Risk Evaluation of Debris Flow Using a Digital Terrain Model

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In order to ensure safe train operation, it is necessary to identify, beforehand, areas along railway lines exposed to various kinds of high risk related to slope collapse during rainfall. A method was developed to evaluate the stability of slope surface layers based on predicting changes in groundwater levels by using a simple calculation model in consideration of three-dimensional geomorphologic features. Risk evaluation of debris flows were then studied using this model.

Keywords: slope collapse, rainfall, calculation model

1. Introduction

In order to ensure safe train operations, it is necessary to identify, beforehand, areas along railway lines most exposed to a risk of slope collapse during rainfall. The movement of water down a slope during rainfall has a major influence on varying forms of slope collapse. One way to evaluate slope stability by taking into account water flow during rainfall is to analyze slope stability by using analytical results obtained from three-dimensional seepage analysis. In order to evaluate slope stability by this method, however, it is necessary to investigate a site in detail. Furthermore, parameters used for this type of calculation are often difficult to determine. In many cases, therefore, slope stability is evaluated by methods which pay most attention to endogenous causes of slope failure, with water flows in or on the slope rarely taken into consideration.

Under these circumstances, a method was developed to evaluate the stability of the slope surface layers based on predicting the changes in groundwater levels by using a simple calculation model in consideration of three-dimensional geomorphologic features. This paper describes the concept underlying this model, and an example calculation of risk evaluation of debris flow using it.

2. Calculation model

2.1 Overview of the model

Okimura et al [1] proposed a method for easy evaluation of the stability of the surface layer of a slope against rain-induced failure. In this method, a topographical map of the slope of interest is divided into square plane elements, a certain thickness is defined for each element, and slope stability is evaluated according to the results of calculated water exchanges within and between these elements. Using this method as a basis, the method in this paper incorporates newly gained knowledge and newly developed techniques. In the newly developed method, the slope of interest is divided into elements as shown in Fig. 1, water flow within and between those elements is calculated, and groundwater movement in the surface layer of the slope during rainfall is estimated.

Figure 2 shows the calculation process. At the outset, data that do not change over time, such as digital terrain data, the permeability coefficient and the thickness of the surface soil layer, are set as initial conditions. The subsequent steps are as follows: (1) calculate the gradient (hydraulic gradient) of each element and the direction of
water flow and specify streams (for the purposes of this study, a stream is defined as a topographic concave), (2) calculate the flow into and out of each element for given rainfalls and then calculate the degree of saturation of elements from the calculation results and (3) calculate the groundwater level in each element. Lastly (4) calculate the failure risk of the slope surface layer in each element based on the calculated groundwater level. The degree of saturation of each element is determined according to the hydraulic gradient of each element, there are cases where water flows from the element \( i \) to the element \( j \) and at the same time from the element \( j \) to the element \( i \). An element boundary where water flows in from both of the adjoining elements in this way is deemed to be a stream (Fig. 3).

(2) Water that flows from an element toward a stream (surface flow and saturated seepage flow shown in Fig. 1(b)) collects in a stream.

(3) Water that collects at the flow end of a stream is divided equally into two streams, each of which flows into one of the two elements, among the four elements adjoining the lower end, that do not include any element boundary constituting the stream.

2.2 Calculation of topographical conditions

The first step in calculating topographical conditions is to calculate the hydraulic gradient of each element in the \( X \) and \( Y \) directions. The hydraulic gradient is calculated as described below.

The four grid points constituting each element are represented by \( P_p (X_p, Y_p, Z_p) \) (\( p = 1 \) to 4), and the hydraulic gradients \( I_X \) and \( I_Y \) in the \( X \) and \( Y \) directions are calculated as follows:

\[
\Delta h_X = \frac{Z_1 + Z_2 - Z_3 + Z_4}{2} \quad I_X = \frac{\Delta h_X}{\sqrt{(X_1 - X_2)^2 + \Delta h_X^2}}
\]

\[
\Delta h_Y = \frac{Z_1 + Z_2 - Z_3 + Z_4}{2} \quad I_Y = \frac{\Delta h_Y}{\sqrt{(Y_1 - Y_4)^2 + \Delta h_Y^2}}
\]

where \( X_1 = X_i, X_2 = X_j, Y_1 = Y_i \) and \( Y_4 = Y_j \).

The direction of water flow in the \( X \) and \( Y \) directions is the same as the positive direction of the hydraulic gradient. On the basis of the direction of water flow, streams are defined as described below.

(1) If the direction of water flow between adjoining elements is determined according to the hydraulic gradient of each element, there are cases where water flows from the element \( i \) to the element \( j \) and at the same time from the element \( j \) to the element \( i \). An element boundary where water flows in from both of the adjoining elements in this way is deemed to be a stream (Fig. 3).

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2.3 Calculation of water flow into or out of each element

In the calculation of water flow into or out of each element (Fig. 1(b)), the degree of saturation of each element is calculated by using the equation (3) and equation (4) shown below. The quantity of water that enters an element equals the combined quantity of water flowing in as rainwater and water flowing in from adjoining elements. The quantity of water that leaves an element equals the combined quantity of water that flows out to adjoining elements and the quantity of water flowing out to the bedrock.

\[
\gamma(i) = \gamma(i-1) + \frac{q_{in}(i) - q_{out}(i)}{V} \cdot \gamma_w
\]

\[
S_{rt(i)} = \frac{\gamma(i) \cdot (1 + e) - G_s}{e \cdot \gamma_w} \cdot 100
\]

where

\( \gamma(i) \): wet unit weight of an element at time step \( i \) (kN/m^3)

\( \gamma(i-1) \): wet unit weight of an element at time step \( i-1 \) (kN/m^3)

\( q_{in}(i) \): quantity of water flowing into an element at time step \( i \) (m^3)
degree of saturation of the slope surface layer and the groundwater level ratio. The relationship was determined from the results of groundwater level and saturation measurements carried out on real slopes and the results of two-dimensional saturated–unsaturated seepage analysis of an idealized slope surface layer. Parameters of $S_{rh}$ and $n$ are set up according to the level of water retentivity of soil as follows. For more details of the studies about relationship between the degree of saturation of the slope surface layer and the groundwater level ratio, see the literature [3].

If the water retentivity of soil is low; $S_{rh}=67.50\%$, $n=1.41$ (9)
If the water retentivity of soil is middle; $S_{rh}=80.63\%$, $n=1.45$ (10)
If the water retentivity of soil is high; $S_{rh}=89.15\%$, $n=1.59$ (11)

### 2.4 Calculation of groundwater level for each element

To calculate the groundwater level for each element, we adopted a method to calculate the groundwater level from the degree of saturation determined as described in Section 2.3 by using the following equations:

$$q_{outX(i)} = k \cdot I_X \cdot \Delta t \cdot 60 - 60 - h_{(i-1)} \cdot \alpha$$

$$q_{outY(i)} = k \cdot I_Y \cdot \Delta t \cdot 60 - 60 - h_{(i-1)} \cdot \beta$$

where

- $q_{outX(i)}$: quantity of water flowing in the $X$ direction due to saturated seepage flow at time step $i$ (m$^3$)
- $q_{outY(i)}$: quantity of water flowing in the $Y$ direction due to saturated seepage flow at time step $i$ (m$^3$
- $k$: permeability coefficient (m/s)
- $I_X$, $I_Y$: hydraulic gradients
- $\Delta t$: time step (h)
- $h_{(i-1)}$: groundwater level measured from bedrock surface at time step $(i-1)$ (m)
- $\alpha$: width of the element adjoining in the $X$ direction (m)
- $\beta$: width of the element adjoining in the $Y$ direction (m)

### 2.5 Calculation of the failure risk of the slope surface layer for each element

The failure risk of the slope surface layer for each element is calculated as a safety factor using the stability analysis method of infinite slope based on the calculated groundwater level by using the following equations:

$$F_{si} = \frac{c_s + c_r + A_{(i)} \cdot \cos \beta \cdot \tan \phi}{B_{(i)} \cdot \sin \beta \cdot \cos \beta}$$

$$A_{(i)} = (\gamma'_{sat} - \gamma_w) \cdot h_{(i)} + \gamma_{(i)} \cdot (D - h_{(i)})$$

$$B_{(i)} = \gamma_{sat} \cdot h_{(i)} + \gamma_{(i)} \cdot (D - h_{(i)})$$

where

- $F_{si}$: safety factor at time step $i$
- $c_s$: cohesion of soil (kPa)
- $c_r$: cohesion of plant roots (kPa)
- $\beta$: slope angle (degree)
- $\phi$: internal friction angle of soil (degree)
- $\gamma'_{sat}$: saturated unit weight of an element (kN/m$^3$)
- $\gamma_{sat}$: unit weight of water (kN/m$^3$)
- $h_{(i)}$: groundwater level measured from bedrock surface at time step $i$ (m)
- $\gamma_{(i)}$: wet unit weight of an element at time step $i$ (kN/m$^3$)
- $D$: thickness of surface layer (m)

### 3. Example of analysis

#### 3.1 Analysis conditions

The risk of debris flow will be high when the risk of slope collapse around a stream is high and water volume of the stream has increased. Calculations were made for a case study example of an area where debris flow had occurred in the past, in order to determine whether increased debris flow risk situations could be simulated using the model described in Chapter 2.

Figure 4 shows the digital terrain model of the analysis area, and Table 1 shows analysis parameters. Analysis parameters were determined according to the slope investigation results. Before conducting the analysis using rainfall data, a preliminary analysis was carried out using a method developed with reference to the method proposed by Okada et al. [4] for the purpose of defining the initial degree of saturation of the soil and the groundwater level.
in the target area. In the preliminary analysis, a rainfall of 0.694mm/h (hourly rainfall obtained by assuming an annual rainfall of 2,000 mm, a rainfall frequency of once every 3 days and rainfall duration of 24 hours) was given at a frequency of once every 3 days until the degree of saturation and the groundwater level distribution reached a steady state. The rainfall data used in the analysis was observation data obtained from a past debris flow.

### 3.2 Results of analysis

Figure 5 shows planar analysis results of slope collapse risk in the analysis area after 10 and 25 hours of rainfall. As shown in the figures, when the rainfall volume increases, the projected area of slope with an increased risk of collapse in drainage areas. Then, referring to the view of Okimura et al. [5], it was decided that the rate of high collapse risk area (= projected area of slope where collapse risk is high in drainage area / projected area of all slope in drainage area) should be used as a representative value for the risk of slope collapse in a drainage area.

Figure 6 shows the calculated changes over time of the rate of projected slope area with high risk of collapse and water volume of the stream. As shown in this figure, when the rainfall volume increases, both the rate of high collapse risk area and water volume of the stream increase. These results indicate that the developed model can indeed be

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**Table 1  Analysis parameters**

| Parameter | Value |
|-----------|-------|
| Unit weight of soil particles $G_s$ (kN/m^3) | 2.624 |
| Void ratio of an element $e$ | 1.08 |
| Thickness of surface layer $D$ (m) | 1 |
| Permeability coefficient $k$ (m/s) | $1.24 \times 10^{-5}$ |
| Coefficient of the relationship between the degree of saturation of the slope surface layer and the groundwater level ratio | Water retentivity of soil [middle] |
| Coefficient of soil strength: internal friction angle of soil $\Phi=30^\circ$, cohesion of soil $c_s$ was set that the value calculated the minimum safety factor $F_s$ was 1.2 when the analysis start. | |
used to estimate the situation when a debris flow risk is increasing.

4. Conclusion

This paper first describes the calculation model to evaluate the stability of the slope surface layer based on predicting the change in groundwater levels using a simple calculation model. Next, calculations were made using the developed model for a case study of an area where debris flow had occurred in the past. This demonstrated that the model can be used to estimate the situation in which debris flow risk would increase.

The next step in this research will include using the model to perform calculations for a range of slope collapse areas, and thus assess its applicability.

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