Chapter

Integrated Analysis Method for Stability Analysis and Maintenance of Cut-Slope in Urban

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Abstract

In the process of constructing roads for the development of the city, cut-slopes are made by excavating mountains. However, these cut-slopes are degraded in strength by time-deterioration phenomenon, and progressive slope failure is caused. This study developed an integrated analysis method for stability analysis and maintenance of cut-slopes in urban. The slope stability analysis was performed using the finite element model, and the progressive slope failure by time-dependent deterioration was quantified by using the strength parameters of soil applying the strength reduction factor (SRF). The displacements until the slope failure by slope stability analysis were quantified by cumulative displacement curve, velocity curve, and inverse velocity curve and, applied to the slope maintenance method. The inverse-velocity curve applied to the prediction of the time of slope failure was regressed to the 1st linear equation in the brittle material and the 3rd polynomial equation in the ductile material. This is consistent with the proposed formula of Fukuzono and also shows similar behavior to the failure case in literature. In the future, integrated analysis method should be improved through additional research. And it should be applied to cut-slope to prevent disasters.

Keywords: cut-slope, slope maintenance, slope stability analysis, progressive slope failure, time-dependent deterioration of slope

1. Introduction

Recently, there have been many natural disasters due to climate change. In particular, slope failure in urban areas has caused loss of lives and of property [1]. The causes of slope failures around the world are intense rainfall, rapid snowmelt, water level changes in rivers or lakes at the foot of slopes, volcanic eruptions, and earthquakes [2]. In the type of slope failure, Soil slope mainly was occurred a deep circular failure and a shallow plane failure. The failure of the rock slope is caused by activity, overturning, and rockfall. In addition, there is debris flow and creep in soft ground [3].

The types of slope failure are determined by the composting materials and exterior conditions of slope. The shear strength of slope soil is decreased as time goes by, especially time-dependent deterioration of cut-slope would greatly happen

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after excavation. These cut-slopes are degraded in strength by time-deterioration phenomenon, and progressive slope failure is caused.

A time-dependent deterioration of soil owing to external environmental change causes progressive slope failure and the traditional analysis of limit equilibrium stability has limitations for an appropriate analysis of the stability [4]. The analysis of progressive slope failure requires finite element analysis that is capable of analyzing the creation and progression of shearing zone [5–7]. The behavior of progressive slope failure can be evaluated through the finite element analysis. Besides, for the analysis of the slope stability, the calculation of safety factor is needed. Zeinkiewicz, et al. [8] have proposed the strength reduction method to calculate the safety factor through finite element analysis and the proposition was followed by many subsequent studies conducted by many researchers [9–11]. Recently, there has been many studies unsaturated slope stability analysis induced by rainfall infiltration [12–16]. In general, rainfall-induced slope failures are caused by increased pore pressure and seepage force during periods of intense rainfall [17, 18]. The factor of safety on the slope is calculated by the equilibrium equation of the force of the failure surface. The pore pressure acting as an active force on the failure surface is increased by seepage of rainfall, and the slope is collapsed when it is larger than the resistance force.

The slope behaviors and exterior environment should be measured continuously to maintain slope. The slope behavior is measured by inclinometer, electro-optical wave distance measuring instrument, groundwater level meter etc., also, the exterior environments, rainfall and temperature are measured by the weather station. The various management criteria of the sensors are developed based on mathematical or statistical methods; the slope reinforcement be done if the management criteria [19]. However, the developments of perfect safety factors and management criteria are very difficult from the analysis of measured data in slope.

In Korea, a lot of researches were done for cut-slope management near roadway [20–22]. The displacements of cut-slope were measured by tension wire, and the data were analyzed by the statistical process control (SPC) method. However, it confirm only the abnormal behaviors of slopes, the factor of safety (FOS) of slope cannot be calculated, therefore, the application of slope reinforcement methods are determined according to extra slope stability analysis.

Also, many studies had also been carried out to predict the time of the failure of slope through displacement velocity [1, 23–28]. The researchers have used the inverse-velocity obtained from measurements to predict the time of the slope failure and verified respective applications of the inverse-velocity through actual cases of the slope failure and experiments. However, in cases of slopes, the prediction of the time of the slope failure by using the inverse-velocity curve derived from such measurement is quite difficult because the behavioral aspects of such slope are diverse and the failure surface has to be assumed. So far, the slope stability analysis methods only estimate the FOS of slope and, maintenance methods based on the measured data do not provide clear management criteria. For these reasons, efficient maintenance and prevention of slope failure in urban areas have not been achieved. To solve this problem, the integrated analysis methods of slope stability analysis and maintenance for progressive slope failure due to time-dependent deterioration should be developed.

This study developed an integrated analysis method for stability analysis and maintenance of cut-slopes in urban. The integrated analysis method for this research treated cut-slope and the failure-inducing factor was considered the shear strength decrease (SRF) by time-dependent deterioration was considered as inducing factor of slope failure. The strength variation of soil slope happens continuously from the variation of weather conditions and infiltration of rainfall. Also, measuring the slope displacements is easier then sensing the capillary force and water content of slope. Therefore, for this research, the slope displacements to progressive failure were calculated, then they were analyzed and applied to criteria of displacements sensing.

To link the slope stability analysis with the maintenance method based on the measured data, the displacement until the slope failure to the finite element model was analyzed and applied to the maintenance method. A flowchart of the integrated analysis method was presented and a case study was conducted. The slope stability analysis was performed by generating a finite element model and, the time-dependent deterioration of slope was quantified by applying the SRF to the strength parameter of the soil. The FOS was calculated by the stress analysis method (SAM) of the finite element model, and the behavior up until slope failure was analyzed by nonlinear static analysis with k_0 condition. Each displacement of slope depth until failure is calculated from slope surface by finite element method (FEM). Accumulated displacement curve is derived each displacement from according to the strength reduction factor (SRF). It can draw the velocity curve and inverse-velocity curve. The three curves derived from FEM are applied to the slope maintenance method. The each displacement of slope depth is applied to the SPC method, and, it is the criterion of inclinometer for slope insides. In addition, it estimates the abnormal behavior of slope. Also, accumulated displacement curve of slope surface until the failure is used to make the mathematical failure model. Next, a mathematical failure model of the slope was predicted using a cumulative displacement curve. And the time of the slope failure was predicted using an inverse-velocity curve and, compared the formulation of Fukuzono [1] and the existing case of slope failure.

2. Theoretical background for stability analysis and maintenance of cut-slope

2.1 Finite element method (FEM) for slope stability analysis

The limit equilibrium method (LEM), a deterministic method, compares the shear stress and shear strength applied to assumed the failure surface of slope to present the FOS. However, because the limit equilibrium analysis provides only the minimum of FOS as the analytic result, it cannot present appropriate safety factor applicable to the analysis of progressive slope failure attributable to concurrent continuous displacement induced by a time-dependent deterioration of soil.

The finite element method can provide the measurement system for the maintenance of slope with proper analytic results. It also is an appropriate method to analyze the behavior of progressive slope failure [29]. The progressive slope failure has been examined through the finite element method. Zeinkiewicz, Humpheson and Lewis [8] had presented the strength reduction method that employed the SRF by which the safety factor was calculated as in the case of limit equilibrium analysis. Thereafter, Griffiths [10] had applied the strength reduction method to his analysis of progressive behavior of slope according to diverse soil conditions and geometries and verified the analytical method through comparative analyses with the chart (s) presented by Bishop and Morgenstern [30].

The SAM is a combination of the advantages of simple limit equilibrium method (LEM) and of finite element method (FEM), the advanced method. The stress state in slope is analyzed through finite element analysis, and the FOS of virtual active surfaces of the limit equilibrium analysis are calculated. Thereafter, the minimum of FOS and critical section among active surfaces in the limit equilibrium analysis are calculated. In the finite element analysis, the model of the material constituting the soil will use the Mohr-coulomb yield criteria identical to the failure criteria used in the limit equilibrium analysis.

The FOS of the slope to be determined by the stress analysis method is as expressed in the following Eq. (1).

$$\text{FOS} = \frac{\int_S \tau_f dT}{\int_S \tau_m dT} \quad (1)$$

Here, FOS, τ_m and τ_f denote the factor of the safety, induced shear stress, and shear strength according to Mohr-Coulomb failure criteria, respectively.

The FEM can analyze the slope behavior until failure, and if the SRF is applied, it also can quantify the time-dependent deterioration of slope. However, until now the FEM is not used for analyzing and comparing to the measured displacement data of slope.

2.2 Statistical process control method for detecting abnormal behavior of slope

The representative method used for the domestic maintenance of slope is the statistical process control (SPC) method broadly employed in manufacturing industries to reduce the level of defects of commercial products. The population for the SPC for the maintenance of slope is a set of measurements of the displacement of slope. The values of the mean and standard deviation of the population is used to judge the stability of slope statistically according to respective values plotted on the region beyond or within the control limit determined by the control chart. By using the control chart, the anomaly in the stability of slope can be found easily.

The method above uses the $\overline{X}$ control chart (of mean values) and the R control chart (of standard deviation, the varying range of measurements) simultaneously.

The control limit and centerline of the$\overline{X}$ control chart can be obtained by using the Eq. (2) represented in the following.

$$\begin{aligned} \text{UCL} &= \bar{\bar{x}} + A_2\overline{R} \\ \text{CL} &= \bar{\bar{x}} \\ \text{LCL} &= \bar{\bar{x}} - A_2\overline{R} \end{aligned} \quad (2)$$

Where, the constant A_2 is a function of sample sizen. $\bar{\bar{x}}$ is an estimation of μ, the mean of the population; and $\overline{R}$ represents an estimation of σ, the standard deviation of the population.

The control limit and centerline of the R control chart can be obtained by using the Eq. (3) represented in the following.

$$\begin{aligned} \text{UCL} &= D_4\overline{R} \\ \text{CL} &= \overline{R} \\ \text{LCL} &= D_3\overline{R} \end{aligned} \quad (3)$$

Where, the constants D_3 and D_4 are the functions of the sample size n.

KICT [20] applied the measured data of real slope to SPC method. After that, Yoo [22] proposed a statistical decision algorithm for maintenance of the slope based on the measured data. Therefore, it is necessary to calculate the management criteria of statistical process control method by integrating it with the finite element analysis which can simulate the failure of the slope.

2.3 Prediction method of the time of slope failure

To predict the time of the slope failure, diverse models employed the correlation between the time and the displacement varying according to the creep behavior of bedrock have been proposed [25, 31]. Since such models were difficult to apply to the prediction of the slope failure as a generalized model, Fukuzono [1] proposed the model of inverse-velocity expressing the changing characteristics of ground displacement as the relationship between time and inverse-velocity. The proposed inverse-velocity model was derived by using the measurements of varying acceleration obtained from the large-scaled actual experiment simulated an artificial landslide. Fukuzono [1] proposed the time of the slope failure as expressed in the following Eq. (4) by taking the trend line of inverse-velocity approaching 0 in accordance with the increasing velocity of displacement into account.

$$\frac{1}{V} = [A(\alpha - 1)]^{1/\alpha - 1} \bullet \left(t_f - t\right)^{1/\alpha - 1} \tag{4}$$

Here, t, t_f, and V denote the time, time of failure, and displacement velocity; and A and α are the constants introduced for curve fitting. When the value of α is bigger than 2, the shape of curve is convex otherwise the shape of curve would be concave with the value of α less than 2.

To exploit the advantage of the value of inverse-velocity becoming 0 at the time of the slope failure, the relevance between time and inverse-velocity has been widely used [32, 33]. Petley, Bulmer and Murphy [32] have analyzed the patterns of trend lines of the cases the slope failure however, since the patterns were analyzed from the measurements of the displacement after the failure of faces of slopes, it would be very difficult to get actual real-time prediction of the time of failure. Therefore, an analysis on the pattern of inverse-velocity curve at the design stage is needed to predict the time of the slope failure in the stage of performing maintenance works based on measurements. Thus, in this study, the procedure to analyze the progressive slope failure was presented in a way to link the procedure to the maintenance methods based on actual site measurements.

3. Integrated analysis methods of slope stability analysis and maintenance

3.1 Introduction

Figure 1 is an integrated analysis method for stability analysis and maintenance of cut-slopes.

The integrated analysis method presented in this study is divided into 14 steps. It is divided into three sections. In the first section, the geometric of the slope and the finite element model of FEM are generated. And, to consider the time-dependent deterioration, the SRF is applied to the strength parameter of the soil (step 1 ~ 3). The integrated analysis method proposed in this study is based on the cut-slope and only the strength degradation caused by the time-dependent deterioration is taken into consideration. The proposed method can be used both as soil and rock as a material of cut slope, but the only soil is considered in this study.

In the second section, slope stability analysis is performed using FEM. The FOS is calculated by the SAM and the behavior up to the slope failure is analyzed by the nonlinear static analysis withk_0 condition. The displacements until the slope failure analyzed using the slope stability analysis plot the cumulative displacement curve,

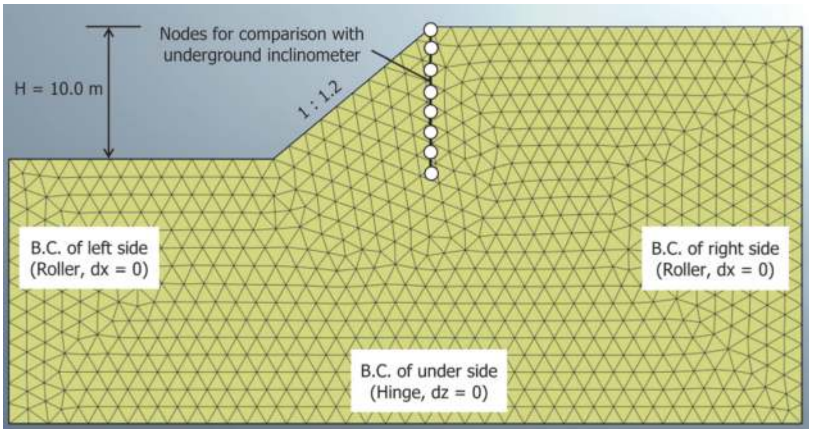

Figure 1.
Mesh and boundary conditions of slope stability analysis.

velocity curve, and inverse-velocity curve and, applied to the maintenance methods of the slope. The strength degradation of the soil due to the time-dependent deterioration phenomenon was quantified by SRF. However, geological factors and strength degradation due to groundwater cannot be considered. Therefore, the proposed method in this study cannot be applied when the groundwater level is located on the predicted failure surface of the slope.

In the last section, the results of the slope stability analysis are applied to the maintenance method. A typical sensor used for slope maintenance is an in-site inclinometer, which is applied to SPC using slope stability analysis results at the same point. Next, a mathematical failure model of the slope was predicted using a cumulative displacement curve. And the time of the slope failure was predicted using an inverse-velocity curve and, compared the formulation of Fukuzono [1]. Finally, the collapse behavior of Selborne in the United Kingdom and Kunini Slope in Japan, as reported by Petley [34], was compared.

Figure 2 in this study improves the problem of the slope stability analysis method that only estimates the FOS and, the problem of maintenance method that fails to evaluate clear management criteria and failure behavior of slope. It also combines the advantages of slope stability analysis and maintenance method based on measured data [35, 36]. Slope stability analysis is used to determine the failure behavior and FOS of the slope. And, it can be applied to the maintenance method to predict the management criteria of statistical process control method, a mathematical failure model of slope, and the time of slope failure.

In the maintenance of the slope, the surface displacement is usually tension wire, and the ground displacement is the inclinometer. Because the displacement of the entire slope is analyzed using the FEM, that can be applied to the management criteria of the displacement measuring instrument installed on the slope. In particular, the displacement at the crown of the slope is very important, which can be measured both by tension wire and inclinometer. There are two maintenance methods presented in this study. First, the failure model is calculated by the cumulative displacement curve of the slope. And the displacement according to the depth is applied to the SPC method to judge the occurrence of abnormal behavior of the slope. If only tension wire is applied to the maintenance of the slope, the formation of the failure surface cannot be confirmed because only the surface displacement of the slope can be measured. Because the inclinometer measures the displacement of the whole underground, it has an advantage that it can easily judge the failure surface. Therefore, the inclinometer was applied to the slope instrument in this study. Please refer to KICT [20] for the advantages and disadvantages of both measurement devices.

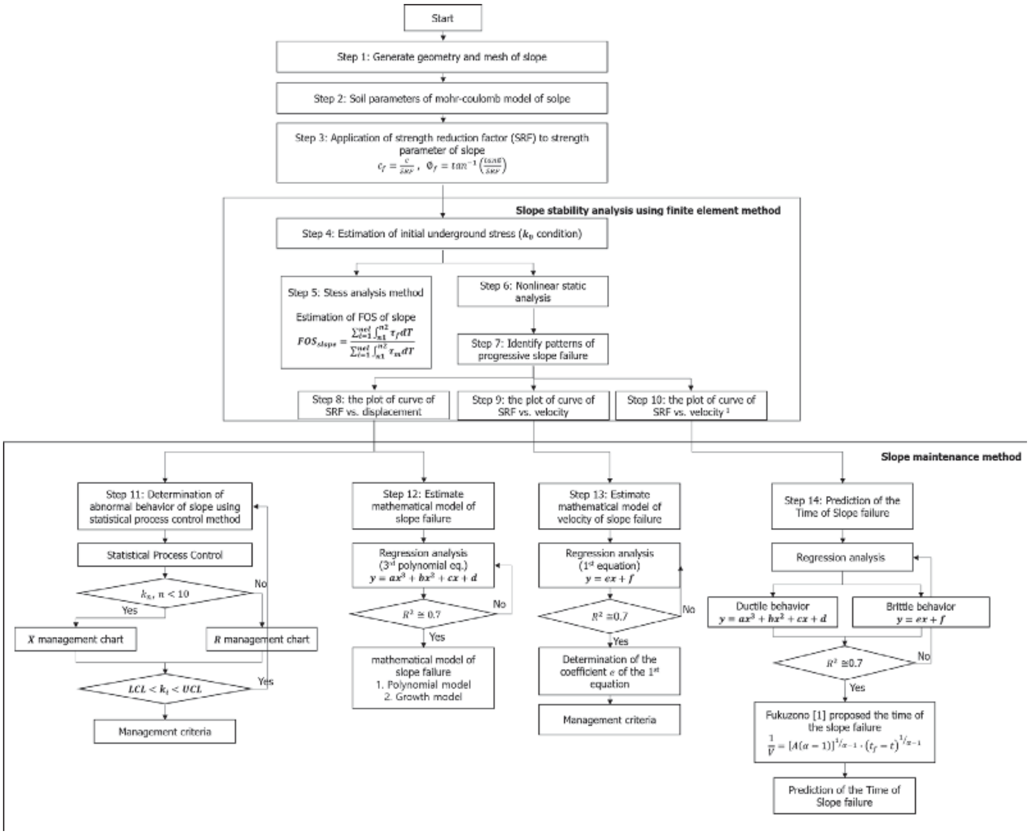

Figure 2.
A flowchart on integrated analysis methods of slope stability analysis and maintenance of the slope.

3.2 Analysis procedure

In this section, detailed description is given for each step according to the flowchart shown in **Figure 2**. The details are as follows:

1. Step 1: This is the step of generating the geometry and mesh of the slope. And the load and boundary conditions acting on the slope. In general, only self-weight is considered. Please refer to the literature on FEM [10, 11, 29].

2. Step 2: In the FEM, the soil uses the Mohr-coulomb model. The soil investigation is performed to calculate the cohesive and internal friction angle, which are the strength parameters of the soil.

3. Step 3: The strength parameters of soil are to be decreased according to the SRF, and the cohesion of soil at the point of failure and the internal friction angle are as expressed in Eqs. (5) and (6), respectively. In the case where the SRF is used, the value of initial strength reduction factor (SRF) and the value of increment should be determined. The values of 1.0 and 0.05 of the strength factor and increment are frequently applied to the method of general strength reduction. The final strength reduction coefficient will be a value at the stage failed to converge in the nonlinear static analysis.

$$c'_f = \frac{c'}{SRF} \tag{5}$$

$$\phi'_f = \tan\left(\frac{\tan\phi'}{SRF}\right)^{-1} \tag{6}$$

where, c', $c_f{}'$, ϕ', and $\phi_f{}'$ denote the cohesion, cohesion at the point of failure, internal friction angle, and internal friction angle at the point of failure, respectively. SRF denote the strength reduction factor.

4. Step 4: To conduct the finite element analysis, the calculation of initial underground stress of slope is important and, the value is calculated under the k_0 condition based on the data obtained from subsurface investigation.

5. Step 5: Based on the calculated initial underground stress of the slope, the FOS is calculated through the SAM [37]. In this case, the decrease in the value of safety factor is identified through an iterative analysis to be conducted according to the reduced strength parameter, and the failure surface will be applied to it as in the case of limit equilibrium analysis.

6. Step 6: The nonlinear static analysis will be conducted to analyze the behaviors of progressive slope failure. The iterative analysis should be continued until the value fails to converge (=until the occurrence of failure) according to the stages of each strength reduction factor.

7. Step 7: The displacement resulted from the progressive slope failure is identified through the iterative analysis conducted according to the strength reduction.

8. Step 8: After completing the calculation of cumulative displacement curve of the points of maximum displacement on slope through following the process in Step 7 above, the obtained results should be linked to the plan of the measurement of slope.

9. Step 9: The failure model of slope is created by using the velocity curve made from the analytic results and then it will be compared with the cumulative displacement curve made from the measurements collected through the stages of maintenance of the slope.

10. Step 10: In this step, plot an inverse-velocity curve for predict the time of slope failure.

11. Step 11: From this stage, the results of the slope stability analysis are applied to the maintenance method. In step 11, the displacement calculated at the point where the in-place inclinometer is installed is applied to the statistical process control method. And judges whether the management criteria is exceeded by depth of slope. Finally, determine whether the slope failure behavior is occurring and the location of the failure surface.

12. Step 12: In this step, we calculate the mathematical failure model of the slope. The calculated mathematical failure model is used as a reference for the displacement results measured by the in-place inclination.

13. Step 13: In this step, first order linear equation is calculated by regression analysis of velocity curve of the slope. It is difficult to derive a clear engineering meaning like the accumulated displacement curve of step 12 and

the inverse-velocity curve of step 14. Therefore, if the slope failure happens, the measured displacement velocity curve changes into the 1st-degree polynomials. It means the slope displacement velocity turns into invariable velocity, and it is estimated that the slope failure happens. Therefore it could be important criterion for slope maintenance.

14. Step 14: This stage predicts the time of slope failure in slope maintenance. Curve fitting is performed by regression analysis of the inverse-velocity curve by slope stability analysis. According to the existing literature, slopes with ductile behaviors are a third polynomial equation and slopes with brittle behavior are a linear equation. Regression analysis results are also compared with Fukuzono [1]'s slope failure prediction formula.

4. Application result of the integrated analysis method

4.1 Generate finite element model for slope stability analysis (step 1 ∼ 10)

In the first section, the geometric of the slope and the finite element model of FEM are generated. And, to consider the time-dependent deterioration, the SRF is applied to the strength parameter of the soil (step 1 ∼ 3).

4.1.1 Step 1: Generate geometry and mesh of slope

For the slope stability analysis of the progressive behavior of slope, the geometry and meshes of the finite slope of 10.0 m in height and 1: 1.2 of standard slope were created (**Figure 1**). For this research, the cut-slope modeling is obliged the standard height and incline suggested by the design manuals [19, 38]. The displacements until progressive failure analyzed FEM are compared to the measured data, the criteria come from the inclinometer data.

The boundary condition of left and right side is dx = 0 and same as roller. The boundary condition of the floor is dz. = 0, which is the same as the hinge. The load applied only its own gravity. In the finite element model, the element at the point where the in-place inclinometer is installed should be identified.

4.1.2 Step 2: Soil parameters of Mohr-coulomb model of solpe

The Mohr-coulomb model was selected for the FEM for which the internal friction angle($\varnothing'$), cohesion (c'), dilatancy angle (ψ), Poisson's ratio (υ), and unit weight (γ_t) are needed. Among such factors, the relative importance of the dilatancy angle that reflects the change in volume resulting from the yield process is less significant in the analysis of the stability of slope that calculates the safety factor [11]. In this study, the value of dilatancy angle was set 0° to let the change in volume to be constantly applied to the analysis. The values of the physical properties of the soil are as summarized in **Table 1**.

The soil slope behaviors are largely divided into two categories; firstly, ductible behavior in case of small particle soils, at second, brittle behavior in case of coarse particle soils. Mohr-coulomb model is used to analyze those two cases, which is the elastic-perfect plastic model. The case 1 is for the ductile behavior of slope, whose cohesion value is applied as 10 kPa to show the behavior small soil particles. The case 2 is for the brittle behavior of slope, whose cohesion value is 0 kPa to show the brittle slope behavior of coarse soil particles.

The soil of Case 1 has a cohesive of 10 kPa and an internal friction angle of 30 degrees. The soil of Case 2 has a cohesive of 0 kPa and an internal friction angle of 40 degrees. The slope of Case 1 shows the ductility behavior due to the cohesive of soil, and the slope of Case 2 shows the brittle behavior because the soil has no cohesive and the internal friction angle is large. The analytical results are compared according to the material characteristics of these slopes.

4.1.3 Step 3: Application of strength reduction factor to strength parameter of slope

In step 3, the time-dependent deterioration of slope was quantified by applying the SRF to the strength parameter of the soil. The strength parameters of the slope shown in **Table 1** were reduced according to the SRF as shown in **Figure 3**. The slope stability analysis is performed with the reduced strength parameters, and iterative analysis is performed until it is not converged. If it does not converge, the slope has collapsed in the finite element analysis. Until now, the modeling is identical to that of the usual strength reduction factor (SRF) method of slope stability analysis. [8, 39, 40].

4.2 Slope stability analysis (step 4 ~ 10)

In the second section, and slope stability analysis using finite element model. The FOS is calculated by the stress analysis method (SAM) and the behavior up to the slope failure is analyzed by the nonlinear static analysis withk_0 condition. The

Parameter	Case 1	Case 2
$\gamma_t (kN/m^3)$	19.0	19.0
E (kPa)	40,000	40,000
υ	0.28	0.28
∅′ (°)	30.0	40.0
c′ (kPa)	10.0	0.0
ψ (°)	0.0	0.0

Table 1.
Physical parameters of the soil of slope applied to slope stability analysis.

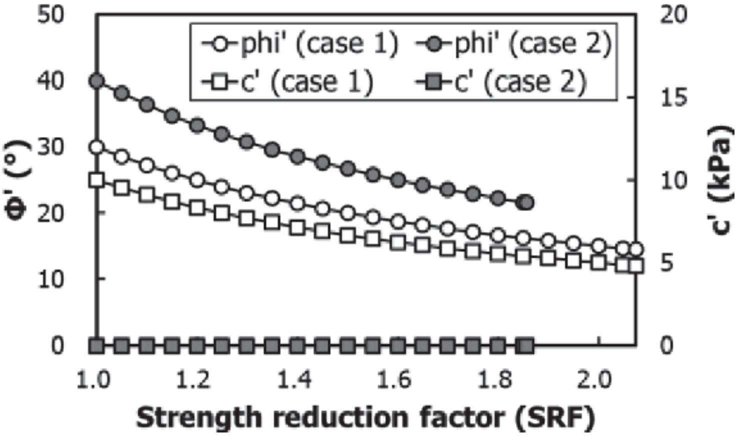

Figure 3.
Variation of the strength parameters of slope according to strength reduction factor.

displacements until the slope failure analyzed using the slope stability analysis plot the cumulative displacement curve, velocity curve, and inverse velocity curve and, applied to the maintenance methods of the slope.

4.2.1 Step 4 ∼ 7: Conduct the slope stability analysis of finite element model and estimation of behavior until the slope failure

In this step, slope stability analysis is performed using the finite element model generated in the first section. In slope stability analysis using FEM, it is very important to estimate the stress distribution in the slope. In Step 5, the initial stress distribution of slope is estimated at k_0 according to the coefficient of earth pressure [37]. Then, the FOS of the slope is calculated by the SAM. As shown in **Figure 3**, the strength parameters according to the SRF is applied, and the FOS of the slope by the SAM is shown in **Figure 4(a)** for case 1 and **Figure 5(a)** for case 2. In Step 6, nonlinear static analysis is performed by gradually reducing the strength parameters of the slope. The nonlinear static analysis is repeated until the analysis is not converged. If the nonlinear static analysis is not converged, the slope has collapsed. As a result of the finite element analysis, the soil failure occurred at SRF 2.075 in Case 1 and SRF 1.856 in Case 2.

Figure 6 is the distribution of displacement and shear strain by finite element analysis under slope failure condition in the slope of case 1. The legend in **Figure 6(a)** shows the amount of displacement, and in **Figure 6(b)** shows the effective shear strain. When the slope stability analysis is performed by the proposed method, the behavior up to the progressive failure of the slope can be analyzed. The distribution of shear strain can predict the failure surface of the slope. One of the greatest advantages is that the failure surface can be estimated by the finite element analysis in the slope consist of the continuous soil. Step 7 is the same as the general procedure for slope stability analysis using finite element analysis. In this study, only 2D finite element analysis was performed. Three-dimensional analysis is also possible. For finite element analysis using the SRF, see the paper by Wei, et al. [40].

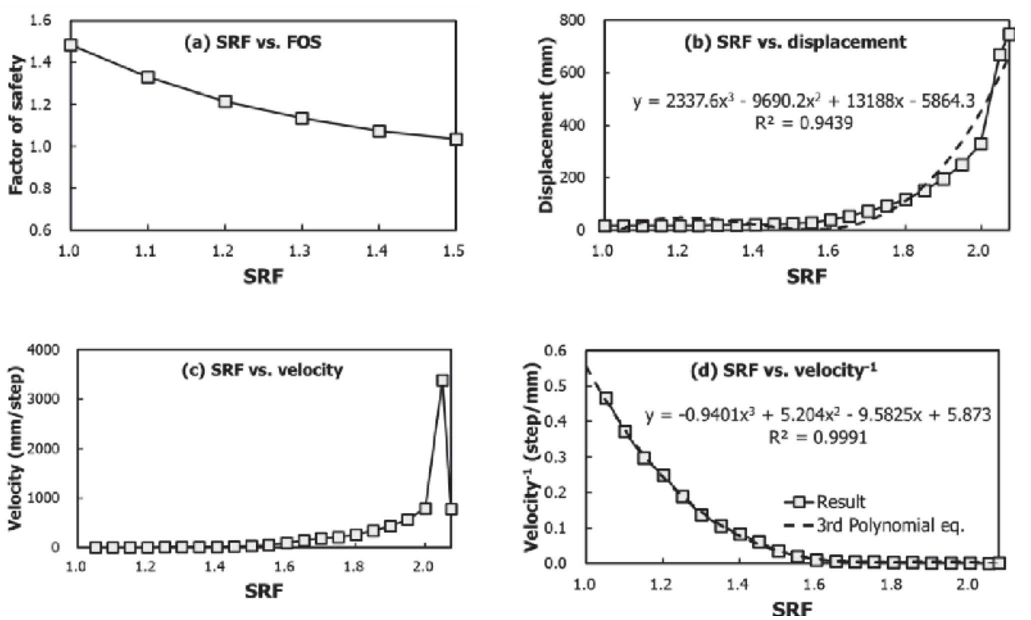

Figure 4.
The results of slope stability analysis in the slope of case 1; (a) factor of safety, (b) SRC vs. displacement curve, (c) SRC vs. velocity curve, (d) SRC vs. inverse velocity curve.

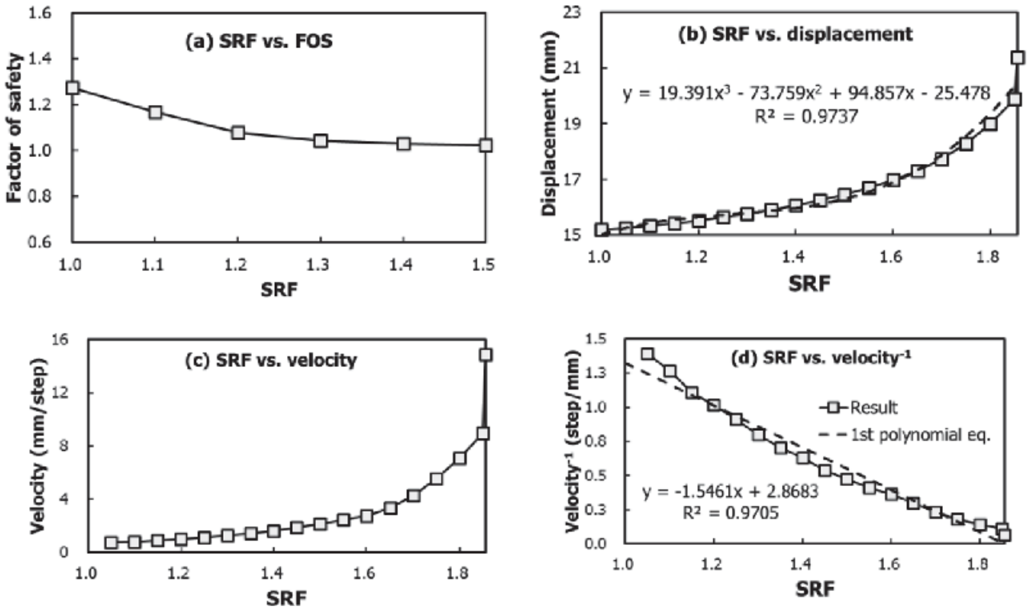

Figure 5.
The results of slope stability analysis in the slope of case 2; (a) factor of safety, (b) SRC vs. displacement curve, (c) SRC vs. velocity curve, (d) SRC vs. inverse velocity curve.

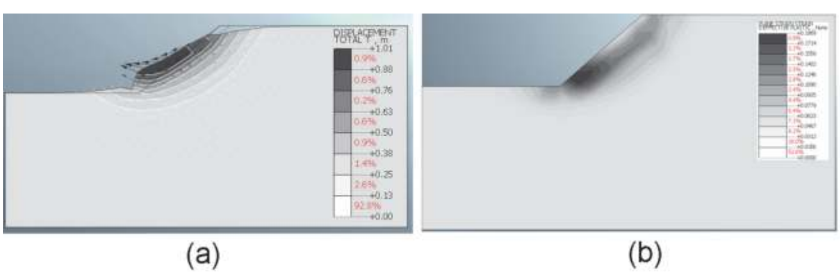

Figure 6.
Distribution of displacement and shear strain by finite element analysis under slope failure condition (case 1).

4.2.2 Step 8 ~ 10: Nonlinear static analysis of slope finite element model and summarization of results

In the third stage, the displacements until the slope failure analyzed using the slope stability analysis plot the cumulative displacement curve, velocity curve, and inverse velocity curve and, applied to the maintenance methods of the slope. In the finite element analysis, the displacements of all nodes are calculated in the finite element model of the slope. Here, only the displacement of the node at the point where the displacement meter such as an inclinometer or a tension wire is installed is used. In particular, the displacement at the crown of the slope is most important. Therefore, in this stage, a graph was created by displacement at the crown of the slope.

Figure 4 shows the result of slope stability analysis in the slope of case 1. Above all, the FOS was calculated by using the stress analysis method and then, the cumulative displacement curve, the displacement velocity curve, and the displacement inverse-velocity curve was plotted to illustrate the displacement of the upper part of the slope. **Figure 4(a)** Represents the reduction in safety factor resulted from the stress analysis. The FOS was 1.0 when the SRF was 1.0 and the FOS reached 1.0 when the SRF was 1.5. The calculated displacement at each stage of reduced strength is as illustrated in **Figure 4(b)–(d)**. In the cumulative displacement curve plotted in **Figure 4(b)**, the rapid progression of displacement, initiated at the stage of 1.6 of strength reduction factor and then evolved rapidly after the stage of 2.0 of SRF, is illustrated. The failure model of the slope was calculated as in the following 3rd order polynomial equation:$y = 2337.6x^3 - 9690.2x^2 + 13188x + 5864.3$. In **Figure 4(d)**, the inverse-velocity curve is estimated as a third order polynomial of $y = -0.9401x^3 + 5.204x^2 - 9.5825x + 5.873$.

Figure 5 shows the result of slope stability analysis in the slope of case 2. **Figure 5(a)** shows the change of FOS according to SRF. Compared with case 1, the decreasing slope was more moderate. When SRF was 1.0, FOS was 1.27, which was smaller than case 1. When SRF was 1.5, FOS reached 1.0 and was the same as case 1. In the cumulative displacement curve plotted in **Figure 5(b)**, compared to that in the case 1 (**Figure 4(b)**), the displacement proceeded continuously from the initial stage and the displacement increased rapidly after the stage of 1.6 of the strength reduction factor. The failure model of the slope was calculated as in the following 3rd order polynomial equation:$y = 19.391x^3 - 73.759x^2 + 94.857x - 25.478$. In **Figure 5(d)**, the inverse displacement velocity curve was calculated as a 1st linear equation of$y = -1.5461x + 2.8683$, unlike case 1. The inverse displacement velocity curve is used to predict slope failure time [1, 24]. The inverse displacement velocity curves of case 1 and case 2 were compared at step 14.

4.3 Slope maintenance method (step 11 $\sim$ 14)

In the last section, the results of the slope stability analysis are applied to the maintenance method. For the maintenance of the slope, the displacement of the slope is measured by tension wire or inclinometer. However, no technique has been proposed to determine management criteria. The typical sensor used for slope maintenance is an in-site inclinometer, which is applied to statistical process control using slope stability analysis results at the same point. The displacement at each depth measured in the inclinometer can be calculated by applying the SPC method to the upper and lower control limits (UCL, LCL). If the displacement exceeds this management criterion, an abnormal behavior has occurred. Next, a mathematical failure model of the slope was predicted using a cumulative displacement curve. The cumulative displacement data of the slope measured over time are compared with the behavior up to the failure estimated by the finite element analysis. This can qualitatively determine whether the slope is causing the failure behavior. And the time of the slope failure was predicted using an inverse velocity curve and, compared the formulation of Fukuzono [1].

The inverse-velocity curve is a method of predicting the time of failure of the slope. If the measured inverse-velocity curve shows this pattern, it can be predicted the time of slope failure. Finally, the collapse behavior of Selborne in the United Kingdom and Kunini Slope in Japan, as reported by Petley [34], was compared.

4.3.1 Step 11: Determination of abnormal behavior of slope using statistical process control method

In step 11, the displacement calculated at the point where the in-place inclinometer is installed is applied to the statistical process control method. In the finite element analysis, the displacement of the entire slope is estimated. Depending on the SRF, the displacement at the point where the inclinometer is installed can be estimated. The SPC method determines the abnormal behavior at the point where the inclinometer is installed, as described in Section 2.2. This abnormal region appears when a failure surface is formed due to the progressive behavior of the slope. SPC method can be statistically evaluated and have the advantage of setting upper and lower control limits. Finally, determine whether the slope failure behavior is occurring and the location of the failure surface.

The in-place inclinometer measures the displacement of the ground at intervals of 1.0 m. From the results of the slope stability analysis, the displacements at each depth were analyzed at intervals of 1.0 m as shown in **Figure 1**. The calculated displacement is applied to the statistical process control method as shown in **Figure 7**. The depth of the horizontal axis shows the depth from the ground surface. The vertical axis shows the displacement of the slope. **Figure 7(a)** shows that when the strength reduction factor is 1.6, **Figure 7(b)** is 1.7, **Figure 7(c)** is 1.8, **Figure 7(d)** is 1.9, **Figure 7(e)** is 2.0 and **Figure 7(f)** is 2.075. **Figure 7(a)** shows the case where the strength reduction factor is 1.6, and the displacement at all depths does not exceed the management criteria of upper control limit. **Figure 7(d)** shows that the strength reduction factor is 1.9 and exceeds the management criteria of upper control limit. From this time, a failure surface of the slope was formed. By applying the SPC method, it is possible to judge the failure behavior of the slope and the generation of the failure surface.

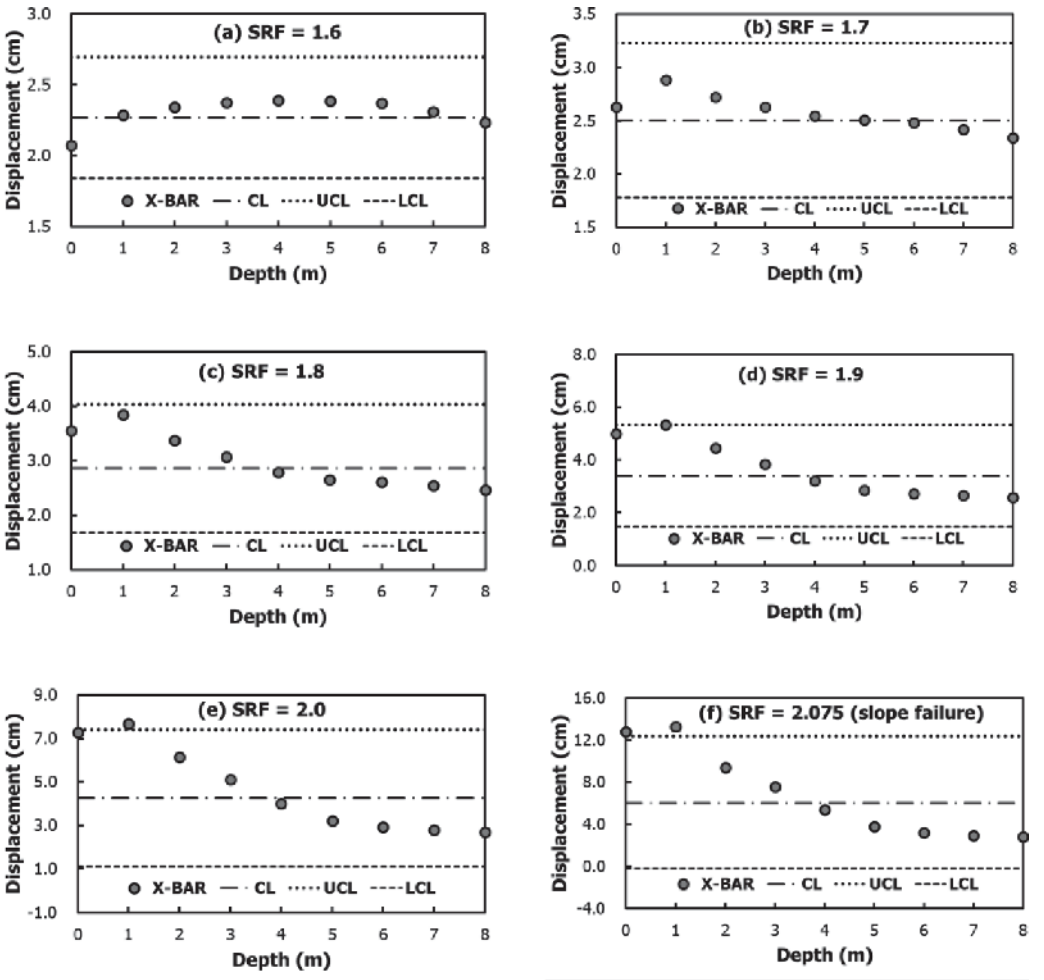

Figure 7.
$\overline{X}$ management chart according to depths (Case 1); (a) SRF = 1.6, (b) SRF = 1.7, (c) SRF = 1.8, (d) SRF = 1.9, (e) SRF = 2.0, SRF = 2.075 (slope failure).

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4.3.2 Step 12: Estimate mathematical model of slope failure

In this Step 12, a mathematical model of slope failure is predicted by the displacement result of the slope stability analysis. As shown in Step 11, the displacement up to the slope failure at the point where the in-place inclinometer is installed is used.

Figure 8 shows the mathematical failure model using the cumulative displacement curves for each depth. The largest displacement occurs on the ground surface, and the displacement is hardly generated below the failure surface of the slope. The location of the failure surface can be determined in step 4 through the slope stability analysis, as shown in **Figure 6(b)**. As shown in **Figure 8(f)**, little displacement occurred at the 5.0 m depth, because it exists below the failure surface of the slope.

The cumulative displacement curve through slope stability analysis can be applied as a management criterion for the measured data of the in-place inclinometer.

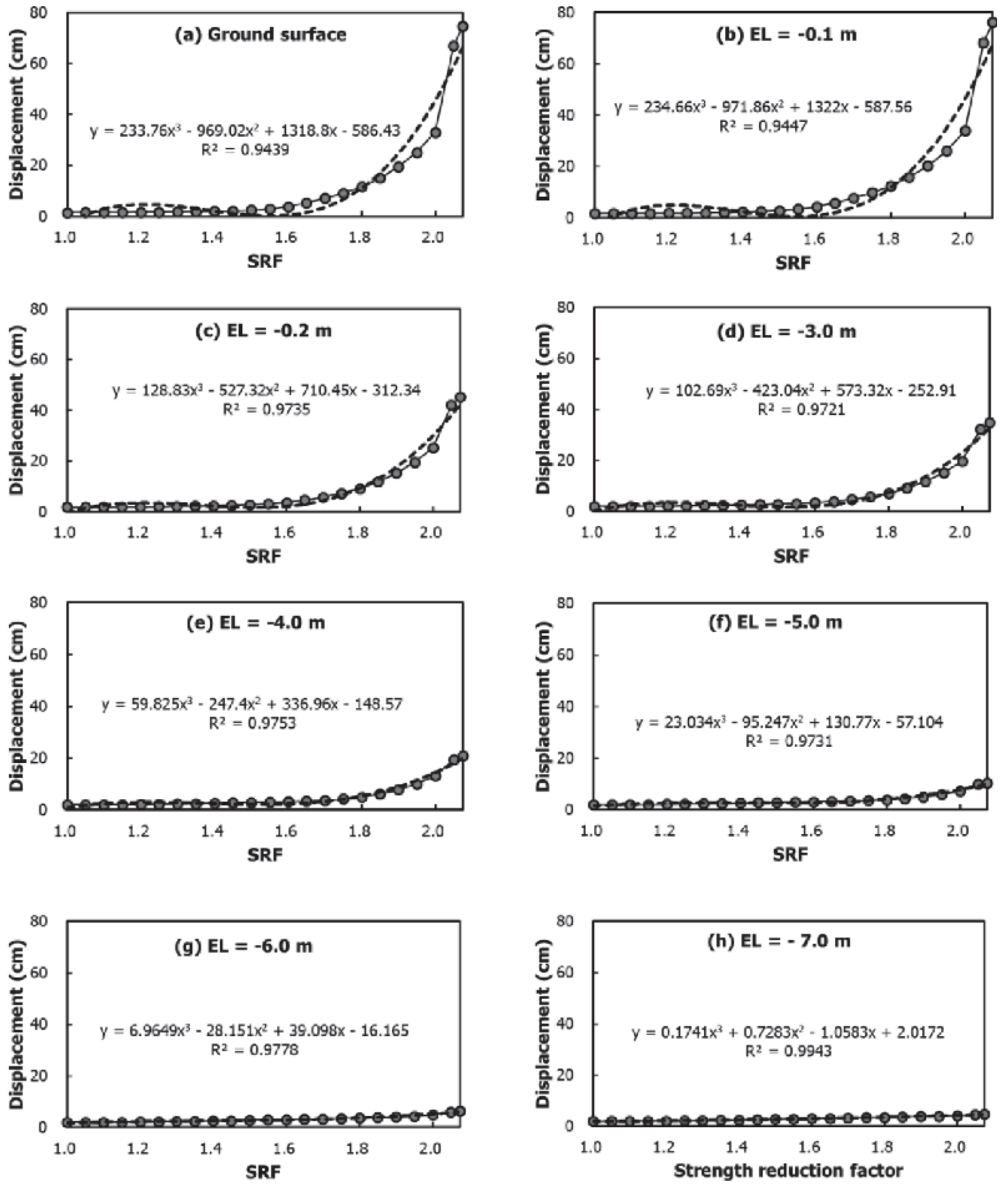

Figure 8.
The mathematical failure model using the cumulative displacement curves for each depth (case 1).

4.3.3 Step 14: Prediction of the time of slope failure

This stage predicts the time of slope failure in slope maintenance. Curve fitting is performed by regression analysis of the inverse-velocity curve by slope stability analysis. According to the existing literature, slopes with ductile behaviors are a third polynomial equation and slopes with brittle behavior are a linear equation. Regression analysis results are also compared with Fukuzono [1]'s slope failure prediction formula.

Fukuzono [1] intended to predict the time of slope failure resulted from progressive behavior with the inverse-velocity curve. The resulted inverse-velocity curves are as illustrated in **Figures 9** and **10**. In the case of the soil strength parameters of the cohesion (10kPa) and internal friction angle (30°) in the Case 1, the displacement inverse-velocity was reduced rapidly to the 3rd order polynomial equation and, the values of $A = 4.0$ and $\alpha = 1.21$ resulted from the equation presented by Fukuzono [1] that showed a convex pattern of the curve (**Figure 9 (a)**). The pattern was similar to the pattern of ductile behavior in the case of 'The Collapse of Kunini Slope' in Japan (**Figure 9(b)**).

And in the case of the soil strength parameters of the cohesion (0kPa) and internal friction angle (40°) in the Case 2, the displacement inverse-velocity was

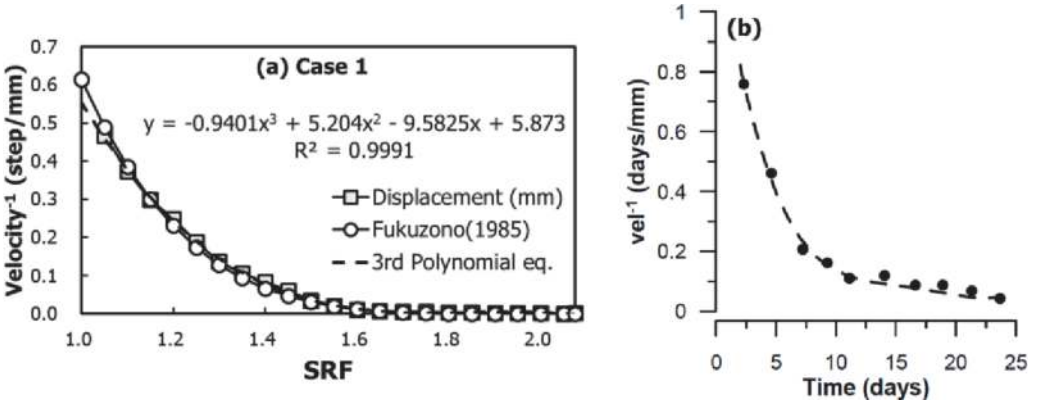

Figure 9.
Results of ductile slope (case 1); (a) displacement-inverse velocity curve, (b) failure case of Kunini slope movement.

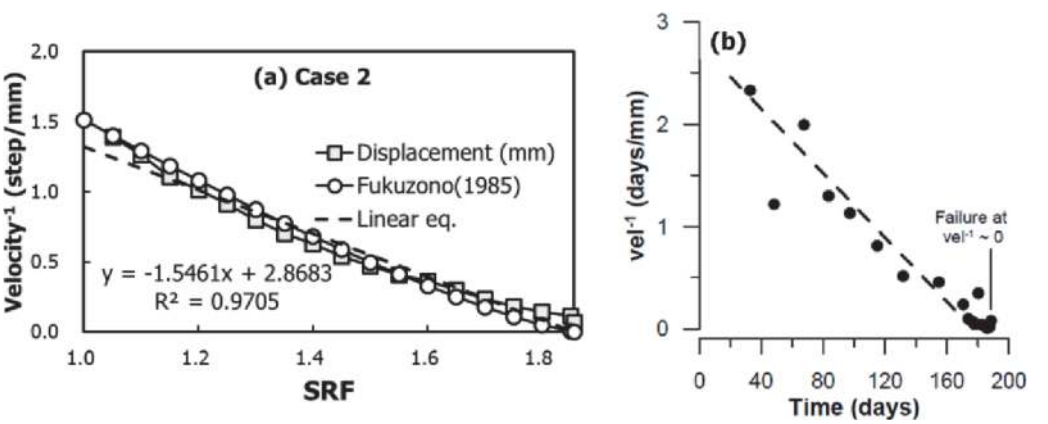

Figure 10.
Results of brittle slope (case 2); (a) inverse displacement velocity curve, (b) failure case of Selborne cut-slope experiment.

reduced to the 1st order linear equation and rendered values of A = 2.05 and $\alpha =$ 1.79 showing linear pattern of the curve (**Figure 10(a)**). The pattern was similar to that in the case of 'The Failure of the Cut Slope of Selborne' in the United Kingdom reported by Petley [34] (**Figure 10(b)**).

5. Discussion

This study developed an integrated analysis method for stability analysis and maintenance of cut-slopes in urban. To link the slope stability analysis with the maintenance method based on the measured data, the displacement until the slope failure to the finite element model was analyzed and applied to the maintenance method. The integrated analysis method proposed in this study is based on the cut-slope and only the strength degradation caused by the time-dependent deterioration is taken into consideration. The proposed method can be used both as soil and rock as a material of cut slope, but the only soil is considered in this study.

The integrated analysis method in this study can complement the disadvantages of the slope stability analysis and integrate it with the maintenance method based on the measured data of slope. The slope stability analysis can be used to quantify the displacement until slope failure as the cumulative displacement curve, velocity curve, and inverse velocity curve. The results of slope stability analysis could be used as management criteria for statistical process control method, mathematical model and the time of slope failure applied to maintenance. Then, the failure behavior of the slope and the generation of the failure surface were confirmed. The displacement of the slope analyzed by the finite element analysis should be the same as the position of the displacement meter installed on the slope.

By the comparison of this model with the failure model based on measured data, the obtained failure model was concluded as a 3rd order polynomial failure model equivalent to that of the site of 'Neureupjae' presented by Han and Chang [41]. **Figure 4(c)** represents the velocity curve. It also shows the rapid progression of displacement velocity at the point of 2.0 of SRF. The corresponding displacement inverse-velocity curve is illustrated in **Figure 4(d)**. The inverse-velocity was generated by the following 3rd order equation,$y = -0.9x^3 + 5.2x^2 - 9.6x + 5.9$ that rendered the rapid decrease in the inverse-velocity.

The behavior of the slope appeared almost identical with that in the Case 1 and, the 3rd order polynomial equation similar to that of the site of 'Neureupjae' presented by Han and Chang [41] was also derived. The equation appeared in 3rd order polynomial equation: $y = 19.4x^3 - 73.8x^2 + 94.9x - 25.5$. **Figure 5(c)** represents the displacement velocity curve of cumulative displacement on which there are two points of inflection at each point of 1.6 and 1.9 of the strength reduction factor. **Figure 5(d)** shows the displacement inverse-velocity curve. Contrary to that in the Case 1, the equation was reduced to the 1st order linear one:$y = -1.6x + 2.9$.

The slope stability analysis conducted with conditions defined in the Case 1 rendered following results of the changes in initial soil strength (cohesion) and internal friction varied from 10kPa to 4.8kPa and from 30° to 14.5°. The mathematical model of slope failure by cumulative displacement curve was reduced to the 3rd order polynomial equation,$y = 2337.6x^3 - 9690.2x^2 + 13188x + 5864.3$. The inverse-velocity curve resulted from the analysis of the Case 1 appeared as the 3rd order polynomial equation,$y = -0.9x^3 + 5.2x^2 - 9.6x + 5.9$. The equation presented by Fukuzono yielded values A = 4.0 and $\alpha = 1.21$ that determined the convex pattern of the curve similar to the pattern of ductile behavior appeared in the case of 'The Collapse of Kunini Slope' in Japan.

The results obtained from the analysis of the Case 2 showed that the failure resulted from the initial soil cohesion of 0 kPa with the internal friction varied from 40° to 21.5°. The resulted failure model corresponded to this cumulative displacement curve was reduced to the 3rd order polynomial equation, $y = 19.4x^3 - 73.8x^2 + 94.9x - 25.5$. Contrary to the Case 1, the displacement inverse-velocity curve of the Case 2 showed the pattern of linear equation,$y = -1.6x + 2.9$, and the values of $A = 2.05$ and $\alpha = 1.79$ were obtained therefrom. The pattern of this curve was similar to that in the case of 'The Failure of the Cut Slope of Selborne' in the United Kingdom.

6. Conclusions

When the road is constructed by the development of the urban, it is essential to cut-slope. However, the slope has gradually degraded the strength of the soil due to the time-dependent deterioration, and progressive slope failure is induced. This study developed an integrated analysis method for stability analysis and maintenance of cut-slopes in urban. The slope stability analysis was performed using the finite element model, and the progressive slope failure by time-dependent deterioration was quantified by using the strength parameters of soil applying the SRF. The displacements until the slope failure by slope stability analysis were quantified by cumulative displacement curve, velocity curve, and inverse velocity curve and, applied to the slope maintenance method. The inverse-velocity curve applied to the prediction of the time of slope failure was regressed to the 1st linear equation in the brittle material and the 3rd polynomial equation in the ductile material. This is consistent with the proposed formula of Fukuzono [1] and also shows similar behavior to the existing failure case.

Recently, sensors and communication technologies for measuring the behavior of slopes have been dramatically developed. However, there is no technique or management method to interpret it. This study aims to solve these problems.

The proposed method integrates the existing slope stability analysis and maintenance techniques. It is difficult to obtain the measurement data of the collapsed slope, but the proposed technique should be verified through the failure of the model slope. And the behavior of ductile and brittle behavior appeared depending on the characteristics of the materials constituting the slope. Research on this part is also necessary. In the future, integrated analysis method should be improved through additional research. And it should be applied to cut-slope of urban to prevent disasters.

In this study, the proposed method was carried out only on homogeneous slopes consist of soil. In the future, research on the slope with the heterogeneous and anisotropic is needed. Also, the proposed method should be verified by applying it to the 3D rock slope which causes collapse along the joint of rock.

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