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Prediction of rainfall-triggered landslides in Korea

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ABSTRACT : The features of landslides occurred in Korea are first reviewed in this paper. Based on the landslides occurred from 1977 to 1987, relationships of rainfall-landslide occurrences are analysed statistically, and a regional features for the disaster is known from the analysis. A correlation of landslide event and rainfall intensity can be established, which can be used as a warning system in predicting rainfall-triggered landslide disaster. In order to understand the failure mechanism of a slope due to heavy rainfall, a series of experiments is performed and the results are shown in the latter part of this paper.

1. INTRODUCTION

The annual rainfall of Korea ranges from 1,100 mm to 1,400 mm, most of which concentrates in wet seasons beginning at June through September. The concentration of the rainfall causes a lot of disasters and brings loss of lives and property damages every year. The heavy rainfall in Korea is due to either by movable troughs of low air pressure or by typhoons.

A survey of rainfall and landslide occurrences is made throughout the whole country with the meteorological records of the period from 1977 to 1987. The effects of antecedent rainfall and rainfall intensity on landslide occurrences are focused in this investigation.

In addition to the statistical approach, a series of experiments is performed for a model slope which can simulate actual rainfall pattern of different rainfall intensities. The objective of this experiment is to investigate seepage behavior when the rain infiltrates into the unsaturated ground. This would contribute to understanding the mechanism of slope instability due to rainfall.

2. LANDSLIDES IN KOREA

2.1 Topography and Geology

The topography and geology of Korea have been described in detail by Um and Reedman (1975), and Lee (1988). Korea covers an area of 221,000 square kilometrs including the peninsula, Cheju and Ulnung islands, and other small islands. About 70 percent of the total area is mountainous. However, the moutains are not very high, averaging 482 meters in altitude. The Taeback Mountains, forming the backbone of the peninsula, run in a north-south direction along the east coastline. Two big rivers, the Han and the Nakdong have their sources in the Taeback Mountains and they flow to the west and south, respectively. Other big rivers such as the Kum, Yungsan, and Sumgin start in the Soback Mountains. The first two flow to the Yellow Sea and the latter to the South Sea (Fig.1).

The Taeback Mountains forms the principal divide in the topography of Korea, and lead to the topographic contrast between the eastern and western areas. The topography of the east area is rugged and steep. The land surface of the western slope represents an old-age terrain with a gentle slope traversed by highly sinuous meandering rivers.

The southern coasts of the Korean Peninsula show extremely irregular shorelines involving points, peninsulas, and bays. Many spotted islands in the western coasts actually represent extensions of onshore mountain ranges. These topographic features suggest the slow submergence of the western part of the peninsula. Meanwhile, the eastern coast is characterized by a steep, nearly straight shoreline with narrow sandy beaches. This indicates an uplift of the eastern part of the peninsula.

Geology of Korean Peninsula consists of various strata aged from Archiozoic to Cenozoic era. Gneiss and Schist complex of Archeozoic to Middle Proterozoic age form the basement of the entire Korean Peninsula, and granite was emplaced during Mesozoic era throughout the Peninsula. Sedimentary rocks are exposed in

Fig.1 Geographic map of Korea

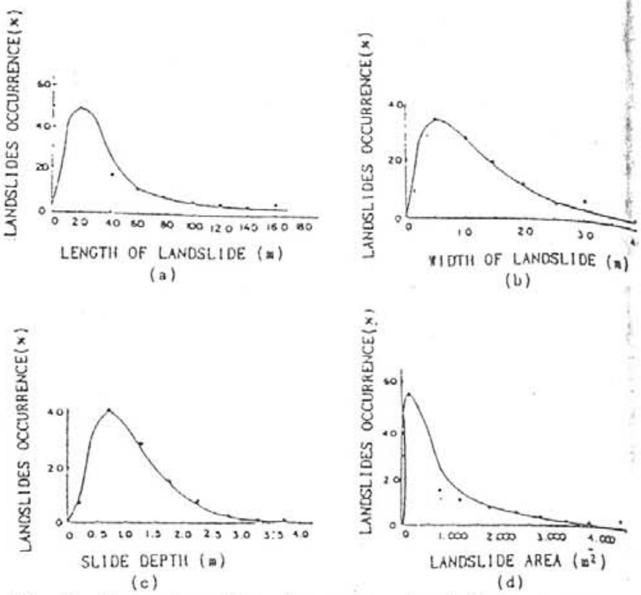

Fig.2 Relationship between landslide occurrence and (a)length (b)width (c)depth and (d)slide area(Choi,1986)

southeast corner of Korea with limited thickness. Thus, the most predominant rock types are gneiss, schist, and granite, which cover two thirds of the total land.

Regardless of soil types, the depth of residual soils on hillsides is limited to a few meters as a maximum. But the weathering depth in Korean granites may exceed 30 m on the lower slopes (Lee, 1987). This is compared with other deeply weathered granitic areas such as Hong Kong (60 to 100 m). The fairly shallow depth of weathering, which greately affect the mode of slope failure, is due to the moderate climate and to erosion. The rate of erosion which occurs mainly during seasonal heavy rainfall, ranges from 1.5 to 4 cm per year at 20 to 30 degree inclination of hillside (Lee, 1987).

2.2 Features of landslides in Korea

Landslide occur in every hilly topography and mountainous area, and thus the occurrence is not restricted to specific areas. 97 percent of the landslides in Korea have occurred during the period of three months from July to September. This is consistent with the rainy season in Korea, and their occurrences are therefore closely related to meteorological phenomena. Also, the frequency and damaged areas vary according to meteorological conditions of the year.

Choi(1986) has studied landslide occurrence throughout the nation from 1980 to 1984. His survey shows that most landslides initiated on the hillside of long slopes and that debris flowed down to the toe of the slope. Their general patterns were shallow and straight, and isolated individual landslides were dominant.

The characteristics of length, width, depth, and slide area of landslides has been well investigated by Choi(1986), as shown in Fig.2. The failed slope length was usually about 20 meters, which accounted for 50 percent of the total landslides. These with a failed length over 100 meters were only 14 percent. About 90 percent of the landslides was below 20 meters in width, and 91 percent of them was below 2 meters in depth. The area damaged by a landslide was usually less than 2,000 m^3. Thus, it is known that landslides in Korea occur frequently but on a relatively small scale.

When the bedrocks are composed of biotite granite, schist, or slate, landslides can take place easier than with other bedrock types. About 77 percent of the landslides occurred in hillsides and concave terrain. A majority of the landslides took place at slope angles between 30 and 35 degrees but there were exceptions that occurred at gentle slopes of below 30 degrees, some of them being large.

3. RELATIONSHIP BETWEEN RAINFALL AND LANDSLIDE

3.1 Rainfall characteristics in Korea

There can be many external causes that trigger natural disasters. During last ten years from 1977 to 1986, the occurrence frequency of heavy rainfall, typhoons, storms, and rainstorms, all of which are related to rainfall, is over 77 percent. The disaster due to earthquake is only one single case reported during the entire period. Total damage is, of course, not proportional to the numbers of disasters, but rainfall-related disasters absolutely dominate all the others in terms of casualities and damage.

Annual precipitation in Korea is highly seasonal, averaging from 1,100 to 1,400mm. Since precipitation depends highly on wind direction and topography, it will be vary widely for different years and places. For example, the rainfall in Seoul in 1940 was 2,135mm but in 1949 only 633.7mm.

There are also great differences in the seasonal distribution of rainfall. About 86 percent of the yearly rainfall is concentrated on the period from June through September. Furthermore, daily rainfall is more than 300mm, which is about one fourth of the average annual rainfall, has often occurred in summer seasons. The maximum, 530mm, was recorded in Echun in September 11, 1990 (MOC, 1991). Such unusual rainfalls present extremely difficult problems in predicting and preventing natural disasters.

The heavy rains in Korea are produced either by movable troughs of low air pressure (seasonal rain front) or by tropical low pressure (typhoons). The seasonal rain front is formed when the warm and moist North Pacific air masses approach the cold moist air masses of the Okhotsk Sea covering the nation. The rain front moves up and down to the north and south and brings heavy rain.

When typhoons pass across the Korean peninsula in the wet seasons, they usually bring heavy rains with storms. The typhoons hit the nation mostly in July through September, and the southern areas of Korea are usually under their influences. But they also have an effect on the central area of Korea from time to time.

According to rainfall pattern, South Korea is divided into three regions as follow:

(a) The central area(Kyonggi-Do, Chungchong-nam-Do, Chungchongbug-Do, northern part of Chollabug-Do, see Fig.1) where heavy rain is mainly produced by the low-pressure troughs.

(b) The southern area(southern part of Chol-labug-Do, Chollanam-Do, Kyongsangnam-Do, Kyongsangbug-Do), which are mainly under the direct influence of typhoons.

(c) The eastern mountainous area (Kangwon-Do) situating along the Taeback Mountains, which is affected less by both troughs and typhoons.

3.2 Effect of antecedent rainfall on landslides

It has been well known that rainfall is the most significant factor affecting on landslide in every country. There has been controversy, however, whether the rainfall intensity or antecedent rainfall governs landslides.

Fig. 3 shows relationship between daily rainfall at failure and 3-day cumulative rainfall before the failure. The plot on a broken line on the figure means daily rainfall at failure and cumulative rainfall are the same at failure. This, therefore, can be used as a guide line about which rainfall governs landslides.

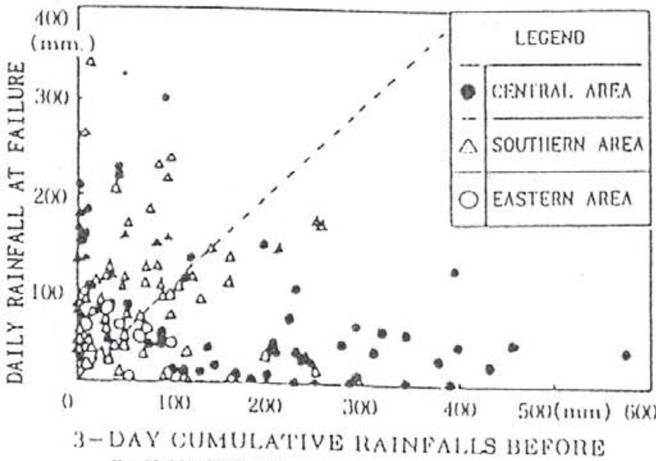

Fig.3 Correlation of daily rainfall at failure and antecedent rainfall

As shown in the figure, the landslides occurred in the central area are mainly plotted below the broken line, which means that those are influenced by cumulative rainfall. It is noted that the heavy rainfall in this area is governed by troughs of low air pressure.

On the other hand, the landslides occurred in the southern area are generally plotted above the broken line. Thus, the landslides occurrences in this area are mainly governed by the intensity of daily rainfall at failure. Heavy rainfall in this area is usually produced by typhoons as said before.

Meanwhile, the occurrence pattern of the landslides in the eastern mountainous area is different from those in above two areas. Frequent landslides can occur even with small amounts of rainfall as shown in the figure. It can be known that both the daily rainfall at failure and antecedent rainfall are below 100 mm. The landslides in this area are less influenced by troughs and typhoons.

3.3 Regional features of landslide occurrences

A typical relationship in the central area is presented in Fig.4, in which most failure occurred one or two days after having reached peak hourly rainfall intensity. In this case, therefore, the antecedent rainfall was more significant than the peak rainfall intensity on the failure day. It is noted that heavy rainfall in this area was mainly caused by troughs.

Fig.5 gives a typical relationship between rainfall and landslide occurrences in neibouring area of Choongmoo, which is in the southern area of Korea. The distribution of both rainfall and its peak intensity in this figure is almost the same as that in the previous figure. In this location, however, the landslide occurrences were mainly governed by rainfall intensity and landslides took place at almost the same time when the peak hourly

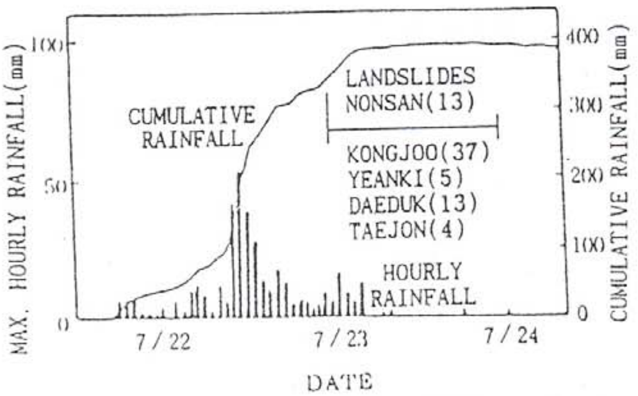

Fig.4 Rainfall data in July, 1987 at Taejon meteorological observatory and occurrence of landslides in neibouring area of Taejon

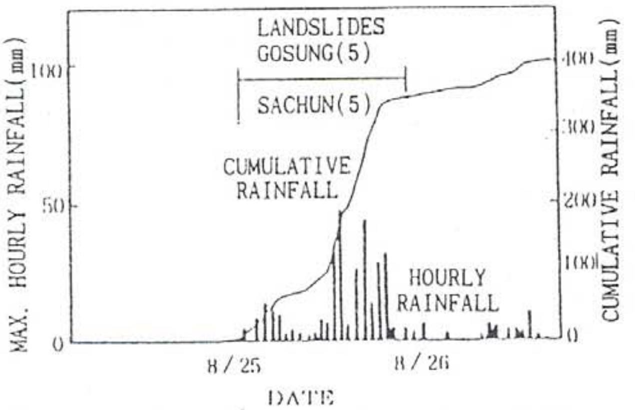

Fig.5 Rainfall data in September, 1979 at Jinjoo meteorological observatory and occurrence of landslides in neibouring area of Choongmoo

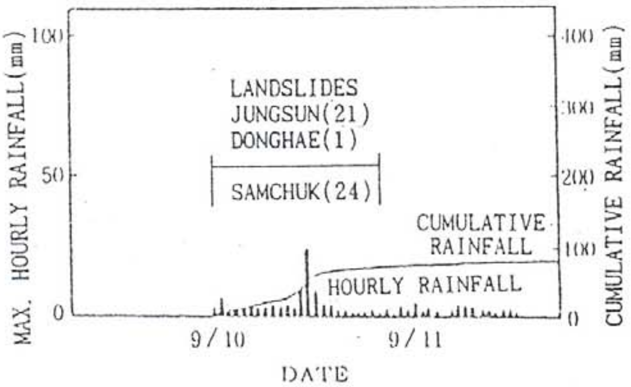

Fig.6 Rainfall data in September, 1980 and occurrence of landslides in neibouring area of Sokcho

rainfall was reached. In this case, antecedent rainfall was not a major factor in triggering landslides.

Rainfall in the eastern area exhibited a completely different pattern from that in above two zones, because both rainfall intensity and cumulative rainfall were considerably low, as shown in Fig.6. This is where annual rainfall is also fairly low compared with other areas of Korea. Landslides, However, might occur even when 24-hour rainfall was below 100mm. This zone has experienced numerous landslides in spite of somewhat neglegible rainfall. One reason for that seems due to the steep mountainous terrain.

It is noted that rainfall varies with geography particularly during rainstorms. Even in a single place the amount varies with ground elevation, as indicated by Brand (1985). In correlating rainfall with landslides, an observatory may be several kilometers away from the landslide areas. It can not be stated that the reliability of the relationship is high enough. But the regional features for landslide occurrences could give a significant suggestion in predicting landslide events in Korea.

3.4 Relationshiop between landslide events and rainfall

In similar way as Lumb(1975) classified the landslide events, those in South Korea also can be divided into 'disastrous', 'severe', and 'minor' according to the numbers of landslides.

The division herein is that the occurrences over 20 is disastrous, 4 to 19 severe, and 1 to 3 minor at an area neibouring an observatory. The number of landslides herein gives the number of individual failures occurring at one time. It is concluded that (Fig.7):

(a) A disastrous event can occur when not only peak hourly rainfall is over 35mm but also 2-day cumulative rainfall over 140mm.

(b) A severe event can occur when not only peak hourly rainfall is over 15mm but also 2-day cumulative rainfall over 80mm.

(c) A minor event can occur when not only peak hourly rainfall is over 10mm but also 2-day cumulative rainfall over 40mm.

The division for the three categories shown in Fig.7 is not so clear because the investigated area covered the whole land of South Korea. It is therefore desirable that a

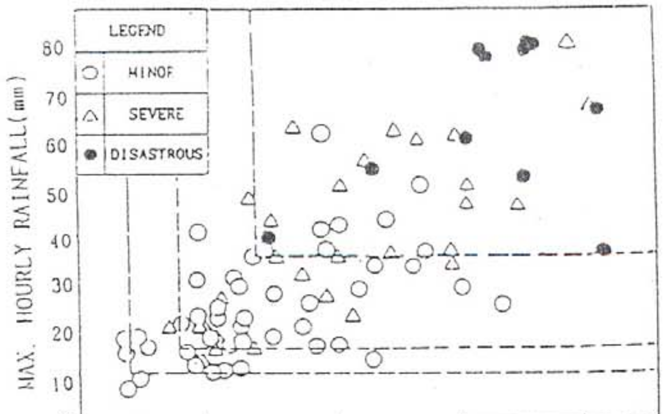

Fig.7 Relationship between landslide event and rainfall

division should be made based also on the regional features which appeared in previous figures. The data which we have now, however, will be available as a crude means of a warning system for predicting landslide disasters.

4. EXPERIMENTS ON MODEL SLOPE

4.1 Description of test equipment and testing programs

A model study is performed to simulate actual rainfall for a inclined slope. The test equipment may be divided into three parts: rainfall controll device, a model slope, and recording systems, as shown schematically in Fig. 8.

The rainfall control device is designed so as to simulate the intensity of rainfall by controlling the amounts of water pumped up to the upper water tank. The rain falls through 121 needles with the inner diameter of 1.3mm, which are attached to the bottom of 10 water suppling boxes. The height of the rainfall control device can be adjusted by use of height control chains.

The main body containing the model slope is 2.0 m long, 0.2 m wide, and 1.0 m high. The box is made of steel frames and acryl plates, and 5 cm-spaced mesh is put on the front side of the box to observe the deformation of slope. On the other side of the plate, standpipes are attached to measure the pore pressure. The surface of the model slope is inclined to be 30 degrees to the horizontal plane.

The soil samples used in the experiment are fine sand taken from the Han river and weathered soil. The coefficients of permeability after the formation of the slope are $6.7x10^{-4}$ cm/sec for the fine sand and $6.3x10^{-5}$ cm/sec respectively.

Soils are put in the box and compacted with constant static energy to keep a constant void ratio. The depth of the slope formed in this manner is 50 cm.

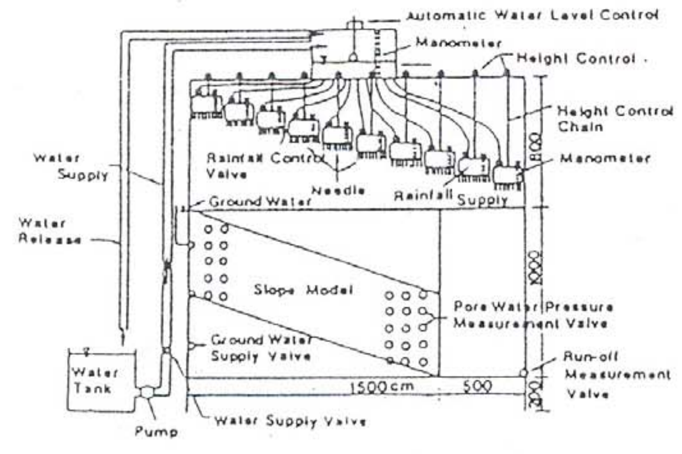

Fig. 8 Schematic view of test equipment

With this apparatus the intensity of rainfall can be intentionally changed from one to 30 times of the coefficient of permeability for fine sand (1k - 30k), and from 0.24 to 20 times for the weathered soil.

4.2 Experimental results

When rain infiltrates into the ground, unsaturated soils become wet and the wetting front advances deeply beneath the ground. The infiltration behavior of rain may be dependent on the rainfall intensity. Presented in Fig. 9 is the advance of the wetting front with elapsed time, under continuous rainfall through the fine sand specimens. Up to the rainfall intensity that is five times of the permeability of soil specimen, the advance rate of the wetting front increases with increment of the rainfall intensity. However, when the rainfall intensity exceed five times of the permeability of soil specimen, the advance rate of the wetting front is not dependent on the

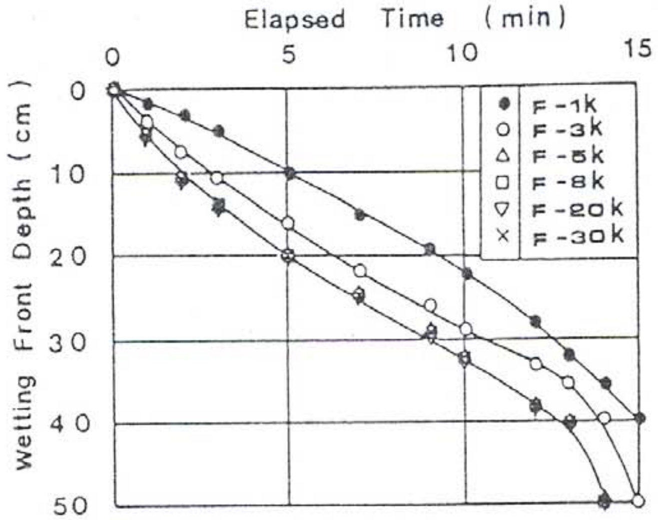

Fig. 9 Advance of the wetting front for fine sand specimens

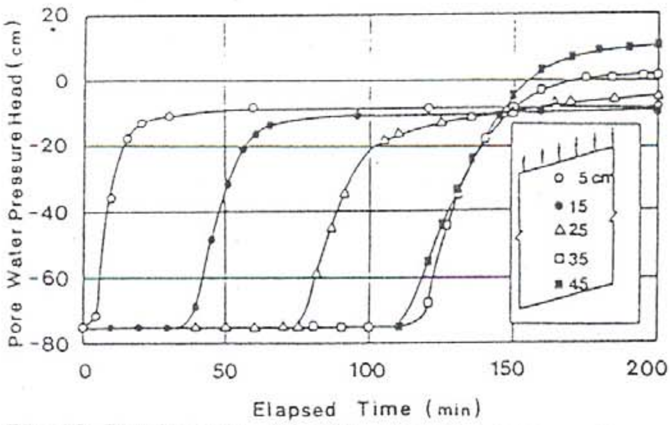

Fig. 10 Development of pore water pressure for weathered soil specimens

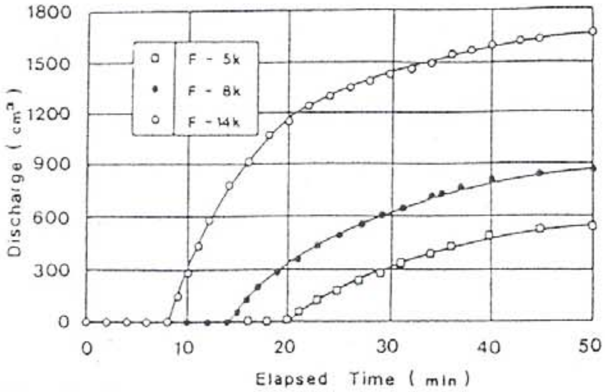

Fig.11 Discharge along the ground surface

rainfall intensity any more. Therefore, it can be seen that the maximum rainfall intensity needed to infiltrate into the ground is five times of the coefficient of permeability of the soil. The maximum rainfall intensity for the coarse sand specimens was four times of the coefficient of permeability (the result is not appeared here).

The wetting front causes the increase of pore water pressure as well as an increase of soil density, which may act as detrimental factors initiating landslides occurrences.

Fig.10 shows the development of pore water pressure for the weathered soil with elapsed time under continuous raining. When the wetting front advances to the depth where the piezometer is installed, the pore water pressure is increased suddenly due to sudden increment of moisture content in soil. The pore water pressure at the depth of 45 cm begins to show positive value at 152 minute, which means the water table begins to rise at that moment. From this moment, the stability of slope is decreased faster. However, the pore water pressures at the depth above 35 cm show still negative value at 200 minute. It means that full saturation did not reach throughout all depth even though the wetting front advances deeper.

Shown in Fig.11 is the relationship between discharge and elapsed time for different rainfall intensities. As expected, the greater the rainfall intensity is, the more the discharge along the ground surface becomes. Also the greater the intensity is, the shorter the time for starting to discharge becomes. The discharge can erode the ground surface, and might be associated with landslides. This simple experiment suggests that high intensity of rainfall occurring in a short duration could be closely related to the erosion of sloping ground surface.

5. CONCLUSIONS

In order to investigate how the rainfall is related to the occurrence of landslides, two kinds of approaches were performed in this paper. One is a statistical analysis on the landslides records from 1977 to 1987 in South Korea, the other is a series of experiments performed on model slope which can simulate various rainfall intensity.

Heavy rainfall can be caused either by troughs of low air pressure or by typhoons and is concentrated on the period beginning at June through September. Because of unique meteorological characteristics and topography of Korea, the rainfall, which can trigger landslide, shows regional features in terms of rainfall intensity and cumulative rainfall. Landslides in the southern area are governed by the intensity of rainfall, and thus they usually occur during or directly after the heavy rain, while those in the central area are governed by the antecedent rainfall. In the eastern area, landslides can occur even with small amounts of rainfall because of rather steep terrains.

The maximum rainfall intensity needed to infiltrate into the ground is four to five times of the coefficient of permeability of soil. The higher intensity of rainfall over the maximum could be closely related to the erosion of sloping ground surface.

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