

The salt concentration is similar with electrical conductivity(EC). The electrical conductivity is changed according to the degree of salination, having correlations each other. That is, as the degree of salination is larger, the electrical conductivity is increased. Moreover, to calculate the salt concentration from the electrical conductivity, 1ds/m = 10mmol/L = 640mg/L =0.064%; if the value of the electrical conductivity is multiplied by 0.064%, the salt concentration is calculated; generally, if the electrical conductivity(EC) of the saturated extracting solution from soil is over 4dS/m, most of the plant can't grow because of the high degree of salt concentration (0.256%) (Kim, K.H. et al., 2006).

The general evaluation of the soil chemical properties used in landscaping, forestry, and agriculture can be summarized as followings Table 9:

Table 9. Collection of soil chemical evaluation.

| Category | Unit | Good | Fair | Bad | Very bad | note |
|---|---|---|---|---|---|---|
| Soil acidity(pH) | - | 6.0-6.5 | 5.5-6.0 | 4.5-5.5 | below 4.5 | 1) |
| | | | 6.5-7.0 | 7.0-8.0 | over 8.0 | |
| | | 5.6-6.8 | 4.5-5.6 | 3.5-4.5 | below 3.5 | 2), 4) |
| | | | 6.8-8.0 | 8.0-9.5 | over 9.5 | |
| | | 5.5-7.0 (Topsoil suitability) | | | | 3) |
| Electronic Conductivity(EC) | ds/m | below 0.2 | 0.2-1.0 | 1.0-1.5 | over 1.5 | 1), 2) |
| | mmho/cm | 0.1-2.0 (Topsoil suitability) | | | | 3) |
| Cation Exchange Capacity(C.E.C) | cmol/kg<br>me/100g[65] | over 20 | 20-6 | below 6 | - | 1), 2) |
| | me/100g | - | 10 (Topsoil suitability) | - | - | 3) |
| Total N | % | over 0.12 | 0.12-0.06 | below 0.06 | - | 1), 2) |
| | | | 0.1 (Topsoil suitability) | | | 3) |
| Avail. P2O5 | mg/kg | over 200 | 200-100 | below 100 | - | 1), 2) |
| | ppm[66] | - | - | - | 50 | 3) |
| Exchangeable potassium(K+) | cmol/kg | over 3.0 | 3.0-0.6 | below 0.6 | - | 1) |
| | mg/100g[67] | - | - | - | 10 | 3) |
| Exchangeable calcium (Ca++) | cmol/kg | over 5.0 | 5.0-2.5 | below 2.5 | - | 1) |
| Exchangeable magensium (Mg++) | cmol/kg | over 3.0 | 3.0-0.6 | below 0.6 | - | 1) |
| Exchangeable lime | me/100g | over 5.0 | 5.0-2.5 | below 2.5 | - | 2) |
| | | - | - | 2.5 (Topsoil suitability) | - | 3) |
| Salt concentration | % | below 0.05 | 0.05-0.2 | 0.2-0.5 | over 0.5 | 1) |
| | | below 0.05 | 0.05-0.2 | over 0.2 | - | 2) |
| | | 0-0.05% (Topsoil suitability) | - | - | - | 3) |
| Soil organic Matter | % | over 5.0 | 5.0-3.0 | below 3.0 | - | 1) |
| | | | | 3.0 (Topsoil suitability) | | 3) |

Source : 1) KILA (2007), 2) JILA (1984) recited by Oh, Koo Kyoon et al.(2008), 3) MOLIT(2004), 4) Kobashi(小橋澄治)[68]. et al., 1983.

65) cmol/kg = me/100g
66) mg/kg = ppm
67) K+(atomic weight) : 39.1 → 1cmol+ : 391mg, Na+(atomic weight) : 22.9 → 1cmol+ : 229mg, Mg++(atomic weight) : 24 → 1cmol+ : 120mg, Ca++(atomic weight) : 40 → 1cmol+ : 200mg, exchangeable potassium(K+) → 10mg/100g≒0.026 cmol+/kg
68) Written by Japanese language

The representative standards for the soil chemical properties in relation with the slope restoration in our country are MOLIT(2009) standard and a standard suggested by Jeon, G.S.(2002);

Table 10. Soil chemical criterion for slope revegetation.

| Category | Unit | MOLIT(2009) | Jeon, G.S.(2002) | Note |
|---|---|---|---|---|
| Soil acidity(pH) | - | 6.0-8.0 | 5.0-7.5 | |
| Electronic Conductivity(EC) | dS/m | below 1.0 | below 1.0 | |
| Salt concentration | % | below 0.5 | below 0.2 | |
| Cation Exchange Capacity(C.E.C) | cmol/kg | over 6 | over 6 | |
| Avail. P2O5 | mg/kg | - | over 100 | |
| Total N | % | over 0.06 | over 0.06 | |
| Organic Matter | % | over 3.0 | - | |
| Exchangeable potassium(K+) | cmol/kg | - | over 0.6 | |
| Exchangeable calcium(Ca++) | cmol/kg | - | over 2.5 | |
| Exchangeable magensium(Mg++) | cmol/kg | - | over 0.6 | |

## 3. Vegetation properties

The vegetation on the ground suppresses the impact of rain drops and surface flow, roots of trees and organic matters increase the resistibility of the soil against the erosion (Selby, 1993). When a localized heavy rain is poured in the natural slope, fewer rainfalls than actual rainfalls reach the topsoil because of the umbrella effect of the trees. The umbrella effect shows non-significant difference in a small amount of rainfalls; but as the rainfalls are increased, it is increased more in the site of broadleaf trees and mixed stand forest than coniferous tree (Lee, M.S. et al., 2009).

As the vegetation density is higher, the amount of rainfalls which reaches the ground is fewer. Moreover, the vegetation reduces and prevents from frozen erosions such as frostbite, freeze, and thaw and wind erosion on the ground; and the complete vegetation coverage absolutely prevents the rain splash erosion and surface erosion (Park, M.S., 2002; Jeon, K.S. et al., 2003). Thus, various vegetation communities in the slope play a key role in erosion control and the elongated roots by the vegetation growth increases the resistibility of the soil.

### 3.1 Plant community

The abundant plants embody the multi-dimensional structure of plant community. The representative form of the plant community shows a multiple layer combined by trees, shrubs and ground cover. The combined layer provides erosion control because it minimizes soil by raindrop impacts (Zheng, 2006). Thus, the multi-layered vegetation could mitigate soil erosion and further it could maintain the safety of a slope.

The plant community of the slope revegetation tried pioneer vegetation which has first colonized a non-vegetated site before permanent community[69] has a self-sustaining form by steady-state succession. Up to now, the plants of the revegetation mainly utilize introduced plants species, which are mostly non-native species like the cold-season grass which has quick-growing properties after its seeds

69) Permanent community is a form of plant community which has not yet reached the climax from whatever cause, remains unchanged for a long time and maintains its community relationships (Evert, 2010).

germinate (Kim, N.C., et al., 2007). The use of excessive non-native species lead to heterogeneous landscape and soil erosion (Kim, N.C., et al., 1998). Therefore, harmonious landscape is helpful to control erosion and offer the stability of a slope.

Lee, S.C. et al.(2012) approached in perspectives of layers and natural beauty for the vegetation community in the slope. In the perspective of layers, it is classified by multi-layer and single-layer; in the other perspective of natural beauty, it is classified by homogeneous and heterogenous. It is summarized in the following Table 11.

Table 11. 5 types of vegetation community(Lee, S.C. et al., 2012).

| Category | Explanation |
|---|---|
| Homogeneous multiple layer | · Multi-layered structure composed of trees, shrubs and ground cover<br>· Plant community similar to surrounding environment |
| Heterogeneous multiple layer | · Multi-layered structure composed of trees, shrubs and ground cover<br>· Plant community different from surrounding environment |
| Homogeneous simple layer | · Simple-layered structure composed of trees, shrubs or ground cover<br>· Plant community similar to surrounding environment |
| Heterogeneous simple layer | · Simple-layered structure composed of trees, shrubs or ground cover<br>· Plant community different from surrounding environment |
| Poor vegetation | · Impossible vegetation environments because of exposure to rocks |

## 3.2 Vegetation coverage

The vegetation coverage prevents the soil erosion caused by rainfalls through the umbrella effect (Toy et al., 2002), showing correlations with biomass of vegetation (Cano et al., 2002). The indicators influencing on the vegetation coverage are number of herb species, number of an individual herb, number of tree species, slope width, slope height, slope angle, aspect, and elapsed year (Jeon, K.S., 2002;

Woo, B.M. et al., 1993). Kil, S.H. et al.(2012) has summarized the indicators affecting the vegetation coverage in consideration only with the significant value of the data from the previous studies, as shown in the following Table 12.

Table 12. Indicators influencing vegetation coverage.

| Category | The degree of vegetation coverage rate | | |
|---|---|---|---|
| | Bad <---------------------------------------------------------------------> Good | | |
| Slope angle | below 1:0.7<br>(over about 60°) | | over 1:1<br>(below about 45°) |
| Length(horizontal) | Extensive | <----------------------------------> | Narrow |
| Height(Vertical) | over 20m | | below 7m |
| Moisture | Low | | High |
| Aspect | South------------------------------->West------------------>North---------->East | | |

Based on the result, it was analyzed according to the independent variables including number of appeared species, soil hardness, soil acidity, soil moisture, slope angle, and thickness of construction by soil texture; the vegetation coverage and number of appeared species have a strong positive impact, and the thickness of construction and soil moisture have a negative impact. As the number of appeared species is higher, the thickness of construction is thinner, and the soil moisture is lower, the vegetation coverage is influenced (Kil, S.H. et al., 2011).

Furthermore, MOLIT(2009) standard classifies the vegetation coverage by 2 types; one of the types is total vegetation coverage and the other types is vegetation coverage only considering the introduced plant species such as cold-season grasses; all are calculated respectively. The score standard is shown in the following Table 13.

Table 13. Score of vegetation coverage rate (MOLIT, 2009)

| Category | | Score | Criterion | | |
|---|---|---|---|---|---|
| Vegetation coverage (total) | herb-oriented<br>Mixed with herbs and shrubs | 15 | over 80%<br>(15) | 60～79%<br>(10) | below 60%<br>(5) |
| | Woody colony<br>Natural landscape | | over 70%<br>(15) | 50～69%<br>(10) | below 50%<br>(5) |
| Partial vegetation coverage rate (Foreign species like cold-temperate grass) | | (0~-5) | Occupied rate of only foreign herbs in total coverage | | |
| | | | below 30%<br>(0) | 30～59%<br>(-3) | over 60%<br>(-5) |

## 3.3 Species Diversity

The species diversity is the indicator shows the healthiness of ecology in the on-site through the survey of the plant density (Kim, J.G et al., 2006). The species diversity is also called as species heterogeneity, indicating that the effective species diversity refers the abundant number of the same or almost-same species (Hill, 1973; Kim, G.G. and Cho, D.G., 2004).

The ways to measure the species diversity are various with index of dominance (McNaughton, 1967), index of species diversity (Shannon, 1948; Simpson, 1949), index of species evenness (Pielou, 1966), and index of species richness (Margalef, 1958). Particularly, Shannon index or Simpson index are transformed as Inverse Simpson index, Gini-Simpson index, and Rényi entropy et al. to be used in various ways. Along with this, Whittaker (1972) has suggested 3 ways of indicating the diversity index with alpha-diversity, beta-diversity, and gamma-diversity. The alpha-diversity indicates the diversity within specific ecology or specific site. Generally, it represents the number of species within the specific ecology. The beta-diversity indicates the changes between the ecologies, that is, comparing the diversity between the ecologies. The gamma-diversity measures the total diversity within the scale of an site, referring the species diversity in scale of geography.

The slope revegetation has a goal to rehabilitate the small unit of ecology. The diversity of plant species has been evaluated by the alpha-diversity (Kim, H.J. and Lee, J.H. 1998). The MOLIT (2009) standard focuses on the number of appeared species such as the number of established arbors and appeared arbor and herb species in the on-site.

# Appendix C : Expert Survey

Development and Application of Assessment Criteria for Slope Stabilization after Revegetation of Devastated Slopes

- Expert Survey-

Hello, I am Sung Ho Kil, a PhD candidate working in landscape ecology & climate change adaptation (LECCA) laboratory at Seoul National University (SNU). My research, in regards to my doctoral thesis, focuses on the application and development of indicators based on assessment criteria for slope stabilization after devastated slopes are restored.

Currently, artificial slopes have been formed due to all sorts of development projects; at the same time, various slope revegetation methods have been implemented to restore damaged sites. Although the slope restoration work is carried out after slope stability analysis is done, the soil erosion, collapse and much more occurs frequently. Accordingly, it is necessary to develop indicators for risk assessment on erosion, collapse and much more arising after the slope restoration work done with the slope stability secured through pre-analysis procedure.

The objective of this survey is to extract indicators. Indicators required for the risk assessment after slope restoration are categorized into four types: (1) slope stability assessment factor (previous research in total), (2) extraction of natural shallow landslide variables (extracted from 42 copies of papers in total), (3) variables relevant to slope revegetation (total of 44 copies of papers), and (4) major factors in general.

The goal of the research is to develop and interpret slope stabilization indicators in regards to slope restoration based on the survey.
Your response to the survey will be kept confidential and will not be used other than for the research purpose. Please feel free to answer the questionnaire based on your own professional background as there's no right answer on this survey. I sincerely appreciate for your attention, cooperation and time.


▣ location : landscape ecology & climate change adaptation (LECCA) laboratory at Seoul National University (SNU)(02-880-4885, 010-8632-2190)

▣ researcher : Kil, Sung Ho (todd219@snu.ac.kr)


※ Please feel free to be well-informed with how to fill in the black.

< Questionnaire Completion Method >

**▣ Fill in the "V" if you think that the indicator is necessary(Example)**

| Upper class | Subordinate class | Necessary? | Upper class | Subordinate class | Necessary? |
|---|---|---|---|---|---|
| Topography | Slope angle | | Geology | Parent rock | |
| | Upper slope angle | | | Rock floor | V |
| | Slope height | V | | Rock type (granite,diorite, gneiss) | |
| | Slope location | | | Joint condition | V |
| | Aspect | V | | Joint orientation | |

**▣ Please write down what the additional indicators are necessary?(Example)**

| Category | Indicators |
|---|---|
| Topography | Wind |

## ■ Variable Arrangement

### (1) Extracted variables related to slope stability

| Major category | Main variables[70] |
|---|---|
| Topography | Slope height, Slope angle, Slope type, Catchment basin |
| Geology | Rock type(granite, diorite, gneiss), Weathered Characteristics, Weathered condition, Joint condition, Joint orientation, Water condition(dampness, seeps, groundwater), Tension crack, Soil texture |
| Environment | Forest stand, Collapse history, Scale of failure, Checking existence of road, Drainage system, Existence of slope protection, Reinforcement condition |
| Meteorology | Rain intensity |

### (2) Extracted variables related to natural landslide

| Major category | Main variables[71] |
|---|---|
| Topography | Slope angle, Aspect, Altitude, Landslide length, Curvature, Landslide width, Location, Slope type, Landslide depth, Landslide type, SPI(Stream Power Index), TWI(Topographic Wet Index), Slope length, Drainage system |
| Geology | Parent rock, Rock floor, Effective soil depth, Soil depth, Permeability coefficient, Air-void ratio, Soil texture, Water content, Porosity, Specific gravity, Grain size, Tensile strength |
| Environment | Forest stand, Timber diameter class, Timber age class, Vegetation density, Land use |
| Meteorology | Accumulated rainfall, Amount of rainfall, Rain intensity |

70) The main variables indicate more than 3 times from variables organized by Jung I.H. (2009) p. 100-108.
71) The main variables indicate more than 3 times from preceding researches

### (3) Extracted variables related to slope revegetation

| Major category | Main variables[72] |
|---|---|
| Topography | Slope angle, Aspect, Slope length, Altitude, Slope location, Slope type, Slope width, Reinforced facility |
| Geology | Parent rock, Soil acidity, Soil hardness, Organic matter, Soil texture, Total nitrogen, Water contents, C.E.C(Cation Exchange Capacity), Available phosphate, Soil moisture, C/N, Grain size, Exchangeable potassium, Exchangeable calcium, Salt concentration, Exchangeable magnesium, Bulk density, Gravel contents, EC(Electronic Conductivity), Exchangeable sodium |
| Environment | Vegetation coverage rate, Individual number, Tree height, Dominance value, Germination percentage, Species diversity, Plant community, Maximum species diversity, Number of trees, Number of herbs, Surrounding vegetation, Crown width, Grass width, Elapsed year |
| Meteorology | - |

### (4) Comprehensive variables

| Category | Slope stability analysis | Landslide | Slope revegetation |
|---|---|---|---|
| Topography | Slope height, Slope angle, Slope type, Catchment basin | Slope angle, Aspect, Altitude, Landslide length, Curvature, Landslide width, Location, Slope type, Landslide depth, Landslide type, SPI(Stream Power Index), TWI(Topographic Wet Index), Slope length, Drainage system | Slope angle, Aspect, Slope length, Altitude, Slope location, Slope type, Slope width, Reinforced facility |
| Geology | Rock type(granite, diorite, gneiss), Weathered Characteristics, Weathered condition, Joint condition, Joint orientation, Water condition(dampness, seeps, groundwater), Tension crack, Soil texture | Parent rock, Rock floor, Effective soil depth, Soil depth, Permeability coefficient, Air-void ratio, Soil texture, Water content, Porosity, Specific gravity, Grain size, Tensile strength | Parent rock, Soil acidity, Soil hardness, Organic matter, Soil texture, Total nitrogen, Water contents, C.E.C(Cation Exchange Capacity), Available phosphate, Soil moisture, C/N, Grain size, Exchangeable potassium, Exchangeable calcium, Salt concentration, Exchangeable magnesium, Bulk density, Gravel contents, EC(Electronic Conductivity), Exchangeable sodium |
| Environment | Forest stand, Collapse history, Scale of failure, Checking existence of road, Drainage system, Existence of slope protection, Reinforcement condition | Forest stand, Timber diameter class, Timber age class, Vegetation density, Land use | Vegetation coverage rate, Individual number, Tree height, Dominance value, Germination percentage, Species diversity, Plant community, Maximum species diversity, Number of trees, Number of herbs, Surrounding vegetation, Crown width, Grass width, Elapsed year |
| Meteorology | Rain intensity | Accumulated rainfall, Amount of rainfall, Rain intensity | - |

72) The main variables indicate more than 3 times from preceding researches

## ■ Please fill in here.

※ **Please fill in "V" if you are regarded as major variables to evaluate slope stabilization.**

| Upper class | Subordinate class | Necessary? |
|---|---|---|
| **Topography** | Slope angle | |
| | Slope height | |
| | Slope location | |
| | Slope type | |
| | Slope width | |
| | Altitude | |
| | Aspect | |
| | Curvature | |
| | Catchment basin | |
| | SPI(Stream Power Index) | |
| | TWI(Topographic Wet Index) | |
| **Environment** | Forest stand | |
| | Tree height | |
| | Plant length | |
| | Species diversity | |
| | Maximum species diversity | |
| | Dominance value | |
| | Number of trees | |
| | Number of herbs | |
| | Grass width | |
| | Crown width | |
| | Vegetation coverage rate | |
| | Vegetation density | |
| | Germination percentage | |
| | Plant community | |
| | Timber age class | |
| | Timber diameter class | |
| | Surrounding vegetation | |
| | Land use | |
| | Drainage system | |
| | Elapsed year | |
| | Scale of failure | |
| | Collapse history | |
| | Reinforced facility for slope protection | |

| Upper class | Subordinate class | Necessary? |
|---|---|---|
| **Geology** | Parent rock | |
| | Rock floor | |
| | Rock type (granite,diorite, gneiss) | |
| | Joint condition | |
| | Joint orientation | |
| | Weathered Characteristics | |
| | Weathered condition | |
| | Soil depth | |
| | Porosity | |
| | Bulk density | |
| | Gravel contents | |
| | Grain size | |
| | Air-voidratio | |
| | Soil acidity | |
| | Soil hardness | |
| | Water content | |
| | Soil texture | |
| | Permeability coefficient | |
| | Tensile strength | |
| | Shear strength | |
| | Specific gravity | |
| | Tension crack | |
| | C.E.C (Cation Exchange Capacity) | |
| | EC(Electronic Conductivity) | |
| | Available phosphate | |
| | Organic matter | |
| | C/N | |
| | Salt concentration | |
| | Total nitrogen(T-N) | |
| | Exchangeable calcium | |
| | Exchangeable magnesium | |
| | Exchangeable potassium | |
| | Exchangeable sodium | |
| **Meteorology** | Accumulated rainfall | |
| | Amount of rainfall | |
| | Rain intensity | |

**※ Please write down what the additional variables are necessary**

| Category | variables |
|---|---|
| Physical characteristic | |
| Soil | |
| Vegetation | |

**※ Thank you for a very long questionnaire. Please answer the simple question for demographic analysis**

| | |
|---|---|
| **Name** | |
| **Position** | |
| **Field** | ※ Please write down the specific majors in the blank<br>① Civil Engineering ( ) ② Landscape Architecture ( )<br>③ Geology ( ) ④ Forest science ( )<br>⑤ Soil science ( ) ⑥ Etc. ( ) |
| **Institution** | ① Public organizations ② Research institute ③ Educational institutions (University, College, etc)<br>④ Company ⑤ Non-profit organization ⑥ Etc.( ) |
| **Research careers (years)** | ① Less than 1 year ② 1-3 years ③ 3-5 years ④ 5-10 years ⑤ more than 10 years |

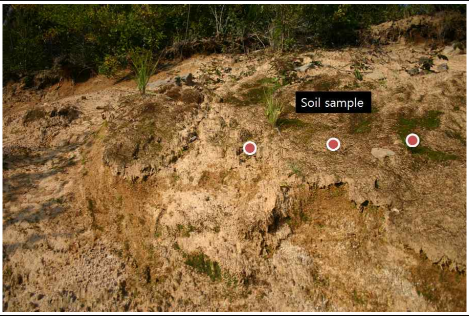
# Appendix D : Correlation between variables

| Category | SA | A | SW | SH | ST | SW | GL | DS | Po | SHard | WC | Sd | St | Cy | TS | PC | SD | pH | SC | SOM | VL | VCR | N.H | N.T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SA | 1.000 | -.127 | .152 | .370 | -.312 | - | .007 | -.174 | -.128 | .552 | .455 | -.139 | .127 | .624 | .188 | .030 | .297 | .091 | -.018 | .103 | -.366 | -.338 | -.085 | -.401 |
| A | -.127 | 1.000 | -.309 | -.321 | -.395 | - | -.121 | -.174 | .305 | -.370 | .358 | -.321 | .321 | .248 | .552 | -.394 | .006 | -.406 | .164 | .236 | .354 | .125 | -.334 | .282 |
| SW | .152 | -.309 | 1.000 | .515 | .090 | - | .141 | .313 | .262 | .406 | -.394 | -.103 | .200 | -.273 | .091 | .018 | .479 | .491 | -.152 | -.418 | -.076 | -.188 | .231 | -.445 |
| SH | .370 | -.321 | .515 | 1.000 | .062 | - | .610 | .035 | .457 | .236 | .042 | -.224 | .164 | .309 | .139 | .370 | .685* | .564 | .018 | .224 | -.063 | .144 | .523 | -.019 |
| ST | -.312 | -.395 | .090 | .062 | 1.000 | - | -.008 | .080 | -.031 | .208 | -.236 | -.347 | .347 | -.472 | -.326 | .146 | -.375 | -.160 | -.361 | -.049 | .116 | .215 | .233 | -.061 |
| SW | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| GL | .007 | -.121 | .141 | .610 | -.008 | - | 1.000 | .115 | .580 | -.255 | .335 | -.348 | .275 | .114 | .462 | .757* | .650* | .650* | .422 | .677* | .244 | .667* | .511 | .218 |
| DS | -.174 | -.174 | .313 | .035 | .080 | - | .115 | 1.000 | .420 | -.174 | .035 | -.383 | .383 | -.383 | .313 | .244 | .383 | .592 | .592 | .104 | .653* | .503 | .594 | .468 |
| Po | -.128 | .305 | .262 | .457 | -.031 | - | .580 | .420 | 1.000 | -.195 | .415 | -.610 | .579 | .232 | .787** | .189 | .793** | .598 | .665* | .518 | .515 | .701* | .303 | .410 |
| SHard | .552 | -.370 | .406 | .236 | .208 | - | -.255 | -.174 | -.195 | 1.000 | .079 | -.030 | .164 | .297 | -.139 | -.430 | .006 | -.103 | -.297 | -.503 | -.695* | -.563 | -.389 | -.765** |
| WC | .455 | .358 | -.394 | .042 | -.236 | - | .335 | .035 | .415 | .079 | 1.000 | -.576 | .539 | .685* | .733* | .103 | .370 | .103 | .636* | .685* | .139 | .431 | -.134 | .182 |
| Sd | -.139 | -.321 | -.103 | -.224 | -.347 | - | -.348 | -.383 | -.610 | -.030 | -.576 | 1.000 | -.976** | -.055 | -.685* | -.200 | -.321 | -.127 | -.333 | -.539 | -.594 | -.613 | -.322 | -.257 |
| St | .127 | .321 | .200 | .164 | .347 | - | .275 | .383 | .579 | .164 | .539 | -.976** | 1.000 | .018 | .685* | .067 | .297 | .091 | .297 | .382 | .493 | .506 | .195 | .107 |
| Cy | .624 | .248 | -.273 | .309 | -.472 | - | .114 | -.383 | .232 | .297 | .685* | -.055 | .018 | 1.000 | .370 | -.212 | .394 | .018 | .297 | .321 | -.366 | -.100 | -.353 | -.056 |
| TS | .188 | .552 | .091 | .139 | -.326 | - | .462 | .313 | .787** | -.139 | .733* | -.685* | .685* | .370 | 1.000 | .127 | .685* | .394 | .721* | .588 | .455 | .569 | .024 | .226 |
| PC | .030 | -.394 | .018 | .370 | .146 | - | .757* | .244 | .189 | -.430 | .103 | -.200 | .067 | -.212 | .127 | 1.000 | .321 | .588 | .261 | .661* | .391 | .625 | .717* | .307 |
| SD | .297 | .006 | .479 | .685* | -.375 | - | .650* | .383 | .793** | .006 | .370 | -.321 | .297 | .394 | .685* | .321 | 1.000 | .842** | .636* | .394 | .202 | .406 | .353 | .151 |
| pH | .091 | -.406 | .491 | .564 | -.160 | - | .650* | .592 | .598 | -.103 | .103 | -.127 | .091 | .018 | .394 | .588 | .842** | 1.000 | .624 | .321 | .253 | .488 | .559 | .194 |
| SC | -.018 | .164 | -.152 | .018 | -.361 | - | .422 | .592 | .665* | -.297 | .636* | -.333 | .297 | .297 | .721* | .261 | .636* | .624 | 1.000 | .576 | .455 | .682* | .195 | .527 |
| SOM | .103 | .236 | -.418 | .224 | -.049 | - | .677* | .104 | .518 | -.503 | .685* | -.539 | .382 | .321 | .588 | .661* | .394 | .321 | .576 | 1.000 | .543 | .813** | .401 | .583 |
| VC | -.366 | .354 | -.076 | -.063 | .116 | - | .244 | .653* | .515 | -.695* | .139 | -.594 | .493 | -.366 | .455 | .391 | .202 | .253 | .455 | .543 | 1.000 | .769** | .627 | .791** |
| VCR | -.338 | .125 | -.188 | .144 | .215 | - | .667* | .503 | .701* | -.563 | .431 | -.613 | .506 | -.100 | .569 | .625 | .406 | .488 | .682* | .813** | .769** | 1.000 | .558 | .699* |
| N.H | -.085 | -.334 | .231 | .523 | .233 | - | .511 | .594 | .303 | -.389 | -.134 | -.322 | .195 | -.353 | .024 | .717* | .353 | .559 | .195 | .401 | .627 | .558 | 1.000 | .573 |
| N.T | -.401 | .282 | -.445 | -.019 | -.061 | - | .218 | .468 | .410 | -.765** | .182 | -.257 | .107 | -.056 | .226 | .307 | .151 | .194 | .527 | .583 | .791** | .699* | .573 | 1.000 |

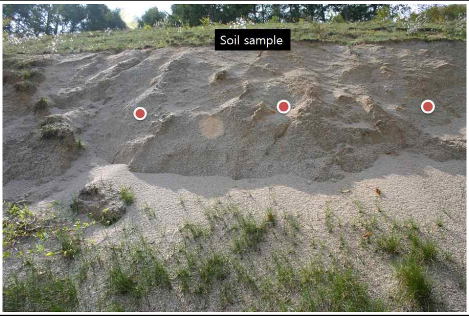
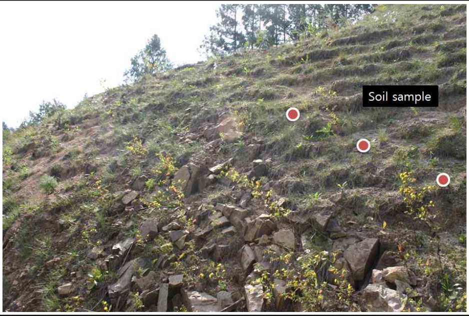
Note → * : p<0.05, ** : p<0.01; SA : Slope angle, A : Aspect, SW : Slope width, SH : Slope height, ST : Slope type, SW : Seepage water, GL : Ground layer, DS : Drainage system, Po : Porosity, SHard : Soil hardness, WC : Water content, Sd : Sand, St : Silt, Cy : Clay, TS : Tensile strength, PC : Permeability coefficient, SD : Soil depth, pH : Soil acidity, SOM : Soil organic matter, VC : Vegetation community, VCR : Vegetation coverage rate, N.H : Number of herbs, N.T : Number of trees

# Appendix E : Photo Images(each site)

## ■ Site 1 : Pyungchang-gun Bongpyung-myeon Mui-ri San 56, Gangwon-Do

| < Failure ><br>(sample location) | < Potential Risk ><br>(sample location) |
|---|---|
| <br> | <br> |

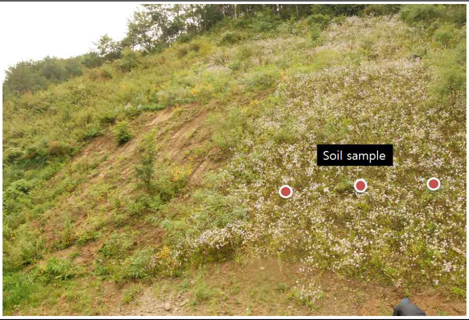
## ■ Site 2 : Pyungchang-gun Jinbu-myeon Songjung-ri San 266, Gangwon-Do

| < Failure ><br>(sample location) | < Potential Risk ><br>(sample location) |
|---|---|
| <br> | <br> |

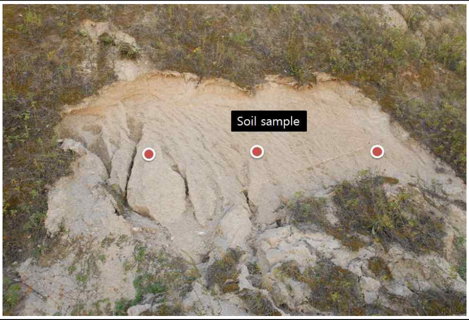
■ Site 3 : Pyungchang-gun Jinbu-myeon Hajinbu-ri San 16, Gangwon-Do

| < Failure ><br>(sample location) | < Potential Risk ><br>(sample location) |
| --- | --- |
|  |  |

■ Site 4 : Pyungchang-gun Jinbu-myeon Hajinbu-ri San 474, Gangwon-Do

| < Failure ><br>(sample location) | < Potential Risk ><br>(sample location) |
| --- | --- |
|  |  |

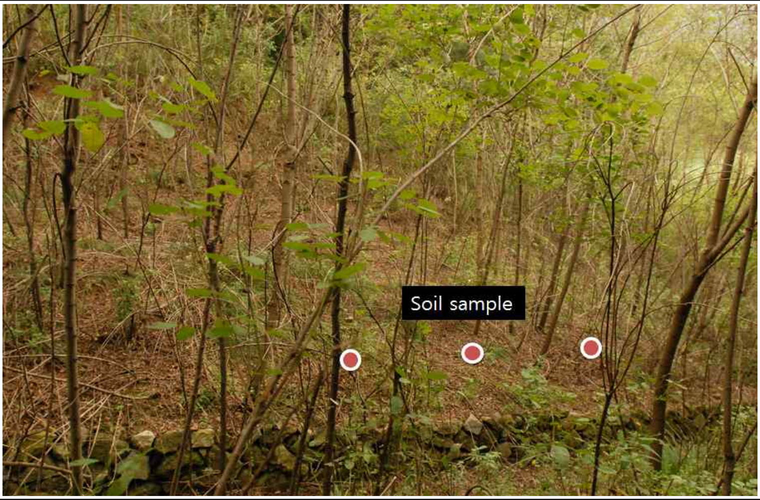
## ■ Site 5 : Yangyang-gun Hyunnam-myeon Juk-ri San 7-1, Gangwon-Do

| < Failure ><br>(sample location) | < Potential Risk ><br>(sample location) |
| --- | --- |
| <br> | <br> |

## ■ Site 6 : Chuncheon-si Onui-dong San 38, Gangwon-Do

| < Non-failure ><br>(sample location) |
| --- |
| <br> |

■ **Site 7 : Pyungchang-gun Jinbu-myeon Homyeong-ri San 64, Gangwon-Do**

| < Non-failure ><br>(sample location) |
|---|
| <br> |

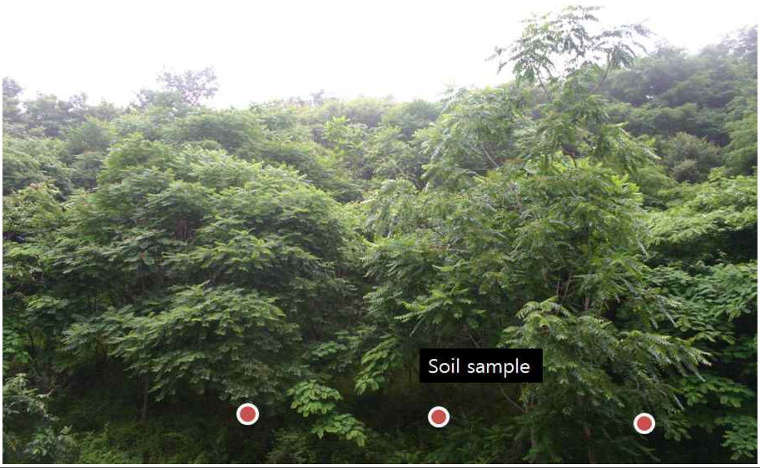
■ **Site 8 : Yangyang-gun Seo-myeon Osaek-ri San 1-27, Gangwon-Do**

| < Non-failure ><br>(sample location) |
|---|
| <br> |

■ Site 9 : Injae-gun Buk-myeon Hangae-ri San 1-59, Gangwon-Do

| < Non-failure ><br>(sample location) |
|---|
|  |

■ Site 10 : Samchuck-si Geunduk-myeon Sangmaegbang-ri San 30-16, Gangwon-Do

| < Non-failure ><br>(sample location) |
|---|
|  |

# Appendix E : Measured data of each site

## ■ Site 1 : Failure

Table 1. Measured data of site 1 (failure)

<table>
<tr><th colspan="2">Category</th><th>Unit</th><th colspan="3">Measured value or description</th><th>Mean value</th></tr>
<tr><td rowspan="9">Construction environments</td><td>Slope angle</td><td>°</td><td colspan="3">72.1, 70.6, 69.5</td><td>70.73</td></tr>
<tr><td>Aspect</td><td>-</td><td colspan="2">212.5°</td><td>S-SW</td><td>S-SW</td></tr>
<tr><td>Slope length</td><td>m</td><td colspan="3">93.4 m</td><td>93.4 m</td></tr>
<tr><td>Slope height</td><td>m</td><td colspan="3">13.3 m</td><td>13.3 m</td></tr>
<tr><td>Slope type</td><td>-</td><td colspan="3">Straight</td><td>Straight</td></tr>
<tr><td>Ground layer</td><td>-</td><td colspan="3">Soil: · Requires physically-based secondary device as degree of the slope is 45° →Not satisfied<br>Geological feature : amphibole-biotite granodiorite</td><td>-</td></tr>
<tr><td>Seepage water</td><td>-</td><td colspan="3">n/a</td><td>-</td></tr>
<tr><td>Elapsed year</td><td>year</td><td colspan="3">0</td><td>0</td></tr>
<tr><td>Drainage condition</td><td>-</td><td colspan="3">· Short height in the slope<br>· No drainage system<br>· Being able to see soil exposed by steep inclination from surroundings forest</td><td>-</td></tr>
<tr><td rowspan="10">Soil physical properties</td><td>Porosity</td><td>m³/m³</td><td colspan="3">0.50, 0.55, 0.45</td><td>0.5</td></tr>
<tr><td>Soil hardness</td><td>㎜</td><td colspan="3">2.5, 3.5, 7</td><td>4.33</td></tr>
<tr><td>Water content</td><td>m³/m³</td><td colspan="3">0.0722, 0.729, 0.604</td><td>0.07</td></tr>
<tr><td rowspan="4">Soil texture</td><td rowspan="4">-</td><td>Sand</td><td colspan="2">84.4, 89.3, 85.3</td><td>86.33</td></tr>
<tr><td>Silt</td><td colspan="2">9.4, 5.1, 8.1</td><td>7.53</td></tr>
<tr><td>Clay</td><td colspan="2">6.3, 5.6, 6.2</td><td>6.17</td></tr>
<tr><td colspan="3">Loamy sand</td><td>LS</td></tr>
<tr><td>Tensile strength</td><td>kPa</td><td colspan="3">1.64, 1.56, 1.59</td><td>1.59</td></tr>
<tr><td>Permeability coefficient</td><td>㎝/s</td><td colspan="3">$7.61{\times}10^{-4}$, $6.69{\times}10^{-4}$, $4.08{\times}10^{-4}$</td><td>$6.13{\times}10^{-4}$</td></tr>
<tr><td>Soil depth</td><td>cm</td><td colspan="3">-</td><td>-</td></tr>
<tr><td rowspan="3">Soil chemical properties</td><td>Soil acidity(pH)</td><td>-</td><td colspan="3">5, 4.87, 5.02</td><td>4.96</td></tr>
<tr><td>Soil concentration</td><td>%</td><td colspan="3">0.0051, 0.0058, 0.0051</td><td>0.005</td></tr>
<tr><td>Soil organic matter</td><td>%</td><td colspan="3">1.2, 1.09, 0.82</td><td>1.04</td></tr>
<tr><td rowspan="4">Vegetation</td><td>Vegetation landscape</td><td>-</td><td colspan="3">Poor vegetation</td><td>-</td></tr>
<tr><td>Vegetation coverage</td><td>%</td><td colspan="3">0</td><td>0</td></tr>
<tr><td>Species diversity: No. of herbs</td><td>No.</td><td colspan="2">-</td><td>0</td><td>0</td></tr>
<tr><td>Species diversity: No. of trees</td><td>No.</td><td colspan="2">-</td><td>0</td><td>0</td></tr>
</table>

## ■ Site 1 : Potential Risk

Table 2. Measured data of site 1 (potential risk)

| Category | | Unit | Measured value or description | | Mean value |
|---|---|---|---|---|---|
| Construction environments | Slope angle | ° | 69.6, 68.7, 69.5 | | 68.30 |
| | Aspect | - | 212.5° | S-SW | S-SW |
| | Slope length | m | 93.4 m | | 93.4 m |
| | Slope height | m | 13.3 m | | 13.3 m |
| | Slope type | - | Straight | | Straight |
| | Ground layer | - | Soil | · Requires physically-based secondary device as degree of the slope is 45° → Not satisfied | - |
| | | | Geological feature : amphibole-biotite granodiorite | | |
| | Seepage water | - | n/a | | - |
| | Elapsed year | year | 1 | | 1 |
| | Drainage condition | - | · Short height in the slope<br>· No drainage system<br>· Being able to see soil exposed by steep inclination from surroundings forest | | - |
| Soil physical properties | Porosity | $m^3/m^3$ | 0.55, 0.50, 0.45 | | 0.5 |
| | Soil hardness | mm | 8.5, 11, 28 | | 15.83 |
| | Water content | $m^3/m^3$ | 0.158, 0.154, 0.158 | | 0.16 |
| | Soil texture | - | Sand | 79.2, 81.9, 81.9 | 81.00 |
| | | | Silt | 14.5, 11.9, 11.9 | 12.77 |
| | | | Clay | 6.3, 6.2, 6.2 | 6.23 |
| | | | Loamy sand | | LS |
| | Tensile strength | $mg/m^3$ | 1.79, 1.7, 1.66 | | 1.72 |
| | Permeability coefficient | cm/s | $1.72\times10^{-4}$, $4.00\times10^{-4}$, $1.42\times10^{-4}$ | | $2.38\times10^{-4}$ |
| | Soil depth | cm | 3.2, 6.2, 3.5 | | 4.30 |
| Soil chemical properties | Soil acidity(pH) | - | 4.95, 4.58, 4.59 | | 4.71 |
| | Soil concentration | % | 0.00512, 0.00576, 0.00512 | | 0.00533 |
| | Soil organic matter | % | 1.12, 0.81, 1.32 | | 1.08 |
| Vegetation | Vegetation landscape | - | Heterogeneous simple layer, Heterogeneous multiple layer, Heterogeneous simple layer | | Heterogeneous simple layer |
| | Vegetation coverage | % | 5, 15, 25 | | 15 |
| | Species diversity – No. of herbs | No. | *Poa pratensis, Humulus japonicus, Artemisia feddei Lev. et Van., Arundinella hirta* | 3, 4, 3 | 4 |
| | Species diversity – No. of trees | No. | *Lespedeza cyrtobotrya* | 0, 1, 0 | 1 |

## ■ Site 2 : Failure

Table 3. Measured data of site 2 (failure)

| Category | | | Unit | Measured value or description | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 58.1, 59.3, 36.5 | | 51.30 |
| | Aspect | | - | 76.4° | NE-E | NE-E |
| | Slope length | | m | 138 m | | 138 m |
| | Slope height | | m | 54 m | | 54 m |
| | Slope type | | - | Convex | | Convex |
| | Ground layer | | - | Soil | · Requires physically-based secondary device as degree of the slope is 45° → Not satisfied | - |
| | | | | Geological feature : granite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 1 | | 1 |
| | Drainage condition | | - | · Very long height and length in the slope<br>· Multi-layered steps and no drainage system in and out<br>· Continuous erosion around steps | | - |
| Soil physical properties | Porosity | | $m^3/m^3$ | 0.5, 0.55, 0.5 | | 0.52 |
| | Soil hardness | | ㎜ | 14, 5.1, 10 | | 9.7 |
| | Water content | | $m^3/m^3$ | 0.049, 0.049, 0.063 | | 0.05 |
| | Soil texture | | - | Sand | 93.2, 94.1, 92.6 | 93.30 |
| | | | | Silt | 2.8, 2.4, 3.8 | 3.00 |
| | | | | Clay | 4, 3.6, 3.6 | 3.73 |
| | | | | Sand | | S |
| | Tensile strength | | kPa | 1.52, 1.38, 1.49 | | 1.46 |
| | Permeability coefficient | | ㎝/s | $5.08\times10^{-3}$, $1.76\times10^{-3}$, $9.08\times10^{-3}$ | | $5.31\times10^{-3}$ |
| | Soil depth | | cm | - | | - |
| Soil chemical properties | Soil acidity(pH) | | ㎜ | 6.13, 6.19, 6.43 | | 6.25 |
| | Soil concentration | | % | 0.00256, 0.00256, 0.00256 | | 0.00256 |
| | Soil organic matter | | % | 0.7, 0.69, 0.76 | | 0.72 |
| Vegetation | Vegetation landscape | | - | Poor vegetation | | - |
| | Vegetation coverage | | % | 0 | | 0 |
| | Species diversity | No. of herbs | No. | - | 0 | 0 |
| | | No. of trees | No. | - | 0 | 0 |

## ■ Site 2 : Potential Risk

Table 4. Measured data of site 2 (potential risk)

| Category | | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 58.6, 67.9, 45.3 | | 57.27 |
| | Aspect | | - | 76.4° | NE-E | NE-E |
| | Slope length | | m | 138 m | | 138 m |
| | Slope height | | m | 54 m | | 54 m |
| | Slope type | | - | Convex | | Convex |
| | Ground layer | | - | Soil | · Requires physically-based secondary device as degree of the slope is 45° →Not satisfied | - |
| | | | | Geological feature : granite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 1 | | 1 |
| | Drainage condition | | - | · Very long height and length in the slope<br>· Multi-layered steps and no drainage system in and out<br>· Continuous erosion around steps | | - |
| Soil physical properties | Porosity | | $m^3/m^3$ | 0.50, 0.60, 0.55 | | 0.55 |
| | Soil hardness | | ㎜ | 6.1, 25, 14 | | 15.03 |
| | Water content | | $m^3/m^3$ | 0.087, 0.098, 0.094 | | 0.09 |
| | Soil texture | | - | Sand | 93.2, 88.3, 88.8 | 90.10 |
| | | | | Silt | 5, 5.8, 5.6 | 5.47 |
| | | | | Clay | 1.8, 5.8, 5.7 | 4.43 |
| | | | | Sand | | S |
| | Tensile strength | | $mg/m^3$ | 1.39, 1.49, 1.54 | | 1.47 |
| | Permeability coefficient | | cm/s | $1.42\times10^{-4}$, $4.44\times10^{-4}$, $1.72\times10^{-4}$ | | $2.53\times10^{-4}$ |
| | Soil depth | | cm | 2.3, 5.6, 5.1 | | 4.33 |
| Soil chemical properties | Soil acidity(pH) | | ㎜ | 5.86, 6.09, 6.02 | | 5.99 |
| | Soil concentration | | % | 0.00384, 0.00704, 0.00512 | | 0.00533 |
| | Soil organic matter | | % | 1.1, 1.11, 1.08 | | 1.1 |
| Vegetation | Vegetation landscape | | - | Heterogeneous simple layer, Heterogeneous simple layer, Heterogeneous simple layer | | Heterogeneous simple layer |
| | Vegetation coverage | | % | 24, 34, 28 | | 28.67 |
| | Species diversity | No. of herbs | No. | *Aster yomena, Poa pratensis, Persicaria hydropiper, Miscanthus sinensis var. purpurascens, Crepidiastrum sonchifolium, Dendranthema boreale, Metaplexis japonica, Artemisia montana Pampan, Picris hieracioides var. glabrescens, Commelina communis, Solidago virga-aurea var. asiatica* | 10, 11, 8 | 11 |
| | | No. of trees | No. | *Lespedeza cyrtobotrya, Rubus crataegifolius Bunge, Indigofera pseudotinctoria* | 1, 3, 2 | 2 |

## ■ Site 3 : Failure

Table 5. Measured data of site 3 (failure)

| Category | | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 59.5, 55.9, 43 | | 52.80 |
| | Aspect | | - | 120° | E-SE | E-SE |
| | Slope length | | m | 29.7 m | | 29.7 m |
| | Slope height | | m | 8.2 m | | 8.2 m |
| | Slope type | | - | Straight | | Straight |
| | Ground layer | | - | Soil | · Requires physically-based secondary device as degree of the slope is 45° → Not satisfied | - |
| | | | | Geological feature : granite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 2 | | 2 |
| | Drainage condition | | - | · Short height and length in the slope<br>· No drainage system<br>· Sporadic erosion in relatively long section | | - |
| Soil physical properties | Porosity | | $m^3/m^3$ | 0.45, 0.55, 0.50 | | 0.5 |
| | Soil hardness | | ㎜ | 11.1, 2, 16.5 | | 9.87 |
| | Water content | | $m^3/m^3$ | 0.044, 0.044, 0.044 | | 0.04 |
| | Soil texture | | - | Sand | 93.7, 94.5, 90.9 | 93.03 |
| | | | | Silt | 4.3, 2.2, 4.2 | 3.57 |
| | | | | Clay | 2, 3.3, 5 | 3.43 |
| | | | | Sand | | S |
| | Tensile strength | | kPa | 1.4, 1.32, 1.41 | | 1.38 |
| | Permeability coefficient | | ㎝/s | $6.47\times10^{-3}$, $2.41\times10^{-2}$, $4.21\times10^{-2}$ | | $2.42\times10^{-2}$ |
| | Soil depth | | cm | - | | - |
| Soil chemical properties | Soil acidity(pH) | | ㎜ | 6.12, 6.21, 6.31 | | 6.21 |
| | Soil concentration | | % | 0.00704, 0.00804, 0.0064 | | 0.00683 |
| | Soil organic matter | | % | 0.65, 0.52, 0.59 | | 0.59 |
| Vegetation | Vegetation landscape | | - | Poor vegetation | | - |
| | Vegetation coverage | | % | 0 | | 0 |
| | Species diversity | No. of herbs | No. | - | 0 | 0 |
| | | No. of trees | No. | - | 0 | 0 |

## ■ Site 3 : Potential Risk

Table 6. Measured data of site 3 (potential risk)

| Category | | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 55.3, 67.8, 52.9 | | 58.67 |
| | Aspect | | - | 120° | E-SE | E-SE |
| | Slope length | | m | 29.7 m | | 29.7 m |
| | Slope height | | m | 8.2 m | | 8.2 m |
| | Slope type | | - | Straight | | Straight |
| | Ground layer | | - | Soil | · Requires physically-based secondary device as degree of the slope is 45° →Not satisfied | - |
| | | | | Geological feature : granite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 2 | | 2 |
| | Drainage condition | | - | · Short height and length in the slope<br>· No drainage system<br>· Sporadic erosion in relatively long section | | - |
| Soil physical properties | Porosity | | $m^3/m^3$ | 0.45, 0.40, 0.40 | | 0.42 |
| | Soil hardness | | ㎜ | 2, 0.5, 8.5 | | 3.67 |
| | Water content | | $m^3/m^3$ | 0.150, 0.045, 0.128 | | 0.11 |
| | Soil texture | | - | Sand | 93.6, 92.5, 91.8 | 92.63 |
| | | | | Silt | 2.3, 3.8, 2.9 | 3.00 |
| | | | | Clay | 4, 3.7, 5.3 | 4.33 |
| | | | | Sand | | S |
| | Tensile strength | | $mg/m^3$ | 1.41, 1.57, 1.44 | | 1.47 |
| | Permeability coefficient | | ㎝/s | $2.43\times10^{-3}$, $9.61\times10^{-4}$, $4.14\times10^{-3}$ | | $2.51\times10^{-3}$ |
| | Soil depth | | cm | 0.2, 0.3, 3.5 | | 1.33 |
| Soil chemical properties | Soil acidity(pH) | | ㎜ | 5.63, 5.28, 5.28 | | 5.4 |
| | Soil concentration | | % | 0.03392, 0.04864, 0.03456 | | 0.03904 |
| | Soil organic matter | | % | 5.76, 7.66, 7.59 | | 7 |
| Vegetation | Vegetation landscape | | - | Heterogeneous multiple layer, Heterogeneous multiple layer, Heterogeneous multiple layer | | Heterogeneous multiple layer |
| | Vegetation coverage | | % | 85, 95, 92 | | 90.67 |
| | Species diversity | No. of herbs | No. | *Chelidonium majus var. asiaticum, Inula britannica var. chinensis, Poa pratensis, Clematis apiifolia, Commelina communis, Humulus japonicus, Impatiens textori, Erigeron annuus, Aster yomena, Dendranthema boreale* | 11, 11, 9 | 11 |
| | | No. of trees | No. | *Indigofera pseudotinctoria, Rubus crataegifolius, Robinia pseudoacacia, Lespedeza cyrtobotrya* | 3, 2, 4 | 4 |

## ■ Site 4 : Failure

Table 7. Measured data of site 4 (failure)

| Category | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|
| Construction environments | Slope angle | ° | 47.1, 35.1, 40.0 | | 40.73 |
| | Aspect | - | 3° | N-NE | N-NE |
| | Slope length | m | 88 m | | 88 m |
| | Slope height | m | 42 m | | 42 m |
| | Slope type | - | Convex | | Convex |
| | Ground layer | - | Weathered soil | · Requirement of physically-based secondary device due to weathered soil → Satisfied | - |
| | | | Geological feature : granite | | |
| | Seepage water | - | n/a | | - |
| | Elapsed year | year | 1 | | 1 |
| | Drainage condition | - | · No drainage system in the stair<br>· Erosion of flow-in water around the stair | | - |
| Soil physical properties | Porosity | m³/m³ | 0.50, 0.45, 0.45 | | 0.47 |
| | Soil hardness | ㎜ | 3.5, 2, 1.5 | | 2.33 |
| | Water content | m³/m³ | 0.067, 0.042, 0.042 | | 0.05 |
| | Soil texture | - | Sand | 92.6, 87.1, 86.8 | 88.83 |
| | | | Silt | 3.9, 7.6, 7 | 6.17 |
| | | | Clay | 3.5, 5.3, 6.2 | 5.00 |
| | | | Sand | | Sand |
| | Tensile strength | kPa | 1.4, 1.58, 1.57 | | 1.52 |
| | Permeability coefficient | ㎝/s | $1.06\times10^{-3}$, $7.25\times10^{-4}$, $2.89\times10^{-4}$ | | $6.92\times10^{-4}$ |
| | Soil depth | ㎝ | - | | - |
| Soil chemical properties | Soil acidity(pH) | ㎜ | 6.56, 6.51, 6.55 | | 6.54 |
| | Soil concentration | % | 0.0064, 0.00448, 0.00512 | | 0.00533 |
| | Soil organic matter | % | 0.35, 0.53, 0.67 | | 0.52 |
| Vegetation | Vegetation landscape | - | Poor vegetation | | - |
| | Vegetation coverage | % | 0 | | 0 |
| | Species diversity: No. of herbs | No. | - | 0 | 0 |
| | Species diversity: No. of trees | No. | - | 0 | 0 |

## ■ Site 4 : Potential Risk

Table 8. Measured data of site 4 (potential risk)

| Category | | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 44.7, 39.7, 44.6 | | 43.00 |
| | Aspect | | - | 3° | N-NE | N-NE |
| | Slope length | | m | 88 m | | 88 m |
| | Slope height | | m | 42 m | | 42 m |
| | Slope type | | - | Convex | | Convex |
| | Ground layer | | - | Weathered soil | · Requirement of physically-based secondary device due to weathered soil → Satisfied | - |
| | | | | Geological feature : granite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 1 | | 1 |
| | Drainage condition | | - | · No drainage system in the berm<br>· Erosion of flow-in water around the berm | | - |
| Soil physical properties | Porosity | | $m^3/m^3$ | 0.45, 0.45, 0.55 | | 0.48 |
| | Soil hardness | | ㎜ | 19, 7, 13 | | 13 |
| | Water content | | $m^3/m^3$ | 0.131, 0.094, 0.083 | | 0.1 |
| | Soil texture | | - | Sand | 92.6, 89.9, 91.8 | 91.43 |
| | | | | Silt | 3.9, 5.1, 4.7 | 4.57 |
| | | | | Clay | 3.4, 5.1, 3.5 | 4.00 |
| | | | | Sand | | S |
| | Tensile strength | | $mg/m^3$ | 1.43, 1.46, 1.41 | | 1.43 |
| | Permeability coefficient | | ㎝/s | $2.25\times10^{-3}$, $6.61\times10^{-3}$, $4.75\times10^{-3}$ | | $3.11\times10^{-3}$ |
| | Soil depth | | cm | 5.5, 3.7, 1.5 | | 3.57 |
| Soil chemical properties | Soil acidity(pH) | | ㎜ | 6.79, 6.88, 6.92 | | 6.86 |
| | Soil concentration | | % | 0.00768, 0.00576, 0.0064 | | 0.00661 |
| | Soil organic matter | | % | 2.37, 1.65, 1.64 | | 1.89 |
| Vegetation | Vegetation landscape | | - | Heterogeneous simple layer, Homogeneous simple layer, Heterogeneous simple layer | | Heterogeneous simple layer |
| | Vegetation coverage | | % | 94, 96, 88 | | 92.67 |
| | Species diversity | No. of herbs | No. | *Artemisia princeps var. orientalis, Centaurea cyanus, Aster yomena, Coreopsis drummondii, Coreopsis tinctoria, Silene armeria, Crepidiastrum sonchifolium, Callistephus chinensis, Humulus japonicus, Medicago sativa, Cosmos bipinnatus, Dianthus superbus var. longicalycinus, Impatiens textori, Persicaria hydropiper* | 14, 13, 14 | 14 |
| | | No. of trees | No. | *Robinia pseudoacacia* | 0, 1, 0 | 1 |

## ■ Site 5 : Failure

Table 9. Measured data of site 5 (failure)

| Category | | | Unit | Measured value | | | Mean value |
|---|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 44.5, 47, 51.2 | | | 47.56 |
| | Aspect | | - | 35° | N-NE | | N-NE |
| | Slope length | | m | 111 m | | | 111 m |
| | Slope height | | m | 10 m | | | 10 m |
| | Slope type | | - | Straight | | | Straight |
| | Ground layer | | - | Soil | · Requires physically-based secondary device as degree of the slope is 45° →Not satisfied | | - |
| | | | | Geological feature : granitite | | | |
| | Seepage water | | - | n/a | | | - |
| | Elapsed year | | year | 2 | | | 2 |
| | Drainage condition | | - | · Well-drained condition in upper and lower drainage | | | - |
| Soil physical properties | Porosity | | ㎥/㎥ | 0.55, 0.55, 0.50 | | | 0.53 |
| | Soil hardness | | ㎜ | 0.087, 0.081, 0.090 | | | 15.67 |
| | Water content | | ㎥/㎥ | 0.09 | | | 0.09 |
| | Soil texture | | - | Sand | 89.5, 87.6, 89.5 | | 88.87 |
| | | | | Silt | 8, 9.9, 8.2 | | 8.70 |
| | | | | Clay | 2.5, 2.5, 2.3 | | 2.43 |
| | | | | Loamy sand | | | LS |
| | Tensile strength | | kPa | 1.43, 1.5, 1.5 | | | 1.48 |
| | Permeability coefficient | | ㎝/s | $5.69\times10^{-4}$, $8.61\times10^{-4}$, $1.92\times10^{-3}$ | | | $1.12\times10^{-3}$ |
| | Soil depth | | cm | - | | | - |
| Soil chemical properties | Soil acidity(pH) | | ㎜ | 7.25, 7.2, 7.11 | | | 7.19 |
| | Soil concentration | | % | 0.00384, 0.00448, 0.00448 | | | 0.00427 |
| | Soil organic matter | | % | 0.17, 0.19, 0.06 | | | 0.14 |
| Vegetation | Vegetation landscape | | - | Poor vegetation | | | - |
| | Vegetation coverage | | % | 0 | | | 0 |
| | Species diversity | No. of herbs | No. | - | | 0 | 0 |
| | | No. of trees | No. | - | | 0 | 0 |

## ■ Site 5 : Potential Risk

Table 10. Measured data of site 5 (potential risk)

| Category | | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 52.6, 53.4, 50.2 | | 52.07 |
| | Aspect | | - | 35° | N-NE | N-NE |
| | Slope length | | m | 111 m | | 111 m |
| | Slope height | | m | 10 m | | 10 m |
| | Slope type | | - | Straight | | Straight |
| | Ground layer | | - | Soil | · Requires physically-based secondary device as degree of the slope is 45° →Not satisfied | - |
| | | | | Geological feature : granitite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 2 | | 2 |
| | Drainage condition | | - | · Well-drained condition in upper and lower drainage | | - |
| Soil physical properties | Porosity | | $m^3/m^3$ | 0.55, 0.55, 0.50 | | 0.53 |
| | Soil hardness | | mm | 22.5, 14.7, 10.2 | | 15.8 |
| | Water content | | $m^3/m^3$ | 0.123, 0.109, 0.117 | | 0.12 |
| | Soil texture | | - | Sand | 91.3, 88.4, 86.4 | 88.70 |
| | | | | Silt | 5.9, 7.7, 11 | 8.20 |
| | | | | Clay | 2.8, 3.9, 2.6 | 3.10 |
| | | | | Loamy sand | | LS |
| | Tensile strength | | $mg/m^3$ | 1.44, 1.51, 1.55 | | 1.5 |
| | Permeability coefficient | | cm/s | $7.58\times10^{-4}$, $4.33\times10^{-4}$, $5.36\times10^{-4}$ | | $5.76\times10^{-4}$ |
| | Soil depth | | cm | 4.5, 5.2, 3.4 | | 4.37 |
| Soil chemical properties | Soil acidity(pH) | | mm | 7.33, 7.41, 7.4 | | 7.38 |
| | Soil concentration | | % | 0.0064, 0.00576, 0.00448 | | 0.00555 |
| | Soil organic matter | | % | 0.41, 0.29, 0.96 | | 0.55 |
| Vegetation | Vegetation landscape | | - | Heterogeneous simple layer, Homogeneous simple layer, Heterogeneous simple layer | | Heterogeneous simple layer |
| | Vegetation coverage | | % | 35, 45, 38 | | 39.33 |
| | Species diversity | No. of herbs | No. | *Cosmos bipinnatus, Trifolium repens, Artemisia princeps var. orientalis, Dendranthema boreale, Silene armeria, Dianthus superbus var. longicalycinus, Chenopodium album var. centrorubrum, Setaria viridis* | 8, 9, 9 | 9 |
| | | No. of trees | No. | *Lespedeza cyrtobotrya* | 0, 1, 0 | 1 |

## ■ Site 6 : Non-failure

Table 11. Measured data of site 6

| Category | | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 38.1, 41.6, 41.8 | | 40.50 |
| | Aspect | | - | 206° | S-SW | S-SW |
| | Slope length | | m | 142.3 m | | 142.3 m |
| | Slope height | | m | 31.1 m | | 31.1 m |
| | Slope type | | - | Straight | | Straight |
| | Ground layer | | - | Weathered rock | · Requirement of physically-based secondary device due to weathered rock → Satisfied | - |
| | | | | Geological feature : granitite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 6 | | 6 |
| | Drainage condition | | - | · Well drainage system | | - |
| Soil physical properties | Porosity | | $m^3/m^3$ | 0.65, 0.50, 0.60 | | 0.58 |
| | Soil hardness | | mm | 3.47 | | 3.47 |
| | Water content | | $m^3/m^3$ | 0.065, 0.057, 0.062 | | 0.06 |
| | Soil texture | | - | Sand | 90.2, 87.8, 89.3 | 89.10 |
| | | | | Silt | 7.5, 10.1, 7.3 | 8.30 |
| | | | | Clay | 2.3, 2.1, 3.4 | 2.60 |
| | | | | Loamy sand | | LS |
| | Tensile strength | | kPa | 1.39, 1.85, 1.63 | | 1.62 |
| | Permeability coefficient | | cm/s | $1.78 \times 10^{-3}$, $1.54 \times 10^{-3}$, $1.61 \times 10^{-3}$ | | $1.64 \times 10^{-3}$ |
| | Soil depth | | cm | 6.7, 8.2, 8.1 | | 7.67 |
| Soil chemical properties | Soil acidity(pH) | | mm | 7.21, 7.09, 7.05 | | 7.12 |
| | Soil concentration | | % | 0.01344, 0.0128, 0.0096 | | 0.01195 |
| | Soil organic matter | | % | 4.12, 7.63, 3.26 | | 5.00 |
| Vegetation | Vegetation landscape | | - | Homogeneous multiple layer, Homogeneous multiple layer, Homogeneous multiple layer | | Homogeneous multiple layer |
| | Vegetation coverage | | % | 98, 99, 100 | | 99.00 |
| | Species diversity | No. of herbs | No. | *Angelica decursiva, Aconitum pseudo-proliferum, Aster ageratoides Turcz. var. ageratoides, Peucedanum terebinthaceum, Crepidiastrum denticulatum, Artemisia princeps var. orientalis, Chenopodium album var. centrorubrum, Potentilla fragarioides var. major, Poa pratensis, Impatiens textori, Erigeron annuus, Persicaria hydropiper, Trifolium repens, Pteridium aquilinum var. latiusculum, Chenopodium ficifolium, Commelina communis, Humulus japonicus, Oenothera biennis, Pilea mongolica* | 18, 19, 19 | 19 |
| | | No. of trees | No. | *Clerodendrum trichotomum, Prunus sargentii, Lespedeza cyrtobotrya, Robinia pseudoacacia* | 2, 4, 3 | 4 |

## ■ Site 7 : Non-failure

Table 12. Measured data of site 7

| Category | | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 23.9, 17.0, 20.2 | | 20.37 |
| | Aspect | | - | 148° | SE-S | SE-S |
| | Slope length | | m | 55 m | | 55 m |
| | Slope height | | m | 1.1 m | | 1.1 m |
| | Slope type | | - | Concave | | Concave |
| | Ground layer | | - | Soil | · Not requires physically-based secondary device as degree of the slope is 45° or less → Satisfied | - |
| | | | | Geological feature : granite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 4 | | 4 |
| | Drainage condition | | - | · Well-drained condition(established in a concave surface as a rehabilitated site after landsliding) | | - |
| Soil physical properties | Porosity | | ㎥/㎥ | 0.55, 0.55, 0.55 | | 0.55 |
| | Soil hardness | | ㎜ | 6.8, 11.8, 1 | | 6.53 |
| | Water content | | ㎥/㎥ | 0.129, 0.131, 0.124 | | 0.13 |
| | Soil texture | | - | Sand | 88.2, 85.2, 88.1 | 87.17 |
| | | | | Silt | 6.5, 9.3, 4.3 | 6.70 |
| | | | | Clay | 5.3, 5.4, 7.5 | 6.07 |
| | | | | Loamy sand | | LS |
| | Tensile strength | | kPa | 1.48, 1.56, 1.57 | | 1.54 |
| | Permeability coefficient | | ㎝/s | $2.33\times10^{-3}$, $6.72\times10^{-4}$, $7.97\times10^{-4}$ | | $1.27\times10^{-3}$ |
| | Soil depth | | cm | 0.2, 0.8, 2.1 | | 1.03 |
| Soil chemical properties | Soil acidity(pH) | | ㎜ | 5.07, 5.01, 5.1 | | 5.06 |
| | Soil concentration | | % | 0.01216, 0.01024, 0.01088 | | 0.01105 |
| | Soil organic matter | | % | 2.99, 2.91, 3.08 | | 2.99 |
| Vegetation | Vegetation landscape | | - | Homogeneous multiple layer, Homogeneous multiple layer, Homogeneous multiple layer | | Homogeneous multiple layer |
| | Vegetation coverage | | % | 88, 95, 98 | | 93.67 |
| | Species diversity | No. of herbs | No. | *Coreopsis drummondii, Lotus corniculatus var. japonicus, Poa pratensis, Echinacea angustifolia, Aster yomena, Dianthus superbus var. longicalycinus, Arundinella hirta, Rubia akane, Geranium sibiricum, Chelidonium majus var. asiaticum, Setaria viridis, Artemisia princeps var. orientalis, Erigeron annuus* | 13, 13, 11 | 13 |
| | | No. of trees | No. | *Rhus chinensis, Albizzia julibrissin, Firmiana simplex, Salix koreensis Andersson, Indigofera pseudotinctoria. Alnus sibiroca* | 4, 5, 6 | 6 |

## ■ Site 8 : Non-failure

Table 13. Measured data of site 8

| Category | | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|---|
| Construction environments | Slope angle | | ° | 54.6, 61.8, 59.6 | | 58.67 |
| | Aspect | | - | 53° | NE-E | NE-E |
| | Slope length | | m | 145.4 m | | 145.4 m |
| | Slope height | | m | 50.5 m | | 50.5 m |
| | Slope type | | - | Convex | | Convex |
| | Ground layer | | - | Hard rock | · Requirement of physically- based secondary device due to hard rock and 45° over →Satisfied | - |
| | | | | Geological feature : granite | | |
| | Seepage water | | - | n/a | | - |
| | Elapsed year | | year | 5 | | 5 |
| | Drainage condition | | - | · Drainage tubes installed to prevent sporadic seepage erosion<br>· Drainage system in intervals<br>· Normal drainage | | - |
| Soil physical properties | Porosity | | $m^3/m^3$ | 0.65, 0.65, 0.60 | | 0.63 |
| | Soil hardness | | ㎜ | 21, 7, 9 | | 12.33 |
| | Water content | | $m^3/m^3$ | 0.666, 0.728, 0.612 | | 0.67 |
| | Soil texture | | - | Sand | 80.9, 78.7, 75.1 | 78.23 |
| | | | | Silt | 14.8, 14.9, 21.2 | 16.97 |
| | | | | Clay | 4.3, 6.5, 3.7 | 4.83 |
| | | | | Sandy loam | | SL |
| | Tensile strength | | kPa | 1.88, 1.93, 2.11 | | 1.97 |
| | Permeability coefficient | | ㎝/s | $9.08\times10^{-3}$, $9.03\times10^{-3}$, $6.58\times10^{-3}$ | | $8.23\times10^{-3}$ |
| | Soil depth | | cm | 16.1, 10.2, 13.2 | | 13.17 |
| Soil chemical properties | Soil acidity(pH) | | ㎜ | 7.77, 7.58, 7.46 | | 7.6 |
| | Soil concentration | | % | 0.06144, 0.05312, 0.09472 | | 0.06976 |
| | Soil organic matter | | % | 13.2, 13.07, 13.29 | | 13.19 |
| Vegetation | Vegetation landscape | | - | Heterogeneous multiple layer, Homogeneous multiple layer, Heterogeneous multiple layer | | Heterogeneous multiple layer |
| | Vegetation coverage | | % | 99, 100, 100 | | 99.67 |
| | Species diversity | No. of herbs | No. | *Artemisia princeps var. orientalis, Lactuca indica var. laciniata, Dendranthema boreale, Impatiens textori, Taraxacum officinale, Prunella vulgaris Linne var. lilacina Nakai, Phragmites communis, Arundinella hirta, Rumex crispus L., Peucedanum terebinthaceum, Humulus japonicus, Coreopsis tinctoria, Silene armeria, Lotus corniculatus var. japonicus* | 15, 13, 14 | 15 |
| | | No. of trees | No. | *Albizzia julibrissin, Alnus sibiroca* | 1, 1, 1 | 2 |

## ■ Site 9 : Non-failure

Table 14. Measured data of site 9

| Category | | Unit | Measured value | | Mean value |
|---|---|---|---|---|---|
| Construction environments | Slope angle | ° | 40.6, 40.1, 41.4 | | 40.70 |
| | Aspect | - | 213° | S-SW | S-SW |
| | Slope length | m | 65.5 m | | 65.5 m |
| | Slope height | m | 20 m | | 20 m |
| | Slope type | - | Straight | | Straight |
| | Ground layer | - | Hard rock | · Requirement of physically- based secondary device due to hard rock → Satisfied | - |
| | | | Geological feature : granite | | |
| | Seepage water | - | n/a | | - |
| | Elapsed year | year | 6 | | 6 |
| | Drainage condition | - | · No drainage system and no drainage<br>· Small-sized revegetation<br>· No seepage erosion and no collapse | | - |
| Soil physical properties | Porosity | $m^3/m^3$ | 0.60, 0.65, 0.70 | | 0.65 |
| | Soil hardness | ㎜ | 7, 5, 4 | | 5.33 |
| | Water content | $m^3/m^3$ | 0.674, 0.617, 0.574 | | 0.62 |
| | Soil texture | - | Sand | 77.9, 81.2, 70 | 76.37 |
| | | | Silt | 16.6, 15.8, 26.5 | 19.63 |
| | | | Clay | 5.4, 3.1, 3.5 | 4.00 |
| | | | Sandy loam | | SL |
| | Tensile strength | kPa | 2.07, 1.97, 2.09 | | 2.04 |
| | Permeability coefficient | ㎝/s | $1.56\times10^{-3}$, $1.51\times10^{-3}$, $1.59\times10^{-3}$ | | $1.55\times10^{-3}$ |
| | Soil depth | cm | 5, 11.2, 6.5 | | 10.40 |
| Soil chemical properties | Soil acidity(pH) | ㎜ | 7.09, 7.06, 7.13 | | 7.09 |
| | Soil concentration | % | 0.032, 0.0288, 0.032 | | 0.03093 |
| | Soil organic matter | % | 13.21, 12.84, 17.37 | | 14.47 |
| Vegetation | Vegetation landscape | - | Heterogeneous multiple layer, Heterogeneous multiple layer, Heterogeneous multiple layer | | Heterogeneous multiple layer |
| | Vegetation coverage | % | 98, 100, 100 | | 99.33 |
| | Species diversity: No. of herbs | No. | *Artemisia princeps var. orientalis, Miscanthus sinensis var. purpurascens, Lotus corniculatus var. japonicus, Erigeron annuus, Lespedeza cuneata, Arundinella hirta (THUNB.) NAKAI* | 6, 5, 4 | 6 |
| | Species diversity: No. of trees | No. | *Albizzia julibrissin, Quercus mongolica, Lespedeza cyrtobotrya* | 2, 3, 4 | 4 |

## ■ Site 10 : Non-failure

Table 15. Measured data of site 10

<table>
<tr><td colspan="3">Category</td><td>Unit</td><td colspan="3">Measured value</td><td>Mean value</td></tr>
<tr><td rowspan="10">Construction environments</td><td colspan="2">Slope angle</td><td>°</td><td colspan="3">65.6, 59.9, 63</td><td>62.83</td></tr>
<tr><td colspan="2">Aspect</td><td>-</td><td colspan="2">87.5°</td><td>NE-E</td><td>NE-E</td></tr>
<tr><td colspan="2">Slope length</td><td>m</td><td colspan="3">75.7 m</td><td>75.7 m</td></tr>
<tr><td colspan="2">Slope height</td><td>m</td><td colspan="3">55 m</td><td>55 m</td></tr>
<tr><td colspan="2">Slope type</td><td>-</td><td colspan="3">Straight</td><td>Straight</td></tr>
<tr><td colspan="2" rowspan="2">Ground layer</td><td rowspan="2">-</td><td>Hard rock</td><td colspan="2">· Requirement of physically- based secondary device due to hard rock and 45° over →Satisfied</td><td rowspan="2">-</td></tr>
<tr><td colspan="3">Geological feature : gneiss</td></tr>
<tr><td colspan="2">Seepage water</td><td>-</td><td colspan="3">n/a</td><td>-</td></tr>
<tr><td colspan="2">Elapsed year</td><td>year</td><td colspan="3">9</td><td>9</td></tr>
<tr><td colspan="2">Drainage condition</td><td>-</td><td colspan="3">· Vegetation on blasted rock<br>· Drainage tubes installed<br>· No seepage erosion and no collapse</td><td>-</td></tr>
<tr><td rowspan="10">Soil physical properties</td><td colspan="2">Porosity</td><td>m³/m³</td><td colspan="3">0.60, 0.65, 0.60</td><td>0.62</td></tr>
<tr><td colspan="2">Soil hardness</td><td>mm</td><td colspan="3">1, 9, 11</td><td>7</td></tr>
<tr><td colspan="2">Water content</td><td>m³/m³</td><td colspan="3">0.131, 0.158, 0.171</td><td>0.15</td></tr>
<tr><td colspan="2" rowspan="4">Soil texture</td><td rowspan="4">-</td><td>Sand</td><td colspan="2">76.9, 78.2, 84.3</td><td>79.80</td></tr>
<tr><td>Silt</td><td colspan="2">18, 17, 12.9</td><td>15.97</td></tr>
<tr><td>Clay</td><td colspan="2">5.1, 4.7, 2.9</td><td>4.23</td></tr>
<tr><td colspan="3">Sandy loam</td><td>SL</td></tr>
<tr><td colspan="2">Tensile strength</td><td>kPa</td><td colspan="3">1.88, 1.96, 1.83</td><td>1.89</td></tr>
<tr><td colspan="2">Permeability coefficient</td><td>cm/s</td><td colspan="3">$3.44\times10^{-3}$, $2.04\times10^{-3}$, $2.27\times10^{-3}$</td><td>$2.58\times10^{-3}$</td></tr>
<tr><td colspan="2">Soil depth</td><td>cm</td><td colspan="3">14.2, 15.6, 11.6</td><td>13.80</td></tr>
<tr><td rowspan="3">Soil chemical properties</td><td colspan="2">Soil acidity(pH)</td><td>mm</td><td colspan="3">7.56, 7.63, 7.56</td><td>7.58</td></tr>
<tr><td colspan="2">Soil concentration</td><td>%</td><td colspan="3">0.0448, 0.05248, 0.04608</td><td>0.04779</td></tr>
<tr><td colspan="2">Soil organic matter</td><td>%</td><td colspan="3">17.3, 17.21, 14.69</td><td>16.4</td></tr>
<tr><td rowspan="4">Vegetation</td><td colspan="2">Vegetation landscape</td><td>-</td><td colspan="3">Homogeneous multiple layer, Homogeneous multiple layer, Homogeneous multiple layer</td><td>Homogeneous multiple layer</td></tr>
<tr><td colspan="2">Vegetation coverage</td><td>%</td><td colspan="3">98, 100, 100</td><td>99.33</td></tr>
<tr><td rowspan="2">Species diversity</td><td>No. of herbs</td><td>No.</td><td colspan="2">Dendranthema boreale, Elsholtzia ciliata, Humulus japonicus , Rubia akane, Persicaria hydropiper, Poa pratensis, Stellaria media, Erigeron annuus, Setaria viridis, Boehmeria tricuspis , Aster yomena, Impatiens textori, Metaplexis japonica, Leonurus japonicus Houtt., Oenothera biennis, Oenanthe javanica, Lactuca indica var. laciniata, Artemisia princeps var. orientalis, Achillea millefolium, Aristolochia contorta Bunge , Imperata cylindrica var. koenigii,</td><td>22, 22, 20</td><td>22</td></tr>
<tr><td>No. of trees</td><td>No.</td><td colspan="2">Albizzia julibrissin, Ailanthus altissima, Alnus sibiroca, Morus bombycis, Alnus sibiroca, Lespedeza cyrtobotrya, Indigofera pseudotinctoria, Zanthoxylum piperitum, Rubus crataegifolius, Robinia pseudoacacia</td><td>8, 10, 8</td><td>10</td></tr>
</table>

# 국 문 초 록


비탈면 녹화는 생태복원의 일환으로서 훼손된 비탈면을 안정화하기 위한 수단 중 하나이다. 우리나라의 비탈면 녹화에서는 토양을 기반으로 한 식생기반재 뿜어붙이기가 많이 이용되고 있다. 그러나 녹화 이후에도 침식 또는 붕괴는 현재까지 계속적으로 나타나고 있다. 이와 같은 이유는 비탈면 녹화공사 시, 사면 안정 해석 및 사방 공학 등 구조적인 안정성 검토는 이루어지고 있으나 환경적 이해를 통한 비탈면 녹화에 대한 안정성은 고려되지 못하고 있기 때문이다. 따라서 본 연구의 목적은 비탈면 녹화 이후 비탈면의 안정화를 위한 안정성 평가 지표를 개발하여 토양을 기반으로 한 비탈면 녹화의 안정성 평가 체계를 고안하는 것이다.

비탈면 붕괴와 관련된 변수들은 선행연구에서 상당히 많이 나와 있다. 하지만, 비탈면 녹화와 관련된 안정성 변수들은 부분적으로만 연구되거나 대부분 물리적 환경 변수들에 초점을 두고 있다. 본 연구는 위와 같은 변수들과 더불어 비탈면 녹화 이후의 안정성을 종합적으로 검토할 수 있는 변수들을 찾고자 하였다. 변수 선택은 여러 변수들 중 사방 안정 해석, 사방공학, 비탈면 녹화의 분야에서 69개의 변수들을 우선 추출하였다. 그 다음 전문가 설문을 통해 23개의 변수들을 선택하였다.

변수는 총 세 개의 카테고리로 분류하였다. 첫 번째는 물리적 환경 변수인데 경사, 향, 비탈면 형태, 비탈면 폭, 비탈면 높이, 건수 터짐, 경과년도, 기반층 형태, 그리고 배수시설 상태로 총 9개였다. 두 번째는 토양 변수로서 공극률, 토양 경도, 수분함량, 토성, 인장강도, 투수계수, 토심, 토양 산도(pH), 염분농도, 그리고 유기물 함량으로 총 10개였다. 마지막 세 번째는 식생 변수로서 식생 군락 형태, 식생 피복률, 목본 종수, 그리고 초본 종수로 총 4개였다.

연구대상지역 총 10 곳을 선정하여 현장조사를 실시하고 23개 변수들에 해당하는 자료를 수집하여 통계분석하였다. 모든 연구대상지역은 비탈면 녹화 시공 이후 2년 이상이 경과 된 비탈면으로 붕괴된 비탈면이 다섯 곳, 안정한 비탈면이 다섯 곳이었다. 붕괴된 곳은 이미 확연히 붕괴 된 지점(“failure“)과 잠재적인 붕괴위험을 가진 지점

("potential risk") 으로 나뉘어 조사하였다. 각 변수들의 상관성을 분석하기 위해 Spearman correlation analysis를 실시하였다. 또한, 각 변수가 붕괴된 비탈면과 안정한 비탈면을 구분 짓는 변수인지를 확인하기 위하여 비모수적 검정 방법인 Mann-Whitney U test를 실시하였다. 마지막으로, 두 통계적 분석에서 유의미한 수준을 통과한 변수들에 대하여 판별분석을 실시하였다. 유의미한 수준을 통과한 변수들은 총 9개로 공극률, 수분함량, 인장강도, 토심, 염분농도, 유기물 함량, 식생 군락 형태, 식생 피복률, 그리고 목본 종수였다.

판별분석은 9개의 변수 중 명목척도인 식생 군락 형태를 제외한 8개 변수에 대해 단계별 분석 방법을 실시하였고, 식생 군락 형태는 차후에 판별 분석된 결과인 판별점수와 함께 비교 분석하였다. 판별분석 결과 총 4개의 변수로 이루어진 판별식이 구해졌다. 4개의 변수는 공극률, 인장강도, 유기물 함량, 그리고 식생 피복률이었다. 4개의 변수를 통해 나타난 판별점수와 식생 군락 형태에 대하여 상자 도표를 그려 비교 분석하였다. 최종적으로 총 5개의 변수가 비탈면 녹화 이후 비탈면에 대한 안정성 평가 지표로 선정되었다. 마지막으로 5개 지표를 이용한 비탈면 녹화 안정성 평가체계와 그 적용성에 관하여 제안 및 고찰하였다.

▣ 주요어 : 생태복원, 생태공학, 비탈면 안정화, 비탈면 녹화, 비모수적 상관분석, 비모수적 검정, 판별분석

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