The Journal of Engineering Geology, Vol.18, No.2, June, 2008, pp. 191-196

A Case Study on Analysis of Landslide Potential and Triggering Time at Inje Area using a RTI Warning Model

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RTI 경보모델을 이용한 강원도 인제지역의 산사태 가능성 및 발생시간 분석 사례 연구

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This study is a case study for application of the RTI warning model to Korea which was previously developed to predict landslide potential and occurrence time during a rainfall event. The rainfall triggering index (*RTI*) is defined as the product of the rainfall intensity I (mm/hr) and the effective accumulated rainfall R_t (mm). This index is used to evaluate the landslide and debris-flow occurrence potential at time t during a rainfall event. The upper critical value (RTI_{UC}) of RTI and the lower critical value (RTI_{LC}) of RTI can be determined by historical rainfall data of a certain area. When the rainfall intensity exceeds the upper critical value, there are high potential to occur landslides. The analysis result can predict landslide occurrence time of an area during a rainfall event as well as landslide potential. The result can also be used as an important data to issue early-warning of landslides. In order to apply the RTI warning model to Korea, this study analyzed rainfall data and landslides data in Inje county, Gangwon province, Korea from July 13 to July 19, 2006. According to the analysis result, the rainfall intensity exceeded the upper critical value 23 hours ago, 11 hours ago, and 9 hours ago from 11:00 in the morning, July 16. Therefore, landslide warnings would be issued three times for people evacuation for avoiding or reducing hurts and damages from landslides in mountainous areas of Inje.

Key words : rainfall event, landslide, RTI warning model, occurrence time, landslide warning

이 연구는 집중호우시 산사태의 발생가능성과 발생시간을 사전에 예측하기 위한 노력의 일환으로 기존에 개발된 RTI 경보모델을 우리나라에 적용 분석한 사례이다. RTI(Rainfall Triggering Index)는 강우강도(I)와 유효 누적강우량(R_t)의 곱으로 정의되는 것으로서, 강우기간 동안 특정 시간(t)에서 산사태가 발생할 가능성을 평가하는데 사용된다. RTI의 상부임계값(RTI_{UC})과 하부임계값(RTI_{LC})은 과거 산사태 발생시 강우자료 분석을 통해 각 지역별로 설정할 수 있으며, 강우강도가 상부임계값을 초과할 때 실제 산사태가 발생하는 것으로 이해할 수 있다. 이러한 분석은 궁극적으로 향후 집중호우가 내릴 경우 특정지역의 산사태 발생가능성은 물론 산사태 발생시기를 예상할 수 있으며, 이를 토대로 사전에 산사태 발생 경보를 발령하는데 중요한 근거로 활용될 수 있다. 이와같은 이론을 우리나라에 적용하기 위해 2006년 7월 13일부터 7월 19일까지 강원도 인제군 일대에 내린 강우자료와 산사태 발생과의 관계를 분석한 결과, 실제 산사태가 발생한 7월 16일 오전 11시경을 기준으로 23시간, 11시간, 9시간 전에 강우강도가 RTI의 상부임계값을 초과하였다. 이를 토대로 이와 같은 세 차례에 걸친 산사태 경보의 발령이 필요하였음을 알 수 있었다.

주요어 : 강우기간, 산사태, RTI 경보모델, 발생시간, 산사태 경보

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Introduction

Korea has been experienced intensive rainfall in almost every summer influenced by global climate change recently. The intensive rainfall induces enormous frequency of landslides that the civilians have seldom experienced in recent. The landslides hazards in Korea have increased abruptly since 2000, occurring huge damage of the lives and the facilities.

According to the statistics issued by National Emergency Management Agency, Korea, human deaths induced by natural hazards are 6,388 in total, 211 in yearly average, from 1976 to 2005 in Korea (Park et al., 2006). Among them, 1,321 people in total, 47 in yearly average, were killed by landslide hazards. The data indicates that landslide is one of the serious natural hazards recording significant percentage of human deaths as much as 22.3% due to natural hazards. The major landslide type occurred on natural terrain in Korea is debris flow that the flow velocity reaches up to 30 m/sec in the maximum (Chae *et al.*, 2005; Jakob and Hungr, 2005). Therefore, once a debris flow occurs, it is almost impossible to avoid its influence on residents and facilities located at the bottom of mountain slopes.

This study tried to predict potential and triggering time of landslides based on analysis of rainfall intensity at the aspect of landslide warning. In order to predict the triggering time, this study used the Rainall-Triggering-Index (*RTI*) warning model which had been proposed by Jan *et al.* (2004). The *RTI* warning model is a rainfall-based warning model, and can be used to estimate the occurrence potential of landslides and debris flows. The analysis result would be applied for determination of appropriate warning times of landslides. The following is an application of the *RTI* warning model on the landslide potential analysis during a rainfall event between July 13 and 19, 2006 at Inje, Korea.

Rainfall-Triggering-Index (*RTI*)

The rainfall triggering index (*RTI*) is defined as the product of the rainfall intensity I (mm/hr) and the effective accumulated rainfall R_t (mm). This index is used to evaluate the landslide and debris-flow occurrence potential at time t during a rainfall event, i.e.

$$RTI(t) = I \text{¥} R_t(t) \qquad (1)$$

where I is the 60-minute rainfall intensity (in mm/hr); R_t is the effective accumulated rainfall (in mm) which is the sum of accumulated rainfall at time t in a considered rainfall event and the weighted antecedent 7-day accumulated rainfall before the considered rainfall event, i.e.

$$R_t = R(t) + \sum_{i=1}^{7} \alpha^i R_i \qquad (2)$$

where $R(t)$ is the amount of the accumulated rainfall at time t in a considered rainfall event; R_i is the amount of the antecedent i day's rainfall; a is a weighting factor that is set to be 0.8 in this study.

The upper and lower critical values of the Rainfall-Triggering Index (RTI) for landslide occurrence potential analysis are needed before one can use the RTI-values to estimate the landslide occurrence potential during a rainfall event. The upper and lower critical values noted as RTI_{UC} and RTI_{LC}, respectively of the Rainfall-Triggering Index (RTI) could be evaluated, according to the historical rainfall events and the debris-flow or landslide occurrence records. Once the upper critical value (RTI_{UC}) and the lower critical value (RTI_{LC}) are given, the occurrence potential of landslides can be classified into three regions, i.e. high occurrence potential, medium occurrence potential, and low occurrence potential regions, as shown in Figs. 1 and 2.

Once the upper and lower critical values of the *RTI* are determined, one uses the *RTI* values as a

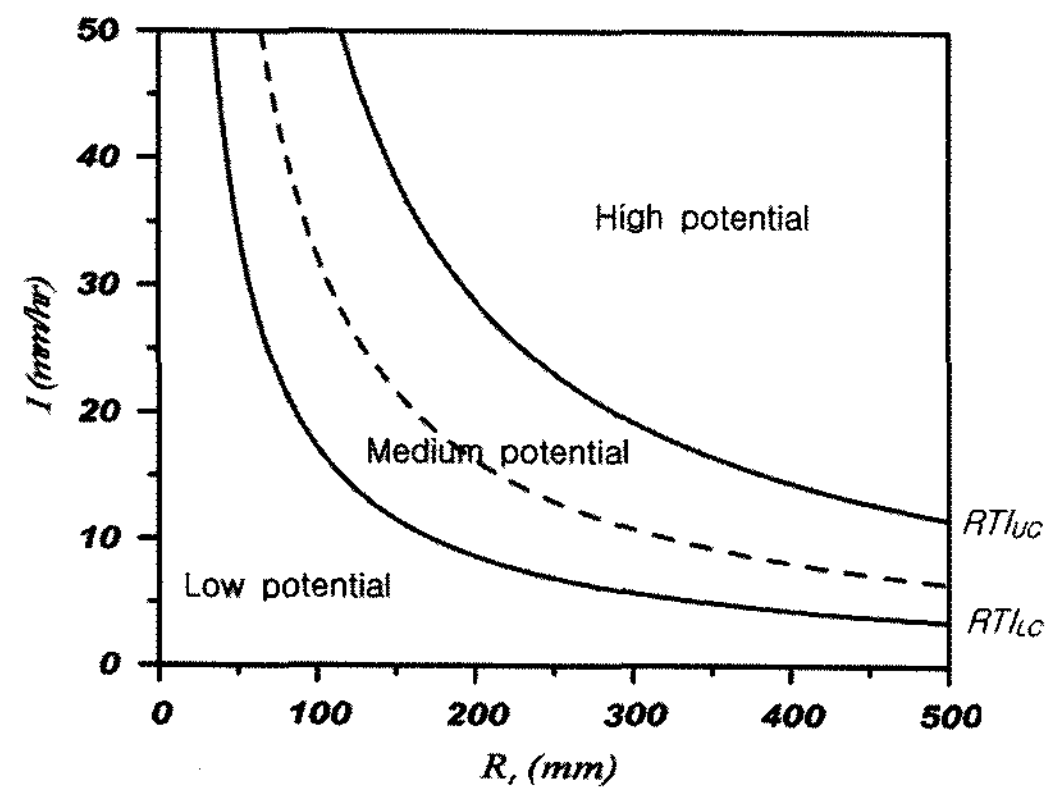

Fig. 1. Occurrence potential of landslides based on the rainfall intensity and accumulated rainfall.

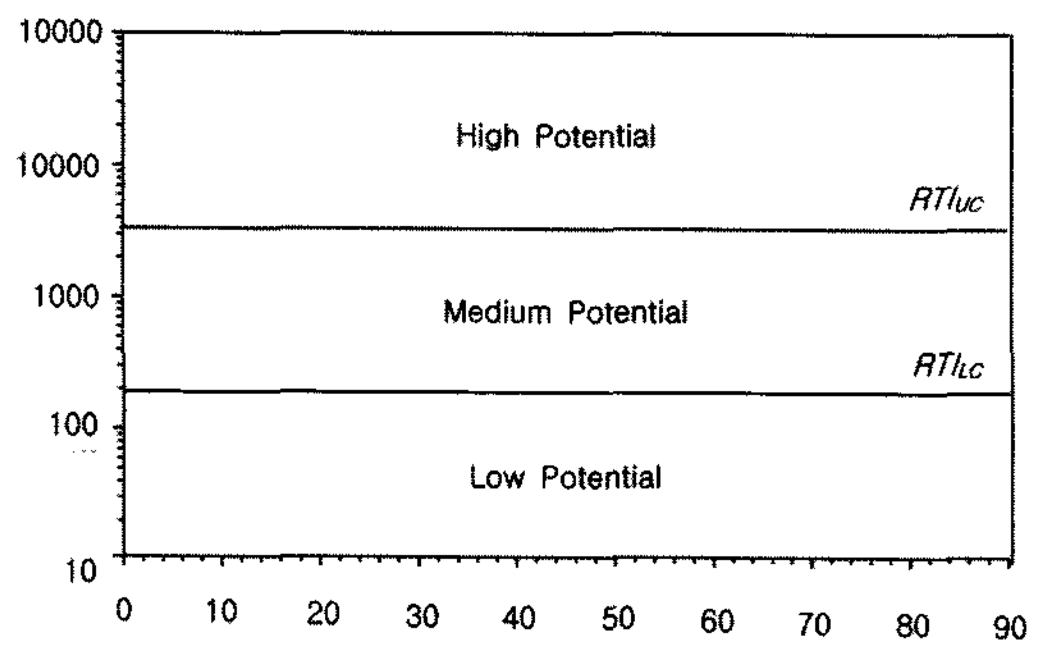

Fig. 2. Landslide potential analysis based on temporal variation of *RTI*-values.

vertical coordinate while the time considered as a horizontal coordinate to form a *RTI* - value warning map as shown in Fig. 2.

The location of the instant *RTI*(t) at time *t* on the *RTI*-value warning map could tell the landslide occurrence potential. When a *RTI*-value at time *t* is smaller than RTI_{LC}, it refers to that the landslide occurrence probability is low. When the *RTI* value at time *t* is larger than RTI_{LC} but smaller than RTI_{UC}, it refers to that the landslide occurrence probability is medium, and then, one could take it as the pre-warning time for landslide occurrence warning. If the *RTI* value at time *t* is larger than RTI_{UC}, it refers to that the landslide occurrence probability is high, and then, one could take it as the warning time for people evacuation for avoiding the damages from landslides.

Analysis of Landslide Potential using the RTI Warning Model

Methods of determining critical RTI-values for Inje, Korea

As mentioned in the previous section, the upper and lower critical RTI-values (RTI_{UC} and RTI_{LC}) could be evaluated from the historical landslide occurrence records and their corresponding rainfall data. However, in order to draw a meaningful line, we must have enough data of debris flows occurred and its corresponding accumulated rainfall. With enough data, the value of RTI_{LC} is the value just below the debris flow with the smallest accumulated rainfall. The RTI_{UC} value is the value for 80% occurrence. This 80% can be interpreted as 80% chance for debris flow to occur. How much the value should be dependent what is the action one wants to take. If this line is used as the standard for compulsory evacuation of the local resident, one usually takes a higher value. If this value is used as the disclaimer "the government will not be responsible for any loss if the local resident still stay there", then one usually takes a lower number. Of course, in practice, we can also use linear interpolation to draw the 10%, 20%, 30% and all the way to 80% lines. Then in the prediction, we honestly state the chance for debris flows in that area. This is another way to use the data. In any case, we do not have enough historical landslide records and rainfall data in the area of Inje, Korea. Therefore, it is impossible to directly decide the upper and lower critical RTI-values, RTI_{UC} and RTI_{LC}, respectively, from the landslide records and rainfall data in Inje, Korea at the moment.

Therefore, the authors look for locations where the geological and weather conditions are similar to that of Inje. The critical values of *RTI* for landslide potential analysis at Nantou County in Central Taiwan could be expended and used at Inje, Korea. For landslide potential analysis at Inje, Korea, the suggested upper critical *RTI*-value (RTI_{LC}) is 2,000 mm^2/hr, and the lower critical *RTI*- value (RTI_{UC}) is 1,200 mm^2/hr.

Results of Landslide Potential Analysis in Inje, Korea

There were many landslides occurred in Inje, Korea at about 11:00 a.m. on July 16, 2006 during a severe rainfall event from July 13 to 19, 2006. The landslides caused severe damages in many mountainous areas of Inje. Both the hourly and 24-hour rainfall data collected by an automatic weather system (AWS) near the mountainous areas were shown in Fig. 3. Fig. 3 shows that the first local maximum value (66 mm/hr) of hourly rainfall intensity in this rainfall event occurred at 10:00 a.m. on July15. After that, even though the rain continuously fell down but the intensity of rainfall rapidly decreased to less 6 mm/hr until 22:00 on July 15. And then, the rainfall smoothly increased up to the second local maximum value of about 18 mm/hr at 06:00 on July 16. Finally, the landslide occurred at 11:00 p.m. on July 16, at which the hourly rainfall and the 24-hour rainfall were 7.5 mm and 171.5 mm, respectively.

The temporal variations of the rainfall intensity, effective accumulated rainfall, and the corresponding

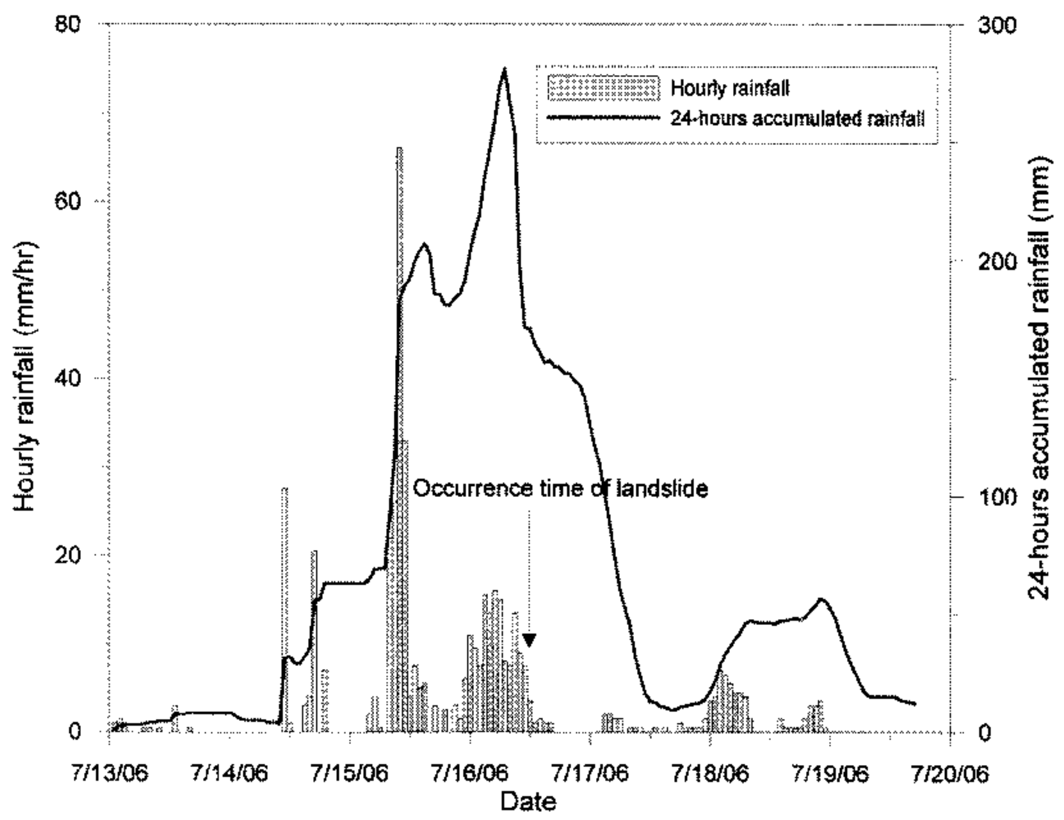

Fig. 3. Temporal variation of hourly rainfall and 24-hour rainfall and the time of landslides initiation during July 13 to July 19, 2006 at Inje, Korea.

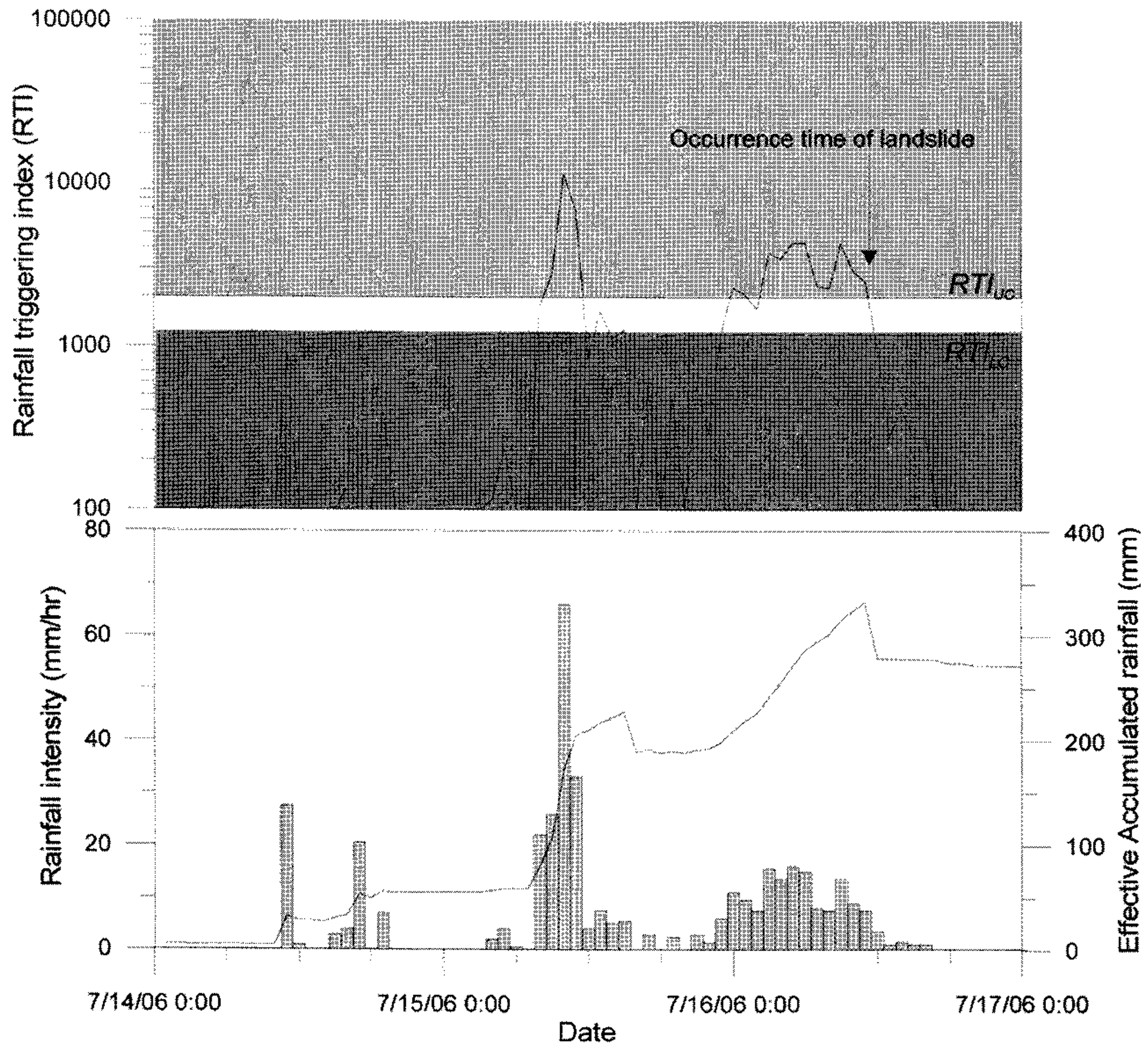

Fig. 4. Temporal variations of hourly rainfall, effective accumulated rainfall, and rainfall triggering index at Inje, Korea during a rainfall event from July 13 to 19, 2006.

Table 1. The time of landslide occurrence and the lag times of the proposed landslide warnings ahead landslide occurrence at Inje, Korea.

Occurrence time of landslides	Rainfall condition at the time of landslide occurrence			Time of landslide warning based on the RTI model			Lag time of landslide warning ahead the time of landslide occurrence		
	I (mm/hr)	R_t (mm)	RTI	First time	Second time	Third time	First time	Second time	Third time
7/16 11:00	7.5	332	2500	7/15 09:00	7/16 00:00	7/16 03:00	23 hours	11 hours	9 hours

RTI values at Inje, Korea during the rainfall event were plotted in Fig. 4. The time of *RTI*-value firstly exceeding the lower critical value of RTI (RTI_{LC}) was 08:00 on July 15, which is the first pre-warning time for landslide during the rainfall. After 08:00, the rainfall intensity kept increasing, the *RTI* value exceeded its upper critical value (RTI_{UC}) at 09:00 on July 15, which is the time of warning for people evacuation so as to avoid hurts and damages from the high potential landslides in subsequent rainfalls. Then, the maximum hourly rainfall occurred at 10:00 on July 15, at which the corresponding *RTI* value reached 11,460 mm^2/hr that is much over the upper critical RTI-value. The mountainous areas at Inje were theoretically in very dangerous situation for suffering landslides damages. But landslides did not happen in the real case because the rainfall intensity decreased rapidly after 10:00, so the situation of Inje areas suffering landslides was transferred from high potential to low potential due to the decrease of rainfall intensity. After 12:00, the *RTI*-value decreased to low landslide potential region.

The rainfall reincreased at 23:00 on July 15, and the corresponding *RTI* values also increased rapidly after that time. The *RTI*-value re-exceeded the lower critical RTI_{LC} at 23:00 on July 15, and exceeded the value of RTI_{UC} at 24:00on July 15, which is the second warning time for people evacuation for avoiding landslide hazards. After 23:00 on July 15, the hourly rainfall intensity was over 10 mm/hr for many hours, and the effective accumulated rainfall increased from 200 mm approaching to 300 mm. The *RTI* values kept exceeding RTI_{UC} after 03:00 for many hours, and finally many landslides almost simultaneously occurred at 11:00 on July 16, at which the corresponding effective accumulated rainfall and the *RTI*-value were 332 mm and 2,500 mm^2/hr, respectively. After 11:00 on July 16 that was the time of landslides occurred, the rainfall decreased gradually, the corresponding *RTI* value decreased, and the situation approached to lower landslide potential.

Table 1 shows the occurrence time of landslides, the rainfall condition at the time of landslides occurrence, and the warning time of landslide based on the proposed model used in this study. During the rainfall event, landslide warnings would be issued three times for people evacuation for avoiding or reducing hurts and damages from landslides in mountainous areas of Inje. The lag time of the proposed landslide warnings ahead the time of landslide occurrence were 23 hours, 11 hours, and 9 hours, respectively. The results of landslide potential analysis at Inje, Korea based on the RTI model has once again showed that the RTI model could reasonably and effectively provide the information of landslide occurrence potential during a rainfall event.

Conclusions

This study tried to predict potential and triggering time of landslides based on analysis of rainfall intensity. In order to predict the triggering time, this study used the Rainall-Triggering-Index (RTI) warning model during a rainfall event between July 13 and 19, 2006 at Inje, Korea. The analysis result would be applied for deter-mination of appropriate warning times of landslides. According to the analysis result, landslide warnings would be issued three times for people evacuation for avoiding or reducing hurts and damages from landslides in mountainous areas of Inje during the rainfall event. The lag time of the proposed landslide warnings ahead the time of landslide occurrence were 23 hours, 11 hours, and 9 hours, respectively. The results of landslide potential analysis at Inje, Korea based on the RTI model has once again showed that the RTI model could reasonably and effectively provide the information of landslide occurrence potential during a rainfall event.

Acknowledgement

This study has been supported by the Basic Research Project of Korea Institute of Geoscience and Mineral Resources.

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2008년 5월 10일 원고접수, 2008년 6월 16일 게재승인

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