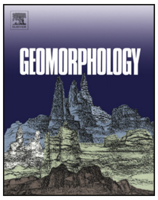
Geomorphology 308 (2018) 1–12

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



Debris flow susceptibility assessment based on an empirical approach in the central region of South Korea

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ARTICLE INFO

Article history:
Received 19 April 2017
Received in revised form 12 January 2018
Accepted 25 January 2018
Available online 31 January 2018

Keywords:
Debris flow
Debris flow susceptibility
Empirical method
Flow-R

ABSTRACT

Many debris flow spreading analyses have been conducted during recent decades to prevent damage from debris flows. An empirical approach that has been used in various studies on debris flow spreading has advantages such as simple data acquisition and good applicability for large areas. In this study, a GIS-based empirical model that was developed at the University of Lausanne (Switzerland) is used to assess the debris flow susceptibility. Study sites are classified based on the types of soil texture or geological conditions, which can indirectly consider geotechnical or rheological properties, to supplement the weaknesses of Flow-R which neglects local controlling factors. The mean travel angle for each classification is calculated from a debris flow inventory map. The debris flow susceptibility is assessed based on changes in the flow-direction algorithm, an inertial function with a 5-m DEM resolution. A simplified friction-limited model was applied to the runout distance analysis by using the appropriate travel angle for the corresponding classification with a velocity limit of 28 m/s. The most appropriate algorithm combinations that derived the highest average of efficiency and sensitivity for each classification are finally determined by applying a confusion matrix with the efficiency and the sensitivity to the results of the susceptibility assessment. The proposed schemes can be useful for debris flow susceptibility assessment in both the study area and the central region of Korea, which has similar environmental factors such as geological conditions, topography and rainfall characteristics to the study area.

1. Introduction

The yearly rainfall and the occurrence frequency of localized heavy rain have been growing worldwide because of global temperature increase and climate change (Nam, 2012). According to Kang et al. (2017), damage from landslides tends to increase with an increase in the occurrence frequency of localized heavy rain. Landslide is recognized as a primary natural hazard in the world due to its destructive impact (Samia et al., 2017). Among various types of landslides, debris flows cause more damage than other types because debris flows have enormous impact force with rapid velocity and long spread distance; these flows consist of a mixture of water, sediment, rocks and soils (Lee et al., 2014). Debris flows both destroy buildings and infrastructure and kill humans. Studies must delineate potential debris flow propagation areas to reduce the huge amount of damage that is caused by debris flows.

Lorente et al. (2003) stated that debris flows can be divided according to their source and deposition areas. Kappes et al. (2011) classified debris flow analyses into two steps: (1) the identification of potential sources and (2) the estimation of the propagation. Diverse methods have been applied for the first step: (1-a) heuristic methods in the field and on aerial photographs (Benda and Cundy, 1990; Chau and Lo, 2004); (1-b) statistical methods that use various factors that are related to possible instabilities in an inventory of past events (van Westen et al., 2006) or are based on bivariate (Guinau et al., 2007; Blahut et al., 2010b) or multivariate statistics (Carrara et al., 2008); (1-c) empirical methods that use a combination of various parameters, such as the slope angle, upslope area and planar curvature (Horton et al., 2008, 2013); and (1-d) physically based methods that are based on coupled hydraulic models to calculate the safety factor (Delmonaco et al., 2003; Carrara et al., 2008). A variety of methods are available for the second step: (2-a) empirical relationships and formulae to estimate the maximum runout distance (Corominas, 1996; Rickenmann, 1999; Prochaska et al., 2008; Horton et al., 2008, 2013), and (2-b) physically based runout models (O'Brien et al., 1993; Crosta et al., 2003; Chau and Lo, 2004; Rickenmann, 2005; Hungr and McDougall, 2009).

Rather high data requirements (i.e., geotechnical and hydrological data) must be satisfied for physically based source identification, which is applicable to any site because of the physical characteristics of the process (Kappes et al., 2011). At a regional scale, using physically-based models to identify sources is not efficient because of the high cost of resources and the time-consuming nature of simulations. Therefore, simplified methods that use the relationships between

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https://doi.org/10.1016/j.geomorph.2018.01.025
0169-555X/© 2018 Published by Elsevier B.V.

topography and debris flow sources have been investigated (Takahashi, 1981; Hungr et al., 1984; Rickenmann and Zimmermann, 1993) because topographic properties have some advantages, such as the convenience of acquiring data and their applicability to regional-scale areas (Kang et al., 2015).

According to Horton et al. (2013), physically-based modelling of debris flow propagation is difficult for various reasons, including the complex properties of the phenomenon (Hungr, 1995; Iverson, 1997), the variability of factors in the modelling, and the uncertainty from modelling parameters (He et al., 2003). Additionally, most of the controlling factors, including material properties such as physical, mechanical and rheological parameters, may not be obtained over wide areas, producing reasonable costs (Lari et al., 2011). By contrast, empirical methods, which use parameters that can be calibrated through inventories of past events, can be applied to regional-scale areas and have the advantage of simple data collection (Blahut et al., 2010b; Park et al., 2016). Therefore, empirical methods can provide an efficient alternative for regional-scale areas. In this study, debris flow susceptibility assessment was conducted by using an empirical GIS-based model called Flow-R, which was developed by Horton et al. (2008, 2013). However, applications of the Flow-R model have some limitations, such as only supporting topographic factors (i.e., a digital elevation model (DEM)) in the debris flow spreading assessment; neglecting local controlling factors such as the material properties of soils and rheological properties, which greatly influence the behaviors of debris flows; and requiring more testing to verify the transferability of the parameters to other study areas (Blahut et al., 2010a).

Debris flows can be simulated depending on Newton's second law (Breien, 2005). The bed shear stress is usually described by an extension of the basic Newton's second law in which a velocity-independent term, which is represented by a traditional Mohr-Coulomb shear stress, is coupled with a velocity-dependent term that is described by viscous properties (Norem and Sandersen, 2012). Runout distance and velocity are determined by a gravitational driving force and a constitutive law, governed by rheological properties (Chen and Lee, 2000). Even though geotechnical and rheological properties can be considered to be critical factors in the debris flow susceptibility assessment, geotechnical and rheological properties are neglected in the Flow-R.

The path and the spreading of debris flows and the runout distance are controlled by spreading algorithms and friction laws, respectively, in the Flow-R. Depending on types of flow-direction algorithms and inertial parameters, which make up the spreading algorithms, and values of parameters used in the friction laws, results of debris flow susceptibility can be diverse (Horton et al., 2013). Blahut et al. (2010a), Kappes et al. (2011), Fischer et al. (2012), and Park et al. (2016) applied the Flow-R model to debris flow cases that occurred in Italy, France, Norway, and Korea, respectively. In these studies, however, algorithms and parameters that have frequently been used in previous studies were applied without analysis to determine the appropriate combination of algorithms and parameters to the corresponding regions. Because algorithms and parameters applied in the previous studies do not always have applicability to other regions, sensitivity analyses in relation to the algorithms and the parameters are required.

According to the results of the lab tests by Ghezzehei and Or (2001) and Markgraf (2011), different rheological properties were shown to depend on the type of soil texture. According to Park et al. (2014), soil texture can be used to explain the relative distribution ratios of clay, silt, sand, etc. and its influences on geotechnical characteristics such as the water content, hydraulic conductivity, strength, etc. Additionally, geological properties affect geotechnical characteristics. In this study, we assumed that the study sites that were classified depending on the types of soil texture or geological conditions could indirectly represent material properties of soils, and assumed that appropriate schemes for each classified site, such as the selection of parameters and algorithms in the Flow-R would be more applicable. These schemes include a variety of algorithms for flow-direction assessment, three types of inertial functions, and travel-angle and maximum-velocity values in the runout distance analysis. The main purpose of this study is to determine appropriate schemes by comparing the results from debris flow susceptibility analyses to the spreading areas of actual events. Then, it was analyzed whether applications of the schemes contribute to increases in the accuracy of debris flow susceptibility assessment to demonstrate the propriety of considering types of soil texture or geological conditions when using the Flow-R model.

2. Study areas

In this study, debris flow susceptibility assessment was conducted for 36 sites in the central region of Korea, where debris flows had occurred. Fig. 1 shows the study areas of Umyeon Mountain, which includes thirty sites, and central Gyeonggi Province, which includes six sites.

Throughout Umyeon Mountain, which is located in the Seocho district of Seoul, approximately 140 catastrophic shallow landslide events occurred because of heavy rain from 26 to 27 July 2011, in which the two-day accumulation was 470 mm. These landslide events were chiefly accompanied by debris flows (Korean Society of Civil Engineers, 2012). On 27 July 2011, sixteen human deaths and property damage were caused by the debris flows. The area of Umyeon Mountain is approximately 5 km^2 and mainly consists of Precambrian banded biotite gneiss and granitic gneiss.

In the city of Gwangju, which is located in the central area of Gyeonggi Province, 13 million US dollars of restoration cost were spent in 2013 because of landslides that were induced by localized heavy rain. In the cities of Icheon and Yeoju, which are located in the central eastern area of Gyeonggi Province, lives and property were lost by debris flows on various sites in 2013. The six study sites in Gyeonggi Province, which are shown in Fig. 1-(c), mainly consist of gneiss and granite. The study areas, including the area of Umyeon Mountain and Gyeonggi Province, which are located at similar latitudes, have similar rainfall characteristics because a stationary front repeatedly ambulates southward and northward during the wet season from June to September in Korea (Korea Meteorological Administration, 2011).

3. Data

3.1. Inventory of debris flow events

Inventory maps, which consist of location information concerning the source, runout and sediment components of debris flows, are essential to obtain a variety of information on debris flow spreading areas and to validate the results of debris flow susceptibility analyses. Location information with respect to debris flow spreading areas was mapped for the area of Umyeon Mountain as a polygon type among feature-class types in the GIS format by comparing satellite images with a resolution of 5 m and aerial photographs with a resolution of 25 cm from Umyeon Mountain before and after the debris flow events, which occurred in 2011. After developing the inventory map, a comparison between the inventory map and the field survey-based debris flows' location information, which was acquired from the Korean Society of Civil Engineers (2012), was conducted to check the suitability of the map. Then, the spreading areas of thirty debris flow events in this area were constructed as a GIS-based inventory (Fig. 2-(a)).

A field investigation was conducted to collect location information for the debris flows' spreading areas to build the inventory for the study sites in the cities of Gwangju, Yeoju and Icheon. In this investigation, the coordinates, width, length and depth of the debris flow source areas, runout section at 30-m intervals and sediment component were collected at each site. Then, the GIS-based debris flow paths of six sites were built as the inventory by using the field survey-based debris flows' location information (Fig. 2-(b)). Throughout the study areas, the total debris flow initiation area was approximately 17,975 m^2