Characterization of Landslides by using Precise DEM Data in Ribira, Hokkaido

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Abstract

We analyzed the slope development in an area of hard sedimentary rock and melange by using precise digital elevation model (DEM) data. The study area is Ribira, western Hidaka in Hokkaido, where many landslides were induced by the rainstorm of Typhoon 10 from 9th to 10th, August, 2003. We applied airborne laser scanner to the area and obtained high resolution DEM data with a mesh size of 1m. By using the DEM data, we characterized the topography in the area and analyzed the distribution and the morphology of landslides that occurred in the past. The airborne laser scanner enabled us to identify landslides as small as only ten meters or less in diameter even when they were hidden by vegetation. We recognized landslides that occurred at the 2003 event and also previous landslides, on which vegetation had recovered.

As a remarkable topographic feature in the study site, we found continuous knick lines that separate gentle upslope and the steep downslope by numerically processing the detailed DEM data. These knick lines are denudation fronts, below which many landslides are concentrated. The geometrical locations of the knick lines are affected by the bedrock geology; they are almost along the main ridges in most of the melange and alternating beds of sandstone and mudstone, while they still stay away from the main ridges in the area of siliceous tuff which is resistant against landslide and erosion. The characteristics of landslides were also strongly dependent on geology; many deep-seated landslides occurred in the area of alternating beds of mudstone and sandstone, while shallow landslides are dominating in the areas of melange and siliceous tuff except for the boundary with underlying sedimentary rocks. These facts suggest that the denudation front has been retreated by many shallow landslides in the melange area and by fewer but deeper landslides in the area of alternating beds of sandstone and mudstone; both types of landslide retreated the erosion front in a comparative rate.

There was no significant difference in the distribution density and shape between landslides occurred by the 2003 event and those by previous events. This suggests that these values indicate long-term susceptibility to landslide, which are characteristic to each geologic unit in the study site and could be obtained by airborne laser scanner.

Keywords: landslide, airborne laser scanner, DEM, topographic feature image, geomorphological feature

Introduction

Geomorphology in mountainous areas is a result of slope development, so it can be interpreted in terms of slope formation processes, such as mass movements and transportation. Previous methodology to analyze the slope formation processes would have relied on traditional interpretation technique of aerial photograph and ground truth, which was not so effective to investigate a wide area particularly when the land is vegetated with trees. An airborne laser scanner recently developed, on the other hand, can scan through the interstices among tree canopies to measure the ground surface with high accuracy, providing a revolutionary tool to analyze the geomorphology in detail (McKean, J. and Roering, J., 2004). By using this technique, small geomorphic features, such as shallow landslides hidden by trees, could be detected (Chigira et al., 2004; Sekiguchi and Sato 2004), and could be quantitatively analyzed for their characteristics, such as gradient, curvature, and elevation. We think that long-term geomorphic processes can be traced by analyzing geological and geomorphological features of an area by this method, obtaining an insights of hazard level in an area. However, application of this technique to analyze landslides has just started.

We selected an area that experienced a heavy rainstorm recently for the investigation of geomorphological features and landslides by using airborne laser scanner. The study area is located in Ribira, western

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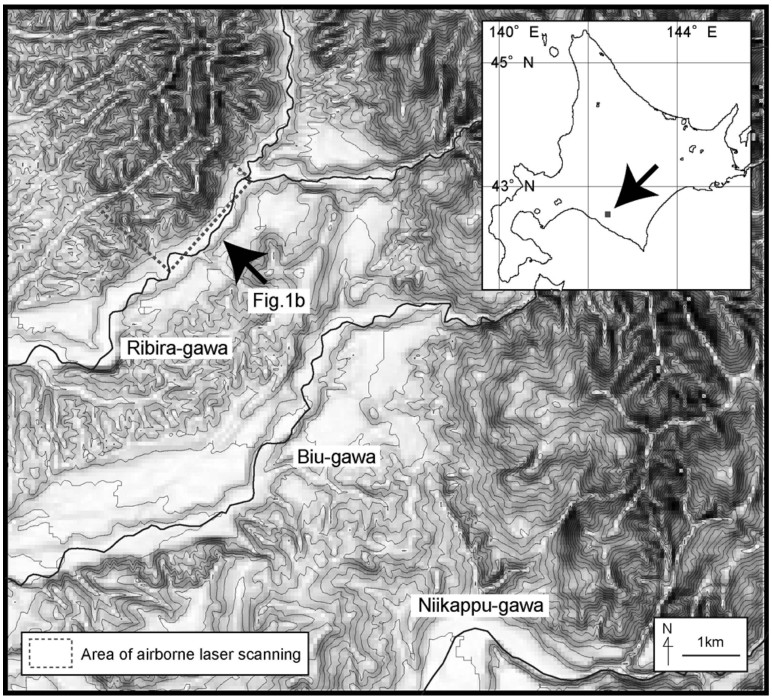

Fig. 1. a Index map of research area

Fig. 1. b An aerial photograph of research area

Hidaka in Hokkaido, where many landslides were induced by the rainstorm of Typhoon 10 from 9th to 10th of August, 2003. This area is underlain by melange, alternating beds of sandstone and mudstone, siliceous tuff and dolerite. Many landslides occurred on the right bank of the Ribira River. Many deep-seated landslides, exceeding 5 meters in depth, were generated in addition to numerous shallow landslides.

We applied airborne laser scanner to the study site, to obtain a high-resolution digital elevation model (DEM) with a mesh size of 1m. By using the DEM data, we characterized the topography of the area and analyzed the distribution and the morphology of landslides. On the basis of these data, we discuss about the effect of geology to the geomorphology and the landslide, and also discuss about slope development.

Airborne Laser Scanner and data processing

The airborne laser scanning is a new measurement technology that acquires high-resolution three-dimensional digital data. The measurement method involves high-frequency laser pulses radiated from an aircraft to the ground and detecting reflected pulses to measures the distance from the aircraft to the ground surface. The position and attitude of the aircraft is measured by the Global Positioning System (GPS) and Inertial Measurement Unit (IMU), respectively (Fig.2a). DEM is generally obtained by complementing the random vector point data with the Kriging method or Triangulated Irregular Network (TIN) (Fig.2b). There are two kinds of DEM: One is DTM (Digital terrain model) made by using last reflection pluses and the other is DSM (Digital surface model) by first reflection pulses. The DTM data is used for analyzing topographic features.

We made 1m-mesh DEM data by applying Kriging method to the random vector point data obtained from the measurements using the laser scanner. The accuracy at the case of our measurement was 30cm horizontally and 15cm vertically.

Topographic feature image

From the DTM data, we made a "topographic feature image" in order to visually analyze the micro topographic features (Fig.3). A topographic feature image map is prepared by superimposing a color elevation map over a gray-scaled slope map. The method of making the slope map is described later. This topographic feature image is not dependent on direction and is suitable for recognizing micro topographic features. By using this image, we can observe the topography with information of slope gradients and elevations on a single map: We can identify landslides on which vegetation had recovered. In addition, this topographic feature image clearly indicated that ridges are very thin in some areas and broad in some areas surrounded by clear slope breaks, so that we analyzed slope angle precisely, which will be described later. A topographic feature image is thus effective to understand the outline of topography and to plan a strategy of geomorphic investigation.

Identification of landslide

The airborne laser scanner data enabled us to identify landslides as small as small as only ten meters or less in diameter even when they were hidden by vegetation. We recognized landslides induced by the 2003 rainstorm event and also older landslides, which were covered by vegetation.

Landslide areas were determined by comparing DTM and DSM as follows. The surface of vegetated areas is jagged and has many steeply dipping parts in the DSM image because of the variable heights of trees (Fig.4). When an upper bound of surface slope angle is set to 60°, most of the slope angle in the vegetated areas exceeded the upper bound. Therefore, we extracted areas with slope angle less than 60° from the DSM image and compared it with DTM, which made it easy to identify landslides induced by the 2003 event (Fig.4). Remaining landslides recognized from the DTM image are older landslides. White features in Fig.4 represent the landslides that occurred during the 2003 event and grey features represent older landslides.

The area and the depth of landslides can be numerically determined by using 1m interval contour line chart and can be seen on the topographic feature image. There was no significant difference in the distribution density and the shape between landslides occurred by the 2003 event and those of previous landslides. This suggests that these values indicate long-term susceptibility to landslide.

Geomorphological features

A slope angle chart was made by calculating slope angles from the DTM data as follows.

Assuming $Z_{ij}$to be an elevation of an arbitrary point (row$i$, column$j$), the slope angle s of the same place is obtained from the following equations:

$$
\begin{aligned}
s &= \tan^{-1}\sqrt{\left(\frac{dz}{dx}^2 + \frac{dz}{dy}^2\right)}, \\
\frac{dz}{dx} &= \frac{1}{6d_x}\left\{(Z_{i-1,j+1} - z_{i-1,j-1}) + (Z_{i,j+1} - z_{i,j-1}) + (Z_{i+1,j+1} - z_{i+1,j-1})\right\}, \\
&\quad \text{and} \\
\frac{dz}{dy} &= \frac{1}{6d_y}\left\{(Z_{i+1,j-1} - z_{i-1,j-1}) + (Z_{i+1,j} - z_{i-1,j}) + (Z_{i+1,j+1} - z_{i-1,j+1})\right\} \qquad (1)
\end{aligned}
$$

in which dx and dy is the mesh interval in each directions, which were 1m in both directions in this study.

For the sake of visual understanding, slope angles were grouped into 4 of 0–30°, 30–40°, 40–50°, and more 50° and are shown as an image in Fig.5. The distribution frequency of the slope angles is also shown as

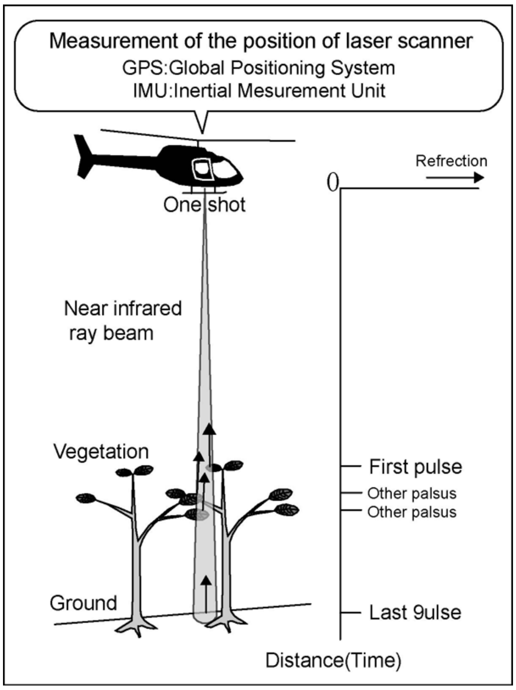

Fig. 2. a Schematic sketch of airborne laser scanner (Geographical Survey Institute, 2004)

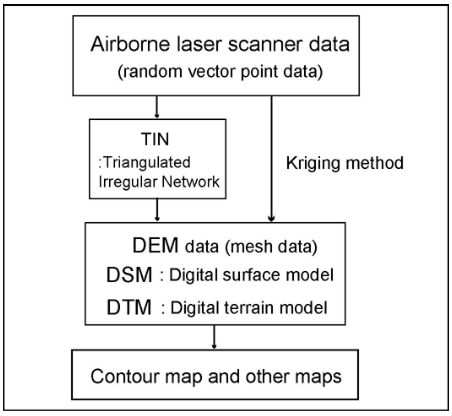

Fig. 2. b Compensation of airborne laser scanner data

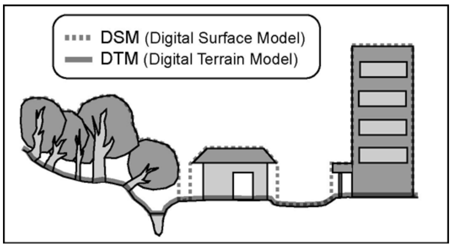

Fig. 2. c DSM and DTM (Geographical Survey Institute, 2004)

a histogram in Fig.5. Figure 5 shows that the slope angles in this investigation area are relatively steep except for higher low-relief slopes and alluvial surfaces; most are steeper than 30°. Slopes surrounding the higher low-relief surfaces incline mostly 30–40°, and most slopes with angles of 40° or more are landslide scars. The higher low-relief surfaces are surrounded by steeper slopes with well-defined boundaries, which are knick lines. We found many landslides are concentrated below these knick lines which is observable in Fig.5. These knick

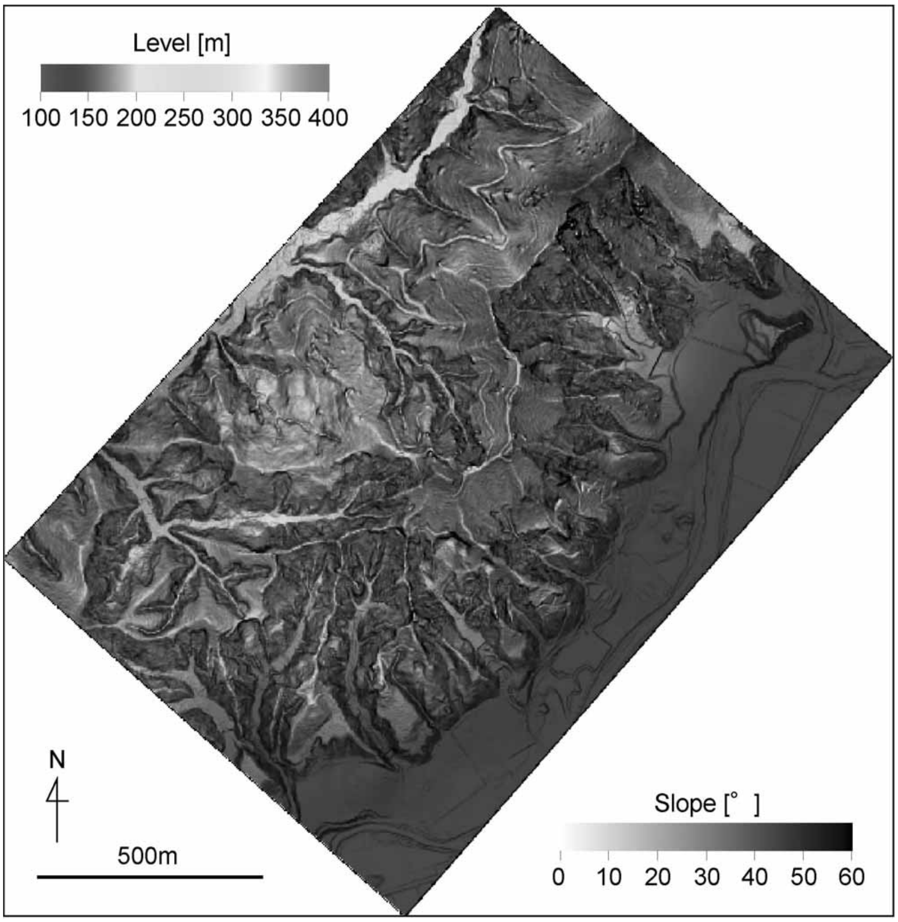

Fig. 3. Topographic feature image made by airborne laser scanner data

lines are thus a denudation front.

Valley lines were chosen from a drainage pattern chart and ridge lines were detected from a slope chart using the mehod developed by Burrough and McDonnell (1998). Fig.6a is Flow chart for the geomorphological analysis by using high-resolution DTM in this research. Fig.6b is the topographic feature map showing knick lines, valley lines, and ridge lines.

Discussion on denudation processes

We divided the research area into five subareas mainly by geology in order to examine the relationships with geology, landslide features and denudation rate, although geologic map we made is still preliminary (Fig.7). But ground truth has taught this area is underlain by melange, alternating beds of sandstone and mudstone, siliceous tuff and dolerite. Table 1 summarizes geology, relative position of knick lines and landslide features in each subareas.

Area1 is the area dominated by melange on the southeastern side of the main ridge. The upper periphery of this area is knick lines along the main ridge top, indicating that denudation front has reached to the ridge top in this area. There are many shallow and small landslides on steep slopes below this knick line; slopes steeper than 40° are mostly landslide scarps. Slopes are steepest near the knick line and steeper than 60° partly. This melange consists of mudstone matrix and sandstone blocks less than a few tens of a centimeter in size, and it is loosened at slope surface with well-defined front in depths of less than 4 meters; these loosened layers were observed at the new outcrop due to the rainstorm.

Area 2 is the area dominated by siliceous tuff and on the northwestern side of the main ridge. Higher level low-relief surface, which descends gradually northwestward, is denudated by shallow landslides near small streams in this area.

Area 3 is dominated by dolerite and on the low-relief surface around the main ridge. There is no landslide in this area.

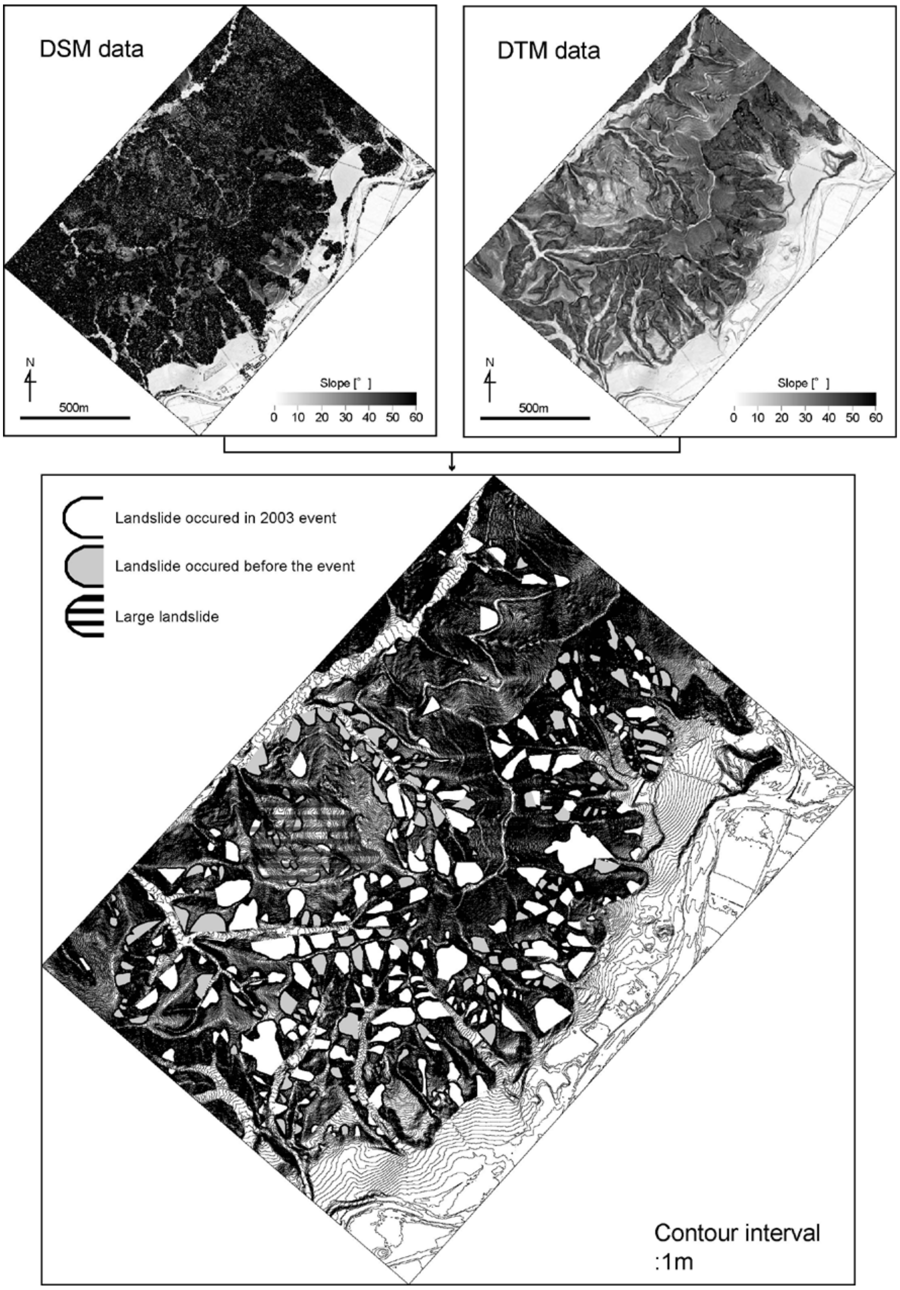

Fig. 4. Landslide distributions by the 2003 event and previous events

Area 4 is the area dominated by siliceous tuff and on the southeastern side of the main ridge. There is a knick line above this area near the boundary with Area 3, and the slopes in this area are relatively steep like Area 1. There are many shallow landslides, but there are large landslides just near the boundary with the alternating beds of sandstone and mudstone in Area 5. Thrust fault is inferred between the siliceous tuff and alternating beds.

Area 5 is the area dominated by alternating beds of sandstone and mudstone. Knick lines are almost along the main ridges in this area. Landslides are mostly deep-seated, and have an eye-brow scarp and a gentle slope of landslide mass below it. We observed mass rock creep of flexural toppling type at some landslide scarp.

There were two types of landslide as mentioned above: shallow (debris slide) and deep-seated (rock) slide. The former occurred in the areas of melange and siliceous tuff, and the latter occurred in the area of the alternating beds of sandstone and mudstone. This difference is due to the behavior of these rocks near slope surface. The chaotic rock of melange is easily loosened near the slope surface by crack development and the loosened layer slid at every heavy rainstorm. The siliceous tuff is intensively fractured, so tends to be loosened near the slope surface. On the other hand, alternating beds of sandstone and mudstone are gravitationally

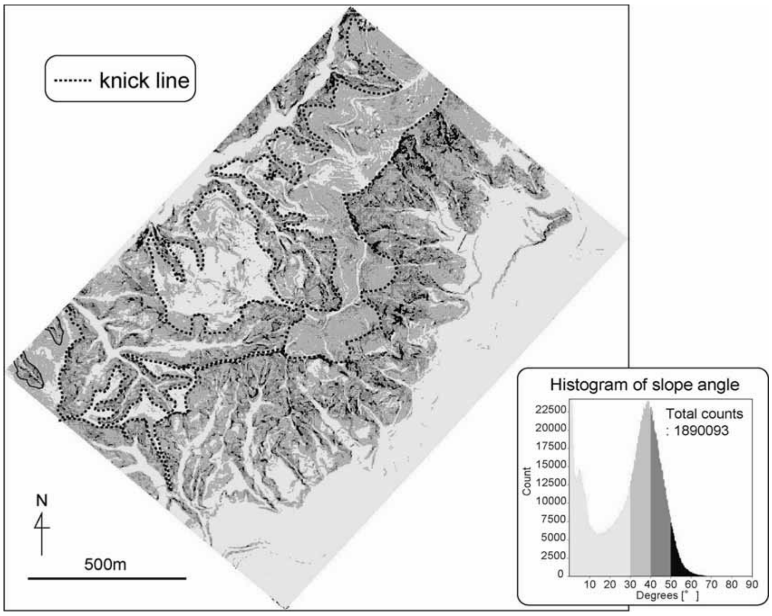

Fig. 5. Knick lines based on inclination value

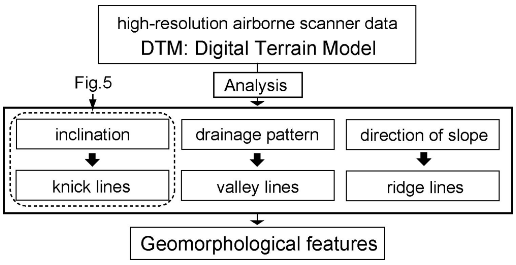

Fig. 6. a Flow chart for the geomorphological analysis by using high-resolution DTM

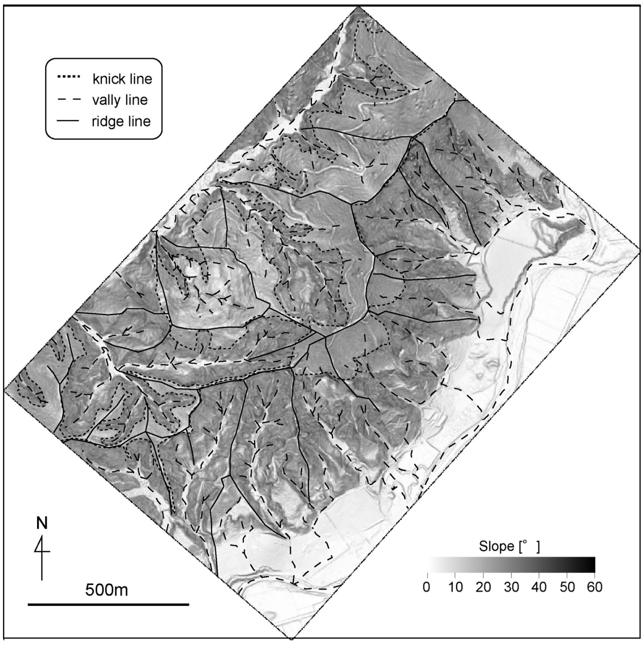

Fig. 6. b Geomophological features map

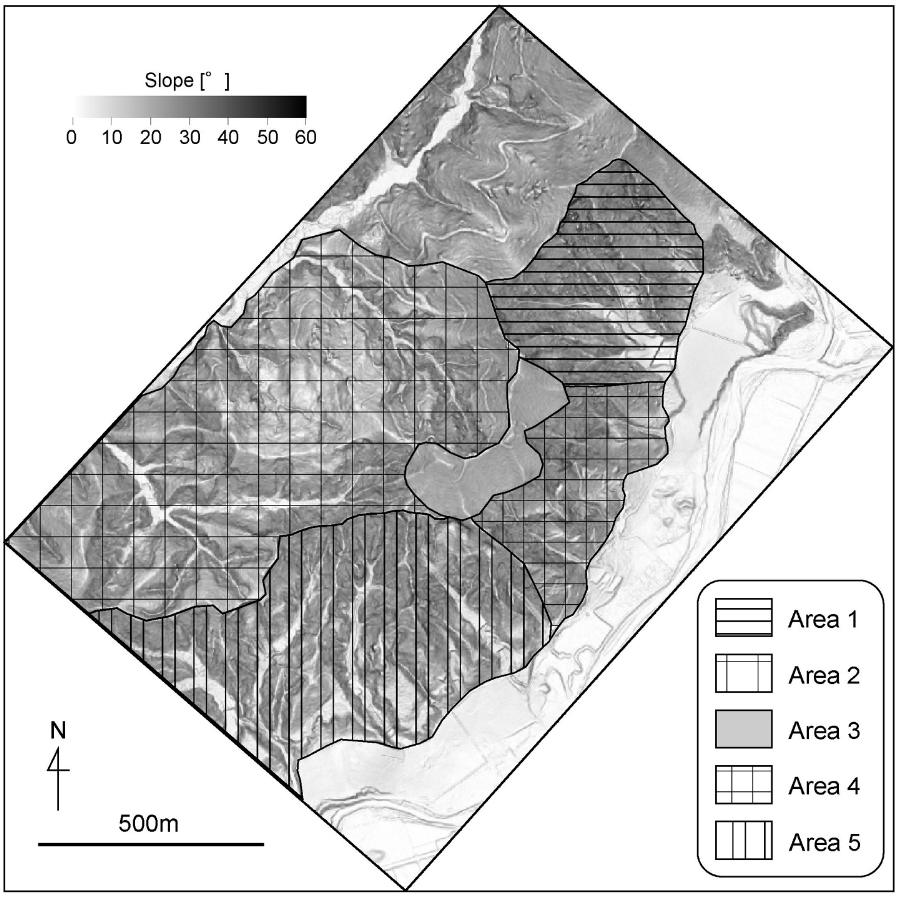

Fig. 7. Geomorphological features and characteristics of area

Table 1. Characteristics of area

	main geological features	geomorphological features (position of knick lines)	landslide
Area 1	melange	along the main ridges	shallow landslides
Area 2	felsic tuff	stay away from the main ridges	shallow landslides
Area 3	dolerite	nothing	nothing
Area 4	felsic tuff	stay away from the main ridges	shallow landslides
Area 5	alternating beds of sandstone and mudstone	along the main ridges	deep-seated landslides

deformed deeply before slide, consequently rain-induced landslide also occur with deep-seated sliding surface.

Conclusions

Airborne laser scanner was successfully applied to detect new and old landslide scars and small-scale geomorphic features in the 2003 Ribira rainstorm disaster area. Using both the DTM and DSM enabled us to easily differentiate old landslides and new landslides induced by this event. There was no significant difference in the distribution density and the shape of landslides occurred by the 2003 event and older ones. This suggests that these values indicate long-term susceptibility to landslide.

We found continuous knick lines that separate gentle upslope and the steep downslope by numerically processing the detailed DTM data. These knick lines are denudation fronts, below which many landslides occurred.

The characteristics of landslides were strongly dependent on geology; many deep-seated landslides occurred in the area of alternating beds of mudstone and sandstone, while shallow landslides were dominating in the areas of melange and siliceous tuff. These facts suggest that the denudation front has been retreated by many shallow landslides in the melange area and by fewer but deeper landslides in the area of alternating sandstone mudstone; both types of landslide retreated the denudation front in a comparative rate.

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