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GIS COMPONENT BASED 3D LANDSLIDE HAZARD ASSESSMENT SYSTEM: 3DSLOPEGIS

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ABSTRACT: In this paper, based on a new Geographic Information System (GIS) grid-based three-dimensional (3D) deterministic model and taken the slope unit as the study object, the landslide hazard is mapped by the index of the 3D safety factor. Compared with the one-dimensional (1D) model of infinite slope, which is now widely used for deterministic model based landslide hazard assessment in GIS, the GIS grid-based 3D model is more acceptable and is more adaptable for three-dimensional landslide. Assuming the initial slip as the lower part of an ellipsoid, the 3D critical slip surface in the 3D slope stability analysis is obtained by means of a minimization of the 3D safety factor using the Monte Carlo random simulation. Using a hydraulic model tool for the watershed analysis in GIS, an automatic process has been developed for identifying the slope unit from digital elevation model (DEM) data. Compared with the grid-based landslide hazard mapping method, the slope unit possesses clear topographical meaning, so its results are more credible. All the calculations are implemented by a computational program, 3DSlopeGIS, in which a GIS component is used for fulfilling the GIS spatial analysis function, and all the data for the 3D slope safety factor calculation are in the form of GIS data (the vector and the grid layers). Because of all these merits of the GIS-based 3D landslide hazard mapping method, the complex algorithms and iteration procedures of the 3D problem can also be perfectly implemented.

KEY WORDS: Geographic Information System (GIS); three-dimensional slope stability; Monte Carlo simulation; slope unit; landslide hazard

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1 INTRODUCTION

Landslide is one of major natural disasters, which has become a topic of major interest for both geoscientists and engineering professionals as well as for the local communities and administrations in many parts of the world. In the recent years, Geographic Information System (GIS), with its excellent spatial data processing ability, has attracted great attention in natural disaster assessment. The stability calculation for the landslide assessment can be performed within or outside the GIS. If the calculations are performed outside the GIS, the GIS is only used as a spatial database for storing, displaying and updating the input data. The main advantage of this approach is that external existing models can be used without losing time in programming the model algorithms into the GIS. A disadvantage of doing model calculations outside the GIS is the complication caused by data conversion to and from external models (VAN WESTEN and TERLIEN, 1996; VAN WESTEN *et al.*, 1997). Data conversion can be a major problem because most programs have their own data format and data structure. Some even have special input modules that only allow manual data entry. Conversion can be relatively straightforward only when these programs require input data to be in ASCII format. Another disadvantage of using external models is the representation of the results of the model calculations, which are normally not spatially distributed, in the form of maps in a GIS. To overcome the problem of data conversion, deterministic model calculations can be performed within the GIS. The disadvantage of this approach is, however, that only simple models can be now easily applied due to the limitations with respect to the use of complex

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algorithms, iteration procedures and the third dimension in the conventional, two-dimensional GIS. Currently, only infinite slope models, which allow for the calculation of the safety factor for each pixel individually, are applied inside such GISs(ALEOTTI and CHOWDHURY, 1999; ANBALAGAN, 1992; CARRARA, 1995; DAI and LEE, 2001). It has been considered that, only when more sophisticated, three-dimensional (3D) model and GISs are used, can this problem be solved satisfactorily. In this research, to overcome the data conversion difficult outside of GIS and the difficult of complex algorithms within GIS, a GIS component is employed in a Visual Basic (VB) program for assessing the landslide hazard. By using the GIS component, the data conversion is no longer necessary because all the data are in the GIS form. On the other hand, because of its flexibility and generality, VB can be used for the complex algorithms of a 3D problem.

In this paper, based on a new GIS grid-based 3D deterministic model, and assuming the initial slip as the lower part of an ellipsoid, the 3D critical slip surface in the 3D slope stability analysis is performed by means of a minimization of the 3D safety factor by using the Monte Carlo random simulation (ESAKI *et al.*, 2001; XIE *et al.*, 2001). All the functions for the 3D safety factor are implemented into a computer program called 3DSlopeGIS. In this system, a GIS component (ESRI's MapObjects) (ESRI, 1999) is used for fulfilling the demanded GIS function, all the slope related GIS data can be managed and analyzed effectively just as the same as in the ordinary GIS software.

The other important problem for the landslide hazard assessment is the study object, but this topic has not received adequate attention in the literature. Many researchers take it for granted that the pixel (or grid) will be the study object, simply because grid-based objects can be easily obtained and managed. Grid-based objects are regularly distributed in space, so computer processing and manipulation is fast and algorithmically simple. But the grid cell does not bear any relation to the mechanism of slope failure and even to geological, geomorphologic or other environmental boundaries, so the results obtained by this approach are relatively inaccurate and unacceptable in physical terms.

Landslide has fixed relations to the geological and geomorphologic aspects of the study area. So, in this research, the slope unit is taken as the study object. The slope unit, that is, the portion of land surface that contains a set of ground conditions that differ from the adjacent units, possesses an explicit topographical (break line, stream, aspect and slope) and geological form. Since a clear physical relationship exists between landslides and the fundamental morphological elements of a hilly or mountain region, namely drainage and dividing lines, the slope unit technique seems most appropriate for landslide hazard assessment. Slope units are basically divided by geomorphological, geological and hydraulic conditions. The appropriate size of a slope unit should be dependant on the average size of the landslide bodies in the study area. Since it is virtually impossible to consistently draw dividing lines on topographic maps covering large regions, an automatic computer procedure is required. In this study, a GIS-based watershed analysis tool has been used to divide the slope unit automatically.

2 GIS GRID-BASED 3D SLOPE STABILITY ANALYSIS MODEL AND ITS IMPLEMENTING

Using the functions of GIS spatial analysis, all input data (such as elevation, inclination, slope, groundwater, strata, slip surface and mechanical parameters) for the 3D safety factor calculation can be available with respect to each grid pixel, while all slope related data are in the grid-based form. By inputting these data into a deterministic model of slope stability, a value of the safety factor can be calculated.

Based on HOVLAND's (1977) model, a GIS-based 3D model, in which pore groundwater pressure is considered, and in which all input data can be easily given in a grid-based form, will be proposed.

The global geometry of a potentially sliding 3D mass and its one 3D column view are illustrated in Fig. 1, the stability of the landslide is related to geological information, geomorphological aspect, geomechanical parameters and hydraulic conditions. By the discretization of the study mass into small soil (or rock) columns as shown in Fig. 1, all the slope related data can be illustrated as shown by the 3D view of one column in Fig. 1. Assuming that the vertical sides of each pixel columns are frictionless (no side forces on the vertical sides of the pixel columns, or with their influence canceling out), the 3D safety factor can be expressed as equation (1):

$$F_{3D} = \frac{\sum_J \sum_I (cA + W\cos\theta\tan\Phi)}{\sum_J \sum_I W\sin\theta} \quad (1)$$

where, F_{3D} is the 3D slope safety factor; W, the weight of one column; A, the area of the slip surface; c, the cohesion; Φ, the friction angle; θ, the dip (the normal angle of the slip surface); and J, I, the numbers

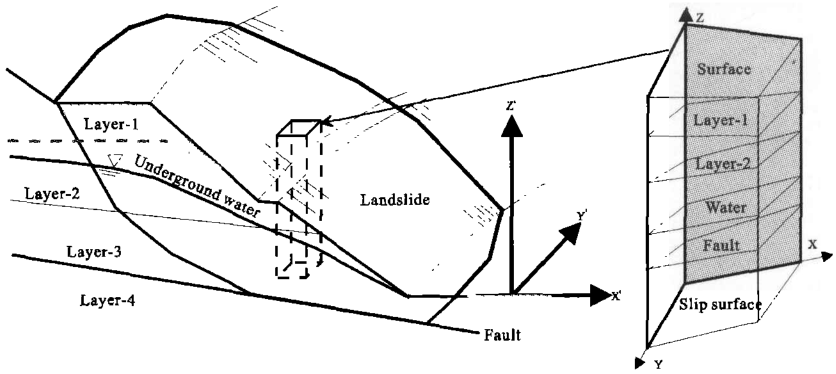

Fig. 1 3D view of slope failure and one grid column

of row and column of the grid in the range of the slope failure. Without GIS, a 3D safety factor calculation based this column-based model would be a tedious and time-consuming task, and the data renewal or a multi-case study would also be inconvenient. But in the GIS system, by using the GIS spatial analysis function, slope stability related data of the whole study area can be represented as GIS vector layers as shown in Fig. 2. For each vector layer, a grid-based layer can be obtained by using the GIS spatial analysis function and the grid size (cell size) can be set with the requisite precision.

The slope failure has now been evenly divided into columns and related to grid-based columns. For each column, with reference to the grid-based column in the Fig. 1, the spatial data of surface, strata, underground water, fault and slip surface can be obtained from the grid-based layers. Because of so many of slope related data, it is not effective to manage all these grid-based datasets, so in this system of 3DSlopeGIS, a point dataset is used to store all these grid datasets (Fig. 2). In this point dataset, a feature table is used to relate all the slope related data. The point shape is set to be the central point of each grid column, the other fields are respectively set to relate each slope related data, such as the elevations for ground, strata, fault, underground water and for slip surface depth. The feature table for the example shown in Fig. 1 can be described in Table 1. In this table, the item of "Point Shape" is the grid central point, the items of "Ground elevation", "Aspect" and "Slope" are related to the geomorphologic parameters, and the geological and hydraulic information are represented by the items of "Stratum 1 elevation", "Stratum 2 elevation", "Fault slip surface depth" and "Underground water head". On the other hand, for confining the landslide boundary and effectively managing the spatial selection and analysis, the landslide boundary (or the slope unit) is in the form of polygon shape file.

Based on this point database, equation (1) can be

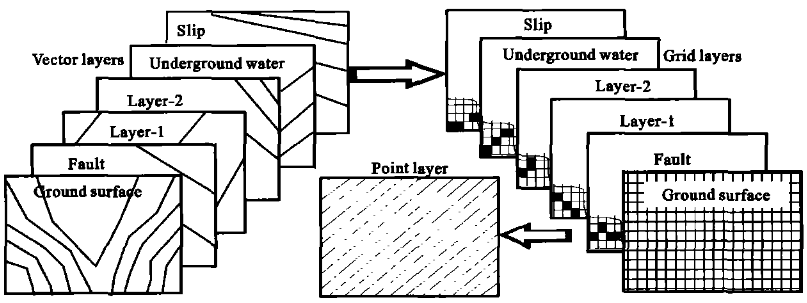

Fig. 2 GIS grid layers for slope stability analysis and point dataset

Table 1 Description of an example point dataset

FID	Shape	Geomorphologic parameters			Geological and hydraulic information			
		Ground elevation	Aspect	Slope	Stratum 1 elevation	Stratum 2 elevation	Fault slip surface depth	Underground water head
No. 23	Point in grid centre	184. 90	249. 77	6. 04	170. 00	164. 22	139. 76	168. 80

changed to the GIS-based equation, all the resistant and sliding forces should refer to the possible sliding direction. Here, the main dip direction of the slope area is assumed to be the possible sliding direction. The 3D slope safety factor can be calculated by equations (2) – (5) (using the equilibrium of the horizontal sliding direction):

$$F_{3D} = \frac{\sum_J \sum_I (cA + [(Z_{ji} - z_{ji})\gamma' \cos\theta - u_{ji}]\tan(\Phi))\cos\theta_{Avr}}{\sum_J \sum_I (Z_{ji} - z_{ji})\gamma' \sin\theta_{Avr}\cos(\theta_{Avr})} \quad (2)$$

the apparent dip of X and Y axes can be derived:

$$\tan\theta_{yz} = \tan\theta\cos(Asp), \quad \tan\theta_{xz} = \tan\theta\sin(Asp) \quad (3)$$

the area of slip surface of one grid column is

$$A = cellsize^2\left[\frac{\sqrt{(1-\sin^2\theta_{xz}\sin^2\theta_{yz})}}{\cos\theta_{xz}\cos\theta_{yz}}\right] \quad (4)$$

and the apparent dip of the main direction of inclination of the landslide area can be calculated by the following equation:

$$\tan\theta_{Avr} = \tan\theta\,|\cos(Asp - AvrAsp)| \quad (5)$$

where, for each grid, Z_{ji}, z_{ji} are the elevations of the ground surface and the slip surface; u_{ji} is the pore water pressure on the slip surface; γ', the unit weight; θ, the dip of the grid column slip surface; θ_{xz}, the apparent dip of X-axis; θ_{yz}, the apparent dip of Y-axis; θ_{Avr}, the apparent dip of the main direction of inclination of the slip surface; *Asp*, the dip direction of the slip surface of the grid column; *AvrAsp*, the average dip direction of the slip surface; and *cellsize*, the grid size.

The slip surface is obtained by detailed geotechnical investigation, but generally speaking, the detail of a slip surface is uncertain, so, in slope stability analysis, it is important, for the hazard evaluation, to identify the critical slip surface.

To detect the 3D critical slip, the search is performed by means of a minimization of the 3D safety factor (which is calculated by equation (2)) using the Monte Carlo random simulation method (BALIGH and AZZOUZ, 1975; ESAKI *et al.*, 2001; GRECO, 1996). The initial slip surface is assumed as the lower part of an ellipsoid slip and the slip surface will change according to different layer strengths and conditions of discontinuous surface. Finally, a critical slip surface will be obtained, and consequently, a relative minimization of the 3D safety factor can be achieved.

3 SLOPE UNIT DIVIDING USING HYDRAULIC MODEL

A slope unit, here, is defined as one slope part, or the left/right part of a watershed. Topologically, the slope unit can be divided by ridge lines and valley lines. In this study, a hydraulic model tool is employed to draw dividing lines for identifying slope units. By using the hydraulic model tool, the watershed (the size of which can be determined by the user) can be obtained from digital elevation model (DEM) data. Topologically, the outline of the watershed polygon is the ridge line. To detect the valley line, reverse DEM data is used. By the DEM grid analysis, high DEM values can be turned into low values, and low DEM values can be turned into high values, so the original valley line can be turned into a ridge line. So, by using this reverse DEM data, the valley line can also be obtained by watershed analysis. As shown in Fig. 3, by using the DEM data, the No. 1 watershed can be obtained, then by the reverse DEM data, No. 2 and No. 3 watersheds can also be obtained. It can be seen that the No. 1 watershed is divided into left and right parts, these two parts representing two slope units.

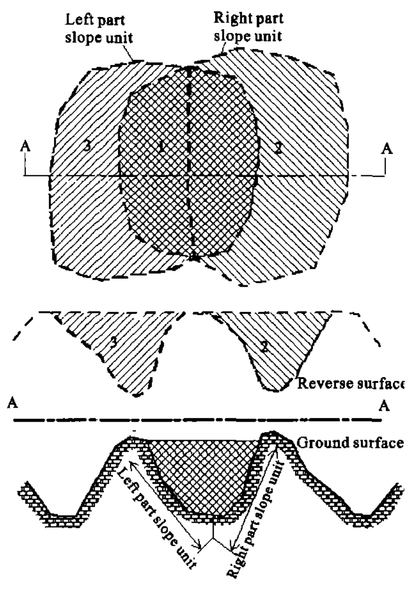

Fig. 3 Watershed by DEM and reverse DEM

By combining the watershed by DEM and the watershed by reverse DEM, the slope unit can be obtained. Fig. 4 illustrates the flow chart for determining the slope unit by DEM. Using a hydraulic model, firstly filling the DEM data, secondly by getting the flow direction by this filled DEM, then by calculating the accumulation, the watershed can eventually be calculated by setting the minimum number of cells that flow to the calculating point (cell). It is certain that with the minimum number of cells increasing, a bigger watershed can be obtained. This implies that, by setting this minimum number of cells, different-size slope units can also be obtained, and then different-size landslides hazard can be studied.

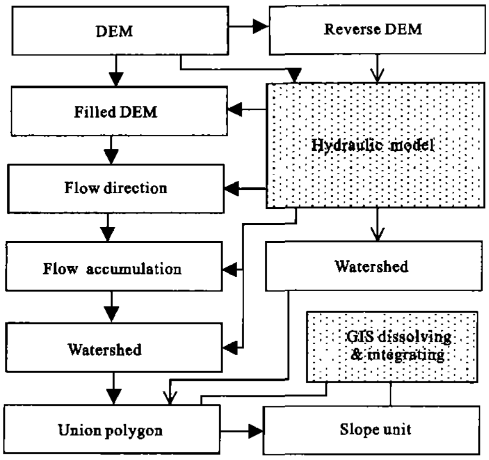

Fig. 4 Flow chart for obtaining slope unit by DEM

The valley line is calculated by the reverse DEM, this reverse DEM is obtained by the following formula:

$$R\text{-}DEM = (-1)\,DEM + DEM_{max} \quad (6)$$

where *R-DEM* is the elevation of reverse DEM, and DEM_{max} is the maximum elevation of DEM.

After two watershed polygon classes are ready, using a GIS function, the union polygon can be obtained. This union polygon process may produce many spurious polygons and small or inharmonic polygons too, but after using "dissolving" and "integrating" GIS functions, the final result slope unit polygon can be correctly determined. By using this slope unit polygon, the main inclination, slope angle and slope height of each slope unit can also be precisely calculated.

4 3D LANDSLIDE HAZARD MAPPING

The whole study area (or the slope failure range) can be evenly divided into small rectangular meshes that are the same as GIS-based grids. For numerical calculation of this grid-based 3D slope stability analysis, all of the above calculation procedures are programmed by Microsoft's Visual Basic (using a GIS components). In this program 3DSlopeGIS, Visual Basic 6.0 and ESRI's MapObjects 2.1 are employed. MapObjects as a GIS component is used for implementing the GIS data management and the spatial analysis. The process for calculating the minimum 3D safety factor and for hazard mapping is illustrated in Fig. 5. In this process, the function of the data module is for obtaining all slope related geological, geomorphologic and hydraulic data and geomechanical parameters; the random variable production module is used for randomly selecting the trial slip surface by the Monte Carlo simulation; the 3D safety factor is calculated in the 3D slope stability module; finally the critical slip surface and its safety factor can be obtained by many trial calculations. Using this 3D safety factor as a mean value, the failure probability of the landslide can be calculated by considering two variables: cohesion c and friction angle Φ. At the same time, taking this 3D safety factor as a static factor, the earthquake-triggered landslide is evaluated based on two parameters (NEWMARK, 1965): the earthquake moment magnitudeand M_w and the source distance (in km) of the epicenter. Also in Fig. 5, it can be seen that all modules are related to a GIS spatial analysis function that implemented by a GIS component, just because a GIS component (ESRI's MapObjects) is implemented in this system of 3DSlopeGIS, the 3D safety factor problem can be computed effectively. By using the slope related GIS data, at the same time, all the related data and results can also be visualized in the system of 3DSlopeGIS.

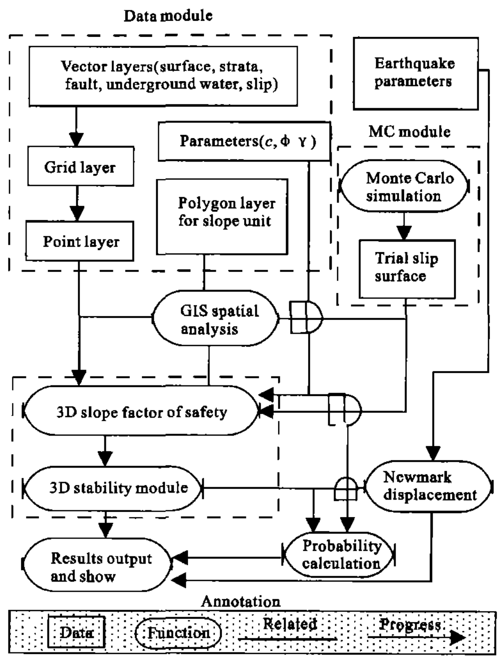

Fig. 5 Computational processes

Located in the northern part of Nagasaki Prefecture, Sasebo is the second largest city in the prefecture and one of the center cities in northern part of western Kyushu of Japan. In this area, there were numerous landslide activities happened in the past, which caused a great loss of economy and life property. Located in the northern part of the Sasebo District, Harabun Town, where one landslide occurred in July 1997, is selected for landslide hazard assessment. In this area, most often occurred landslide can be summarized to be the Hokusho type landslide, which is shown in Fig. 6. The landslide hazard in this paper is concerned about the second landslide that is the main reason of the slope failure now. The thickness of the alluvium layer is about 5 – 15m. Because the boring data is very limited in this area, the distribution of the thickness of the alluvium layer is not definite. The Tertiary strata and the alluvium are mainly consisting of the weathered materials and the clay, and their interface served as the slide surface of the second landslide. It is very critical, in the landslide assessment, to determine the spatial distribution of the slide surface.

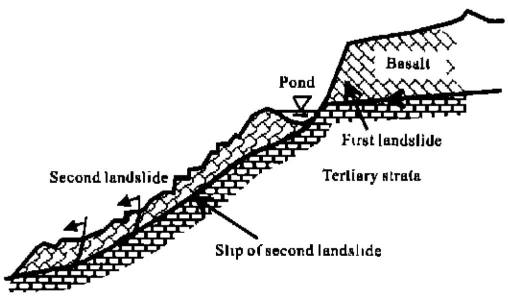

Fig. 6 Hokusho type landslide model

According to the field investigations, in this area, due to the rainfall and the long-term erosion, a complicated stream network has been formed, and the Tertiary strata can be seen at the streambed. In another word, along the stream network, the bed position of the alluvium is nearly equal to the streambed elevation. Then interpolating the stream network can identify the slide surface or the bed position of alluvium. By overlaying the stream network with the DEM data, the elevation in each pixel of stream network can be obtained. Finally, the slide surface can be determined by the Kringing interpolation method. The preciseness of the interpolation results is verified by comparing with eight boring data and the difference is acceptable. The digital elevation data is newly produced with the scale of 1: 500 that is suitable for detail study of the landslide, the DEM used in this research is in the grid form with 2m of the pixel size. The map of houses (or buildings) distribution at the scale of 1: 2500 is scanned and read in GIS as a polygon dataset. The underground water is assumed to be 30 percent of the landslide depth. The properties for the clay and bedrock are decided by collecting the past in-situ test and laboratory test results for the slide surface clay.

Fig. 7 shows the boundary distribution of all the critical landslides that their 3D safety factors are smaller than 1, one place with the mark of asterisk had been verified that a landslide failure had taken place in 1997. From Fig. 7, it is clear that there are mainly eight positions, which will have a high susceptibility of the landslide in the future, this results would be a effective reference for the action of the landslide prevention. By using the result of sections of landslide, besides the 3D safety factor and the failure probability, the possible landslide boundary and body can also be quantitatively assured.

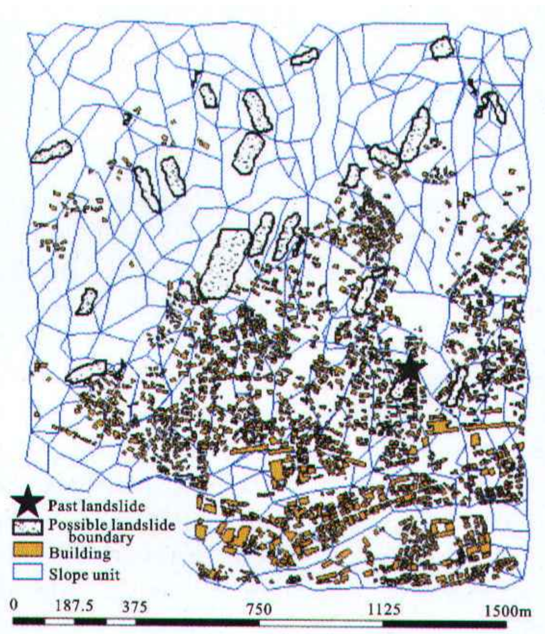

Fig. 7 Boundary of critical landslide

5 CONCLUSIONS AND DISCUSSIONS

A new Geographic Information System (GIS) grid-based 3D deterministic model has been developed for mapping the landslide hazard by the index of the 3D safety factor. Unlike most researchers had been done that taking the rectangular pixel as a study object, in this study, the slope unit, which has a fixed relationship with the landslide, has been used for the study object. Using the hydraulic model tool for the watershed analysis, an automatic process has been developed for identifying the slope unit. Assuming the initial slip as the lower part of an ellipsoid, the 3D critical slip surface in the 3D slope stability analysis is performed by means of a minimization of the 3D safety factor by using the Monte Carlo random simulation in which three parameters and the central point of an ellipsoid are taken as random variables. As a result of landslide hazard mapping, the 3D safety factor, the failure probability and the Newmark displacement of each slope unit can be spatially mapped in the system of 3DSlopeGIS, the critical landslide body can also be three-dimensionally detected. A computational program called 3DSlopeGIS, in which a GIS component is used for fulfilling the GIS spatial analysis function and effective data management, has been developed to implement all the calculations of the 3D slope problem. Taking the advantage of the spatial analysis functions, the data management and the visualization of GIS for processing the complicated slope related data, the 3D slope problem becomes easier to be studied. Beginning with this new GIS grid-based 3D slope stability analysis model, a new study field and a new database method will be opened up for slope stability researchers who have been using the traditional numerical methods.

The concept of the slope unit, taken as a study object for landslide hazard mapping, has here been proposed. Compared with the grid-based landslide hazard mapping method, the slope unit possesses clear topographical meaning, so its results are more credible. The slope unit can not only be used for the slope stability problem, because it possesses an explicit topographical concept, but it also can be useful for other research fields such as land use, agriculture, and the best site selection. Slope unit deriving is based on the watershed analysis. Because the polygon size of watershed in the watershed analysis will be changing with the minimum number of cells that flow to the calculating point (grid), the best method used for setting this minimum number of cells is still a problem. In this thesis, based on the average size of landslide presented in the study area, this minimum number of cells is determined by calculation trying. These trying are very time-consuming, so this is necessary to develop an automated method or a practical criterion to set this minimum number of cells.

Considering the landslide hazard, most of the landslides are triggered by earthquake or rainfall. In this thesis, only the underground water has been considered in the GIS grid-based 3D model, and only a simple method has been introduced for earthquake-deduced landslide analysis, so the study of mechanism of earthquake-deduced landslide is one of challenges too in the future. The study of rainfall-deduced landslide has not been concerned in this GIS grid-based 3D model, it is one of the future studies too.

REFERENCES

ALEOTTI P, CHOWDHURY R, 1999. Landslide hazard assessment: summary review and new perspectives[J]. *Bull. Eng. Env.*, 58: 21 - 44.

ANBALAGAN D, 1992. Landslide hazard evaluation and zonation mapping in mountainous terrain [J]. *Engineering Geology*, 32: 269 - 277.

BALIGH M M, AZZOUZ A S, 1975. End effects on the stability of cohesive slopes [J]. *ASCE journal of the Geotechnical Engineering Division*, 101 (GT11): 1105 - 1117.

CARRARA A, 1995. GIS technology in mapping landside hazard [A]. In: CARRARA A, GUZZETTI F (eds.). *Geographical Information Systems in Assessing Natural Hazards*[C]. Dordrecht: Kluwer Acad. Publ., 135 - 176.

DAI F C, LEE C F, 2001. Terrain-based mapping of landslide susceptibility using a geographical information system: a case study[J]. *Can. Geotech. J.*, 38: 911 - 923.

ESAKI T, XIE Mo-wen, ZHOU Guo-yun, 2001. 3D critical slope stability analysis based on GIS and Monte Carlo simulation[A]. In: DEREK E, JOHN P T, KEITH A H(eds.). *The 38th U. S. Rock Mechanics Symposium "Rock Mechanics in the National Interest"* [C]. Washington D. C.: A. A. Balkema Publishers, 1137 - 1143.

ESRI(Environmental System Research Institute), 1999. *Map Objects Programmer's Reference: GIS and Mapping Components* [R]. Redlands: ESRI Press.

GRECO V R, 1996. Efficient Monte Carlo technique for locating critical slip surface[J]. *Journal of Geotechnical Engineering*, July: 517 - 525.

HOVLAND H J, 1977. Three-dimensional slope stability analysis method[J]. *Journal of the Geotechnical Engineering, Division Proceedings of the American Society of Civil Engineers*, 103 (GT9): 971 - 986.

NEWMARK N M, 1965. Effects of earthquakes on dams and embankments [J]. *Geotechnique*, 15: 139 - 160.

VAN WESTEN C J, TERLIEN M T J, 1996. Deterministic landslide hazard analysis in GIS: A case study from Manizales (Colombia) [J]. *Earth Surface Processes and Landforms*, 21: 853 - 868.

VAN WESTEN C J, RENGERS N, TERLIEN M T J, 1997. Prediction of the occurrence of slope instability phenomena through GIS-based hazard zonation[J]. *Geologische Rundschau*, 86: 404 - 414.

XIE MO-wen, ZHOU G, ESAKI T, 2001. Landslide hazard assessment using Monte Carlo simulation based on GIS [A]. In: CHANDRA S D *et al.* (eds.). *The 10th International Conference of IACMAG* [C]. Arizona: A. A. Balkema Publishers, 169 - 173.