Development of the heavy rainfall induced slope failure hazard maps for the villages located in the mountainous area close to Median Tectonic Line

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ABSTRACT

This paper describes the case study in which hazard maps for heavy rainfall induced slope failure were developed for the villages located in the mountainous area close to Median Tectonic Line. The purpose of creation of the hazard map is to discuss evacuation system at the village. The risk for slope failure was evaluated for 10 m grids of the villages as a safety factor based on the mechanical model which is an infinite length slope with ground water. For the analysis of the risk for slope failure field survey were carried out to obtain the parameters for different geological conditions close to Median Tectonic Line. The created hazard maps were used effectively to discuss the evacuation rules at the villages.

Keywords: slope failure, heavy rainfall, hazard map, mountainous area, Median Tectonic Line

1 INTRODUCTION

Recently amount of rainfalls and those intensities increase and sediment disaster often occurs in Japan. It is difficult to predict time and place where heavy rainfall occurs. The authors were proposed in the study on mitigation of the sediment disaster proposed by an official organization for disaster prevention of the east part of Aichi prefecture. When the evacuation system is discussed to mitigate the disaster it is required to create a hazard map by proper risk assessment method and to prepare evacuation rules in advance based on the hazard map.

For the risk assessment of sediment disaster, analytical model and required accuracy depend on the purpose and the size of assessed area. For example those are different for the case in which the purpose is designation of the high risk slopes by law for the all area of a country and for the case in which the purpose is the plan of the shelter at a village located in mountainous area.

In this study hazard maps for heavy rainfall induced slope failure were developed to set up evacuation system of the villages located in the mountainous area close to Median Tectonic Line. The purpose of risk assessment is to discuss evacuation system at a village. It is required to evaluate the risk precisely for many slopes and to be understood clearly by residents at the village. In this study the risk for slope failure was evaluated for 10 m grids of the villages as a safety factor based on the mechanical model which is an infinite length slope with ground water. The height of the water table was estimated considering hourly rainfall, the catchment area of the slope upper reaches and infiltration rate of the slope surface. When the risk assessment is performed using a mechanical model, selection of the parameters used in the analysis is important to obtain reliable results. In this study the mechanical properties of the slopes were determined from the results of the field survey in which undisturbed sampling of the soils, sounding tests and topograpical survey of the slope were performed. Those surveys were conducted at S village located in Ryoke belt and T village in Sanbagawa belt close to Median Tectonic Line. The stratum of S village is made of granite and in T village the stratum is composed of pelitic schist and serpentine.

This paper describes a case study on creation of heavy rainfall induced slope failure hazard map for discussion of evacuation system at the villages.
In this paper the method to evaluate risk of slope failure is described at first. Then the field survey to determine the parameters are explained. Finally the application of the hazard map developed based on the risk assessment for evacuation system is discussed. Locations of Median Tectonic Line and the study area are shown in Fig.1 (Miki, 1986).

2 RISK EVALUATION FOR SLOPE FAILURE

To evaluate risk for slope failure an infinite length slope with water table is considered as shown in Fig. 2 and the risk is estimated by the safety factor $F$ which represents mechanical stability of the slope using the following equation;

$$
F = c + \left( \gamma_t (h - h_s) + \gamma_{sat} h_s \right) \cos^2 I \tan \phi \\
\left( \gamma_t (h - h_s) + \gamma_{sat} h_s \right) \sin I \cos I
$$

where $c$ and $\phi$ are cohesion and angle of shear resistance of surface soil. $\gamma_t$, $\gamma_{sub}$ and $\gamma_{sat}$ are wet, submerged and saturated unit weight of surface soil respectively. $h$ is thickness of surface soil layer and $h_s$ is height of water table. $I$ is inclination angle of slope.

$F$ is estimated for 10 m grids which cover the village. Referring to the study by Public Works Research Institute (Team for volcano and sediment flow, 2009), the height of the water table $h_s$ is calculated by Eq.2 introducing catchment area of upper reaches $A$, width of grid $b$ and infiltration rate $\eta_s$.

$$
h_s = \eta_s \frac{A}{b} \frac{r}{K_s \cos I \sin I}
$$

where $K_s$ is coefficient of permeability of surface soil.

The catchment area is estimated by D-infinity Flow Direction method after eliminating depressed area. Digital topography data is 10 m DEM which is provided by Geospatial Information Authority in Japan.

Okimura, T. et al developed the real-time hazard system for slope disaster (Okimura, 2011). In the real time hazard system an infinite length slope is used and a height of a water table is calculated by seepage flow analysis with infiltration of rainfall through the surface. In this study a height of a water table is calculated by the method which is developed by Public Works Research Institute, as mentioned above. The objective of this study is to find out proper risk assessment method applied to the villages where the geological condition and topography are complicated. It is not to find out totally new risk assessment method.

3 FIELD SURVEY

3.1 Field survey at S village

S village is located at the east mountainous area of Aichi Prefecture and in Ryoke belt which is the inner belt along Median Tectonic Line as shown in Fig.1. The bed rock of S village is made of granite. For the field survey at S village seven sites were selected in the sites...
Table 1. Parameters for risk evaluation at S village.

| Parameter                        | Value        |
|----------------------------------|--------------|
| cohesion $c$                     | 4.9 kN/m²    |
| angle of shear resistance $\phi$ | 20.7 deg     |
| saturated unit weight of soil $\gamma_{sat}$ | 20.0 kN/m³ |
| wet unit weight of soil $\gamma_i$ | 16.0 kN/m³  |
| unit weight of water $\gamma_w$  | 9.81 kN/m³   |
| hourly rainfall intensity $r$    | 80 mm/hr     |
| coefficient of permeability $K_s$ | $3.32 \times 10^{-5}$ m/sec |
| thickness of surface soil layer $h$ | 2.20 m    |
| catchment area of upper reaches $A$ calculated every mesh | 
| width of grid $b$ equal to mesh width $b$ | 
| height of water table $h_w$ calculated every mesh | 
| inclination angle of slope $I$ average in each polygon | 

where occurrence of slope failure was presumed by topographical map and observed by the preliminary field investigation. At three sites where the permission of the survey is provided from the land owner, the field survey was conducted and the undisturbed surface soils were tested in the laboratory to obtain the mechanical property of the soils.

(Field survey)
· Topographical survey by laser range finder
· Simple cone penetration test

(Laboratory Tests)
· Tests for physical properties
  Density test, water content test, grain size distribution test
· Tests for mechanical properties
  Triaxial compression test, permeability test

Fig. 3 shows operation of simple cone penetration test at the slope. Fig. 4 shows typical result of the simple cone penetration test.

Parameters for risk evaluation which were obtained from the field survey at S village and the laboratory tests, are shown in Table 1.

The thickness of the surface soil layer was determined from thickness of the layer in which simple cone penetration test result is less than 2. The parameter $h$ was selected as the maximum value of the depth at three sites. The hourly rainfall intensity 80 mm/hour which is the standard for evacuation advisory at S village, was used in this analysis. Safety factor $F$ was estimated for one hour duration of the precipitation and the initial value for height of water table was assumed zero. Angle of shear resistance of subsurface soil was chosen as the average converted value of simple cone penetration test results at three sites. Cohesion of surface soil was determined by back analysis of slope failure presuming the failure zone by the survey results and assuming the angle of shear resistance as mentioned above. The value of permeability coefficient was selected referring to the laboratory test and Creager’s equation. The parameter for infiltration rate was assumed not to cause number of slope failure at the area due to small amount of precipitation.

Table 2. Parameters for risk evaluation at T village (pelitic schist).

| Parameter                        | Value        |
|----------------------------------|--------------|
| cohesion $c$                     | 3.8 kN/m²    |
| angle of shear resistance $\phi$ | 20.2 deg     |
| saturated unit weight of soil $\gamma_{sat}$ | 20.0 kN/m³ |
| wet unit weight of soil $\gamma_i$ | 15.0 kN/m³  |
| unit weight of water $\gamma_w$  | 9.81 kN/m³   |
| hourly rainfall intensity $r$    | 80 mm/hr     |
| coefficient of permeability $K_s$ | $5.00 \times 10^{-6}$ m/sec |
| thickness of surface soil layer $h$ | 1.60 m    |

Table 3. Parameters for risk evaluation at T village (serpentine).

| Parameter                        | Value        |
|----------------------------------|--------------|
| cohesion $c$                     | 2.8 kN/m²    |
| angle of shear resistance $\phi$ | 21.2 deg     |
| saturated unit weight of soil $\gamma_{sat}$ | 20.0 kN/m³ |
| wet unit weight of soil $\gamma_i$ | 16.0 kN/m³  |
| unit weight of water $\gamma_w$  | 9.81 kN/m³   |
| hourly rainfall intensity $r$    | 80 mm/hr     |
| coefficient of permeability $K_s$ | $5.52 \times 10^{-6}$ m/sec |
| thickness of surface soil layer $h$ | 1.00 m    |

Fig. 5. Distribution of bed rock at T village.
3.2 Field survey at T village

T village is located at the east mountainous area of Aichi Prefecture close to S village and in Sanbakawa belt which is the outer belt along Median Tectonic Line. The bed rock at T village is composed of pelitic schist and serpentine. The distribution of the bed rock at T village is shown in Fig. 5. The number of sites surveyed at T village was four respectively for the two different type of bed rock. Field survey at T village and laboratory tests were carried out as same as those at S village. Parameters for risk evaluation at T village are shown in Table 2 and Table 3.

4 CREATION OF HAZARD MAPS

4.1 Hazard map for S village

Heavy rainfall induced slope failure hazard map for S village was created by the analysis with the results of the field survey and laboratory tests, as shown in Fig.6. In the map red zone denotes that the safety factor of the slope $F$ is less than 1.2 and risk of slope failure is high. Safety factor of yellow zone is between 1.2 and 2.0. That of blue zone is larger than 2.0. In the case that hourly rainfall intensity is 80 mm/hour the risk of slope failure becomes high at whole area of the slopes in S village.

At S village slope failures were caused by the typhoon No.15 in September 2011. The sites where the trace of slope failure was observed during the field investigation in March, 2012, are plotted with black circles in Fig. 6. All the sites marked with black circles are included in red zone which is high risk area. This suggests that possibility of slope failure at red zone of the hazard map is high as safety factor indicates. An example of slope failure due to the typhoon is shown in Fig. 7.

4.2 Feature of slope failure

Feature of slope failure observed by the field survey for different type of bed rock is shown in Table 4. Depth and height of failed area at the slope in the case that the bed rock is granite, are larger than those in the case for pelitic schist and serpentine. The amount of failed area in the slope in the inner belt along Median Tectonic Line is larger than that in the outer belt. The difference of the amount is related to strength of the surface soils which are severely weathered layer of the different bed rock.

4.3 Discussion for evacuation system

Risk of slope failure at whole slope of S village becomes very high in the case that hourly rainfall intensity is 80 mm/hour. Risk of sediment flow at S village is also high because the risk at the slopes along the stream is very high. At S village the many houses are located close to the slope and many evacuation roads pass close to the slope. In the case that heavy rainfall is predicted by the weather forecast residents should move to the evacuation facilities in advance.
Table 4. Relationship between bed rock types and feature of slope failure.

| bed rock     | pelitic schist | serpentine | granite |
|--------------|----------------|------------|---------|
| area of failure (m²) | 6.28          | 2.45       | 10.22   |
| maximum thickness of collapsed soil layer (m) | 1.56          | 1.01       | 2.03    |
| height of slope (m)     | 6.26          | 4.40       | 10.83   |
| inclination angle of slope (deg) | 43.0          | 46.3       | 46.0    |
| cohesion (kN/m²)        | 3.8           | 2.8        | 4.9     |

When the rainfall intensity increases rapidly without any notice, residents are recommended to stay at their home and to move to the place higher and far from a slope in their home because evacuation route becomes dangerous by the slope failure and the water flow.

Fig. 8 shows the hazard map for T village. The risk of slope failure is very high at whole slope of T village similarly with S village. At T village most of houses and roads are located at low and flat area. Comparing with S village the number of houses to be required to evacuate is small at T village. It is important for small number of houses close to the slope to follow the evacuation rules similar with S village.

When a hazard map is prepared officially, high risk area is determined with height of slope, slope angle and distance between toe of the slope and the house adjacent to the slope. There is no quantitative information for mechanical stability of slope and rainfall intensity. Development of detailed hazard map based on the mechanical analysis and field survey is effective for the residents to understand the risk of slope failure clearly and to discuss the evacuation system.

5 CONCLUSIONS

In this study heavy rainfall induced slope failure hazard map for the village located in the mountainous area were developed. To evaluate the risk for slope failure mechanical analysis and field survey were carried out to obtain reliable results for the complicated geological conditions close to Median Tectonic Line. The created hazard maps were used effectively to discuss the evacuation rules at the villages. It is considered that the result of this study is useful for accumulation of technical information for disaster prevention of the region.

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