論 文 の 内 容 の 要 旨

論文題目 Evaluation of rainfall-induced mass movements and sediment yields in Taiwan
（台湾における降雨で生じたマスムーブメントと土砂流出の評価）

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Rainfall-induced mass movements are significant natural hazards in Taiwan. However, few studies have explored the rainfall conditions associated with mass movements for a broad area in Taiwan. This dissertation presents results of studies for the whole of Taiwan, to establish the relationship between the initiation of mass movements and rainfall conditions, apply a useful index to Taiwan which may contribute to a future warning system of mass movements, identify dimensional characteristics of landslides, and discuss the effects of landslides on the sediment discharge in rivers.

This study analyzed mass movements caused by rainfall events in Taiwan during a seven-year period from 2006 to 2012. Data from 263 mass movement events, including 172 landslides and 107 debris flows (16 events with both), were collected from the reports of the Soil and Water Conservation Bureau of Taiwan. After confirming the location of each event, we compiled relevant rainfall data by interpolating data from >400 rain gauges. Subsequently, the rainfall intensity–duration (*I*–*D*) relationship was examined to establish the rainfall threshold for mass movements using random sampling: $I = 18.10(\pm 2.67)D^{-0.17(\pm 0.04)}$, where *I* is mean rainfall intensity (mm/h) and *D* is the time between the beginning of a rainfall event and resulting mass movements (h). Significant differences in the rainfall intensity and the thresholds were detected between landslides and debris flows. For short duration rainfall events, higher mean rainfall intensities were required to trigger debris flows. Contrastingly, for long duration rainfall events, similar mean rainfall intensities triggered both landslides and debris flows. We also rescaled mean rainfall intensity using mean annual precipitation (*MAP*), which defined a new threshold calculated as $I_{MAP} = 0.0060(\pm 0.0009)D^{-0.17(\pm 0.04)}$, where I_{MAP} is the rainfall intensity rescaled by a *MAP* value of 3,000 mm, the minimum *MAP* of mountainous areas in Taiwan. Although the *I*–*D* threshold for Taiwan was high relative to those for other areas around the world, the I_{MAP}–*D* threshold tended to be lower. Our results indicate that Taiwan is highly prone to rainfall-induced mass movements. This study also shows that most of the mass movements occurred around the period when rainfall intensity was highest, but some events occurred significantly before and after the rainfall peak. Both the antecedent and peak rainfall played important roles in triggering landslides, whereas debris flow occurrence was more related to peak rainfall than antecedent rainfall.

We also used the soil water index (*SWI*) which can represent the conceptual soil water contents as

influenced by the present and antecedent rainfall. *SWI* is used by the Japan Meteorological Agency to assess mass movement hazards in Japan. Previous studies show that *SWI* can successfully predict the occurrence of mass movements in Japan. Therefore, this study examines whether *SWI* can be also applied to Taiwan. We used the mass movement data in 2006–2012 for analyses and those in 2013 (n = 19) for verification. The values of *SWI* before the rainfall events which triggered mass movements were used as the indicator of the antecedent rainfall condition. We found that under different values of *SWI* before rainfall events, the rainfall conditions needed for triggering mass movements, such as the rainfall intensity, duration, and cumulative rainfall, are different. Then we classified rainfall conditions for triggering mass movements into two types, short duration–high intensity (SH) and long duration–low intensity (LL), based on the principal component analysis. The SH type is associated with a rapid increase of *SWI* within a short duration, and the LL type is with a gradual rise and subsequent constancy of *SWI*. Based on this result, we modeled the general trend of changes in *SWI* for the two types. We then verified the model by analyzing the mass movements in 2013, with 14 SH types and five LL types. We also checked hourly changes in *SWI* for these events and found that they all followed the general trend of the inferred SH and LL curves. From these results, it seems possible to predict a mass movement of the SH or LL type at an early stage of a rainfall event. Our results indicate that *SWI* is applicable to Taiwan in assessing regional mass movement hazards.

Both *I–D* thresholds and *SWI* contribute to mass movement warnings. For the *I–D* threshold, once the rainfall conditions exceed the threshold, it can provide warnings of a potential mass movement hazard. According to our results, both antecedent rainfall and peak rainfall intensity play important roles in triggering mass movements. The results of *SWI* also showed that soil water contents for many cases of LL type increased rapidly before mass movements. However, this phenomenon cannot be found in the *I–D* threshold because it is defined as the minimum-level of the rainfall conditions, and the *I–D* plots represent average rainfall event conditions and do not necessarily reflect some sporadic high rainfall intensities. Thus, predicting the exact time of mass movements using only the *I–D* threshold is difficult. On the other hand, *SWI* is a long-term and dynamic index that reflects effects of antecedent rainfall and temporal rainfall intensity variations. Therefore, real-time monitoring using *SWI* together with the *I–D* conditions allows local authorities to make appropriate decisions about mass movement warnings.

Among the 263 mass movements during 2006–2012, this study identified dimensional characteristics of 172 landslides. The area of each landslide was mapped and calculated using FORMOSA–II satellite images. The volume and depth were also calculated using empirical formula. Comparing the landslide size with rainfall conditions, this study found that deep landslides usually occurred due to long duration and moderate intensity rainfall, whereas shallow landslides occurred due to short duration and high intensity rainfall. This observation is consistent with some previous studies and is ascribable to the fact that deep landslides need a high groundwater level, soil moisture, and pore water pressure caused by a prolonged rainfall. Concerning the area of landslides, their frequency–area distribution correlates well with a power-law relation having an exponent of −1.1, over the range 6.3×10^{2} m^2 < A_L < 3.1×10^{6} m^2. The slope of the

power-law relation for Taiwan is lower than those for other areas around the world. It indicates that for the same total area or total number of landslides, the proportion of large landslides will be higher in Taiwan than in other areas. To assess landslide events particularly historical ones, this study has also proposed a landslide-event magnitude scale $m_L = \log V_a$, where V_a is the average volume of landslides associated with an event. The average m_L for all landslides during 2006–2012 was estimated to be 6.4.

Debris sourced from mass movements will result in environmental problems such as increased sediment discharge in rivers. This study analyzed the sediment discharge of the 17 main rivers during the 15 typhoon events that caused the mass movements collected in this study. The measured suspended sediment and water discharge, collected from hydrometric stations of the Water Resources Agency of Taiwan, were used to establish rating-curve relationships. Then sediment discharge during typhoon events were estimated using the rating-curve method and the measured data of daily water discharge. Positive correlations between sediment discharge and rainfall conditions for each river indicate that sediment discharge increased when there was a greater amount of rainfall or a higher intensity rainfall during a typhoon event. In addition, the amount of sediment discharge during a typhoon event is mainly controlled by the total amount of rainfall, not peak rainfall. Differences in the correlation equations among the rivers suggest that the catchments with larger areas and steeper slopes produce more sediment. Catchments with relatively low sediment discharge show more distinct increase in sediment discharge in response to increase in average daily rainfall.

The positive correlation between the average sediment discharge and the average area of landslides during typhoon events indicates that when larger landslides are caused by heavier rainfall during a typhoon event, more loose materials from latest landslide debris are flushed into rivers resulting in higher sediment discharge. However, the correlation between landslides and sediment discharge is not very high and is lower than the correlation between sediment discharge and rainfall conditions. This means that the latest landslides caused by each of the 14 typhoon events are not an only single source of sediment discharge. Previous studies in Taiwan pointed out that the latest landslide debris have not been delivered completely to rivers but have been successively delivered to rivers by following heavy storms. Therefore, the condition of landslide debris staying on slopes since previous heavy storms also affects sediment discharge. According to our result of the frequency–area distribution of landslides, the proportion of large landslides is high in Taiwan. Previous studies in Taiwan indicated that when the lowest point of a landslide reaches a location with the drainage area > 1 km^2, produced sediment are delivered to channels. This means that debris of large landslides have higher opportunity to reach such locations and supply sediment to rivers. Therefore, large landslides in Taiwan contribute significantly to the high annual sediment yield of the world top class, in spite of the small area of Taiwan.