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Paper:

New Approach for the Extraction Method of Landslide-Prone Slopes Using Geomorphological Analysis: Feasibility Study in the Shikoku Mountains, Japan

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In recent years, airborne laser scanning has been used for terrain surveys of broad areas in Japan. This study attempted to extract the landslide-prone slope based on geomorphological and slope stability analyses using Digital Elevation Model obtained by airborne laser scanning. The study site is located in the mountainous region of the Shikoku Mountains, where landslides occur on the gentle slope deformed by mass rock creeps. Implementing slope stability analysis to incorporate "potential to increase pore water pressure" found that landslides occur in areas with low factor of safety. In the future, it is expected that the method developed in this study could contribute to the planning of basin-based disaster management.

Keywords: deep-seated landslide, digital elevation model, potential to increase pore water pressure, slope stability analysis, Kochi Prefecture

1. Introduction

About 75% of the land in Japan comprises mountainous areas, and owing to its warm and wet climate, a landslide disaster caused by heavy rainfall occurs frequently. Therefore, it is crucial to extract a slope where a landslide disaster could occur and grasp its distribution while planning disaster management in the river basin scale.

In recent years, the airborne laser has been used for terrain measurement of broad areas in Japan. Moreover, a high-accuracy Digital Elevation Model (DEM) can be procured relatively easily if it is intended to be used for a study. This study attempted to develop a method to analyze the topographical data using Geographic Information System (GIS) with DEM and extract a slope with a high possibility of a landslide. Concretely, the development process of a landslide in the area to be surveyed was grasped, the "potential to increase pore water pressure" was estimated based on the geomorphological analysis, and a landslide-prone slope was identified using the equation for slope stability analysis. The potential to increase pore water pressure and the frequency of the distribution of landslide-prone slopes were evaluated in each basin for ranking. The test field was set in the basin of the Nahari River, located in the eastern part of the Shikoku Mountains (**Fig. 1**). A landslide is classified into various types [1]. The characteristics of the landslide surveyed in this study are that it develops from a rockslide into a debris avalanche. The movement distance is long, and almost all the landslide body is slipped out from the source area; such landslides frequently occur [2, 3]. As a landslide body like this moves rapidly and behaves like debris flow, a sediment disaster occurs along the river channel. It is called a "rapid landslide" in this study. The type of landslide which blocks neighboring areas and reactivates the generating area is called "slow landslide." It is widely distributed in Japan [4, 5]; however, slow landslides are not covered in this study.

2. Study Site

The study site is located in the mountainous area of Muroto Peninsula in Kochi Prefecture, Shikoku Island (**Fig. 1A**). The surrounding area has an altitude of 100–1,000 m, and old and new coastal terraces have developed along the coast. The uplift rate of the Muroto Cape located at the tip of the Muroto Peninsula is 1.4 mm/year [6], one of the distinguished uplifting locations in Japan [7]. In the 1946 Nankai Earthquake, the ground uplifted by 1.3 m [7]. The geology is mainly composed of sandstone and mudstone of the Muroto Peninsula

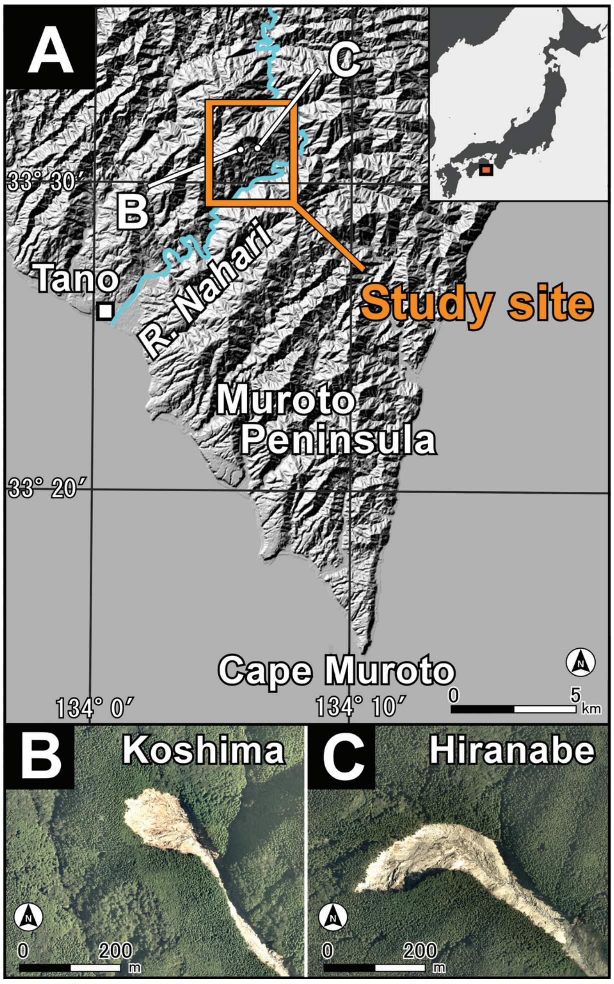

Fig. 1. A: Study site. The base map is created based on DEM using AW3D 30 m. B: Aerial photograph of Koshima landslide. C: Aerial photograph of Hiranabe landslide. Aerial photographs of B and C were taken by the Forestry Agency in 2012.

Group of the Paleogene Period and their alternations. It is an accretionary wedge formed by the process wherein the materials filled in the trench are added to the overriding plate by its subduction [8]. The climate is characterized by high rainfall. According to the AMeDAS weather data of the Japan Meteorological Agency in Tano Town located near the survey site, the mean annual precipitation during the period from 2010 to 2019 is 2,422 mm, and the mean monthly precipitation in September, a month with the most rainfall in a year, is 369 mm.

In the Muroto Peninsula, the slopes of the mountainous area have become more unstable due to the uplift caused by earthquakes and the accompanying downward erosion. The bedrock has also been deformed due to the geological features of the accretionary wedge. Moreover, there is substantial rain in the area. From the perspective of both causative and contributing factors, the survey site is prone to landslides. The topography of mass rock creeps [9, 10] is prone to large-scale landslides, and its precursory phenomenon is widely observed in the study site [2, 3, 11, 12].

The study site (**Fig. 1A**), where the extraction of the landslide-prone slope was carried out in this study, is located in the basin of Nahari River. Here, rapid landslides occurred at two locations on July 19, 2011. Termed as the Koshima (**Fig. 1B**) and Hiranabe landslide (**Fig. 1C**), these landslides were caused by the heavy rainfall at the time of the 2011 Typhoon Ma-on [10]. According to the AMeDAS weather data in Tano Town, the 48 hours precipitation during the period from 00:00 on July 18 to 00:00 on July 20, 2011, was 539.0 mm. The maximum hourly precipitation was 55.5 mm from 14:00 to 15:00 on July 19, 2011.

3. Understanding Landslide Development Using Topographical Interpretation

3.1. Topographical Interpretation of Survey Site

The topographical interpretation was conducted around Koshima and Hiranabe landslides to understand the location and process of rapid landslides in the study site (**Fig. 2A**). For the topographical interpretation, slope maps were used (**Figs. 2B** and **C**). These maps were created by ArcGIS 10.8 manufactured by Esri, Inc. (GIS, hereafter) based on DEM with 1 m accuracy of airborne laser scanning carried out by the Forestry Agency in 2018. In this study, the landslide topography is divided into three types caused by a rapid landslide, slow landslide, and mass rock creep. The scarp of a rapid landslide with clear formation is shown with solid orange lines, and the scarp with unclear formation resulting of dissection – with broken orange lines. The landslide body of rapid landslide cannot be seen along the scarp because landslide materials are thought to have flown down. The scarp and landslide body of slow landslide is shown with solid green lines with hachures and solid green lines, respectively. As for the topography formed by mass rock creep, up-hill and down-hill facing scarps are shown with solid red lines with hachures. The topography, which can be interpreted as a moving block caused by mass rock creep, is shown by solid pink lines.

3.2. Characteristics of Location and the Process of Landslide

In the study site, the Nahari River flows from northeast to southwest; the west side of the river comprises mountainous areas with the main ridgeline stretching similarly from northeast to southwest (**Fig. 2**). The highest location in the survey site is Mt. Kouzenmori with an altitude of 1,029 m, and the altitude at point R of the riverbed of Nahari River is 110 m.

Koshima landslide (Ko in **Fig. 2B**) is located on the right bank of a valley stretching in the direction from north-northwest to the south-southeast, and the size is 125 m in width and 180 m in length. The slopes above the scarp are gentle compared to the surroundings, and the head of the scarp is located along the convex break

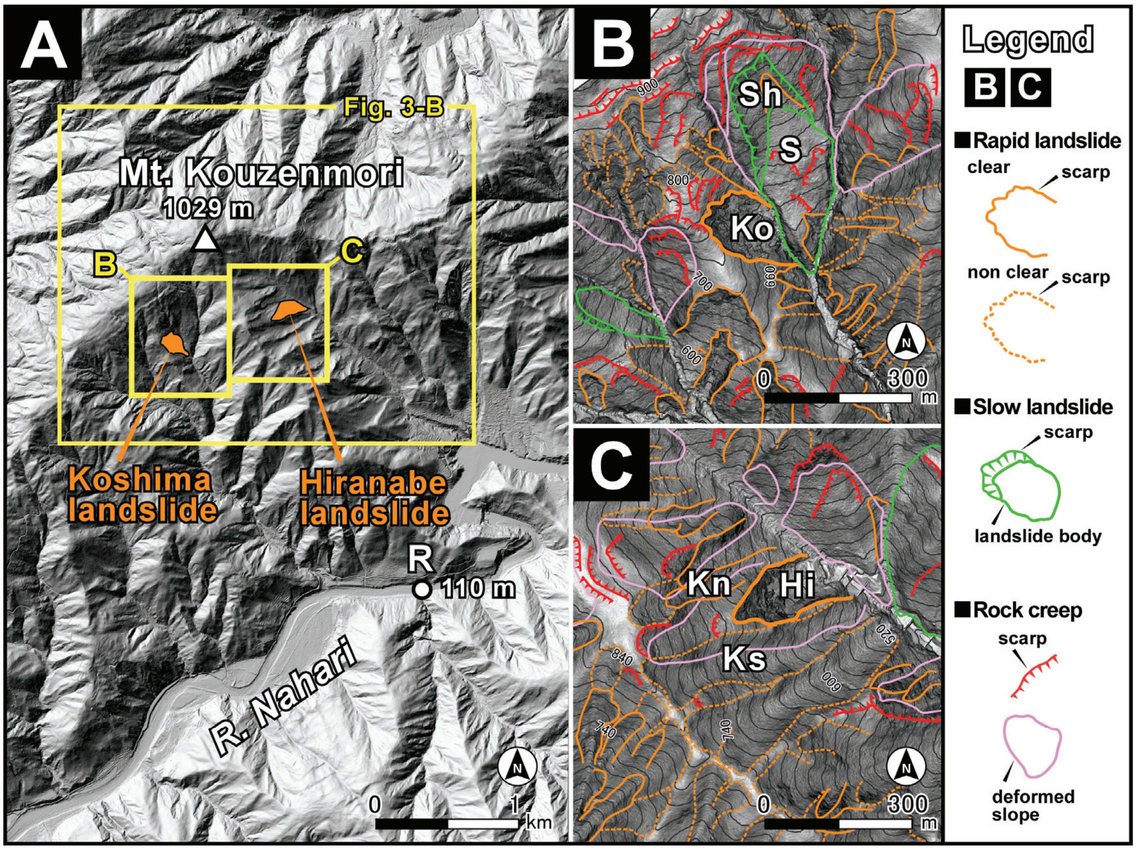

Fig. 2. A: Study area. The base map is created based on DEM with 1 m accuracy of airborne laser scanning carried out by the Ministry of Land, Infrastructure, Transport and Tourism in 2011. B: Results of topographical interpretation around Koshima landslide. C: Results of topographical interpretation around Hiranabe landslide. Slope maps of B and C are created based on DEM with 1 m accuracy of airborne laser measurement carried out by the Forestry Agency in 2018. The contour interval is 20 m.

line. Interpretation from the topography, three down-hill-facing scarps can be seen on the slopes above the scarp. Moreover, on the west-facing slope located on the west side of the Koshima landslide, there is a deformed slope where mass rock creep has been formed. Although the Koshima landslide is not located within a deformed slope caused by a mass rock creep, it is estimated from the existence of scarps in the surroundings that the mass rock creeps formation would have proceeded. Furthermore, on the opposite bank of the Koshima landslide, there is a landslide body (S) moving slowly. The scarp corresponding to this landslide body is steep, and its height difference is also large. Therefore, it is assumed that these materials would have originally moved as rapid landslides and now exist as a landslide body (S). On the slopes behind the scarp (Sh), many scarps are distributed, forming a deformed slope caused by a mass rock creep. In the future, rapid landslides could happen within the area of this mass rock creep.

Hiranabe landslide (Hi in **Fig. 2C**) is also located on the right bank of a valley stretching from north-northwest to south-southeast. The width of the scarp is 150 m, and the distance from the scarp to the valley bottom is 200 m. A part of the sediment caused by the landslide flowed down along the valley as debris flow. As shown in **Fig. 2C**, multiple check dams have been constructed after the landslide along the valley bottom. The scarp of the Hiranabe landslide is located near the convex break line within a mass rock creep area. The shape of the slopes surrounding the scarp is convex in both the inclination and lateral directions. The slopes are convex in the lateral direction because the slopes neighboring the Hiranabe landslide on the north and south sides have been dissected by the landslide on the north (Kn) and south side (Ks). It is supposed that the slope of mass rock creep where the Hiranabe landslide is located would be deformed to topography similar to that of its neighboring landslides. It may cause a landslide in the future.

As described above, the typical characteristics of topography are recognized in the Koshima and Hiranabe landslide and their surroundings. The rapid landslides occur on the gentle slope existing from ridgeline to mid-slope, influenced by the mass rock creep. Therefore, there is a high possibility that a rapid landslide would occur on a gentle slope distributed from ridgeline to mid-slope. Sasahara [3], who surveyed Koshima and Hiranabe landslides, has a similar opinion as well.

4. Extraction of Landslide-Prone Slope

4.1. Construction of Analysis Method

How can the geomorphological data acquired from DEM be analyzed to extract a landslide-prone slope? Landslides do not dissect a gentle slope ranging from ridgeline to mid-slope, and gully erosion is not significantly generated compared to the surrounding area. That is because, in such topography, the number of locations for discharge of groundwater is limited, so large pore water pressure would be generated within the bedrock during heavy rainfall, and a rapid landslide would be triggered. Therefore, this study attempted to estimate landslide-prone locations by incorporating the concept of potential to increase pore water pressure (**Fig. 3A**). The concept was proposed by the authors Mayumi and Yokoyama among others. According to this concept, a valley head is located on the boundary between a weak rock zone deformed by mass rock creep, weathering, and bedrock; and the hydraulic head of the river channel is regarded as zero. The surface created by connecting the valley head and the river channel is considered as the surface of the zero hydraulic head. Furthermore, there is a potential to increase groundwater level within a weak rock zone above the surface of zero hydraulic heads at the time of heavy rainfall. The larger the differential value (H) between the surface of zero hydraulic head and ground surface, the larger the potential to increase hydraulic head, contributing to the occurrence of a landslide. This differential value is equivalent to the maximum water level (hydraulic head) at the time of heavy rainfall. In this study, the differential value (H) between the surface of zero hydraulic head and ground surface was calculated as follows. First, a slope map was created using GIS-based on DEM with 1 m accuracy measured by the Ministry of Land, Infrastructure, Transport and Tourism in 2011 before the occurrence of Koshima and Hiranabe landslides (**Fig. 3B**). Next, after the locations of valley heads and river channels were extracted by the topographical interpretation of the slope map, Triangulated Irregular Network (TIN) was created from the positional relation with each valley head and river channel, and DEM of the surface of zero hydraulic head was generated. Lastly, the differential value between the surface of zero hydraulic head and the ground surface was measured in each 5 m grid. The results expressed two-dimensionally are shown in **Fig. 4A**. This is regarded as the map of potential to increase pore water pressure. While interpreting the valley head in this context, the head hollow located at the uppermost part of the dissected valley was extracted.

However, the evaluation cannot be made by simply replacing the risk of landslides with the potential to increase pore water pressure. If there is a gentle slope where neither dissected valley nor gully have developed, the potential to increase pore water pressure is high. Accordingly, in this study, slope stability analysis was conducted by incorporating the potential to increase pore water pressure and the inclination of slip surface into the parameters. The geological structure influences a slip surface in the actual slope, and the depth of a weak rock zone formed in the slip surface cannot be grasped. The stability analysis was conducted by assuming the differential value between the ground surface and zero hydraulic head in each column in a 5 m grid as the maximum potential of the hydraulic head. Specifically, the factor of safety was calculated using the equation below.

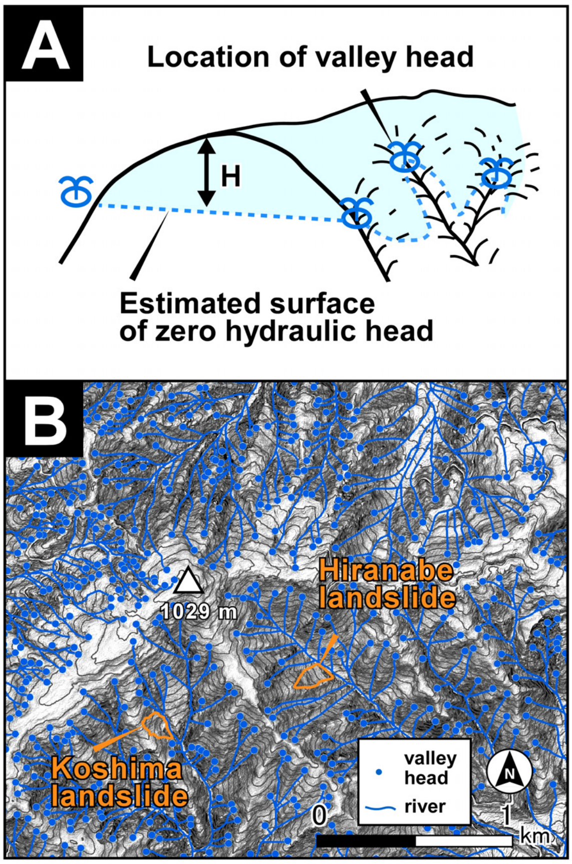

Fig. 3. A: Concept of potential to increase pore water pressure. B: Example of distribution of valley heads and river channels estimated from topographical interpretation. The base map is created based on DEM with 1 m accuracy of airborne laser scanning carried out by the Ministry of Land, Infrastructure, Transport and Tourism in 2011. The contour interval is 20 m.

Considering that the groundwater level at the time of heavy rainfall would promote sliding the weak rock zone above the zero hydraulic head, the factor of safety (F_s) for slope failure assuming semi-infinite slope was calculated with the following equation.

$$F_s = \frac{c' + (\gamma_t + \gamma_w) H \cos^2\theta \tan\phi'}{\gamma_t H \sin\theta \cos\theta}.$$

In this equation, γ_t indicates the wet unit weight of soil (kN/m^3); γ_w, unit weight of water (kN/m^3); c', effective cohesion (kN/m^2); ϕ', effective internal friction angle (°); H, level of groundwater (m); and θ, inclination of the slope. The adhesive force and internal friction angle are based on effective stress. For γ_t, 22 kN/m^3, the value

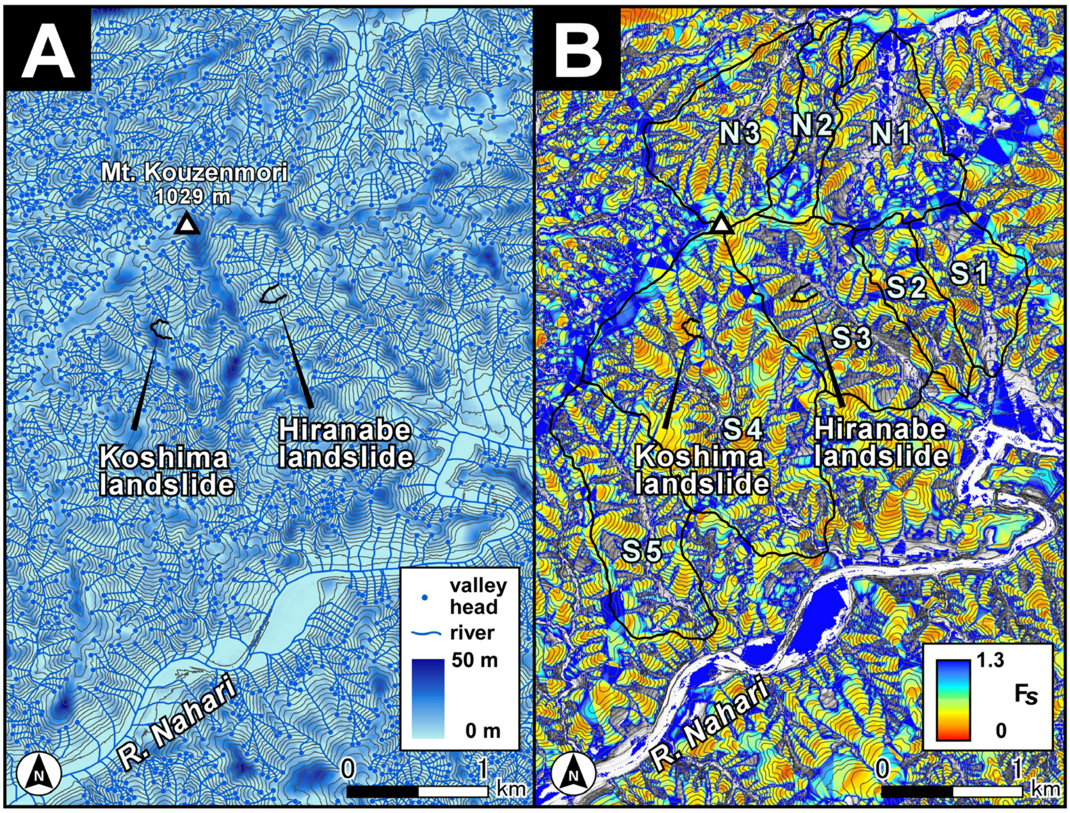

Fig. 4. A: Map of potential to increase pore water pressure. B: Map of results of slope stability analysis. Base maps of A and B are created based on DEM with 1 m accuracy of airborne laser scanning carried out by the Ministry of Land, Infrastructure, Transport and Tourism in 2011. The contour interval is 20 m.

for rock indicated by the Ports and Harbors Bureau of the Transport Ministry [13], was used and for γ_w, 9.81 kN/m^3. In the test site, the geotechnical research was carried out by the Shikoku Regional Forest Office, and the values for c' and ϕ' of Hinanabe landslide were measured using the one-plane sharing test device manufactured by Marui & Co., Ltd. possessed by Japan Conservation Engineers & Co., Ltd. The results were 29.3 kN/m^2 for c' and 15.2° for θ', and the same were used in this study. As for H, the differential value between the surface of zero hydraulic head and the ground surface calculated as potential to increase pore water pressure was regarded as groundwater level [m]. The angle of inclination of the surface of zero hydraulic head at each grid is used as θ. It is calculated based on the DEM of the surface of zero hydraulic head used in creating the map of potential to increase pore water pressure, using the maximum average method in each 5 m grid.

The factor of safety was calculated using these parameters in each 5 m grid, and the results expressed spatially (**Fig. 4B**). The equation as mentioned above for stability is used to find the factor of safety (F_s). It is usually recognized that the slope concerned could trigger a landslide if the factor of safety falls below 1. However, as this study aims to evaluate landslide-prone slope relatively from the viewpoint of hydrogeomorphology, the factor of safety is used as an index expressing that the lower the calculated value, the easier the landslide.

4.2. Results of Analysis and Spatial Distribution of Landslide-Prone Slope

After observing the map of potential to increase pore water pressure (**Fig. 4A**), it was recognized that the differential value between the surface of zero hydraulic head and ground surface is high along the ridgelines. Concerning the differential value at the Koshima landslide, a high value was expressed near the scarp, at about 50 m. Similarly, for the Hiranabe landslide, the differential value showed a high value near the scarp, at about 20 m. After observing the map of results of slope stability analysis (**Fig. 4B**), it was clear that the factor of safety (F_s) of the slopes near the ridgelines shows low value, reflecting the results that the differential value indicating the potential to increase pore water pressure shows high value near the ridgelines. As shown in the topographical interpretation of Koshima and Hiranabe landslides and their surroundings, the rapid landslides occur on a gentle slope ranging from ridgeline to mid-slope. In such gentle slopes, the factor of safety shows low value. The factor of safety of Koshima and Hiranabe landslides showed low value near the scarps of each landslide, at about 0.3–0.5. Conversely, the factor of safety is high on the slopes where the landslide occurred. Although more cases of landslides should be examined in the future, it was concluded that the method to evaluate landslide-prone slopes using this method has a certain degree of appropriateness.

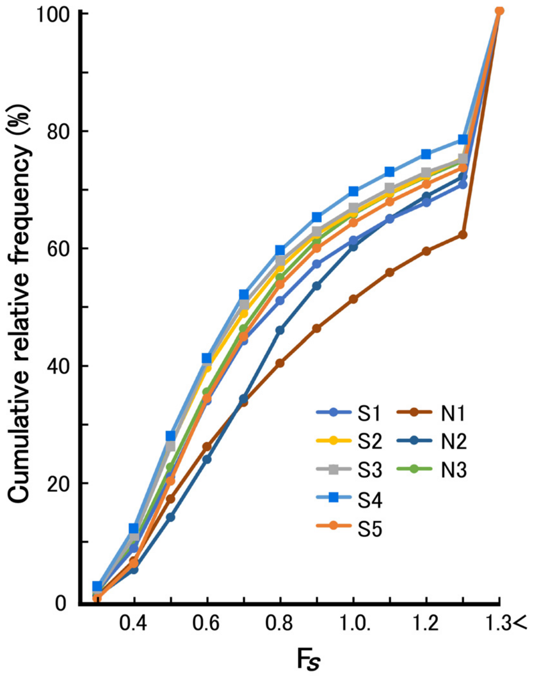

Fig. 5. Cumulative relative frequency of factor of safety in every 5 m grid of each basin.

Next, viewing the map of results of slope stability analysis (**Fig. 4B**), comparing the north and south side of the main ridgeline stretching from northeast to southwest, where Mt. Kouzenmori is located, it seems that more slopes with low factor of safety are distributed on the south side. While planning the measures for disaster management against sediment disasters in a unit basin, the geomorphological and geological surveys should be conducted preferentially in the basins with more slopes with low factor of safety, and the interpretation of microtopography and the field survey should be carried out with high priority for these slopes.

Accordingly, in this study, the basins of the study site are divided into eight areas as shown in **Fig. 4**, and the factor of safety in every 5 m grid of each basin is expressed as cumulative relative frequency (**Fig. 5**). In **Fig. 5**, N1–N3 and S1–S5 indicate the values of the basins on the north and south of the main ridgeline, respectively. Results prove that compared to N1, N2, and N3 on the north side, the slopes with the relatively low factor of safety are more widely distributed in the S3 and S4 basins where Hiranabe and Koshima landslides are located, respectively.

4.3. Limitations of Analysis Method

The evaluation method proposed in this study consists of a simple model. The difference in elevation between zero hydraulic head estimated from the topographical data and ground surface is regarded as the maximum potential of hydraulic head, and the slope stability analysis was conducted in each 5 m grid. This method is highly useful because it can be applied to an area where geological and geotechnical data are difficult to acquire. However, there are some limitations. The result that the slopes with the factor of safety less than 1.0 are widely distributed indicates that the shear properties of soil used in the calculation for slope stability, c and ϕ, should be examined, and the angle of inclination of the slip surface be set appropriately. As for the inclination of the slip surface, if the surface of zero hydraulic head is created based on the valley heads distributed on either side of a ridge, the inclination direction of slope and that of the surface of zero hydraulic head could cross obliquely at the grids of the valley head located at higher altitude. In this case, the method described in this study is suitable to explain a large-scale landslide that would cut a ridge line, but there is a problem that the factor of safety is likely to be evaluated higher for the sliding in the inclination direction of the slope. Therefore, it is necessary to examine these points in future studies.

5. Conclusions

This study attempts to calculate the factor of safety of slope based on the geomorphological and slope stability analysis using DEM obtained by airborne laser scanning and extract a landslide-prone slope. As a result, the following conclusions were found.

1) In recent years, Koshima and Hiranabe landslides occurred on gentle slopes ranging from the ridgeline and mid-slope, and on such gentle slopes, the landforms have been formed by mass rock creeps.

2) As a result of the slope stability analysis incorporating potential to increase pore water pressure, it was found that both Koshima and Hiranabe landslides occurred in areas with a low factor of safety. Although a larger survey site and more training data of the cases of landslides should be assessed, it is concluded that the method proposed in this study is appropriate to some extent.

3) The survey site was divided into basins, and the percentage of area with a low factor of safety was calculated for each basin. Thus, the slopes with relatively low factor of safety are widely distributed in the basins where Koshima and Hiranabe landslides are located.

4) If the inclination angle of the slip surface estimated from the surface of zero hydraulic head is used for stability analysis, it is supposed that there are some areas where the inclination direction of the slip surface would not coincide with that of the slope. In future studies, this has to be examined.

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Selected Publications:

- "Prompt report on the roof falling induced slope movement on August 24, 2019 in Iwaki City, Japan," J. of the Japan Landslide Society, Vol.57, No.4, pp. 9-18, 2020.
- "Remains of the Iwasa checkpoint on the Noneyama-kaido as an ancient road located in ridge-top area formed by gravitational deformation, the Muroto Peninsula, Japan," J. of the Japan Landslide Society, Vol.57, No.1, pp. 19-23, 2020.

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