경기지역 산사태 발생가능성의 정량적 예측

Quantitative Prediction of Landslide Probability in Gyeonggi Province, Korea

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요 약

경기지역에 발생한 약 1,600개의 산사태를 1:50,000 지형도와 1:5,000 지형도를 이용해 정밀 조사하였다. 대부분의 산사태는 토석류(debris flow)로 분류되지만, 산사태 시작부는 전이형(translational) 사태의 성격을 띤다. 강우 이외에 산사태를 발생시키는 지질학적 요인을 찾고자 하루동안 250-300mm의 강우량을 가진 6개 지역을 세부연구지역으로 선정하였다. 이 지역 내 198개의 산사태를 대상으로 현장정밀 조사와 실내실험을 실시한 후, 이를 바탕으로 지구통계학 기법을 이용해 사태발생 원인을 선정하였고, 이에 대한 정량적 가중치를 각각 결정하였다. 분석결과에 의하면 7개 요소가 산사태 발생원인으로 선정되었고, 원인별 정량적 가중치를 부여한 산사태 발생확률을 계산식을 도출했다. 이를 통해 일부지역의 산사태 발생 확률을 구한 후, 실제 발생기록과 비교한 결과 90.74%의 정확성을 나타냈다.

주요어 : 산사태, 산사태 발생원인, 정량적 가중치, 산사태 발생확률

INTRODUCTION

There have been many studies to characterize landslides for several decades throughout the world. The ultimate goal of these studies was to predict and mitigate landslide hazards. Since landslides are caused by many complex factors, it is not a simple problem to solve.

In Korea, it is necessary to reduce damage induced by geological hazards because many landslides during last five years were accompanied by heavy rainfall. The landslides incurred large losses of life and damaged many private and public properties. With these repeated natural hazards, landslide potential areas need to be determined and prediction and prevention techniques need to be developed according to the characteristics of the landslides. To meet these needs, detailed studies, such as the following, have to be performed; 1) examination and systematization of influential factors on landslides; 2) computation of weighting values of the factors; 3) establishment of hazard index; and 4) production of landslide probability map.

The detailed studies mentioned above have been performed in Korea. The study area is the Gyeonggi province, in the central part of Korea, where many severe landslides occurred after heavy rainfall. More than 1,600 landslides were surveyed. Among these landslides, detailed investigations were carried out at over 800.

PRECIPITATION OF RAINFALL

Olivier et al. (1994) suggested a method to calculate landslide potential using annual precipitation and intensive precipitation of an event. They reported that intensive precipitation more than 20 % of mean annual precipitation during 24 hours tends to produce large landslides. For example, an analysis of precipitation in the Chulwon area, northern Korea in 1996 revealed that the coefficient of final landslide response is 1.41. The coefficient of intensive precipitation records 37 %, although the cumulative precipitation record from January to June does not show much difference from mean annual precipitation. This means that the intensive rainfall for one day caused the landslides near Chulwon in 1996 (Kim et al., 1998).

During August 1998, intense rainfall attacked the Gyeonggi province including Seoul. The rainfall lasted for three days. Most landslides concentrated in areas where rainfall was more than 250 mm in twelve hours (from 18:00, August 5, to 06:00, August 6) over the three days. The highest record of precipitation was 534 mm in the Kanghwa area. This precipitation caused more than 500 debris flows on the mountain slopes.

TYPES OF LANDSLIDES

89 % of the landslides in the study area exhibit translational flow. Most of these slides initiated as translational flow at the head and proceeded as debris flow toward the center and toe of the slides. Translational flow showed a type of non-circular failure which the sliding plane formed a planar shear plane. This type of slide is produced by intense rainfall or an earthquake (Canine 1980). The landslides in this area are also mainly caused by intense rainfall that suddenly increases pore pressure and abruptly reduces the shear strength of the soil.

Debris flows usually took place along V-shaped valleys on mountain slopes. Translational slides iniatiated on relatively planar mountain and gradually changed into debris flows composed of a mixture of coarse rock fragments and fine soil material. Fig. 1 shows an example of the transition of a translational slide on the mountain slope (circular ends at the eastern part) into debris flows in the valley.

In case of the landslides in the southern Gyeonggi area, 75 % of the landslides are less than 60 m in length, among which about half are less than 30 m. More than 80 % of the slides are narrower than 10 m, and 6 to 10 m wide landslides are most common.

Nearly almost all landslides cut below the 1 m thick surface material. On the other hand, the maximum size of landslides is more than 250 m long in northern Gyeonggi area. These features are thought to result from the steeper slopes that occur in the northern area. Although most of the landslides are quite small in size, they destroyed a lot of property and many lives were lost suddenly and unexpectedly. It is because, in Korea, many residential areas are located near foots of mountains and along mountain valleys (Kim and Chae 1998).

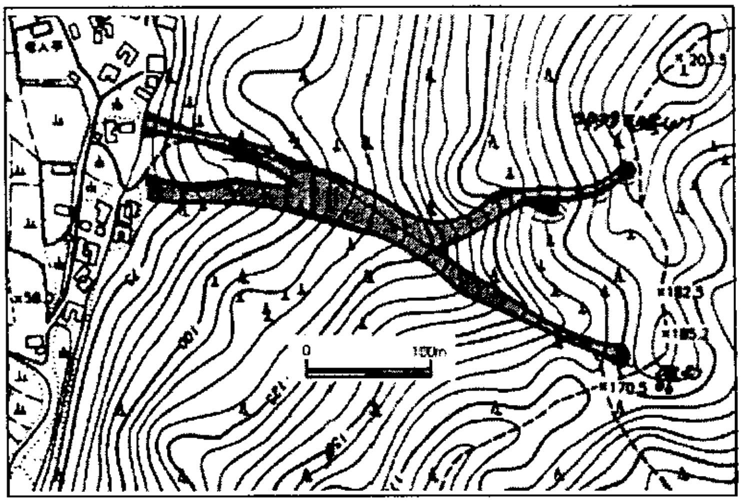

Fig. 1. Example of a landslide. Translational sliding in the upper part changes into debris flow moving down to the valley.

INFLUENTIAL FACTORS ON LANDSLIDES

A detailed field survey was carried out to identify the influential factors on the landslides. The field surveys were conducted at two scales, 1:50,000 and 1:5,000. The regional survey at the 1:50,000 scale allowed identification of the distribution and general characteristics of the landslides, whilst the mapping at the 1:5,000 scale was performed to obtain detailed information for critical causes of landslides.

As mentioned above, rainfall is the key factor producing landslides. However, the authors tried to discover important geological factors in addition to rainfall. Although there is similar quantity of rainfall in some areas, the features and frequencies of landslides are different. This might be due to geologic conditions. To recognize the effects of geologic conditions and differences, analyses of geomorphology and soil properties were performed in relation to lithology.

To exclude effect of rainfall, six sites of equal amounts of rainfall precipitation were selected. Fig. 2 shows three sites of the pilot sites. The pilot sites have about 250 mm of precipitation for 12 hours. Moreover, areas composed of different lithologies have been selected to identify factors of landslides. The detailed survey of the pilot sites was performed at the 1:5,000 scale.

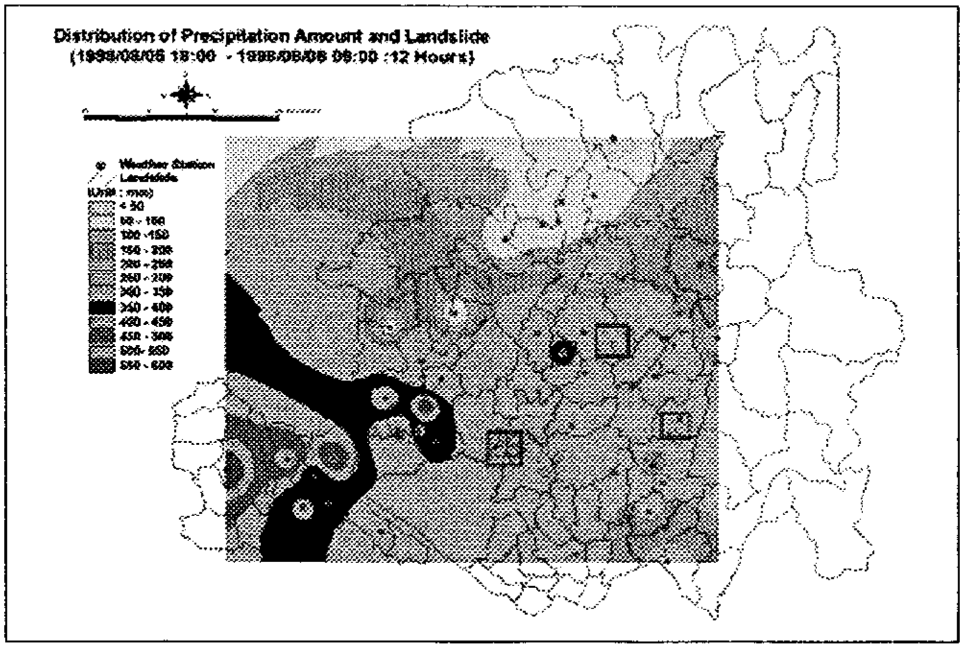

Fig. 2. Contour diagram of precipitation for 12 hours at the study area. Boxes are pilot sites of detailed survey of landslides.

Geomorphology

Geomorphology of the triggering position controls magnitude and direction of landslides as well as occurrence. The frequencies of landslides tend to increase with higher elevation in the mountains. The ratio between landslide elevation and mountain ridge elevation shows that the levels of 90 % of the ratio have the highest frequency of landslides. The frequency decreases with lower elevation ratios. The frequency of landslides abruptly decreases below 70% of the elevation ratio.

With respect to absolute elevation, for example, the southern Gyeonggi area consists of low mountains, approximately 200-300 m in height above sea level, except small portion of high mountains. According to the statistical analysis of the 665 landslides, 78 % of the landslides occurred at altitudes below 300 m. Among these, 85 % were initiated on the flat flanks of mountains, and then flowed down to the valley, whilst 14 % of the landslides initiated in the valleys. The reason why most of the landslides triggered on the flanks of mountains might be that top soil on the flat flanks does not have enough density and compaction to resist against sliding. Top soil on the flanks whose thickness is very shallow (50 cm of less) is in contact with bedrock. Loosely compacted top soil and the boundary between rock and soil are very susceptible to sliding (Chae et al. 1998).

In the case of average slope inclination, 32 % of the landslides occurred on slopes between 26 and 30 degrees, the angle most susceptible to landslides. In terms of the triggering position, about 33 % of landslides also occupied slope angles between 26 and 30 degrees. Landslides seldom occur below 20 degrees; slope angles steeper than 20 degrees show an abrupt increase in landslide frequency. The increasing trend changes gradually into a decreasing one with slope angle steeper than 30 degrees.

Soil property

The landslides in the study area are classified as debris flows with respect to their compostion (Varnes, 1978). The slide materials mainly consist of debris mixed with soil sediments and rock fragments derived from top soil and colluvium. The shallow top soil is underlain by basement rock, whereas relatively thick colluvium has been deposited along the narrow valleys. As sliding proceeds, the debris of the area is eventually formed with mixed materials such as top soil on the flanks and colluvium in the valleys.

Lithology of the area consists predominantly of granites, schists, and biotite gneisses. The gneisses contain the highest frequency of slides per unit area at 45 %, and landslide frequencies in the schists and granites are 32 % and 23 %, respectively. In order to investigate soil properties, 81 samples of landslide material and 64 samples of non-landslide material were taken from lithologically different areas. Laboratory tests for eight items per sample made it possible to compare physical properties of landslide material with that of non-landslide material. Plotting grain sizes of the samples shows a scatter pattern on the diagram of gravel-sand-slit/clay. However, in general, amounts of gravel are less than those of sand and silt/clay.

Many papers have reported that permeability plays a major role in landslide occurrence. The permeability coefficients of the study area are distributed with a broad range according to lithology. The permeability of granite is higher than that of gneiss and schist with one order difference (Fig. 3). Comparison of permeability with landslide frequency reveals that the high permeability seldom occurs in the landslides. This corresponds to the facts that the areas composed of granite have the lowest landslide frequency per unit area in the study area.

PROBABILISTIC PREDICTION OF LANDSLIDE

Statistical Method of Determining Weighting Values

Many studies have been done to determine the factors inducing landslides and to predict the probability of landslide occurrence. However, most of these studies determine probability or susceptibility using subjective and qualitative methods. In particular, many landslide susceptibility maps were made with a relative index of susceptibility, not with

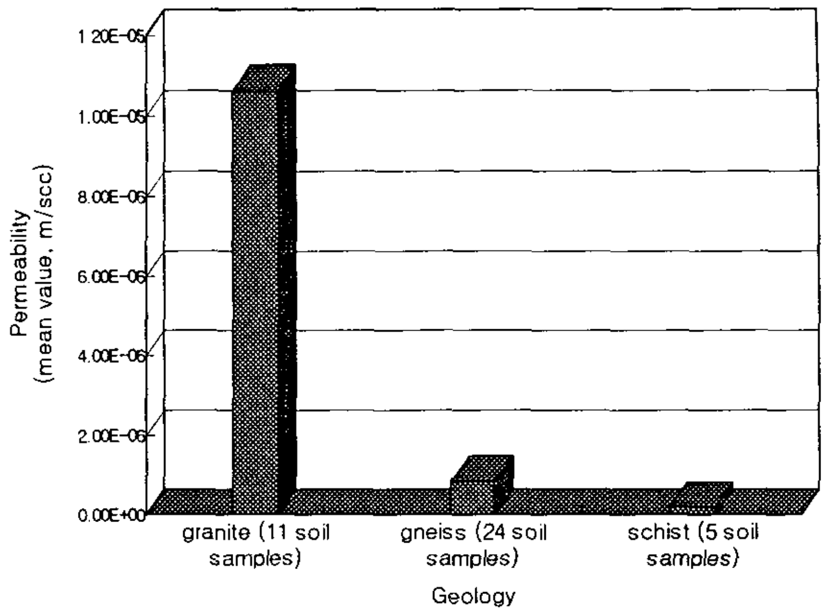

Fig. 3. Permeability values of the three different lithologies. Granites have higher values, as much as one order than the other lithologies.

a quantitative one. In this study, the authors tried to determine theinducing factors of landslides and to develop a quantitative probability index of landslide occurrence using statistical methods.

The data obtained from the field survey were treated with analysis of correlation. 116 samples, 79 samples of landslide points and 37 samples of non-landslide points, were used for statistical analyses. Factors with high correlation were selected based on the results of correlation analysis. The selected factors were then analyzed to determine the weighting value of the factors using logistic regression analysis.

Correlation analysis showed seven factors as influential factors of landslides. Among the factors, lithology and grain size distribution are categorical data, and elevation, slope angle, dry density, porosity and permeability, are numeric data. Then, the principal analysis and logistic regression analysis were performed using these factors. Logistic regression analysis was used to develop a model equation to calculate the probability of landslide occurrence (Eq. 1).

$$LOGIT = 1.6703 \times LITHOLOGY1 - 0.9297 \times LITHOLOGY2 - 0.0478 \times POROSITY + 8.0563 \times DDENSITY - 3.8434 \times USCS\_1 - 1.1759 \times USCS\_2 - 2.7296 \times USCS\_3 - 4.1590 \times USCS\_4 + 19294.09 \times PERMEABILITY + 0.0136 \times ELEVATION + 0.1867 \times SLOPE\_ANG - 12.9838 \quad \text{(Eq. 1)}$$

The coefficient of logistic regression can be used as the weighting value of a factor. Substitution of logit value into Equation 2 allows calculation of the probability of landslide occurrence at a position.

$$Ps = EXP(LOGIT) / (1+EXP(LOGIT)) \quad \text{(Eq. 2)}$$

The importance of the above method is that quantitative weighting values are assigned to the influential factors.

Probabilistic Map of Landslide

The probabilistic map of landslides, the final product of this study, was made using GIS tools on the basis on the statistical analysis. Two maps were made in northern Gyeonggi area at the 1:5,000 scale (Fig. 4) as examples of probabilistic maps of landslides. The distinguishing point of these maps is that they were made with a calculated, quantitative probabilistic index of landslides. The index was calculated using a very scientific and correct method, not by a subjective and qualitative one. Probability of landslides makes it easy to understand the meaning of the hazard index.

Verification of the applicability of the suggested method shows that it has high value of correctness. For further studies, the method needs to be modified to include more various geologic conditions such as volcanic rocks and sedimentary rocks as well as rainfall effect. Moreover, a representative logit equation to cover Korean peninsula has to be developed.

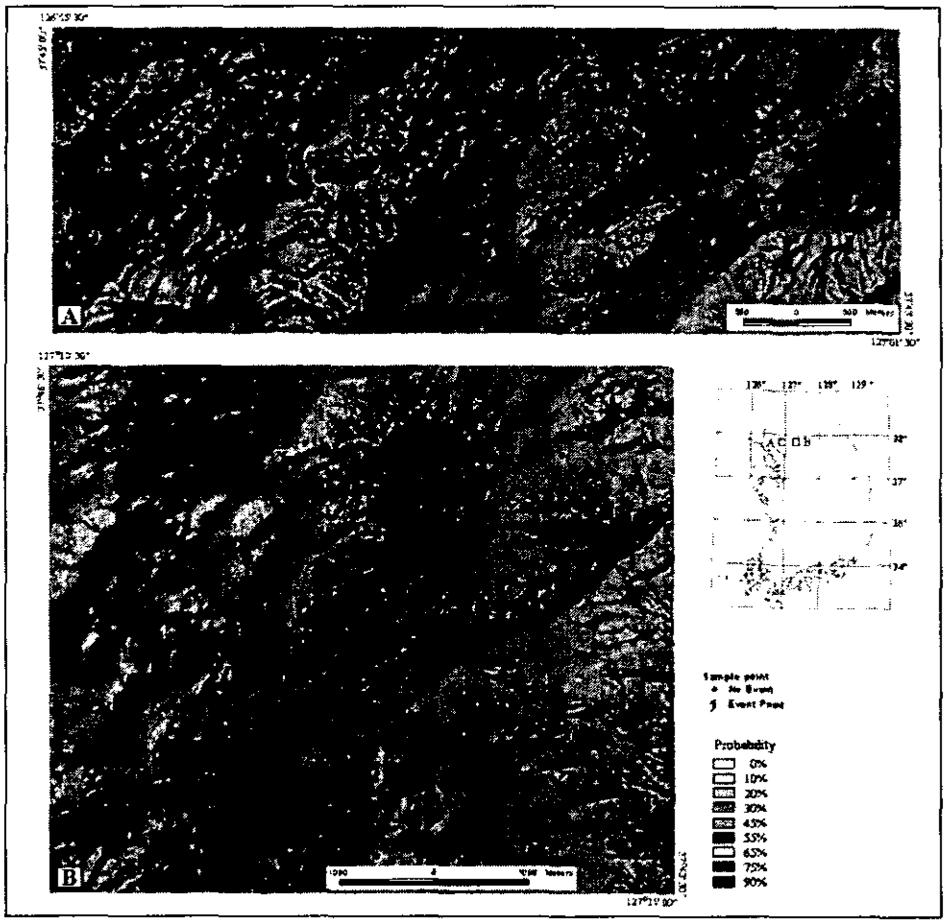

Fig. 4. Probabilistic map of landslide potential. This map was drawn using the quantitatively determined index of probability.

CONCLUSIONS

Most landslides are induced by intensive rainfall during the rainy season. Landslides are typically translational at the triggering position, then change into debris flows as they move down slope. The geomorphology at the triggering location strongly controls the frequency and magnitude of landsliding on the basis of the down slope change in landslide type.

The influential factors of landslides were selected using a statistical method. The factors can be grouped as geomorphologic and soil properties. The geomorphologic factors include elevation and slope angle, whilst the soil properties are dry density, porosity, lithology, permeability, and grain size distribution. The weighting value of each factor was determined by logistic regression analysis. This method assigns quantitative weighting values to the influential factors, which makes it possible to set up a quantitatively correct index of landslide probability.

The probability maps of landsliding in the study area were made using statistical methods and GIS tools. The distinctive mark of the maps is that they are based on a quantitative probability index of landslides calculated using a very scientific and correct method, not by a subjective and qualitative one. This form of presentation using landslide probability makes it easy to understand the meaning of the hazard index.

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