Development of analysis method using LiDAR data for three dimensional measurement of slope movement

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Abstract

Three-dimensional laser group point data obtained by an airborne laser survey system have been utilized as measurement data for disaster mitigation measures. For example, the airborne laser survey is an effective method for estimating the volume of clods moved by a wide-area landslide. The measurement accuracy of the laser group points, however, is not sufficiently high to detect the precursory phenomena of slope failure. We propose a data processing method to improve the accuracy of the laser group point data in order to estimate minute movements of the slope. Our proposed method is an application of DEM data processing, in which detailed topography can be extracted using only the laser data set from below a certain height from the ground surface. Next, we compute the accurate displacement vector of the slope by matching the processing for the laser data image. We analyze the movement of the actual debris slide and demonstrate the effectiveness of the proposed method.

Keywords: laser group point data, slope failure, minute topography, displacement vector

1. Introduction

In recent years, disasters associated with abnormal weather such as “guerrilla rainstorms” have occurred. In particular, in Japan there is an increasing risk of occurrence of various slope failures such as slope collapses of shallow depth and debris slides, but it is difficult to predict the occurrence of slope failures and take preventive measures because it is difficult to capture phenomena that are prognostic of slope failure. Moreover, after the slope disaster, the risk of occurrence of a secondary disaster remains high for a few days after the torrential rain stops. Observation methods for wide-area slopes using ground-installed equipment such as extensometers have not been in widespread use because of the cost and labor involved. Therefore, the development of a new slope monitoring approach is needed.

Airborne LiDAR systems have been applied to ground altitude measurements and topography surveys since the 1960s by using the travel time of a laser mounted on an airplane, along with GNSS (Global Navigation Satellite System) and IMU (Inertial Measurement Unit) to measure its position. LiDAR surveying has the advantage of being able to obtain ground surface information from laser data with little influence from vegetation, and to create a topographic map with detailed land features. The topographic map and analysis of the laser data makes it possible to measure the volume of clods moved by the landslide on the surface using time series data of the DEM (Digital Elevation Model) (Chigira et al., 2004; Chigira et al., 2015; Lucieer et al., 2013). However, a LiDAR survey system that can monitor the initial minute displacement of landslides has not yet been established (Jaboyedoff, 2012). To detect or predict the occurrence of a landslide or slope collapse, further efforts are necessary to improve the measurement accuracy of LiDAR data. From the measurement method viewpoint, increasing the number of lasers reaching the ground surface is effective for improving measurement accuracy, but is expensive and time consuming because it requires a high performance laser scanner with high density and measurement conditions uninfluenced by vegetation. As an alternative, improvement of the analysis method has been proposed. For example, the use of a procedure to create a mesh model of the slope and analyze the movement of the mesh model as the displacement of the slope has often been carried out.

It is easy to analyze the displacement by tracing the movement of the mesh. However, the accuracy of the model depends on the size of the mesh data, and it is difficult to analyze the displacement of a steep slope such as a cliff.

In this paper, we propose a measurement and analysis method for computing the movement of slopes, including cliffs, with a high degree of accuracy. We discuss the results of an experiment in an actual slide debris field and report the applicability of our proposed method.

2. Method for analysis of slope displacement

We developed a method that can extract the minute topography from the original laser data by using only the laser data from below a certain height from the ground surface, as shown in Fig. 1. Fig. 2 shows the difference between the results of the conventional method using the original DEM data and those of our proposed method in the case of the analysis of minute topography. All laser data was used in the conventional method, while in our proposed method, data reflected by objects within a certain height range, for example 2 to 5 m from the surface, were deleted in the analysis process. The right-hand figure indicates that it is possible to detect falling rocks and depressed and protruding parts of the original topography using our proposed method, compared with the result shown in the left-hand figure. The result from the method developed here has a resolution of 10 cm (Mukoyama, 2011; Zhang et al., 2003).

Fig.3 shows the advantage of our proposed method. The figure shows that it is hard to read the detailed land features by using the conventional laser data, while it is easy to detect a concave topography which is several meters deep and a tub-shaped minute topography by using our method.

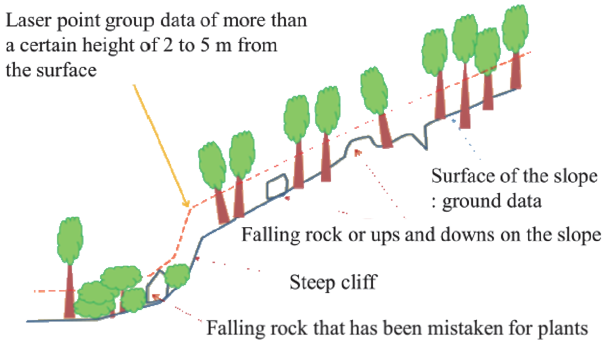
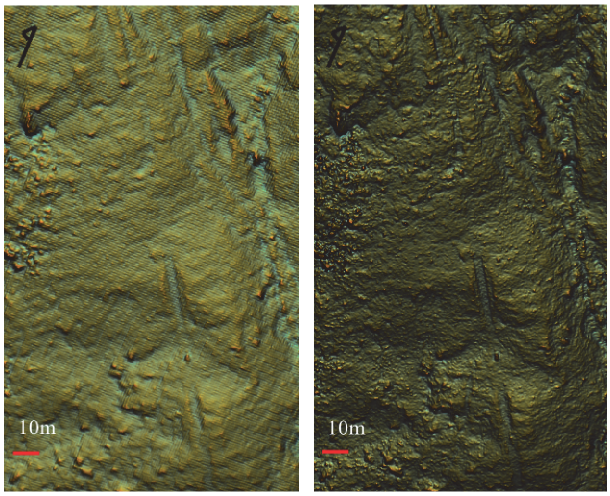


Fig. 1 Concept of method for extracting detailed topography

Fig. 2 Difference in detected minute topography.



Left: analysis result of conventional method. Right: analysis result of proposed method

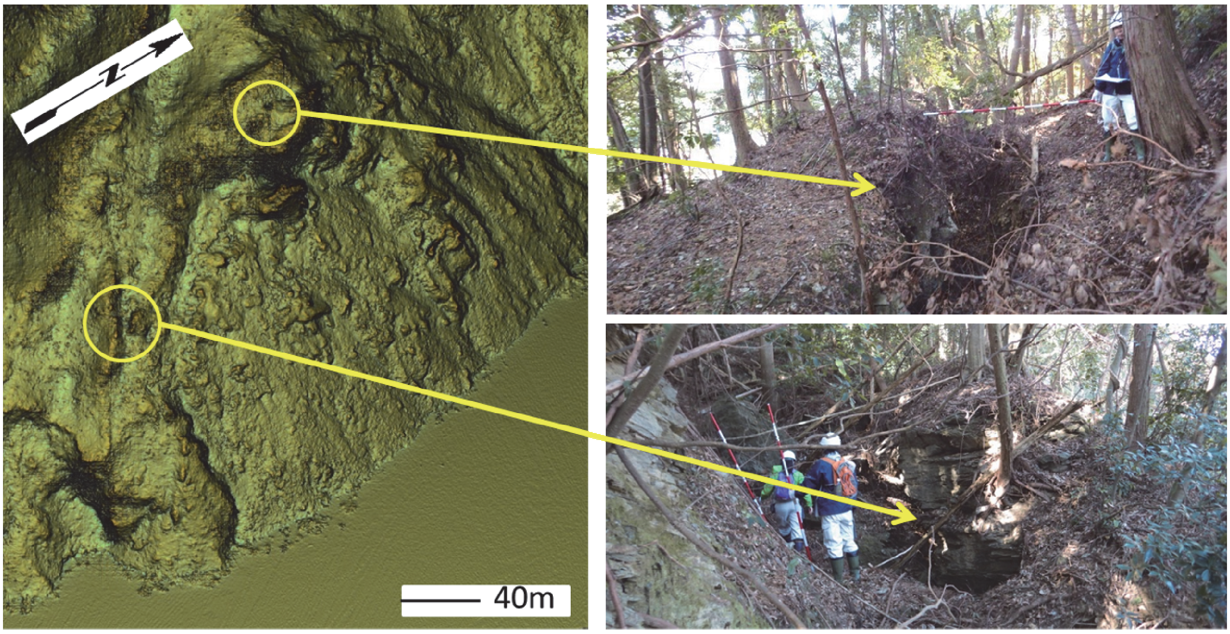


Fig.3 Example of reading the detailed land features using the method shown in Fig.1.
It was possible to read 2 m deep concave topography and 3 m wide tub-shaped topography.

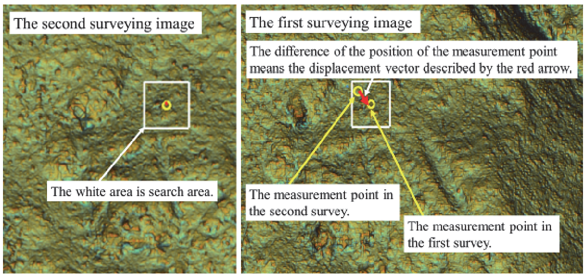


Fig. 4 Matching method for image. The amount of movement of the measurement point represented by the yellow circle is computed using the first and second surveying images. The white square is specified as the search area in the second surveying image and in the first surveying image. The same point in the first and second images is specified as the measurement point using the angle of inclination and the degrees of ups and downs.

Next, we developed a data processing method for the laser point group data to compute the displacement at each measurement point on the surface of the slope. The topography of the slope has been generally represented in a mesh model, whereas we measured the displacement directly from the laser group created by the method described above. The displacement of the measurement point is calculated using the matching method for image data created using the laser data as follows: we select an arbitrary measurement point in the area obtained by the second survey, then search for that point in the image from the first survey, as shown in Fig. 4. The search is performed within a radius of 50 pixels from the selected measurement point. The parameters in the matching method processing are the angle of inclination between pixels adjacent to each other, the degree of depressed and protruding parts within the narrow area of 5 pixels, and the degree of depressed and protruding parts within the wide area of 25 pixels. The three-dimensional displacement is calculated from the amount of movement of the measurement point detected by the processing described above. The proposed method has the advantage of being able to measure the displacement of measurement points on a variety of land features, including a vertical cliff with overhang topography, by calculating the displacement of the measurement point directly from the laser point group data without using a mesh model (Hsiao et al., 2004; Palenzuela at el., 2014; Ventura et al., 2011).

3. Application of our method

3.1 Topography and geology of test field

The landslide area is located on the southern margin of the Akaishi Mountains in western Shizuoka Prefecture, Japan. Most of the major summits in the area range in altitude from 700 to 800 m. A principal river, the Tenryu River, cuts into the mountains with v-shaped valleys and steep slopes. Its morphological landscape has a youthful form. The Tenryu River flows to the Pacific Ocean from north to south. The comparable height difference between the Tenryu River and peaks in the area is about 700 m. Large landslide scars are found sporadically on both slopes along the Tenryu River. The measurement object is a large landslide mass on a tributary of the Tenryu River. The maximum size of the mass is 250 m in width, 900 m in length, and 580 m in height. The

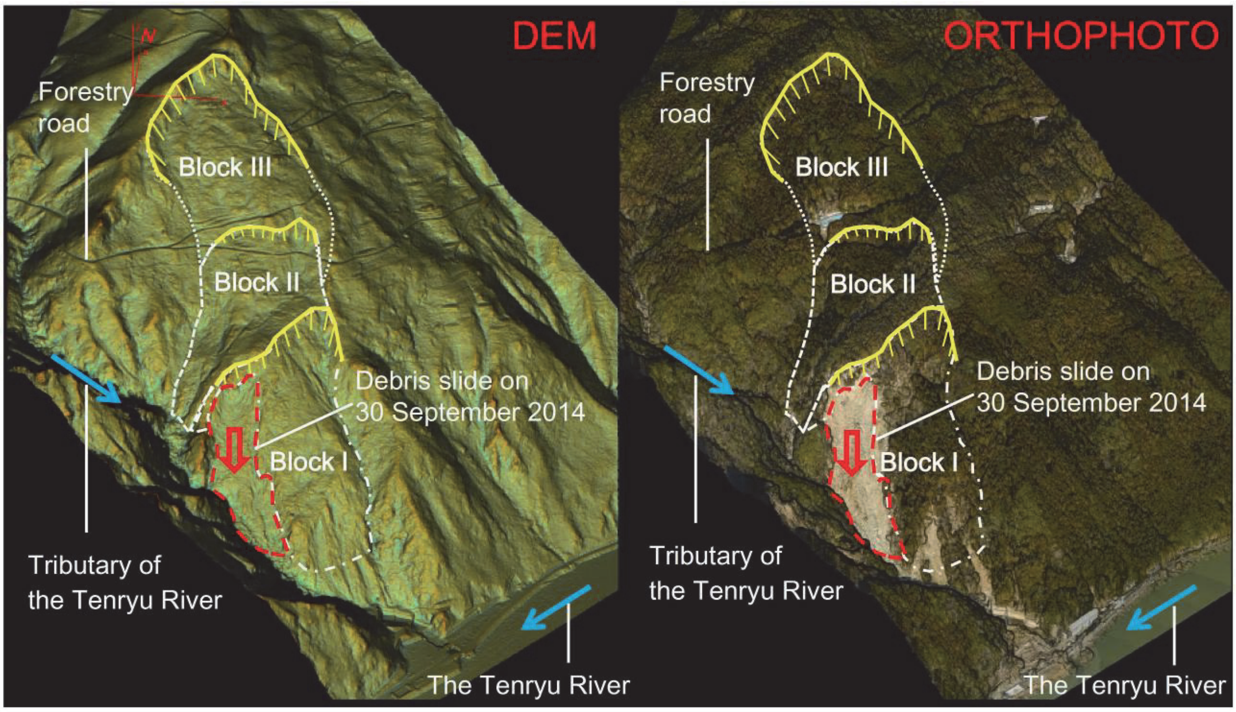


Fig. 5 Bird's eye view image of the landslide area produced from DEM and Orthophoto data

average slope angle is 33°. The landslide has had a long history of sliding and flowing. The terrain of the mass is divided into three landslide blocks. The area is underlain by crystalline schist of the Sanbagawa Metamorphic Belt, which forms the outer zone of Southwest Japan. The schist is commonly fragile or soft owing to schistosities, cleavages, close joints, and weathering near the surface. Bedrocks in the landslide area are composed of basic schist and pelitic schist. The pelitic schist is partially found on the upper part of the slope. The schist strikes NE–SW and dips 40°–60°NW. The slope of the landslide has an anti-dip slope. A debris slide occurred in the landslide area on September 30, 2014 as shown in Fig. 5. The geology and Landslide map is shown in Fig. 6. The debris slide mass, which consisted of sand and gravel with residual soils, was on the western part of Block I that was the latest landslide block. The crown of the slide was 380 m and its toe was 220 m in altitude. The slope angle before the slide was about 40°. The dimensions of the slide were within 250 m in length, 90 m in width, and 13 m in depth. The volume of the moved clod was about 30000 m^3. Four days previously, on September 26, heavy rainfall triggered the slide. The precipitation near the site registered 166 mm. The base of Block I had been strongly eroded by a tributary that flows into the Tenryu River, from west to east. Debris slides occurred frequently on Block I along the tributary. In the first two months after the slide, a forest road on Block II was displaced by tens of centimeters. Movement of slides or flows within Block I and Block II around the debris slide area have been active up to now. Movement within Block III was inactive because mitigation measures that included drainage and anchor works had been implemented for Block III at 510 m in altitude.

3.2 Result of experimental trial and discussion

Fig. 7 shows the analysis result of the distribution of altitude differences in the slope failure area using our proposed method that deleted the laser point group data from over a certain height. The laser point group data density of the laser scanner on the airplane in the specification was in the range of 100 to 120 m^2, and 5 to 10% of them reached the ground surface. This figure shows the difference of the altitude between the first and second surveys. It was found that it was possible to measure the minute topography from the limited laser point group data.

Fig. 8 shows the distribution of displacements in the area where the debris slide occurred. Arrows in the figure indicate the magnitude and direction of the displacement. The upper figure shows the displacement calculated using all the laser point group data, while the lower figure shows the displacement estimated using laser data analyzed by our proposed method. In the case of the analysis result shown in the upper figure, it is clear that there are several locations where displacement was not detected because it was impossible to represent the minute topography. On the other hand, the lower figure shows that it was possible to calculate the displacement at all locations, including the steep cliff where the debris slide occurred. These results show the benefit of analyzing a collapse phenomenon using our technique. Fig. 9 shows the distribution of displacements over the entire area analyzed using our technique. This result coincides with the following results of the field survey shown in Fig. 5: the dimensions of the debris slide were within 250 m long, 90 m wide, and 13 m deep. At the center of

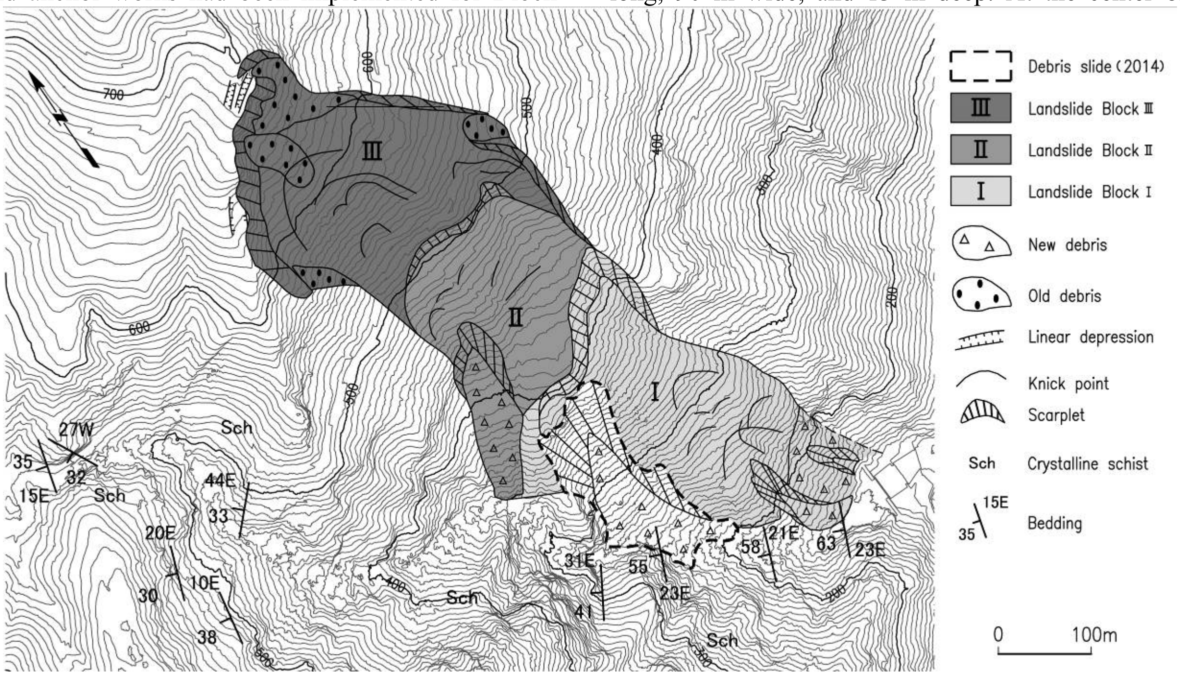


Fig. 6 Geology and Landslide map of the area where the landslide occurred

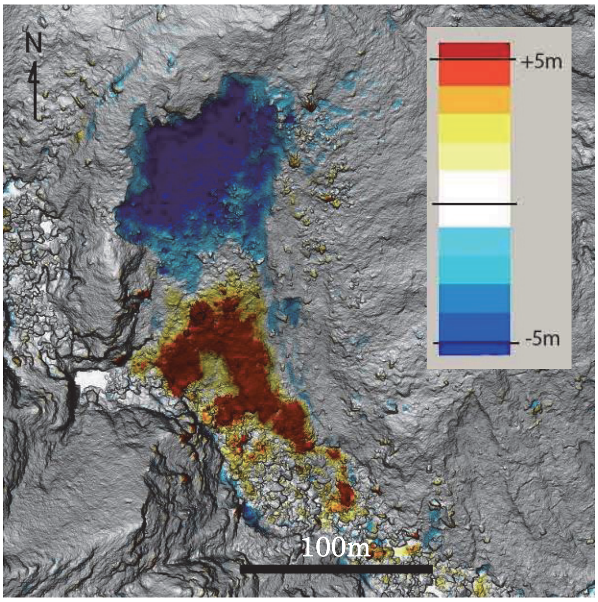


Fig.7 Distribution of altitude change after debris slide. Blue areas show the locations where the altitude was5 m lower, while red areas show the locations where the altitude was 5m higher after debris slide.

Landslide block I, deformation of more than 4 m was observed, and at the end of Landslide block I, deformation was not observed. Displacement of tens of centimeters on a road in Landslide block II occurred, as shown in Photo 1. Non-moved block was inactive because mitigation measures had been implemented. Fig. 9 shows the characteristics of the above-mentioned topography, and it can be seen that

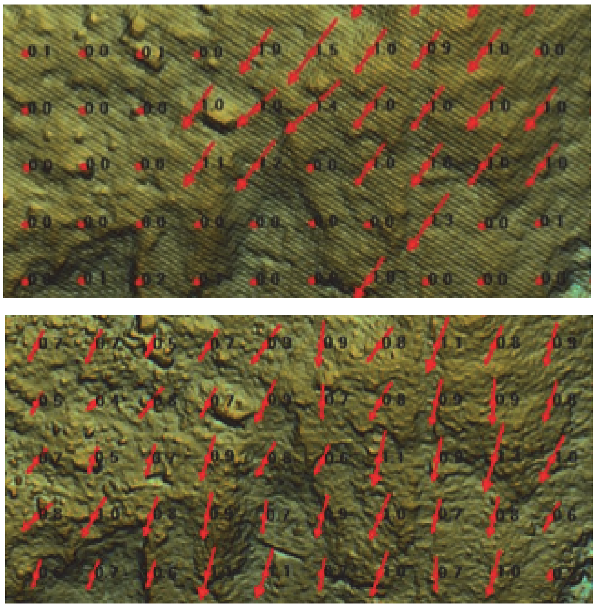


Fig.8 Distribution of displacement in the area where debris slide occurred. The upper figure show the analysis result by using all laser point group data. The lower figure show the result by our proposed method.

our technique can express extensive topography changes in detail.

Verification of measurement accuracy of the proposed method was carried out in the area shown in Fig. 9. Table 1 shows the analysis results in each area shown in Fig. 8. In the table, the computed minimum and maximum displacements in each area are shown, as well as the analysis result of the displacement of

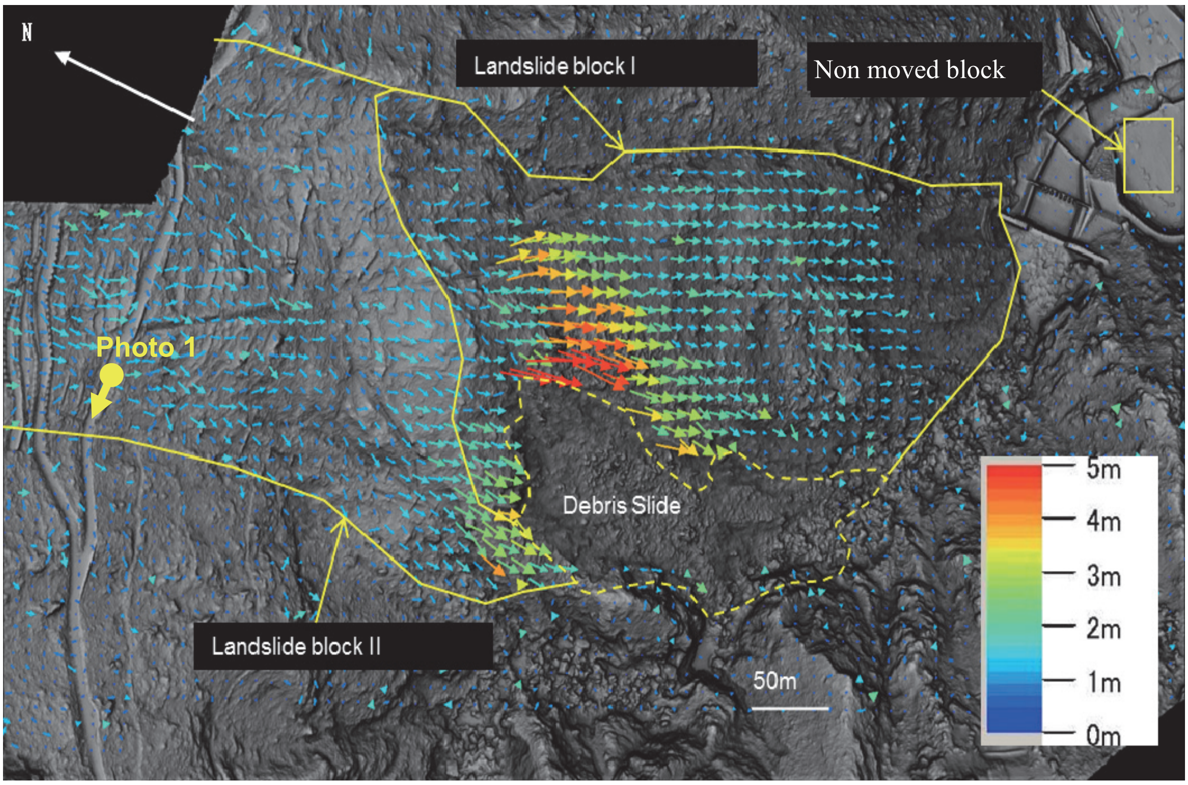


Fig. 9 Distribution of analyzed displacement vectors

Table 1 Displacement vector computed by our proposed method in each landslide block. "Minimum" and "Maximum" indicate minimum and maximum magnitudes of displacement. Units are m.

	Landslide block I	Landslide block II	Non-moved block
Number of measurement points	533	287	22
Minimum	0.06	0.06	0.03
Maximum	4.93	2.07	0.35

Photo1 Deformation appeared on the surface of the road in Landslide block II area.

the measurement points in Non-moved block, where topographical change has not occurred. In other words, the amount of displacement at the measurement point in Non-moved block indicates the accuracy of our measurement technique. It is found that it was possible to detect displacements of more than about 0.4 m. This result demonstrates that our technique can detect movements of the landslide with a high degree of accuracy.

4. Conclusions

In this study, we developed a technique for measuring slope displacements using three dimensional laser point group data, or LiDAR data. In this technique, we used only the laser data that is reflected from objects at heights of 2–5 m from the ground surface. Moreover, we developed a matching method for images created from the limited laser point group data in order to compute displacements using time series laser data. Experimental trials were performed to verify the applicability of our proposed method, and the results show that more than approximately 0.4 m changes in the displacement of the slope could be detected in the area where a debris slide occurred. We have demonstrated that it is possible to expand the applicability of airborne laser surveying to monitor slope failure by using the method proposed here.

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