E3S Web of Conferences **415**, 04004 (2023) https://doi.org/10.1051/e3sconf/202341504004
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Study on the relationship between rainfall, topography and landslide volume in the recent debris flow disasters in Hiroshima, Japan

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Abstract. Three types of sediment volume estimation equations were developed by analyzing the relationship between rainfall, topography (e.g. slope gradient, relative height) and the volume of collapsed sediment in 1 km grid for heavy rainfall events (2014 and 2018 events) in Hiroshima Prefecture where intensive slope failures and debris flows occurred. All three equations showed a tendency for the volume of collapsed sediment per unit area to increase with increasing rainfall. However, some equations showed the rate of increase tends to gradually plateau.

1 Introduction

Slope failures are considered to be closely related to the amount of rainfall (triggering factor) and the amount of topography (predisposing factor). Many studies have been conducted in this field, and various prediction equations [1-3] have been proposed to predict the area of slope failures. On the other hand, caused by recent global warming, large-scale landslides associated with an unprecedented record-breaking heavy rainfall have been occurring in many regions of Japan. Therefore, it is important to predict the amount of sediment yield during extreme weather events associated with climate change.

In this study, we analyzed the relationship between predisposing factors and triggering factors with the amount of sediment yield for two torrential rainfall occurred in August 2014 (hereinafter referred to as "2014 disaster") and July 2018 (hereinafter referred to as "2018 disaster"), which caused significant damage in Hiroshima Prefecture. Then we formulated the relationship among rainfall, topographic characteristics and amount of sediment yield.

2 Study area

The study area is a 596 km^2 area in Hiroshima Prefecture shown in Fig.1. In this study area, slope failures and debris flows occurred extensively during the 2014 and 2018 disasters. For setting the study area, consideration was given to ensure that triggering factors and predisposing factors such as rainfall and geology (granite, rhyolite, etc.) were no biased in specific areas during the 2014 and 2018 disasters.

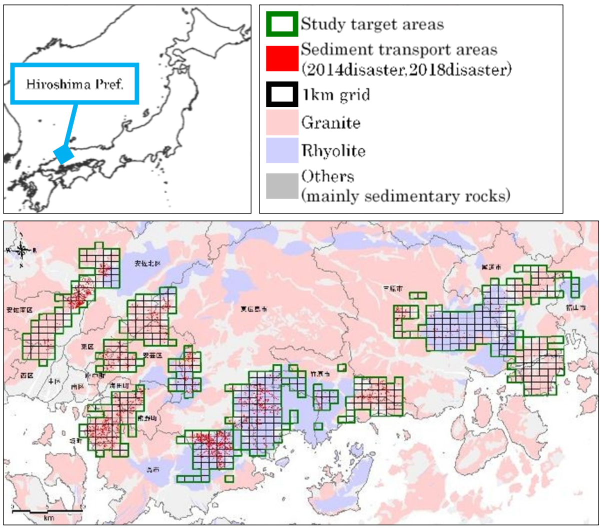

Fig. 1. Study area.

3 Landslide area classification and sediment volume calculation

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Landslide areas (1,463 sites) within the study area from the 2014 and 2018 disasters were classified into collapsed, transported and deposited areas based on photographic interpretation using aerial orthophoto imagery and difference analysis of airborne laser measurements at two different periods (before/after events), and then the volume of collapsed sediment and transported sediment was calculated (Fig. 2).

The volume of collapsed sediment is expressed as the volume of sediment discharged in downstream from the end of the collapsed area (originated zone), and the volume of transported sediment is expressed as the volume of sediment discharged in downstream from the end of the transported area.

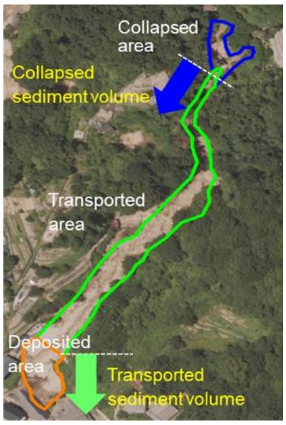


Fig. 2. Schematic map of landslide area classification and sediment volume calculation

4 Creating grid unit area

The basic unit for calculating the volume of collapsed sediment is the 1 km grid shown in Figure 1. The following attributes were given to each grid as basic data for the analysis.

□Sediment volume: Volume of collapsed sediment per 1km^2, volume of transported sediment per 1km^2 (hereinafter Unit collapsed sediment and Unit transported sediment)

□Rainfall amount: Maximum rainfall of 1, 3, 6, 12, and 24 hours, maximum soil water index [4], and cumulative rainfall at the time of the 2014 disaster and 2018 disaster

□Topographic characteristics: Maximum slope gradient, average gradient, relative height, percentage of area where the gradient more than 5°, 10°, 20°and 30°

□Geology: Granite, rhyolite, others

5 Analysis of the relationship between rainfall, topography and collapsed sediment

Based on the results of the previous section, equations relating the amount of rainfall and topography to the volume of Unit collapsed sediment and the volume of Unit transported sediment (hereafter referred to as "Sediment Volume Estimation Equations, SVEEs") were developed.

5.1 Expression type of sediment volume estimation equations

Three types of equations were used in the sediment volume estimation equation: "power function" and "multinomial power function," in which the Unit collapsed sediment increases cumulatively with increasing rainfall, and "logistic function," in which the Unit collapsed sediment reaches its peak when rainfall becomes extremely large. The reason why these 3 equations are selected are as follows:

Power function and multinominal power function were adopted because previous studies have proposed these functions to express the relationship between landslide volume and rainfall and topography. On the other hand, logistic function was adopted because the sediment volume is not expected to increase without limit as rainfall increases. This is because the landslide length does not exceed the slope length and there is an upper limit to the sediment volume. In view of this, logistic function was adopted as the function that causes the sediment yield to reach a ceiling when the rainfall is very large.

$$V=a(R-R_{min})^b \tag{1}$$
$$V=a(R-R_{min})^b S^c \tag{2}$$
$$V=V_{max}/[1+exp\{-(c_0+c_1R+c_2S)\}] \tag{3}$$

Where, V: Sediment volume, R: Rainfall, R_{min}: Minimum rainfall, S: Topographic characteristics, a,b,c: Regression coefficient, V_{max}: Maximum sediment volume

The power function(1) is only for rainfall factors only, while the multinomial power function(2) and logistic function(3) are functions of rainfall and topographic factors.

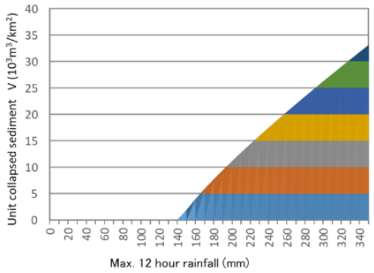
5.2 Result of Sediment Volume Estimation Equation

The SVEEs were developed using multivariate analysis by combining the sediment volume, rainfall and topography by grid organized in Section 4 (480 cases in total). Based on the evaluation method shown in Table 1, the most appropriate estimation equations were then selected for each sediment quantity (Unit collapsed sediment, Unit transported sediment), geology (granite, rhyolite, others) and equation type (power function, multinomial power function, logistic function). As an example, the equations and graphs for estimating the Unit collapsed sediment of granite are shown in Fig. 3.

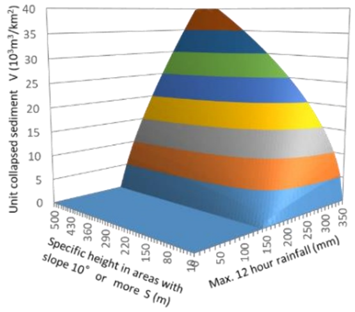
Table 1. Evaluation methods for SVEEs.

Evaluation items	**Evaluation approach**
Signs of regression coefficients	Qualitatively uninterpretable equations with negative regression coefficients (e.g. the smaller the rainfall, the larger the sediment volume) are excluded.
Coefficient of determination	Adopt a formula with a coefficient of determination of 0.5 or more and significance of the correlation at least at a risk rate of 5% in a t-test.
Residual standard deviation	Adopt a formula with the smallest residual standard deviation among the formulae satisfying the above two items.

a) Power function
$V=0.3615(R-143)^{0.8470}$



b) Multinomial power function
$V=0.0310(R-143)^{0.7503}S^{0.5200}$



c) Logistic function
$V=33/[1+\exp\{-(-3.2402+0.0319(R-195)+0.6830S\}]$

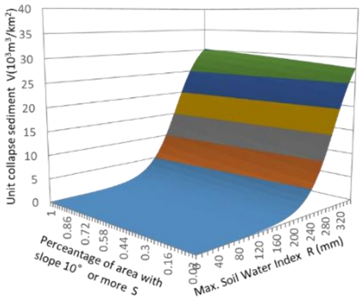


Fig. 3. Unit collapsed sediment estimation equation (example for granite).

The rainfall factors employed were maximum 12-hour rainfall for the power and multinomial power functions and maximum soil water index for the logistic function, both of which were considered as long term rainfall. The topography factor employed was the relative height in areas with a slope of 10° or more for the multinomial power function and the percentage of area with a slope of 10° or more for the logistic function. The equations obtained show that the Unit collapsed sediment reached a ceiling at 33,000 m^3/km^2 for the logistic function, and that the power exponents of rainfall and topography were less than 1 for the power function and multinomial power function, resulting in the Unit collapsed sediment gradually reaching a ceiling as rainfall increased.

5.3 Verification of the accuracy of the SVEEs

To verify the accuracy of the SVEEs, a scatter diagram (Fig.4) was created with the measured values (true values) from the airborne laser survey data on the horizontal axis and the estimated values obtained from the SVEEs on the vertical axis. Both values are close to a 1:1 straight line, indicating good estimation accuracy. The mean absolute error (Fig.5) was also relatively small, ranging from about 3,000 to 7,000 m^3 per km^2. These results indicate that under the conditions of rainfall (maximum 12-hour rainfall: less than 300mm, maximum soil water index: less than 260mm) and collapsed sediment volume (less than 33,000m^3/km^2) experienced during the 2014 and 2018 disasters, relatively similar results can be obtained using power function, multinomial power function and logistic function.

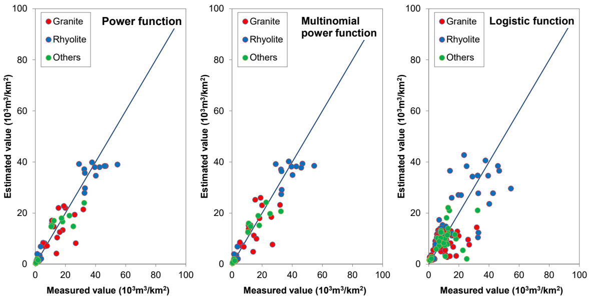


Fig. 4. Comparison results between measured and estimated values.

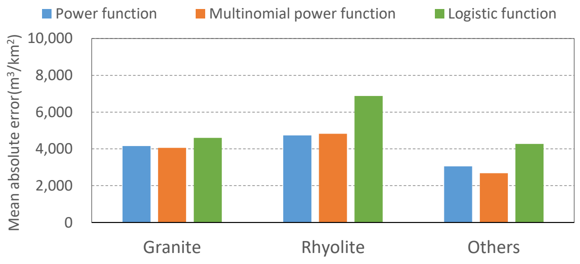


Fig. 5. Mean absolute error.

6 Conclusions

In this study, SVEEs (Sediment Volume Estimation Equations) were developed to calculate Unit collapsed sediment (collapsed sediment volume per $1km^2$) from rainfall and topographic factors using three equation types with different characteristics (power function, multinomial power function and logistic function). This study showed the possibility of estimating the volume of collapsed sediment per $1km^2$ according to amount of rainfall by analysing the difference analysis data from airborne laser surveys before and after a disaster and the spatiotemporal distribution data of rainfall in detail. In the future, it is important to further improve the accuracy by selecting an equation type that assumes an increase in rainfall due to climate change and by analysing more various types of disasters.

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