Development of a Hazard Mapping System Related to Meteorological Disasters

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A new hazard mapping system related to landslides, strong winds, avalanches and rockfalls has been developed. Firstly, meteorological conditions, e.g. intensities of rain, wind and snow, are estimated based on meteorological simulation or meteorological statistics. Secondly, potential hazards for the railway system are evaluated with consideration of topographical factors calculated by using a digital elevation model. Finally, the evaluated hazards are mapped onto a geographical information system. This hazard mapping system is helpful for engineers to identify the locations where surveys need to be conducted and where countermeasures against the disasters need to be applied.

Keywords: hazard map, natural disaster, digital elevation model, geographical information system

1. Introduction

Meteorological disasters come in various forms: landslides and floods due to rain, strong wind, avalanches etc. However, it is difficult to grasp synthetically the basic factors which means elements underlying the occurrence of a natural disaster, such as slope angle, level of vegetation, and snow depth, and external forces which means the forces triggering the natural disaster, such as rain, wind and snow. Visualizing this type of information along a railway line makes it easier to grasp characteristic features and weak points of the railway line in terms of meteorological disasters, and makes it possible to design more efficient countermeasures.

Thus, a new hazard mapping system was developed for landslides, strong winds, avalanches and rockfalls. This system allows visualization of basic factors, external forces, and the results of hazard analyses for each type of natural disaster. A data processing flow was designed as a first step for the hazard mapping system. Then methods were tried and tested to estimate the external forces and to evaluate the hazards, making use of digital elevation models for more efficient hazard mapping. Finally, a mapping system and potential applications for its use were proposed.

2. Data processing flow

The data processing flow of the hazard mapping system is shown in Fig. 1. Firstly, a digital elevation model, DEM, was prepared as input data. The DEM is raster data, consisting of grid of cells that hold elevation values of a ground surface. The DEM is created from airborne light detection and ranging data as shown in Fig. 2. The DEM is also publicly available via the Geospatial Information Authority of Japan [1] website. Depending on the type of disaster, a digital surface model, DSM, is prepared as input data, which represents the elevation values of objects on the ground including plants, as shown in Fig. 2. The difference in DSM and DEM values, called a digital canopy model, DCM, then gives the height of plants, etc.

Secondly, external forces, such as rain, and wind direction and speed, are estimated by using a meteorological simulation [2] or estimated from the probability of the precipitation based on the meteorological statistics.

Thirdly, disaster hazards are evaluated considering the estimated external forces. In this step, geomorphic analysis, using the DEM, supplies parameters for the hazard system.
Finally, the evaluated hazards are mapped using a geographical information system, GIS. The estimated external forces and the results of geomorphic analysis are also mapped onto the GIS.

3. Estimation of external forces

The following two methods were applied to estimate external forces: the meteorological simulation-based method [3] and the meteorological statistics-based method.

3.1 Meteorological simulation-based external force estimation

Meteorological simulations calculate weather conditions, e.g. rain, snow and wind, for grid cells which are the subdivisions of the area under investigation. Using the simulation, external forces were estimated as following the steps below:

1. Collecting observed time-series weather data for significant weather events, e.g. heavy rain and strong wind, from the rain gauges and anemometers along the railway line or the meteorological agency weather observation points.
2. Reproducing the significant weather events using the meteorological simulation.
3. Estimating the return periods and the expected values for each cell by statistical analysis on the simulated results.

In this research, a weather research and forecasting model [2] was adopted as the meteorological simulation code, and a modified Jensen & Frank method [4], a method of extremal statistics, was employed to estimate the return period and the expected value.

One of the advantages using meteorological simulation for estimating external forces is that the external forces can be estimated for each cell including those for which there is no observed data. For instance, strong winds often occur in areas which are narrower (between several hundred meters and several kilometers) than the intervals between meteorological observation points (between several kilometers and up to 25 km). As such, a meteorological simulation-based method makes it possible to estimate the external forces with the required spatial resolution according to the meteorological phenomenon.

3.2 Meteorological statistics-based external force estimation

The maximum probable snow depth was statistically estimated from the accumulated weather data, and was employed as the external force for the avalanche as written in the section 4.3.

The meteorological statistics-based method allows estimation of external forces as the expected values for the various return periods, e.g. 30 years, 50 years and 100 years, which is easier than the meteorological simulation-based method. Further, the probable precipitation data is publicly available from the Japan Meteorological Agency [5].

4. Evaluation of hazards

4.1 Landslides (surface failure)

Landslides were evaluated in the following two ways: Method-1 and Method-2. The objective of Method-1 was to evaluate the landslide hazard over a broad area based on the basic factors associated to landslide [6]. Based on a statistical analysis, slope angle, type of slope and vegetation on the slope were revealed to strongly contribute to landslides; and the degree to which each of these factors contribute to landslides, was quantified [6]. Thus, these basic factors were analyzed using a one-meter mesh DEM and DSM, and the relative probability of a landslide was evaluated using the degree to which each of these basic factors contributed to the landslide.

Method-2 aimed to evaluate the landslide hazard considering rainfall [7]. In this method, the relative safety factor was evaluated based on a time-dependent simulation of the degree of saturation of the ground and groundwater levels due to rain infiltration using 10 m mesh grid cells, into which the mechanical and hydraulic properties of the slope were input.

The results of the landslide evaluation with Method-1 and Method-2 for the study area are compared in Fig. 3 (a). For Method-2, rain data was collected and input from the nearest observation point of the automated meteorological data acquisition system, AMEDAS, when a landslide occurred in the study area. From Fig. 3 (a), the relative safety factor using Method-2 was more than 1.5 in the area where the relative probability of a landslide according to Method-1 was 2 and 3. Further, appearance ratio of the area where the relative safety factor using Method-2 was less than 1.05, was less than five percent in the region where the relative probability of a landslide according to Method-1 was 4 and 5. Thus, it is rare to find a low relative probability of a landslide according to Method-1 in areas where the relative safety factor using Method-2 is small. In other words, evaluations according to Method-1 rarely miss areas evaluated as hazardous using Method-2. Hence,
Method-1 should be adopted for broad areas as a screening method, and Method-2 should be applied to the hazardous areas found through Method-1 for more detail as shown in Fig. 3 (b). This flow utilizes the advantages of both Methods because evaluations using Method-1 require only DEM and DSM and is simple whereas Method-2 considers rain infiltration and variation in slope saturation by inputting its mechanical and the hydraulic properties.

4.2 Strong winds

Wind as an external force was estimated using a meteorological simulation-based method. Firstly, the expected value (Fig. 4 (a)) and the return period of the strong wind were estimated based on the calculated results obtained by applying a meteorological simulation to 25 cases of past strong wind events in the study area, with the horizontal width of the square cell in the simulation set to 250 m.

Secondly, the critical wind speed of the overturning of a vehicle [8] determined on the basis of vehicle and railway structure characteristics, was calculated for the cells through which the railway line passed, as shown in the Fig. 4 (b). The minimum value was selected as the representative value of the critical wind speed of the overturning if various values were obtained in the same cell due to the existence of various kinds of railway structures.

Thirdly, return periods for strong winds exceeding the...
critical wind speed of the overturning of a vehicle. Finally, the obtained return period was mapped onto the GIS as shown in Fig. 4 (c). Cells with shorter return periods were interpreted as being areas where there was a higher possibility of occurrence of a strong wind exceeding the critical wind speed of the overturning of a vehicle.

4.3 Avalanches

The conventional and practical method to evaluate avalanche hazards along railway lines is to take into consideration two probabilities, namely the occurrence probability and the reaching probability [9]: the occurrence probability is the probability of an avalanche occurring at origin on the slope, and the reaching probability is the probability of the avalanche reaching the railway line from its point of departure. This research improves the conventional method in terms of efficiency by utilizing the DEM and the DSM.

In the conventional method, the occurrence probability is estimated on the basis of three parameters, namely slope angle, crown density, and maximum probable snow depth, by adopting a score table obtained through a statistical method based on the characteristic features of the slope where the avalanche occurred [9]. In this research, slope angle and crown density were selected as objects for analysis using DEM and DSM. Firstly, using the 10 m mesh DEM, the slope angle (Fig. 5(a)) was calculated applying the following equation (1) [10].

\[
s = \arctan \left( \frac{z(i+1,j) - z(i-1,j)}{2d} \right)
\]

where \(z(i,j)\) is the elevation of a square cell \((i,j)\), and \(d\) is the width of the cell. Secondly, the crown density was calculated by making reference to Kobayashi et al. [11]. After creation of the one-meter mesh DCM by subtracting the one-meter mesh DEM from the one-meter mesh DSM, cells were classified to “cells with trees” or “cells without tree” based on whether its DCM value was larger than two meters or not. Thereafter, the ratio of the number of “cells with trees” to the number of all the cells in the area of 10-by-10 cells was regarded as the crown density (Fig. 5(b)). Finally, the occurrence probability (Fig. 5 (c)) was estimated based on the obtained slope angle and crown density, and the maximum probable snow depth which was estimated separately, using the score table [9].

The path of the avalanche was estimated on the assumption that avalanches run down a drainage line. The start point of the path was set to a cell where the occurrence probability was higher than 50%. The drainage line was obtained by successively connecting cells in the direction of maximum downward gradient which was determined by comparing eight slope angles with a center cell and its surrounding eight cells. The reaching probability was estimated based on the ratio of the falling height to the falling distance along the slope according to the conventional method [9].

The probability of the occurrence of an avalanche disaster on a railway line (Fig. 5 (d)) was evaluated by multiplying the occurrence probability (at origin on the slope) by the reaching probability (to the railway line). Although this result was obtained for a path with a 10m resolution, it was deemed to represent the hazard for the whole slope where the pathway was located because an avalanche generally has a width of approximately 10 m or more.

4.4 Rockfalls

The evaluation of rockfalls [12] consists of three components: an estimation of the distribution of rock outcrops [13], an analysis of the pathway of a falling rock from each rock outcrop, and an evaluation of the reach probability using rockfall simulation. The estimation of the distribution of rock outcrops [13] was based on the slope angle and the curvature of the ground surface calculated using one-meter mesh DEM (Fig. 6(a)). A cell in which an outcrop is estimated to be located is called an “outcrop cell”.

The pathway of a falling rock from each rock outcrop cell (Fig. 6 (a)) was analyzed using the one-meter mesh DEM on the assumption that the falling rock moves along the drainage line.

The reach probability was evaluated using an existing simulation method for rockfalls [14, 15] based on the Monte Carlo method for a two-dimensional section along the
The pathway analysis and the rockfall simulation were implemented for all the estimated rock outcrops. Thus, the reach probability of a falling rock to the railway line was mapped along the railway lines (Fig. 6(C)).

5. Hazard map

The results of the external force estimation and hazard evaluation were mapped using GIS as shown in Fig. 7. In this research, ArcGIS, developed by Esri, was adopted.

This system enables a synthetic visualization of landslide, strong wind, avalanche, and rockfall hazards, offering clearer understanding of characteristics of a railway line in terms of natural disasters, weak points, and insight to aid the design of efficient countermeasures. Further, it clarifies the basic factors related to disasters through their mapping, e.g. slope angle, type of slope, and vegetation on the slope, allowing countermeasures to be designed suitably.

The application examples of the hazard map are given as follows. Firstly, the landslide disaster hazard map helps engineers to find the slope where they should survey because the map shows the hazard as a source of landslide (Fig. 7 (a) and (b)). Secondly, the hazard maps for strong winds (Fig. 7(c)) and for avalanches (Fig. 7(d)) are informative for deciding the priorities and areas for applying counter measures because these maps show the return period for strong winds exceeding the critical wind speed of the overturning of vehicles and the probability of avalanche disasters on railway lines. Thirdly, the hazard maps for rockfalls (Fig. 7(e)) are useful for selecting which outcrops require regular surveys because it shows the probabilities of a rock blocking a track if it falls from an outcrop. The distribution of outcrops needs to be confirmed by field survey because it is also an estimated result.

With this system, basic factors can be found for a wide range, and not only for areas adjacent to railway tracks. Therefore, it can provide necessary information for areas where little information is currently available due to their long distance from the railway line.

This hazard mapping system provides a static hazard map for estimated and fixed external forces. A further subject for research is the development of a dynamic hazard mapping system which refreshes the hazard map in line with updated weather data and weather forecasts.

6. Conclusions

A new hazard mapping system has been developed for landslides, strong winds, avalanches, and rockfalls. This system offers a synthetic visualization of hazards with respect to basic factors and external forces. It gives a comprehensive understanding of the characteristics of a railway line regarding natural disasters, allows the detection of vulnerable spots, and the design of efficient countermeasures.

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