A probability based early warning system for rain-induced landslides– a case study of Taipei City

Une probabilité fondée système d'alerte rapide pour les pluies induites par les glissements de terrain - une étude de cas de la villa de Taipei

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ABSTRACT
On September 15, 2001, Typhoon Nari struck Taiwan with heavy rainfall inducing more than 400 landslides in Taipei City. In order to reduce the landslide hazards, the early warning system is much needed. To develop the warning criteria, the landslide events caused by Typhoon Nari along with events occurred in 2004 were used. Field investigations and documentation of the occurring time of each event were conducted carefully to validate the data. By cross-comparisons of the rainfall records from different rain gauge stations, Taipei City was divided into 3 subzones taking into account the geomorphological condition, distribution of the geological formations, and characteristics of rainfall pattern. Methods for determining the representative and effective rainfall parameters at the landslide sites were determined based on the rainfall records of the rain gauge stations. The probability-based early warning criteria were established using the rainfall intensity and effective cumulative rainfall at the occurring time of the events as the key parameters. The criteria were verified by simulating the landslide event induced by typhoon Crosa on October 7, 2007, and proved to be effective and feasible with satisfactory results. The resulting early warning system for landslide in Taipei City can be used to support decision making during the emergency response and for hazard mitigation of rainfall induced landslide.

RÉSUMÉ
Typhon Nari a frappé Taïwan le 15 septembre 2001, avec de fortes pluies provoquant plus de 400 glissements de terrain dans la ville de Taipei. Afin de réduire les risques de glissement de terrain, le système d'alerte rapide est nécessaire. Pour développer les critères d'alerte, les glissements de terrain causés par les événements Typhon Nari avec les événements survenus en 2004 ont été utilisés. Investigations en place et de la documentation qui se produisent de temps de chaque événement ont été réalisées avec soin afin de valider les data. En contre-la comparaison des records de pluie provenant de différentes stations de pluviométrique, la villa de Taipei est divisée en 3 sous-zones, en tenant compte de la situation géomorphologique, la distribution des formations géologiques, et les caractéristiques de pluviométrie. Méthodes de détermination des paramètres pluvieux de la représentativité et effective des sites de glissement de terrain ont été déterminées sur la base des enregistrements des pluies de l'pluviomètrique stations. La probabilité d'alerte rapide sur des critères ont été établis en utilisant des intensité de précipitations et efficace cumulé des pluies qui se produisent au moment des événements, comme les paramètres clés. Les critères ont été vérifiés par le glissement de terrain de simulation des événements induits par le typhon Crosa sur 7 octobre 2007, et se sont avérés efficaces et réalistes avec des résultats satisfaisants. Le système d'alerte rapide pour les glissements de terrain dans la ville de Taipei peut être utilisée pour appuyer la prise de décision au cours de l'intervention d'urgence et pour l'atténuation des risques de glissements de terrain induits par les précipitations.

Keywords: rain-induced landslides, probability-based early warning criteria, rainfall intensity, effective cumulative rainfall

1 INTRODUCTION

The landslide hazard caused by the heavy rainfall carried by typhoons and other weather systems has a long record in Taiwan. The Taipei Municipal Government documented 232 historical landslide events during the time period from 1959 to 2001. On September 5, 2001, the heavy rainfall carried by Typhoon Nari induced more than 400 landslides in the Taipei City. In view of hazard reduction and management, the development of an early warning system for the landslide would be important. Studies on landslide warning systems were developed using remote sensing, ground-base monitoring, or rain gauge station methods (Caine 1980; Cannon & Ellen 1985; Keefer et al. 1987; Wieczorek 1987; Sugiyama et al. 1995; Ba Mamoudou & Sharon, 1998; Singhroy et al. 1998; Fan et al. 2002; Jan 2002). However, the factors affecting slope stability are various and often mutually related, and it is difficult to establish a simple and practical systematized landslide warning system. Among these methods, due to the densely distributed rain gauge stations established in Taipei City by different government agencies and readily available precipitation records, using rainfall data to develop the landslide warning criteria is a more convenient, practical, and economic method. A preliminary landslide warning system was proposed by Lin et al (2003) for Taipei City based on the landslide events and rainfall intensity and effective cumulative rainfall measured at the rain gauge stations. In this research, the rainfall distributions caused by different typhoons were examined for characteristic analysis, and method for determination of the representative rainfall data at the locations of landslide events was established. The probability based landslide warning criteria was then constructed accordingly.

2 STUDY AREA AND LANDSLIDE EVENTS

Taipei City situated in the north of Taiwan with 55% of the area located in the mountain area. The topography of Taipei City is as shown in Figure 1. There are three rivers, Danshui river, Keelung river, and Jingmei stream, flowing into the basin and

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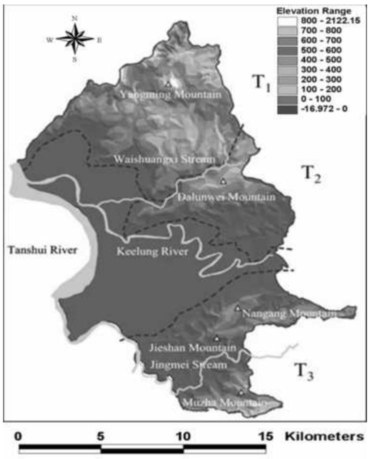

Figure 1 The topography map of Taipei City

cutting through the mountain area into four individual slopeland areas. An alluvial plain was deposited by the rivers in the central area of the basin. The aspect of topography follows the tendency of mountain ranges and approximately along the north to west–southwest direction. The highest elevation located in northern Taipei City with the elevation varying from 500 to 1100 m. In the central Taipei City, the elevation varies from 400 to 600 m. In the southern Taipei City, the elevation varies from 100 to 500 m.

The main geological formation in the north most of Taiwan and thus in north Taipei City is igneous rock formed by the Ta-Tuen Volcano. Sedimentary rock is mainly deposited in the piedmont of west Taiwan, and so is in the central and south of Taipei City. The geological map of Taipei City is as shown in Figure 2. The main geology in the north Taipei City is formed by pyroclastic flow and tuff, and both the central and south Taipei City are sedimentary rock mainly. There are four major thrust faults and a series of dip slope structures crossing through the mountain. Dense joints and fissures developed in most rock mass result in weak resistance against weather and erosion.

The geological characteristic of different formations can be classified using unconfined compression strengths of rock material by different researchers (Hsu 1983, Weng 2002). Based on the distribution of different geological formations and the strength characteristics of rock material, Taipei City could be divided into four geological zones, i.e.: igneous rock zone, I (Andesite and Tuff Braccia formations); sedimentary rock 1, S1 (Wuchishan, Mushan, and Taliao formations); and sedimentary rock 2, S2 (Shihti, Nankang, and Nanchuang formations); alluvium, A; and the four sub-regions as shown in Figure 2. The sedimentary rock region is divided into two regions, the formations in S1 region are the older formations with higher strength located in the north of Keelung River area, and the formations in S2 region are the younger formations with lower strength located in the south of Keelung River area.

A total of 426 landslide events induced by Typhoon Nari, 2001 were recorded by Taipei Municipal Government. The data were screened, and 63 landslide cases were identified with reliable occurrence time. Field investigations were performed on the 63 cases, and. database of rainfall records from near-by gauge stations, initiation time, and magnitudes of landslide were generated and analyzed. Comparing with the landslides caused by Typhoon Nari, there were fewer and with smaller scale landslide events occurred in Taipei City since 2002. However, Typhoon Aere, Typhoon Haima, and Typhoon Nock-Ten induced about 100 landslide events in Taipei City in 2004. Through conducting field investigation, 66 landslide data were documented and verified. Among those events, 31 cases were selected for which the closest landslide initiating-time and magnitude were recorded in detail. Therefore, a total of 94 cases were selected for analysis and construction of the early warning system. Additionally, based on the rainfall records of the

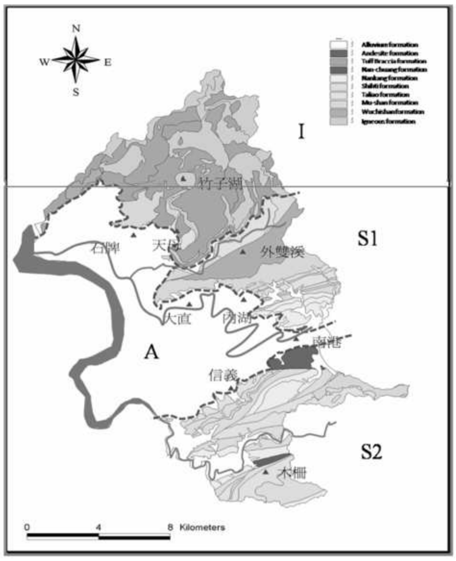

Figure 2 Geological map of the Taipei City

previous 232 historical landslide events documented by the Taipei Municipal Government during the period from 1959 to 2001 before Typhoon Nari, it was found that a threshold rainfall intensity of 50 mm/hr was the minimum rainfall intensity for triggering of the landslides. Also from the mean cumulative rainfall of the historical landslide events, a critical effective cumulative rainfall was found to be 550 mm for triggering of landslides.

3 DETERMINATION OF REPRESENTATIVE RAINFALL

The rainfall intensity and effective cumulative rainfall at the most possible initiation time of landslide event were used as the parameters to develop the preliminary criteria. The representative rainfall data at the landslide events were determined by interpolation of the data from nearby rain gage stations. Data from a total of 63 rain gage stations were gathered and analyzed; the distribution of the rain gage stations in Taipei City used in this study was as shown in Figure 3. Due to the difficulties of confirming the exact initiation time of landslide, it is assumed that 1 hour before the case reporting time as the most possible initiation time, partly also due to that the hour intensity was used in development of the warning criteria. Definitions of the effective cumulative rainfall and rainfall intensity are as follow:

(1) effective cumulative rainfall

The effective cumulative rainfall is defined as the effective antecedent rainfall plus the cumulative rainfall, which is expressed as follow:

(a) effective antecedent cumulative rainfall

A continuous rainfall record segmentation is defined as with no rainfall within 24 hours before and after the incident. The antecedent rainfall is the rainfall occurred 2 weeks before the beginning of a continuous rainfall, and its effects declined with the time span between the antecedent daily rainfall and the beginning of a continuous rainfall. The effective antecedent cumulative rainfall, RWA, is expressed as follow:

$$RWA = \alpha_1 d_1 + \alpha_2 d_2 + \alpha_3 d_3 + ... + \alpha_{14} d_{14} = \sum_{1}^{14} \alpha_t d_t \tag{1}$$

where α_t : recession coefficient (= 0.5^t), t: time in day(s) before the beginning of a continuous rainfall, and d_t: daily cumulative rainfall on the t-day (mm)。

(b) cumulative rainfall

The cumulative rainfall is the rainfall accumulated from the beginning of a continuous rainfall till the initiation time of landslide.

Figure 3 Distribution of the rain gage stations used in rainfall analysis (CWB: Central Weather Bureau, WRA, MOEA: Water Resource Agency, Ministry of Economic Affairs, PWD, TMG: Public Works Department, Taipei Municipal Government, DED, TMG: Department of Economic Development, Taipei Municipal Government)

(2) rainfall intensity 1 hour before the initiation time of landslide

After collecting the landslide data from the field investigation and the official report of police department, the reported initiation time and rainfall intensity 1 hour before the initiation time of landslide for each case is determined.

Due to the rainfall records at the rain gauge stations may be different from the rainfall at landslide locations; a study on the representative rainfall determination was conducted by Lin et al 2005. Cross comparisons were made for different interpolation methods from known data using rainfall records from surrounding rain gage stations. It was found that the inverse-distance-weighting-method provides satisfactory results for calculating the representing data at the landslide location. Thus, the representative rainfall intensity and effective cumulative rainfall at the initiation time of each landslide event are calculated accordingly.

4 ZONING OF RAINFALL CHARACTERISTICS

Due to the effects of topography, variations of typhoon path and the width of cloud band, the resulted rainfall distributions through out the Taipei City for different typhoon vary widely. In order to obtain representative warning criteria, characteristic analysis of the rainfall induced by different typhoon events was performed. The cross correlation analysis was used for the correlation of rainfall records of given event between two adjacent rain gage stations. A high value of coefficient of correlation suggested the rainfall records having similar characteristics. Grouping of the rain gauge stations with similar rainfall characteristic was conducted for each typhoon event. For most typhoon event, typically three groups of stations are derived as illustrated in Figure 4. Following above process, the 14 typhoon events were selected and analyzed. The coverage area of each rain gauge station can be delineated using Thiessen's polygon method as shown in Figure 5, where the polygon of the representing area was determined with equal distance to the adjacent three rain gauge stations. Each polygon represents areas having similar rainfall characteristics as the rain gage station included in the polygon. Combining the grouped rain gauge stations, Taipei city could be zoned into three sub-regions of rainfall characteristic as illustrated in Figure 5.

Based on the results of cross correlation analysis of the rainfall records from all rain gauge stations on 14 typhoon events, it is suggested that the city can be divided into three

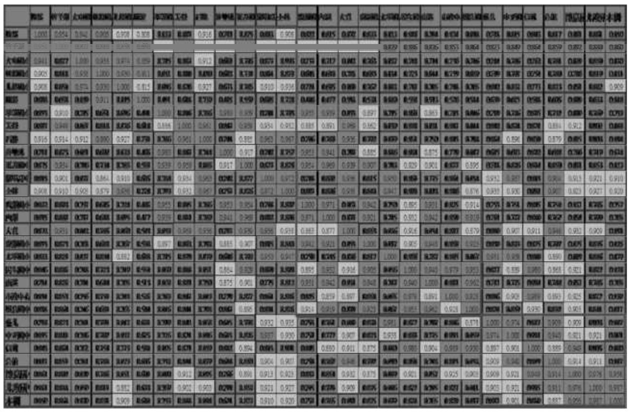

Figure 4 Grouping of rain gage stations with similar rainfall characteristics based on cross correlation analysis for typhoon Matsa, 2005

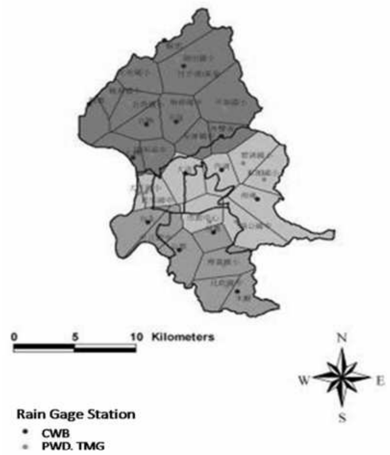

Figure 5 Zonation based on rain gage station coverage area for typhoon Matsa, 2005

subzones taking into account the geomorphological condition, distribution of the geological formations, characteristics of precipitation record, and resources of disaster management. The resulting zonation of the Taipei City is shown in Figure 6, where the north region includes Beitou and Shilin; the central region includes Zhongshan, Neihu, and Nangang; and the south region includes Xinyi, Daan, and Wenshan (Lin, et al 2005).

5 THE EARLY WARNING CRITERIA

For the development of early warning system, the magnitude and types of failure along with other information of the 94 landslide events were analyzed. It was found that the shallow failures were usually triggered by short-duration high-intensity rainfall, while deep-seated landslides were affected by long-term rainfall. In addition, the landslide induced by high intensity rainfall is of smaller magnitude compared to the medium to massive landslides triggered by high accumulation rainfall. Such results are consistent with that by Brand et al 1984, Cannon & Ellen 1985, Wieczorek 1987, and Bonnard & Noverraz 2001.

Based on the previous analysis, the representative rainfall intensity and effective cumulative rainfall at the most possible initiation time of landslide as defined previously were calculated for each case, respectively. Pre- analysis of the data revealed that no artificial or unnatural factors were involved in causes of landslide, however, cases with landslide area smaller than 50 m^2 were typically local soil fall with minor damages, and some events were identified as rockfall type of failure. These cases were removed from the database for development of a proper warning criterion. After the screening process, the

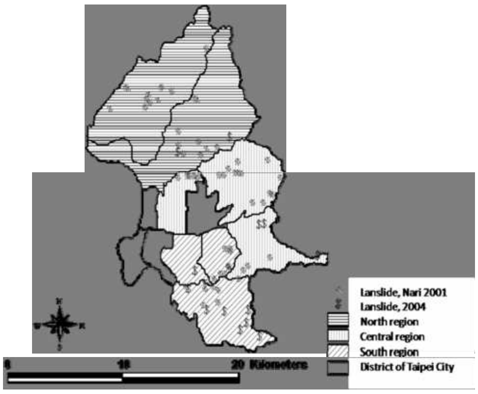

Figure 6 Results of zonation and distribution of landslide events

number of events from 2004 reduced to 13, and a total number of 76 events were used in the analysis. The distribution of the 76 events is as shown in Figure 6, with 22 events in north region, 27 events in both central and south regions.

Warning criterion for each region was developed by assuming a linear relationship between the rainfall intensity and effective cumulative rainfall at the initiation of the landslide. The linear regression of the rainfall parameters was preformed to establish the relation for critical rainfall condition for each region. The regression lines were considered as probability of 50%, by taking 1 standard deviation toward the smaller rainfall values provided 84% occurrence coverage, and the line of 70% probability coverage was drawn considering operation practice. The resulting set of warning criteria is as shown in Figure 7 with the 16% probability line as precaution alert, and the 30% probability line as warning criterion. Comparing the results to the historical cases from 1959 to 2001, the left margin of the warning criteria were close to the threshold of 50mm/hr, however, the right margin already exceeded the 550 mm critical effective cumulative rainfall. Therefore, the critical margin of 550 mm for the north and central regions, and 500 mm effective cumulative rainfall for the south region were added to the warning criteria as illustrated by the dash lines in Figure 7.

In order to verify the feasibility of the early warning system, a landslide event at Guitzikern area in the north region caused by Typhoon Crosa in 2007 was used. The representative rainfall data was generated from the rain gage stations nearby, and the time record of the rainfall intensity versus the effective cumulative rainfall was traced. It was found that the rainfall record passed the warning line several times, and eventually landslide occurred about 5 hours after the record first passed the warning line, and 3 hours after passing the warning line the second time. The warning criterion in this case appeared to be satisfactory, and the time lead was enough for necessary action.

6 CONCLUSIONS

In this paper, the method for determination of representative rainfall data at landslide event using nearby rain gage stations was proposed and representative rainfall parameters for each landslide event was analyzed. Zonation of the study area was conducted based on the rainfall characteristics, geomorphological, and geological conditions. The landslide warning criteria were established based on statistic analysis of the landslide rainfall parameters in each zone for Taipei City. Verification of the warning criteria was made using event in 2007 with satisfactory results. Furthermore, the limit of this criterion and timing for issuing landslide warning appeared to be feasible. However, the criteria are not applicable to landslides with area smaller than 50 m^2 and with rockfall type of failure. The warning criteria suggested in this research provides the landslide warning system for Taipei City, which can be used to support decision making during the operation of emergency response center for hazard mitigation of landslide.

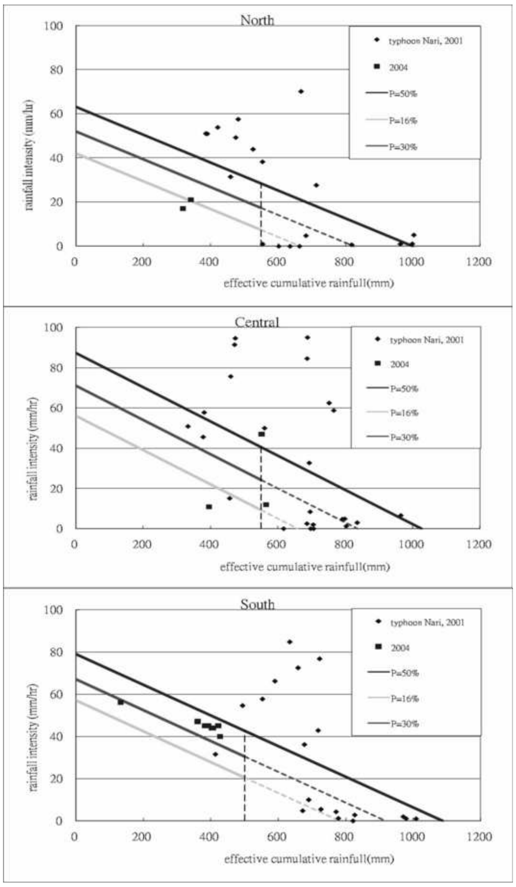

Figure 7 Early warning criteria for the north, central, and south regions of the Taipei City

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