The fractal characteristics of landslides induced by earthquakes and rainfall in central Taiwan

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Abstract: The event of landslide is controlled by numerous factors such as the geological structure, landform, rainfall and earthquake. The landslide in a specific site is the nature result involving these number factors in this site. The mechanism of a landslide is complicated. It is not so easy to predict. However, it is a nature phenomenon. The fractal theory is to describe a complicated event, but nature. The distribution of landslide in mid-Taiwan induced by typhoons or earthquakes is analyzed using the fractal theory. The box dimension is employed to describe the size distribution of the landslide areas. The box-counting method is used to sieve the size of landslide areas in this study. Usually, the larger box dimension implies that there are various sizes of landslides in a single event. On the other hand, the correlation dimension is used to describe the location distribution of landslides. The pair number of each two-landslide is sieved by its distance and counted. The correlation dimension responds the distance relationship between the neighbor landslides. The larger correlation dimension indicates a homogeneous distribution for a landslide location. The smaller one implies the distribution of landslides is cluster. The aim of this study is to explain the landslide distributions in scale and location using the fractal concept. The landslide examples caused by typhoon and earthquake are shown in this paper. The difference of landslide caused by rainfall and earthquake is discussed.

Résumé: L'événement de l'éboulement est commandé par de nombreux facteurs tels que la structure géologique, forme de relief, précipitations et tremblement de terre. L'éboulement dans un emplacement spécifique est le résultat de nature impliquant ces facteurs de nombre dans cet emplacement. Le mécanisme d'un éboulement est compliqué. Il n'est pas aussi facile de prévoir. Cependant, c'est un phénomène de nature. La théorie de fractale est de décrire un événement compliqué, mais nature. La distribution de l'éboulement dans mi-Taiwan induit par des ouragans ou des tremblements de terre est analysée en utilisant la théorie de fractale. La dimension de boîte est utilisée pour décrire la distribution de grandeurs des secteurs d'éboulement. La méthode decompte est employée pour tamiser la taille des secteurs d'éboulement dans cette étude. Habituellement, la dimension plus grande de boîte implique qu'il y a de diverses tailles des éboulements dans un événement simple. D'autre part, la dimension de corrélation est employée pour décrire la distribution d'endroit des éboulements. Le nombre de ciseaux de chaque deux-éboulement est tamisé par sa distance et compté. La dimension de corrélation répond le rapport de distance entre les éboulements voisins. La dimension plus grande de corrélation indique une distribution homogène pour un endroit d'éboulement. Le plus petit implique la distribution des éboulements est faisceau. Le but de cette étude est d'expliquer les distributions d'éboulement dans la balance et l'endroit en utilisant le concept de fractale. Les exemples d'éboulement provoqués par ouragan et tremblement de terre sont montrés en cet article. La différence de l'éboulement provoquée par des précipitations et tremblement de terre est discutée.

Keywords: landslides, earthquakes, engineering geology

INTRODUCTION

Taiwan is located at the oblique convergent boundary of Eurasian Plate and the Philippine Sea Plate. The mountain building process is active and the geological condition is fairly fragile. The Central Mountain Range is up-heaved with elevations exceeding 3000m. The area of mountain covered this island is about 70% (see Figure 1). The landslide and debris flow caused by earthquake and typhoon in Taiwan are numerous and recurring. Heavy rainfall, particularly those brought by typhoons, often leads to debris flows and landslides. The other type of landslide is usually triggered by the earthquake. For example, a large number of landslides were triggered by the Chi-Chi earthquake with a moment magnitude of 7.6 in 1999. Thus, landslides in Taiwan can be triggered by two different mechanisms of the intense rainfall and the ground motion from earthquakes.

Landslides are serious natural hazards, so it is important task for geotechnical engineering to assess landslide risks and mitigate disasters. However, the size and location of landslides are complex in estimation during a landslide event (Bhandrari & Kotuwegoda 1996; Yokoi, *et al.* 1996). The fractal is a mathematical theory developed to describe the quality of complex shapes or images in nature. The fractal character of landslides from mapping of natural landslides has been used for their geometrical description. Yokoi *et al.* (1995) stated that the fractal character of landslides can be explained by a self-similar geometry. A number of authors (eg., Pelletier, *et al.* 1997; Rouai & Jaaidi 2003) have examined the frequency-size distribution of landslide areas. The frequency of landslide occurrence as a function of their size can be described by a power law. In Japan, Kubota (1994) found a self-similar geometry with fractal dimension D ranging from 1 to 1.5. He suggested that the fractal dimension of landslides could be a valuable tool for investigation of landslide susceptible area. Yokoi *et al.* (1995) concluded that the fractal dimension in length (or width) for a huge landslide area is independent of the base rock geology.

In this paper, several landslide distributions in size and location in mid-Taiwan induced by typhoons or earthquakes are analyzed using the fractal theory. The box dimension (D_b), a fractal dimension, is employed to describe the size distribution of the landslide areas. The box-counting method is used to sieve the size of landslide areas in this study. In addition, the two-point correlation dimension (D_{corr}) is employed to describe the distance relationship between the neighbour landslides. The aim of this study is to explain the characteristics of landslide distributions in size and location caused by rainfall and earthquake in Taiwan.

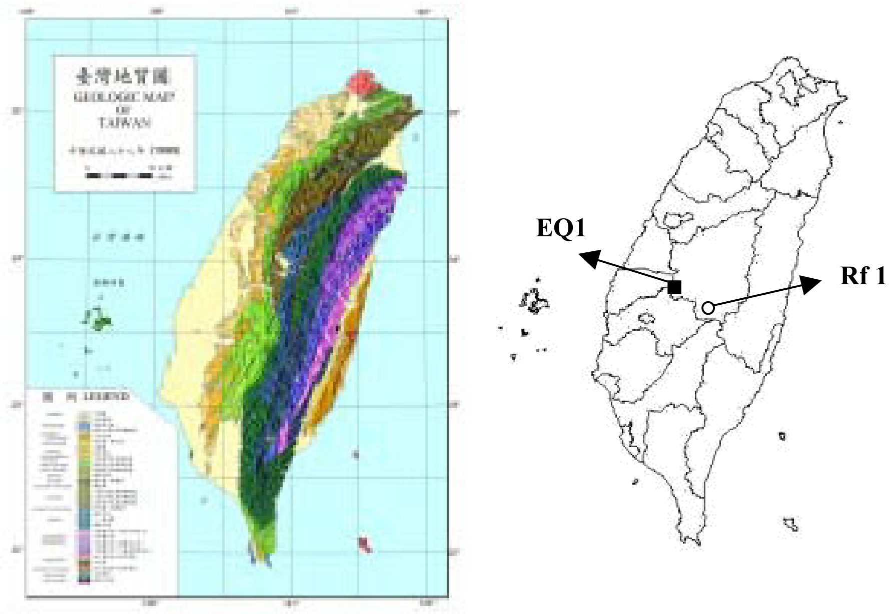


Figure 1. The geological map of Taiwan and the case studied sites

FRACTAL DIMENSIONS

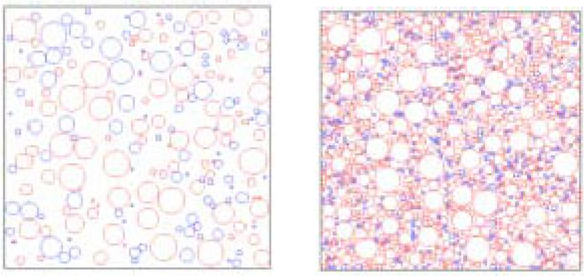
Box dimension

The box-counting method used in fractal theory is a method estimating the fractal dimensions of a plane set. In order to compute the box dimension in two dimensions, this method uses squares or boxes of various sizes to place over a figure. The equal sized boxes required to cover the picture are numbered. Usually, the number of boxes required to cover every portion of the fractal object is dependent upon the box width. As the box size (d) decreases, the number of boxes (N) grows according to a power law,

$$N \propto d^{-D_b}$$

The exponent (D_b) in this power law is the box dimension, a real number that characterizes the level of complexity of the fractal shape. Very roughly, the box dimension provides a description of how much space the set fills. This fractal dimension reflects how rapidly the complexity develops as box size decreases. The greater the fractal complexity of a figure, the higher is its fractal dimension.

In geotechnical applications, the particle-size distribution curve is used to characterize a group of soil particles. This is the relationship between the cumulative finer fraction of the particle mass and the particle sizes. Yang & Juo (2001) showed that the fractal dimension of a given soil collection can be obtained from the classical particle-size distribution curve. That is, we can use log(finer %) instead of (finer %) as an ordinate in the particle-size distribution curve. The fractal dimension (D_b) is calculated from the slope of the linear regression, D_b=3-slope. In this study, the box-counting method and thus the box dimension (D_b) are employed to sieve the size of landslide areas. Usually, the larger box dimension implies that there are various sizes of landslides in an event (see examples in figure 2).



(a)D_b =0.97 (b)D_b =1.96

Figure 2. Box dimension and the degree of grain packing

Two-point correlation dimension

The correlation dimension (D_{corr}) is used to describe the landslide distribution in location. Each two-landslide pair is sieved by its distance and counted the pair number. The correlation dimension responds the distance relationship between the neighbour landslides. The larger correlation dimension indicates a randomly distributed landslide event. The smaller one implies a cluster distribution.

Recently, a number of studies have shown that spatial distribution of landslides is fractal(Rouai & Jaaidi 2003). That is, if the landslide location is considered as a point pattern in space, there is self-similarity of this point pattern over a range of spatial scales. One way to demonstrate spatial self-similarity is to examine the distribution of distances between pairs of points in a data set over a range of distances. This has been carried out in the landslide domains (km) using a spatial two-point correlation function (Kagan & Knopoff 1980). This procedure of calculating the two-point correlation dimension is summarized as following.

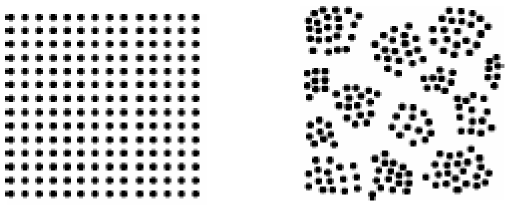
$$s(i, j) = |X_i - X_j|$$

Where the $s(i, j)$ is the distance of two points (two locations of landslides). The two-point correlation function C(R) is expressed as

$$C(R) = \frac{2}{n(n-1)} \times N(r<R)$$

Where N(r<R) is the number of point pairs with a distance r=s(i,j) less than R, and n is the total number of points (landslides). If N(r<R) is proportional to a power function of R, then the double logarithmic plot of C(R) versus R should be linear. For the range of R over which it is linear, the point pattern can be considered as self-similar or fractal. The slope of the log(C(R)) versus log(R) plot is the fractal dimension, called correlation dimension D_{corr}, of the points distribution in space.

A random distribution of points in two-dimensional space will have a linear slope of 2. Fractal point patterns with slopes less than 2 displaying a cluster distribution. The degree of cluster increases with decreasing correlation dimension (D_{corr}). Two examples are demonstrated to find the difference of clustering degree in Figure 3. Rouai & Jaaidi (2003) calculated the fractal dimension of 1.6 for Morocco landslides. It means the distributed behaviour of landslides in Morocco is clustering.



(a) Homogeneous (D_{corr} =1.79) (b) Clustering (D_{corr} =1.54)

Figure 3. Example for demonstrating the degree of clustering by correlation dimension

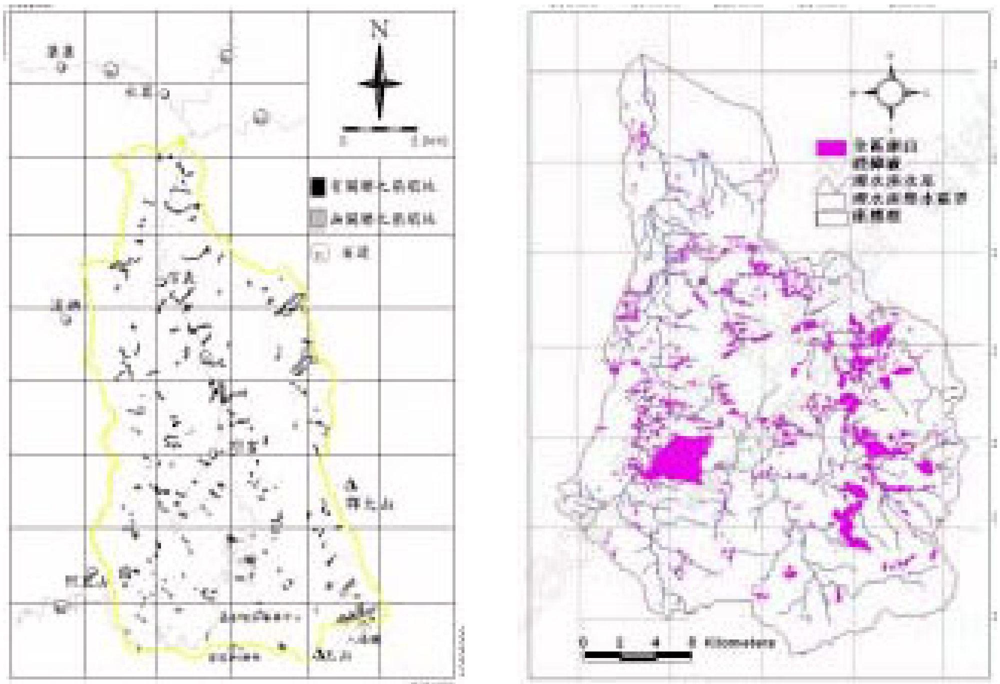
DIGITIZE SPATIAL GEOMETRY OF LANDSLIDE

Cases of landslides

This paper obtains seven aerial maps of landslides, three induced by heavy rainfall (Rf series) and four trigger by earthquake (EQ series), in Taiwan (see Figure 1(b)). To demonstrate the difference of landslides caused by rainfall and earthquake, Two examples located in the mountainous terrain of central Taiwan, Rf1 and EQ1 (see figure 1(b)), are discussed and shown as Figure 4(a) and 4(b).

Case 1 (Rf1): In 1996, on 31 July and 1 August, Taiwan was struck by a strong typhoon named Herb. Herb was a strong typhoon with a highest speed sustained wind speed up to 60 m/s. Herb caused 1315 landslides, more than 20 debris flows, 101 road closures and 73 deaths (Lin and Jeng, 2000). The landslide Rf1 in Chenyulan river watershed in central Taiwan is shown in figure 4(a). The number of landslides involved in case Rf1 is 468 identified from the aerial photographs.

Case 1 (EQ1): The September 21, 1999, Chi-Chi earthquake (M_L=7.3) triggered more than 10,000 landslides in the mountainous terrain of central Taiwan. The 189 landslides in Chinsui river watershed is identified from the aerial photographs and shown in figure 4(b).



(a) rainfall type (Rf1) (b) earthquake type (EQ1)

Figure 4. Two photographs of landslide distributions determined from aerial maps for two different mechanisms

Digitalize the landslide geometry

The photo-image technique of eVision software was used to obtain the spatial geometry of landslides (see Figure 5). The centre of each landslide is determined by eVision to have the central coordinates of landslide (a point). The numerous landslides are thus represented by a point set. The two-point correlation dimension is then calculated from the pair-landslide distances. For each landslide, the area and length (corresponding to its equivalent ellipse area) are calculated using eVision technique. The area of landslide is then sieving to get the particle size distribution curve. A box dimension to respond the size character of landslide areas is obtained.

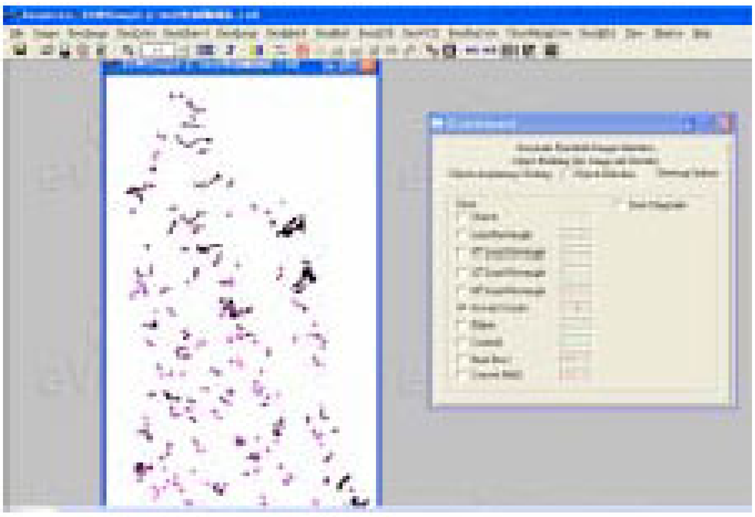
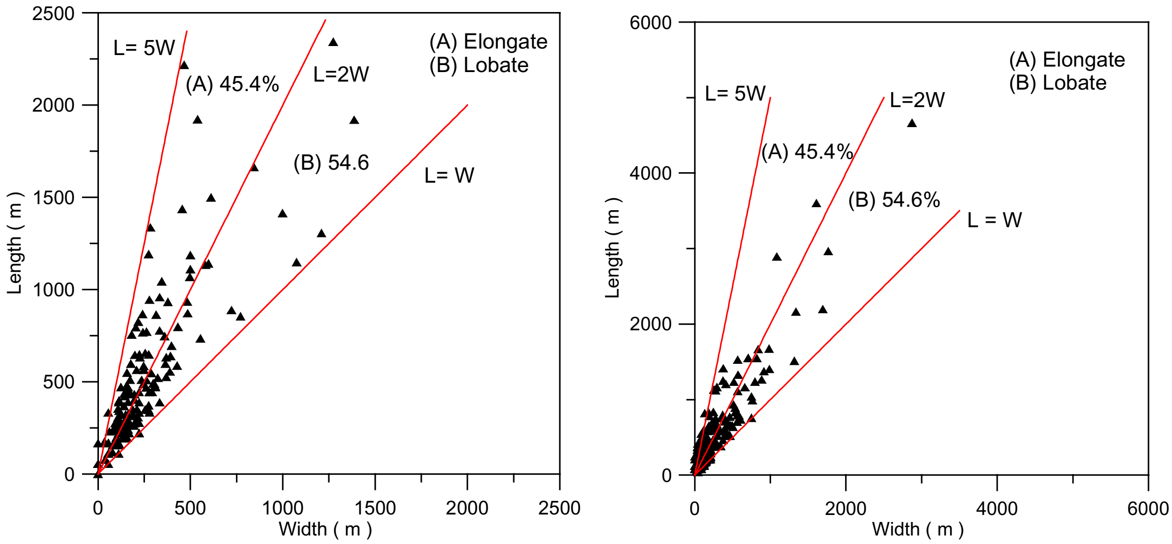


Figure 5. Coordinating the geometrical properties (area, centre) for each landslide using eVision.

Geometry of landslides by heavy rainfall and earthquake

The preliminary message of landslides is related to its shape, such as the length/width ratio (called landslide elongation). Figure 6 displays the length/width ratio for these two studied cases. It is found that the width of landslides induced by heavy rainfall ranges up to 1400 m. The landslide width triggered by earthquake is up to 3000m. The landslide elongation (L/W) in both types is less than 5. This implies that the landform and geology in these two sites are close. The shape of landslide in central Taiwan is elongate and lobate. The possible landslide mechanism is debris flow and earth flow (Bhandrari & Kotuwegoda 1996). Figure 7 shows that the ratio of elongation/width is less than 8 for rainfall-type landslides and is less than 5 for earthquake-typed landslides.



(a) rainfall type (Rf1) (b) earthquake type (EQ1)

Figure 6. Elongation of landslides triggered by heavy rainfall and earthquake

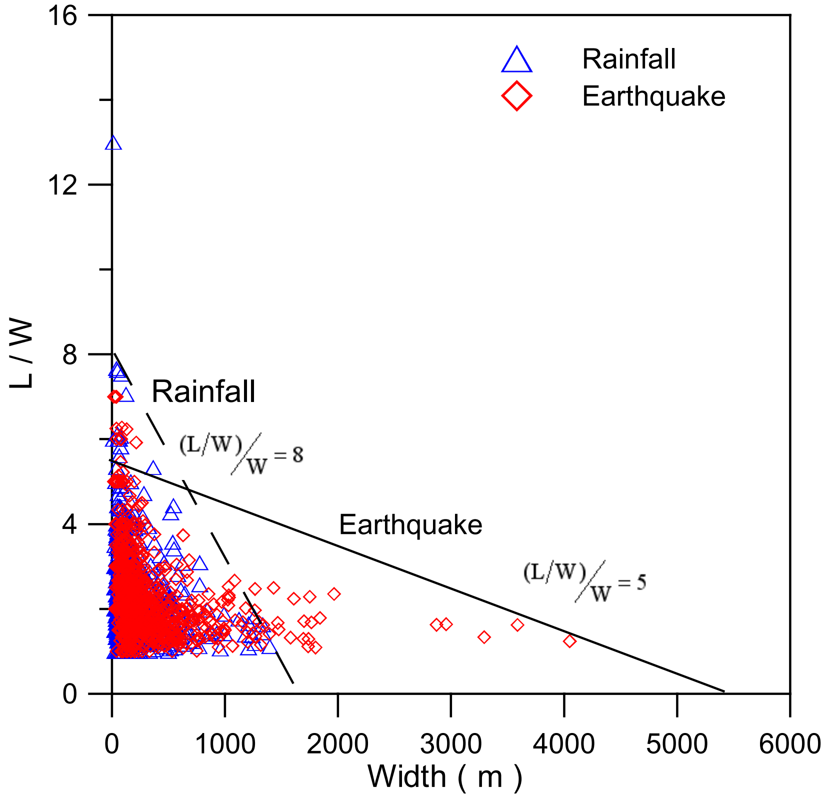


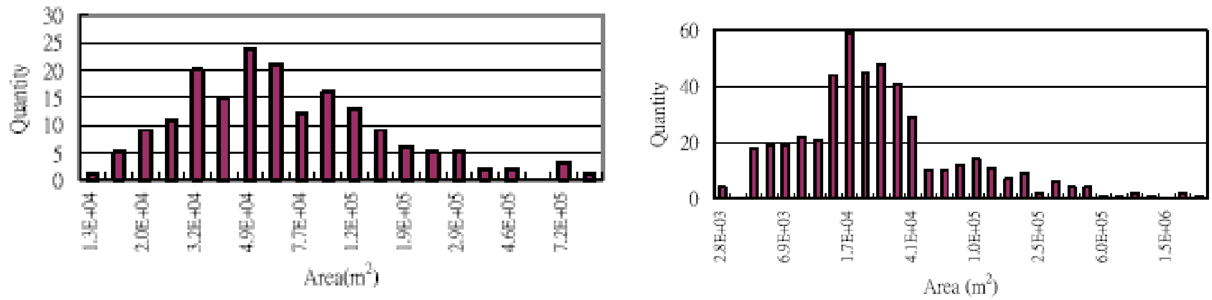
Figure 7. Elongation of landslides triggered by heavy rainfall and earthquake

RESULT OF FRACTAL ANALSIS

Size distribution of landslides

We sieve the landslide area for these two studied cases using several specified area and show results in figure 8 and figure 9. It is found that the distribution in sizes more or less is bell-shaped (i.e., standard distribution). This means that the size distribution of landslides is fractal. The particle-size distribution curves (see figure 9) indicates that the landslide area triggered by earthquake is smaller than that caused by heavy rainfall.

Figure 10 shows that the linearity of the regression line. It means that the size of landslides in area is fractal. The box dimension (D_b) for rainfall-typed landslide is 0.53 and 0.9 for earthquake-typed landslide obtained from the slope of linear regression line. This implies the size distribution of landslides by earthquake is more uniformly-graded than those triggered by earthquake forces. This reason could be that landslides caused by heavy rainfall are primarily controlled by the distribution of rainfall intensity. However, the sizes of landslides triggered by earthquake are determined by the regional geology.



(a) rainfall type (b) earthquake type

Figure 8. Distribution in landslide area by heavy rainfall and earthquake

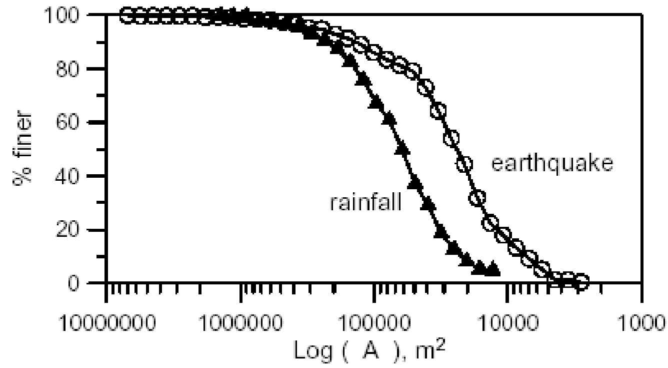


Figure 9. particle- size distribution curve of landslide area

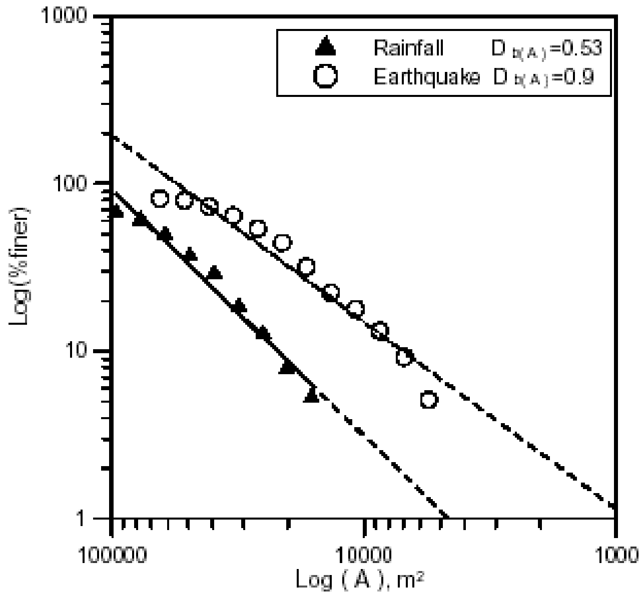
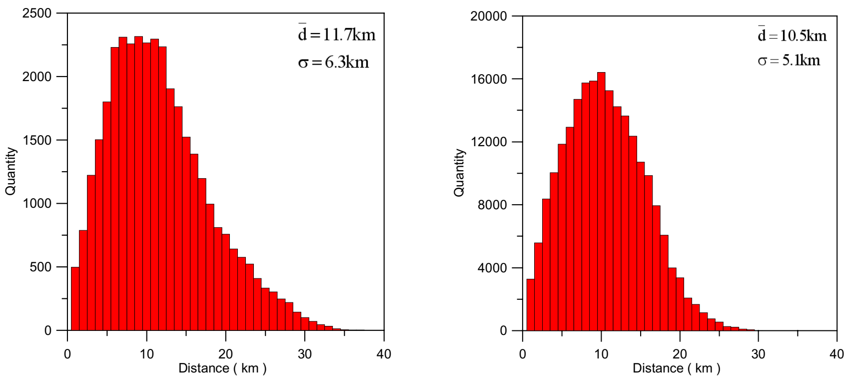


Figure 10. Box dimension of landslide area triggered by heavy rainfall and earthquake

Fractal character of landslide distribution

In the same manner, we calculate the distance of each pair of landslides using the digital data and show the results in figure 11. It is found that the distribution more or less is bell-shaped (i.e., the standard distribution). This means that the distance distribution of landslide locations is fractal. The distance between neighbor landslides has a fractal distribution character. The mean distance between two landslides 11.7 km for rainfall-typed landslides and is 10.5 km for earthquake-typed landslides.

The two-point correlation dimension (D_{corr}) for rainfall-typed landslide is 1.28 (see figure 12) obtained from the slope of linear regression. The value of D_{corr} is 1.41 for earthquake-typed landslide. This means that the distance of landslides in Taiwan is clustering, because both D_{corr} values are smaller than 2. There is the preferable region of slope sliding. The degree of clustering for rainfall type is more serious than earthquake type. This could be that landslides caused by heavy rainfall are mainly controlled by the concentrated intensity of rains in a specified area. However, the landslides triggered by earthquake are primarily controlled by the existing geology condition.



(a) rainfall type (b) earthquake type

Figure 11. Distribution of each two landslide distance triggered by heavy rainfall and earthquake

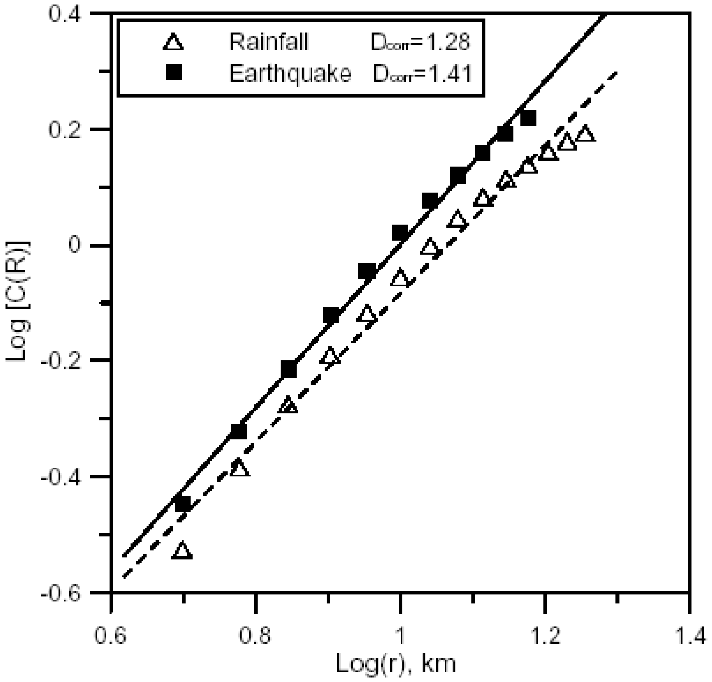


Figure 12. Two-point correlation dimension of landslide area triggered by heavy rainfall and earthquake

CONCLUSIONS

This study shows that both the distribution of landslide in size and distance are fractal in Taiwan. That is, the number of landslide is proportional to the landslide are in power law. The relationship of landslide number and the distance between landslides is also in a power law.

The box dimension for rainfall-typed landslide (0.53) is less than earthquake-typed landslide (0.9). This means that size distribution of landslides by earthquake is more uniform than those by earthquake. The two-point correlation dimension for rainfall-typed landslide (1.28) is less than earthquake-typed landslide (1.41). The distance of landslides in Taiwan is clustering, because both values are smaller than 2. The degree of clustering for rainfall type is more serious than earthquake type. This reason could be that landslides caused by heavy rainfall are mainly controlled by the concentrated intensity of rains in an area. However, the landslides triggered by earthquake are controlled by the geological condition.

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