A GIS System Development for Evaluating 3D Slope Stability

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Abstract

When using a 3D deterministic model to evaluate the landslide susceptibility of regional area, processing large amounts of spatial data and identifying the objective for applying the deterministic model would be arduous works. In this research, an enhanced hydrology tool is developed to automatically identify the objectives of research, which are called slope units, from terrain raster data. A new grid-based 3D slope stability model is applied to evaluate the failure probability. Finally, the landslide susceptibility map showing the location and the shape of potential slope-failures is obtained. All the approaches are implemented by an integrated system which has been developed in ArcGIS 9.0 using ArcObjects. This system convert all related input data, including topographic and geological raster data, to a point dataset for calculation. The output will be a polygon shapefile of the critical slip surfaces with the attributes of failure probability and the minimum safety factor.

Introduction

In Japan, about 70% of the total national territory is composed of mountainous terrain, where catastrophic slope failures occur on an annual basis. The identification of potential slope failure zones has long been an important issue in landslide mitigation in Japan. So far, a large number of methods for slope stability calculation have been developed. Basically, they can be categorized to two types: statistical methods and deterministic models. Considering the statistical method has the shortage of mechanical meaning, the deterministic model, which calculates a safety factor quantitatively, is a more reasonable method for an individual slope. However, applying the deterministic model to a regional slope can be particularly difficult or sometimes even impossible because of the difficulties in obtaining, checking and processing large spatial data sets, defining the applied objective of deterministic model and identifying unknown slide surface. Therefore, a helpful tool is expected for resolving these problems.

The Geographic Information System (GIS), with its power and versatility for processing spatial data, has attracted significant attention for the assessment of natural disasters. The GIS provides strong functions both in geostatistical analysis and database processing. In addition, the extension of the analysis to include environmental impact assessment of a slope failure can be easily and effectively performed using GIS.

In this paper, a new GIS method is proposed for identifying the applied objectives of deterministic model, which are called slope unit, from the DEM (Digital Elevation Model) data. After dividing the study area to many slope units, a GIS-based 3D slope stability evaluation system is developed to identify a critical slip surface which has the minimum 3D safety factor for each slope unit, and as the result, a map that shows the distribution of probability of slope failure is obtained. As a case study, the probability of slope failure of a wide weathered granite zone along the route No.49 in Gouto area of Japan is evaluated quantitatively. The location and the shape of potential slip surfaces also are predicted effectively.

Hydrological Tool for Dividing Slope Units

(1) Concept of Slope Unit

In the 3D slope stability studies focus on a large mountain area with complicated geometry and soil and water conditions, a very important problem is how to extract appropriate study objects. These study objects are usually called slope units. The slope unit, namely, the portion of land surface that contains maximum internal homogeneity differing from the adjacent units, has relatively similar topographic and geological characteristics respectively. The significance of partition of the slope units for landslide hazard assessment and for other land-related study has been recognized.

(2) Method of Dividing Slope Unit

Breaks of slope are often identified as significant topographic features, namely dividing lines, indicating the boundaries between adjacent geomorphological units on a map. Since it is virtually impossible to consistently draw dividing lines on topographic maps covering large regions, an automatic computer procedure is required. In this paper, a new method based on GIS spatial analysis and hydrology modeling has been proposed for identifying slope units from DEM (digital elevation model) data automatically.

The slope unit can be considered as the left or right side of a sub-basin of any order into which a watershed can be partitioned, therefore, it can be identified by a ridge line and a valley line. By using the hydraulic model tool of ArcGIS 9.0, the watershed polygon and the stream line of a study area can be obtained easily from the DEM data. Topologically, the outline of the watershed polygon can be considered as the ridge line. Considering water always flows downhill along the path of the steepest descent, the stream line can be looked upon as a part of the valley line in a mountain area. After dividing the watershed polygon by the valley line, two slope units can be obtained. However, the stream line which can be created by the ready-made GIS hydraulic model tool is not a single line but all lines that consist of cells whose flow accumulation value are greater than a specified threshold value. Because there is not a ready-made application that can extract the valley line from watershed and create slope unit automatically, a GIS-based program has been developed to implement this task. **Fig.1** shows the distribution of slope units extracted from a study area by this program.

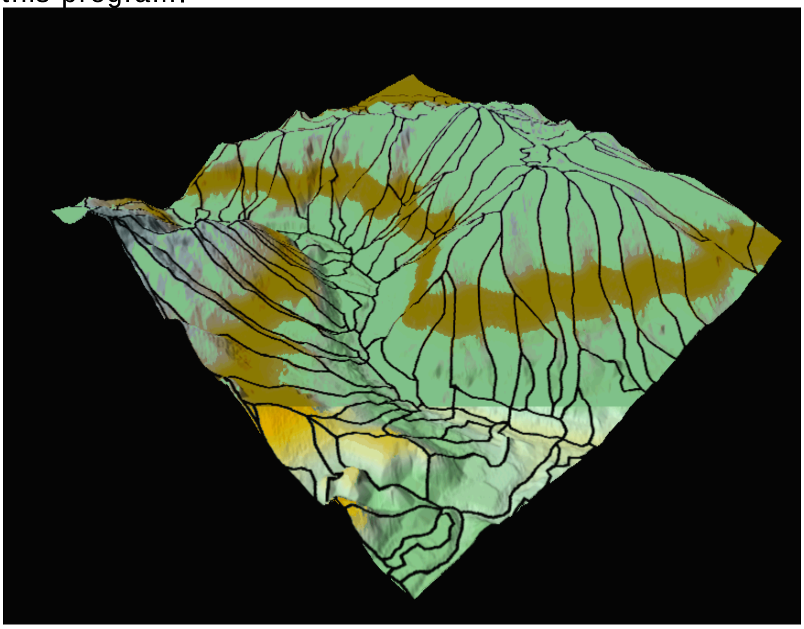

Fig.1 3D view of slope unit distribution

3D Slope Stability Model

All slope failures have a three-dimensional (3D) geometry, which varies in space even along a short distance. Therefore, it is rational to use a 3D model to analyze slope stability. Since the middle of the 1970s, increasing attention has been directed toward the development and application of three- dimensional stability models. Several three- dimensional methods of analysis have been proposed in geomechanical literature. However, these methods are commonly limited on being applied for an individual site due to the difficulties in large spatially distributed data processing. Considering that most of the methods have used the column method and all of slope-related GIS data can be changed to grid-based data, it is possible that these column–based 3D models can be used for the 3D stability calculation by using the GIS grid-based data. By combining the GIS spatial analysis function with an improved Hovland (1977) 3D slope stability analysis model, a new GIS-based 3D deterministic model is applied.

(1) GIS-based 3D Model

Using the functions of GIS spatial analysis, all original data (such as elevation, underground water, strata etc.) for the 3D safety factor calculation are available with respect to each grid pixel. By inputting these data into a deterministic model of slope stability, a value of the safety factor can be calculated. The global geometry of a potentially sliding mass is illustrated in **Fig.2(a)**. In GIS system, by using the GIS spatial analysis function, the slope-stability- related data of the whole study area can be represented as the GIS vector layers. For each layer, a grid-based layer (see **Fig.2(b)**) can be obtained by using the GIS spatial analysis function and the grid size can be set with the requisite precision. The stability of the landslide is related to the geological information, the geomorphological aspect, the geomechanical parameters, and the hydraulic condition, by the discretization of the study mass to the small soil column, as shown in **Fig.2(c)**. The slope failure has now been evenly divided into columns and related to grid-based columns. With reference to the grid-based column in **Fig.2(d)**, the spatial data of surface, strata, underground water, fault, and slip surface can be obtained from the grid-based layers. Because there are so many of slope-related data, it is not effective to manage all these grid-based datasets. Therefore, a point dataset is used to store all these grid datasets. In this point dataset, a feature table is used to manage all the slope-related data.

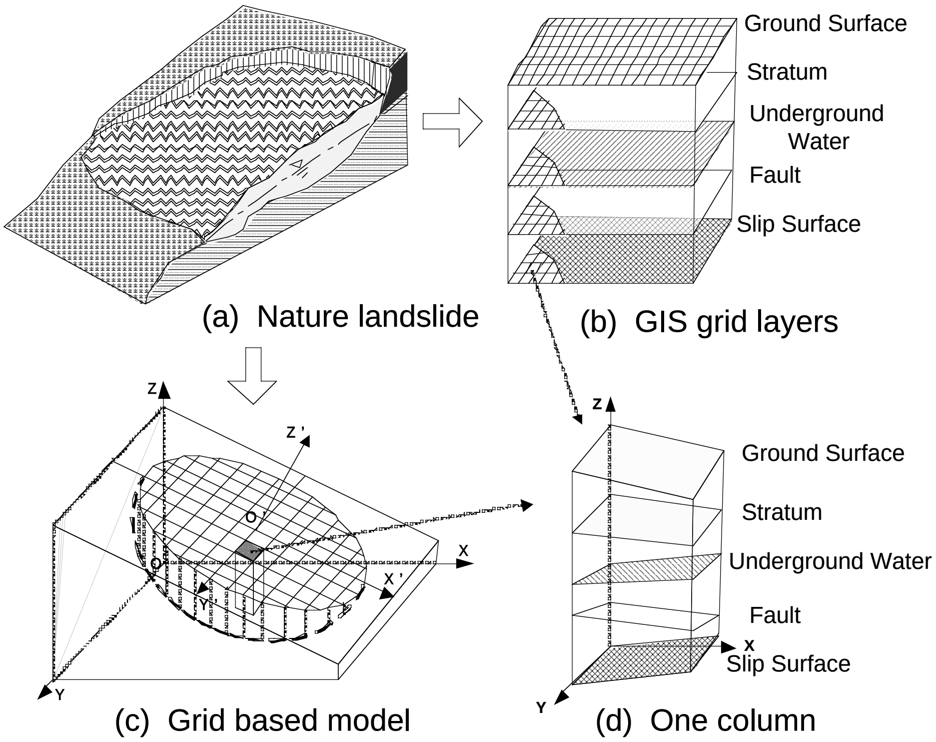

Fig.2 GIS-based 3D slope stability model

(2) Identifying the Critical Slip Surface

To detect the 3D critical slip surface, a searching method is performed by means of a minimization of the 3D safety factor using the Monte Carlo simulation method. The initial slip surface is assumed to be the lower part of an ellipsoid and the shape of slip surface will change according to various layer strengths and conditions of the discontinuous surface. After enough times' trial calculation for assumed slip surfaces, finally, the critical slip surface will be obtained and, consequently, relative minimization of the 3D safety factor can be achieved.

For critical slip surface identification, the Monte Carlo simulation is used to choose the variables for simulating ellipsoid. These variables are the central point, the geometrical parameters, and the inclination angle of the ellipsoid. The central point of the ellipsoid is randomly chosen within a certain range in the slope unit. The geometrical parameters a, b, c axes of the ellipsoid are randomly chosen from a certain range defined by user. The inclination angle of the ellipsoid is set as a random variable on a uniform distribution. The mean of this uniform distribution range is the main inclination angle and its variable is changed between a certain fluctuation.

System Development Using ArcObjects

For accomplishing the purpose of using GIS spatial function components to develop an enhancive tool, Microsoft COM (Component Object Model) technology has been used. COM is a protocol that connects one software component, or module, with another. With this protocol we can build reusable software components that are interchangeable in distributed systems at a binary level, so third-party developers do not require access to source code. Any language capable of manipulating computer memory can implement the COM specification. There are no restrictions on how the components are developed or what language is used to develop them. COM components can be clients and servers. The server provides functionality, and the client uses that functionality. The client only needs to know that the functionality is available; with that knowledge, the client can make calls to the server and expect the server to honor them.

In this research, ArcObjects, the framework that forms the foundation of the ArcGIS applications (a GIS software developed by ESRI) with more than two thousands COM based components providing, has been used.

The analysis system of 3D slope stability was developed using Visual Basic 6.0 based on ArcGIS 9.0 platform. For easy-distribution, the tool has been compiled to a DLL (Dynamic Linked Library) file. After being registered on a client machine, the DLL can work in ArcMap as a custom tool. This system can reading all of the slope-related geological, geomorphologic, hydraulic data, and geomechanical parameters, randomly generating the trial slip surface, calculating the 3D factor of safety using the 3D slope stability model, and identifying the critical slip surface by many calculation trials.

Case Study

The route No.49 connects the Iwaki city and Niigata city of Japan. The Goto section of the route No. 49 is the nearest site to Iwaki city, about 10 km westward, where the landslide hazard had been taken place in the past. To assess the slope stability for the purpose that the future action can be taken for preventing the slope failure, the developed system was applied.

The existing datasets of study area are (1)the DEM data in the form of ESRI grid with 2m mesh size; (2)the depth distribution of the weathered stratum in ESRI grid form with 2m mesh size; (3)the geomechanical parameters of the surface soil stratum. The bedrock geology of the study area is the granitic rock which is hard in fresh state but often heavily weathered in situ to form deep residual deposits. According to the character of geological formation, the possible collapse mode was considered to be a shallow slope failure because the mean value of the surface soil depth is about 1m. The sliding surface was assumed along and confined on the lower surface of the soil layer.

For the range where the detail soil depth data is available, the slope unit distribution was identified and a critical slip surface with the minimum 3D safety factor was predicted through 500 times' trial searching for each slope unit. The slope failure probability distribution map was obtained as shown in **Fig.3**.

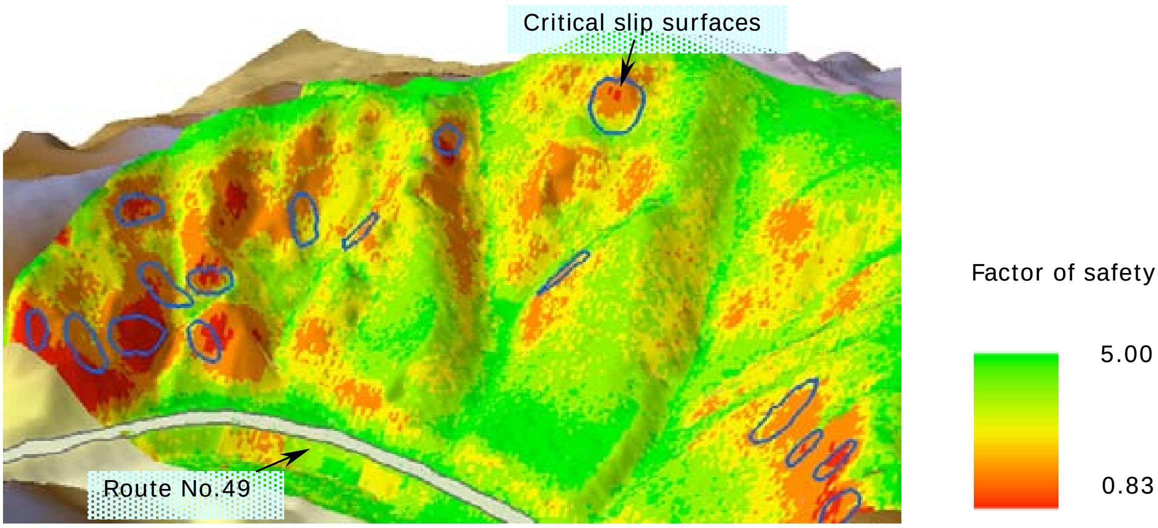

Fig.3 slope failure probability distribution map

Conclusion

This paper presents a new approach for evaluating slope failure probability of wide study area using the 3D deterministic model, in which all calculation procedures are processed automatically and effectively by applying GIS technique. The work reported herein would be virtually impossible without the aid of GIS. The slope unit, taken as the study objective for the deterministic model, can be identified by an automatic method proposed here. However, the appropriate size of the slope unit that should be dependent on the average size of the landslide bodies present in the study area is not easy to be determined. Based on GIS grid data, an advanced 3D deterministic model has been used to predict the critical slip surface with the minimum 3D safety factor and to calculate the slope failure probability. The results obtained in this study indicate that taking advantage of the spatial functions of GIS, the 3D slope stability analysis becomes easier to study.

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