Rainfall Criteria Variation of Debris Flow Occurring at Mt. Ninety-Nine

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Abstract

On 21 September 1999, Mt. Ninety-Nine was suffered a severe raid from the Chi-Chi earthquake, and plenty of slope failures and landslides were occurred at the same time. The percentage of landslide area was approximately 50% of whole area, and the original vegetations were damaged by such an event. Debris flows which are triggered by unstable sediments are occurred frequently in rainy or typhoon seasons. This paper applies "effective rainfall intensity — effective accumulation precipitation" as index to establish the rainfall criteria of debris flow occurring after the earthquake, and compares the result with the original criteria before the earthquake. The result presents that the criteria after the earthquake in 1999 was only 1/4 of the original. Comparatively, with the decreasing of unstable sediments, the criterion was recovered to 1/2 of the original, in 2004. Understanding the variation of the occurring criteria is the main purpose of this research. Numerical simulation is used to estimate the yields and discharges of sediments, and SPOT satellite images are applied to surveillance the quantitative changes of sediments in this area. The result shows that the bared slopes did not be enlarged after the earthquake, even encountering storms or typhoons. Besides, the amount of sediments was decreased due to mass movements with runoffs. Therefore, the relationship between decrement of unstable sediments and recovery of occurring criteria are tidily connected, and this explains the phenomenon of variation of occurring criteria.

Keywords: Earthquake, Debris Flow, Occurring Criteria, Landslide

Introduction

The Chi-Chi earthquake, occurred on 21st Sep. 1999, caused severe damage in the central Taiwan. The amount of landslides were about 2630 in quantities, and the area of landslides, totally, were roughly estimated about 14300 hectares. Mt. Ninety-Nine is located in the edge between Taichung and Nantou County in the central Taiwan, and its watershed belongs to the Wu River (Fig.1). The highest mountain peak, Fire Mountain, is about 780 meters above sea-level here. The east side of Mt. Ninety-Nine is almost river terraces of the Wu River, and the west side is foothills.

Geographically, Mt. Ninety-Nine belongs to conglomerate rock of the Pleistocene Epoch, and, due to well catastrophic characteristic, it is easily suffered from rainfall events eroding. Due to the terrain features of irregular peaks and sheer valleys, its name, Mt. Ninety-Nine, was called. During the earthquake, plenty of slope failures and landslides were triggered. The percentage of landslide area was approximately 50%. Debris flows which are triggered by unstable sediments are happened frequently in rainy or typhoon seasons. The original landforms were damaged by such events.

Before the earthquake, original sparse forests and dense bamboo grass dominate the majority area of Mt. Ninety-Nine, and only a few proportions had been developed by human. In the case, debris flows were not virtually triggered. However, after the earthquake, debris flows are easily triggered because of large amount of unstable sediments which were yielded by the earthquake. With the strong comparison between two period, this paper applies "effective rainfall intensity — effective accumulation precipitation" as index to establish the rainfall criteria of debris flow occurring after the earthquake and compares the result with the original criteria before the earthquake. Five subbasins, Yentukeng (Basin-I), Yuchukeng (Basin-II), Tienweikeng (Basin-III), Shihshuikeng (Basin-IV) and Peishihkeng (Basin-V), were selected as research areas. Occurrence of debris flow is investigated through field work, and then the occurring criteria were established per year. Finally, the reason

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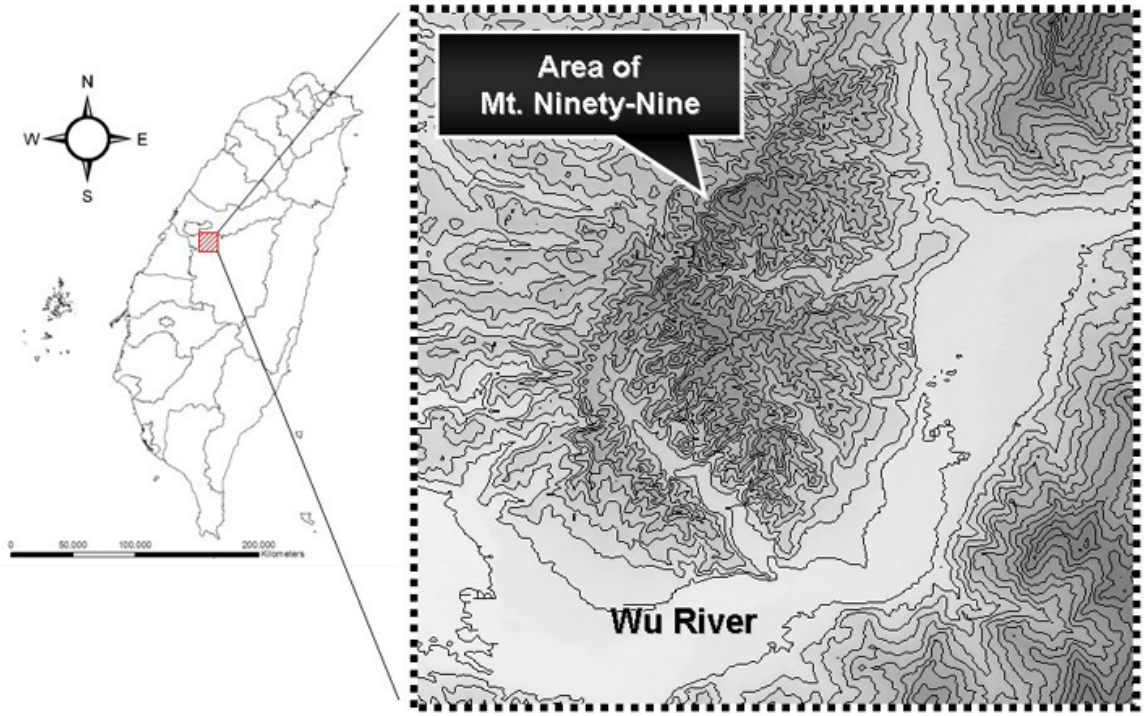

Fig. 1. The location of Mt. Ninety-Nine in Taiwan

of criteria variation with different temporal and spatial conditions was discussed. Futher, SPOT satellite images are applied to surveillance the quantitative change of sediments in this area, and numerical simulation is used to estimate the generation and transportation of sediments. The relationships between sediments, rainfalls and occurrences of debris flow can be established.

Occurring Criteria of Debris Flow

There are three major factors to trigger debris flow : sufficient sediments, water and slope. Above all, water is not only the major component of debris flow but also the key point to trigger debris flow. The friction force and soil cohesion force would be reduced by water after infiltration occuring. Therefore, debris flow was triggered through such kind of mechanism. Lots of researches about relationships between rainfalls and debris flow have been conducted. According to different indexing method, these researches can be simply classified into three catalogues. The first method applies rainfall intensity and rainfall duration as index to establish the criteria (Cain, 1980 ; Cannon and Ellen, 1985 ; Wieczorek, 1987 ; Keefer et al., 1987). The second method applies rainfall intensity and accumulative precipitation as index (Takahashi, 1981 ; Shieh, 1995). The final method applies pre-precipitation as index (Wu, 1990). In Taiwan, the duration of storm is usually a short period of time, so the second method, applying rainfall intensity and accumulative precipitation, is chosen in this paper to establish the occurring criteria.

The effective accumulative precipitation by the time of debris flow occurring, which not only concerns about the rainfall in such event but also has the relationship with the pre-precipitation, can be presented as the sufficient water condition of occurrence. The effective accumulative precipitation should include the following two terms: the one is precipitation in the current event, and the other is pre-precipitation. Precipitation in the current event should be calculated from the moment, rainfall starts, to the moment, debris flow is triggered and duration can also be derived through the same method (Fig.4a). Finally, we can derive effective rainfall intensity through dividing precipitation by effective duration. Otherwise, if debris flow does not be triggered in such event, precipitation in the current event is equal to the total precipitation (Fig.4b).

The definition of pre-precipitation in this paper is effective cumulative rainfall which is calculated from two weeks previous a rainfall event to the moment, rainfall starts. The formula, calculated as rainfall times a decrease coefficient, is attached below, where α is the decreasing coefficient and dn is the daily precipitation

Fig. 2. Aerial photography of Mt. Ninety-Nine (by Mr. Chi)

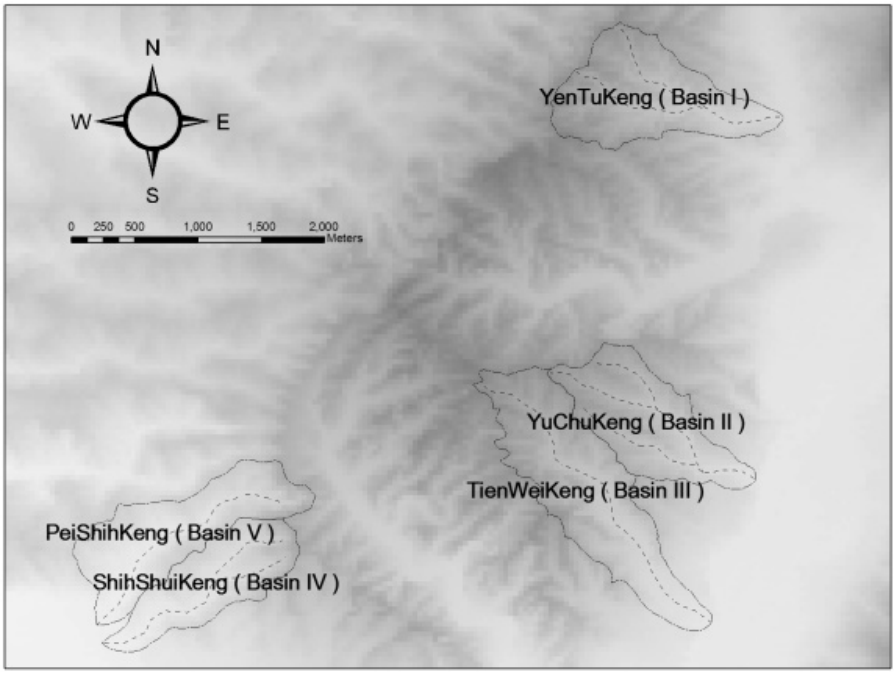

Fig. 3. The five subbasins selected as research areas at Mt. Ninety-Nine

n days previous.

$$PRE = \alpha_1 d_1 + \alpha_2 d_2 + \cdots \alpha_n d_n = \sum_{i=1}^{n} \alpha_i d_i$$

Debris flow triggered in a rainfall event is so called happened event. Conversely, non debris flow triggered in a rainfall event is unhappened event. According to the classification of happened and unhappened event, debris flow critical line can be established. From Fig.5, critical line is defined as a dividing line between these two classification. Further, Fisher distinguish function is applied in this research, and a conservative dividing line of unhappened events is build as critical line. After field investigation, there are six serious debris flows at Mt. Ninety-Nine, and listed below (Table 1). In order to establish the critical line before earthquake, fieldwork and interview with local residents were conducted. The result shows that debris flow did not been triggered at this area between 1992 and 1999. Therefore, precipitation data from 1992 to 1999 was analyzed and applied to establish the critical line, which could be considered as standard to compare with criteria after earthquake.

From the Fig.6, critical condition before earthquake is much higher. The maximum effective accumulative precipitation is reached up to 800 mm. Due to the effect of earthquake, the effective accumulative precipitation in 2000 (first year after earthquake) was only a quarter of the original. However, the critical line

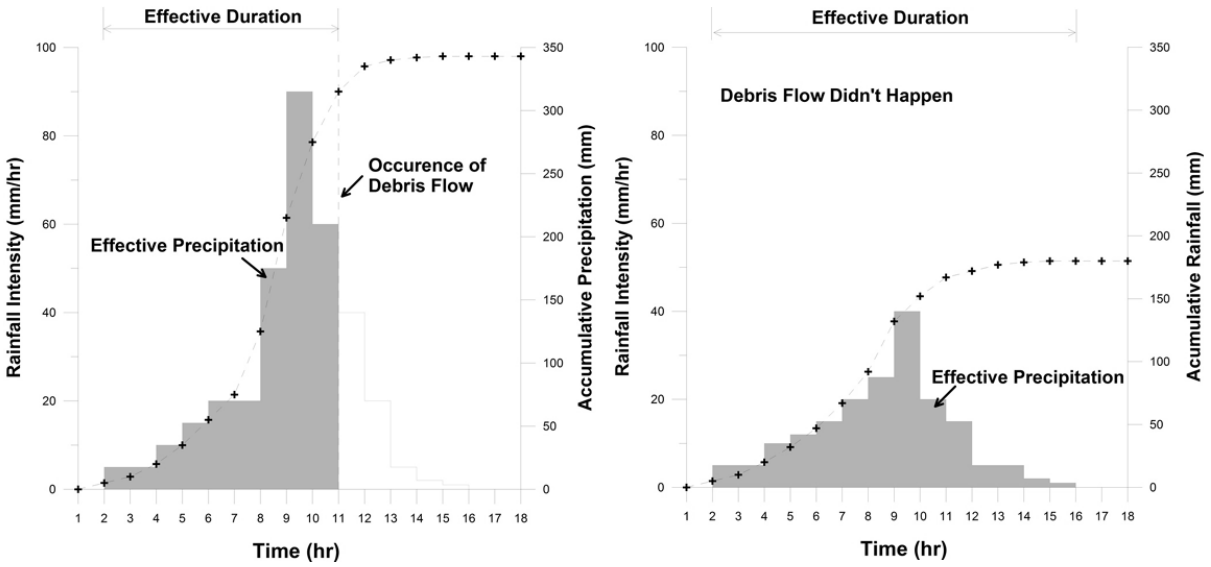

Fig. 4. (a) Precipitation in current event if debris flow does be triggered (b) if debris flow does not be triggered

Table 1. Hazard time of debris flow at Mt. Ninety-Nine

	Event	Basin I	Basin II	Basin III	Basin IV	Basin V
2000-02-23	Storm	O	O	O	O	O
2000-06-13	Storm (due to front)	O	O	O	O	O
2000-08-12	Storm (due to front)	O	O	O	O	O
2001-07-30	Toraji Typhoon	O	O	O	O	O
2003-04-10	Storm	O	O	X	O	O
2004-08-26	Aere Typhoon	O	O	X	X	X
PS. "O" means happened event , and " X" means unhappened event						

was recovered quickly during 2001 and 2002 with the decreasing of unstable sediments. The criteria have been recovered to 1/2 of the original, and the maximum effective accumulative precipitation was about 400 mm. After 2002, the critical condition didn't vary appreciably, that shows the recovery during these three years is almost stopped.

Through analyzing the spatial location of debris flow, debris flows were only appeared in Basin-I and Basin-II in 2003 and 2004. There are no debris flow at Basin-III $\sim$ Basin-V in 2004. Since the geologic and hydrologic conditions of these basins were the same, the rainfall criteria of occurrence must be the same, but, actually, there are quite different. There must be some reasons, except for rainfall, to make such the result. In this paper, sediment conditions are discussed to explain the difference.

Variation of Landslides

Sediments yielded from landslide are the major materials of debris flow, so there must be relationships between occurring criteria, sediment condition and landslide. SPOT satellite images are applied to surveillance the quantitative changes of landslides in this area. The NDVI were calculated, and were compared with each image to mark the variably point, the possible location of landslide. However, there still are some improper results, such as buildings, tilled land, roads and streams. Therefore, GIS system is applied in this paper to calculate the exactly landslide location by subtracting improper area from variably result. All the improper area is adjusted through fieldwork and topography.

One image before the earthquake and six images after the earthquakes were chosen to analyze the quantitative changes of landslides. The results were shown in Fig.7, which x-axis presents time in year and y-axis presents percentage of landslide area. From the diagram, landslides were enlarged to 47.5% while the

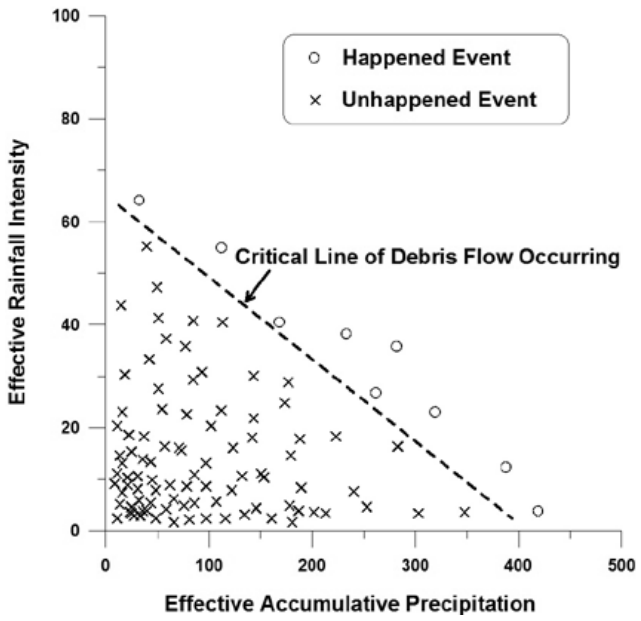

Fig. 5. Diagram of critical line of debris flow occurrence

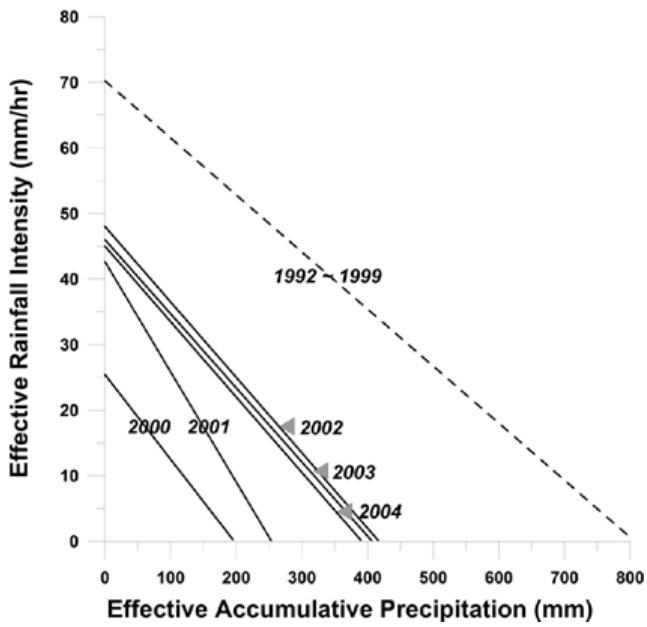

Fig. 6. Critical line of debris flow occurrence at Mt. 99

earthquake, and, after the earthquake, it was still enlarged contiguously in 2001 and 2002. Percentage of landslide area reached 54.0%, which means half area of Mt. Ninety-Nine is bared already. However, these enlarged landslides are occurred by second erosion of deposits and failure of river bank. Landslides on slopes were not enlarged anymore during these two years. After 2002, percentage of landslide area was maintained 54%, even if heavy rainfall and typhoons. So the unstable sediments were almost yielded by earthquake, and were unreplenished since 2003. It seems that the sediment condition of basins are closed to quantitative changes of landslides, because there has no debris flow at Basin-III $\sim$ Basin-V since 2003. But there still has severe debris flow at Basin-I and Basin-II without enlarged landslides. That shows sediment conditions at these two basins must be different from others, and more detail analysis to estimate the sediment conditions in basins is needed.

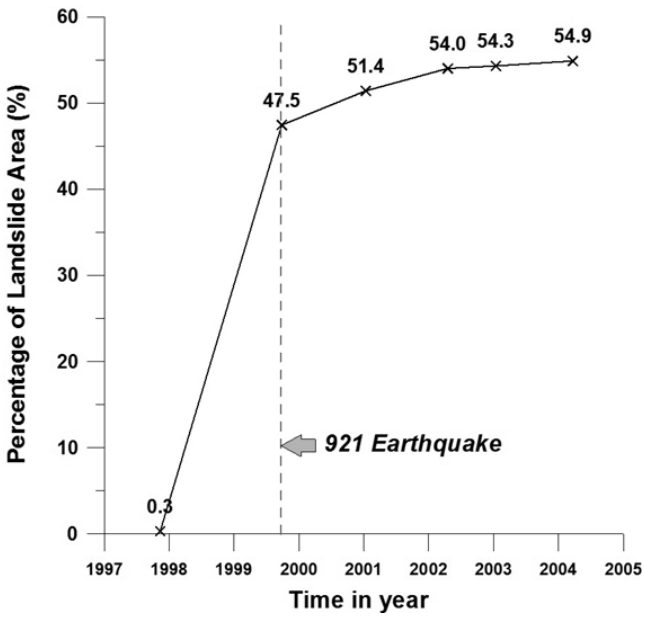

Fig. 7. Diagram of quantitative changes of landslides at Mt. Ninety-Nine

Table 2. Equations/Methods of the Integrated Sediment Evaluation Model

	Equations or Methods
Surface Runoff	Kenimatic Wave
Soil Erosion	MUSLE
Shallow Landslide	Ranged by Remote Sensing
Stream Runoff	Kenimatic Wave
Sediment Transpotation	Equilibratory Concentration Equation

Variation of Remnant Sediment Upstream

The former result shows that there must are strong relationship between variation of occurring criteria and sediment yielded from landslide, but, practically, there are still some exceptions. Therefore, in order to assess the variation of occurring criteria of debris flow, the temporal and spatial unstable sediments condition must be deliberately considered.

Takahashi (1984) applied the unlimited slope theory to classify mass movement into several types with slopes. After that, the slope classification was usually used in research or engineering. Generally, the slope of stream bed which is over 15 degree is defined as occurring section of debris flow. For degree from 8 to 15 is defined as transporting section of debris flow, and degree between 5 and 8 is depositing section of debris flow, and for those degree below 5 degree is considered as normal section of sediment transporting. Applying this classifying method, the chosen basins are classified into four sections, and each section represents each kind of the movement characteristics. The classified result is attached below (Fig.8).

After subbasin is successfully divided, numerical simulation is applied to analyze the sediment yielding and transporting, and assess basin sediments distribution in different temporal and spatial condition. The "Integrated Sediment Evaluation Model" is developed by Shieh (2002), which is applied in this paper. The concept of this model is considered a basin as a joint system of subbasins, and firstly, calculates the sediments yielding and transporting of each subbasin, and then combines the results into final estimation. Simulation must begin in the upper-stream subbasin, and then procedure proceeds along down-stream way until a confluence has been reached. The process of this model (Fig.9) is attached below, where precipitation is the input of model, and the response, sediments yielding by soil eroding on slope surface and shallow landslide, can be calculated. Finally, discharge and sediment transporting could be derived after simulation. This process contains lots of phenomenons, and it could be simplified into five major mechanisms: surface runoff, soil erosion, shallow landslide, and stream runoff and sediment transportation. Each equation/method is listed below (Table 2).

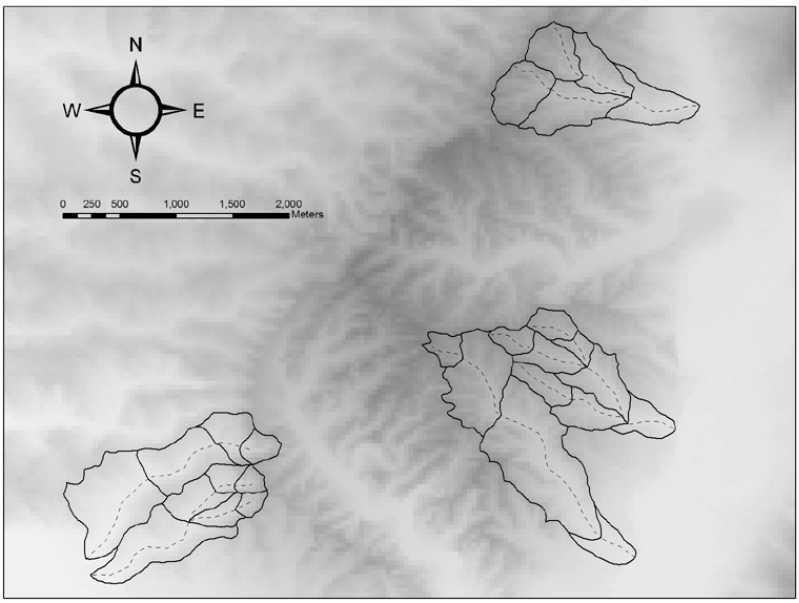

Fig. 8. Result of dividing sections

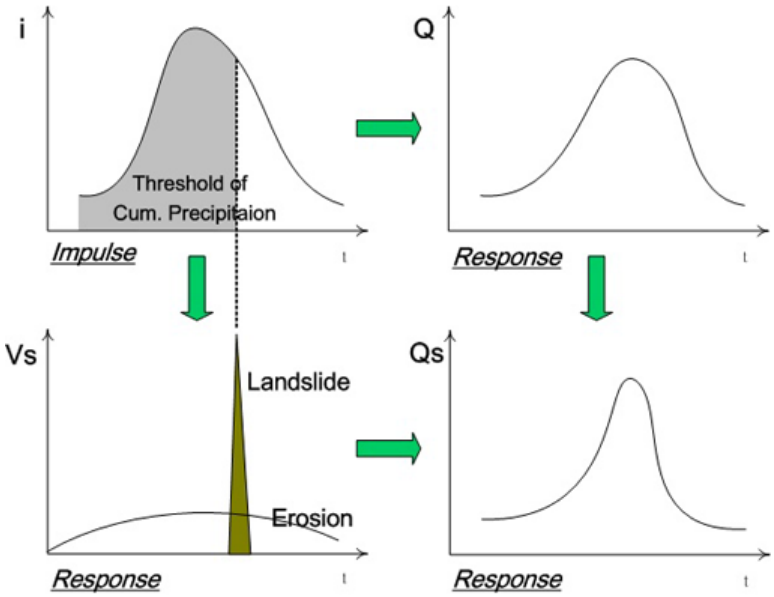

Fig. 9. Basic conception of the Integrated Sediment Evaluation Model

This research applies this model which uses the datum of time series rainfall from 1st Jan. 2000 to ends on 31st Oct. 2004 as input to stimulate the sediments transporting process. Therefore, the sediment transporting process can be easily solved in any temporal and spatial condition. Further, the sediment distribution in basin before a debris flow event is the sediment condition of basin in such event. The percentage of remnant sediment on basin with different sections are attached below (Fig.10 and Fig.11), where y-axis presents percentage of unstable sediments.

From the diagram, sediments in each subbasin have been gradually transported to downstream. Remnant sediments of occurring sections are getting lesser by degrees, and lots of sediments, now, are deposited on transporting or depositing sections. Sediments at Basin-IV and Basin-V were all transported to downstream, that's why debris flow wasn't triggered in 2004 in these two basins. On the contrary, the amount of sediments at Basin-I and Basin-II were still so plentiful that provides the materials for triggering debris flow in the same event. In this figure, the reason of spatial difference of debris flow can be clearly explained, and shows that the remnant sediments still play important role of debris flow, even if in the same geologic and hydrologic

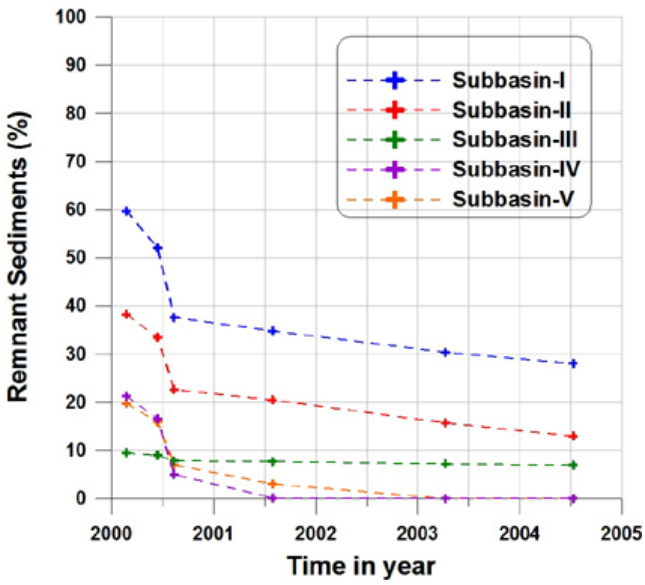

Fig. 10. Remnant sediment at occurring sections

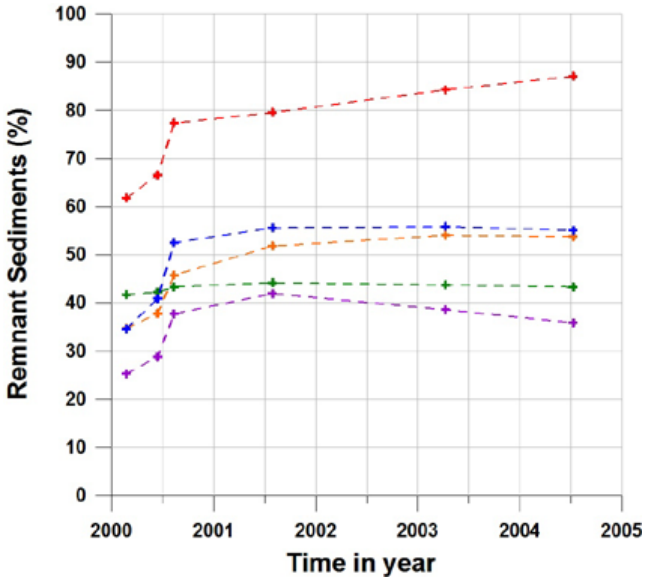

Fig. 11. Remnant sediments at transporting sections

conditions. Fig.12 is taken at Basin-IV, July 2004. The left picture shows the sediments at a transporting section, and the right one shows the sediments at a occurring section. It can be easily found that sediments at an occurring section are almost transported to a transporting section. Therefore, debris flow is not triggered while Aere Typhoon, 2004, but Basin-I and Basin-II are suffered severe damage by debris flow during Aere Typhoon.

Conclusion

Mt. Ninety-Nine was severely damaged by the Chi-Chi earthquake in 1999, where original vegetations were almost abolished and the percentage of landslide area was over 50%. Plenty of sediments yielded by landslide make debris flow easily be triggered while heavy rainfalls and typhoons coming. This paper applies "effective rainfall intensity — effective accumulative precipitation" as index to establish the occurring criteria of debris flow after the earthquake and compare the result with the original criteria before the earthquake. The result presents that the criteria after the earthquake in 1999 is only 1/4 of the original. Comparatively, with the decreasing of unstable sediments, the criteria, 2004, has been recovered to 1/2 of the original. Five basins

Fig. 12. Pictures at Basin IV on July 2004. Left is taken at transporting section and right is taken at occurring sections at the same time

at Mt. Ninety-Nine are chosen to analyze the criteria variation of debris flow. Besides, "Integrated Sediment Evaluation Model" and remote sensing technology are applied to analyze the temporal and spatial distribution in each basin. The result shows that remnant sediment at occurring section is the most sensitive factor of the occurrence of debris flow. In 2004, debris flows were triggered easily at Basin-I and Basin-II because of plenty sediment at occurring section, but on the contrary, Basin-IV and Basin-V were not suffered from the damage of debris flows in the same event. The result presents that the occurrence of debris flow and remnant sediment at occurring section has strong relationship.

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