Use of a GIS-based 3D Deterministic Slope Stability Predicting Tool for Landslide Hazard Assessment in Zagreb Hilly Area, Croatia

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The hilly slopes of Mt. Medvednica are located in the northwestern part of Zagreb City, Croatia. In this area, landslides, e.g. Kostanjek landslide and Črešnjevec landslide, have brought damage to many houses, roads, farmlands, and grassland. Therefore, it is necessary to predict the potential landslides and to enhance landslide inventory for hazard mitigation and security management of local society in this area. We combined deterministic method and probabilistic method to assess potential landslides including their locations, size and sliding surfaces. Firstly, this study area is divided into slope units that have similar topographic and geological characteristics using hydrology analysis tool in ArcGIS. Then, a GIS-based modified 3D Hovland's method for slope stability analysis is developed to identify the sliding surface and corresponding 3D safety factor for each slope unit. Each sliding surface is assumed to be the lower part of each ellipsoid. The direction of inclination of the ellipsoid is considered to be the same as the main dip direction of the slope unit. The center point of the ellipsoid is randomly set to the center point of a grid cell in the slope unit. The 3D safety factor and corresponding sliding surface are also obtained for each slope unit. Thirdly, since a single value of safety factor is insufficient to evaluate the slope stability of a slope unit, the ratio of the number of calculation cases in which the 3D safety factor values less than 1.0 to the total number of trial calculation is defined as the failure probability of the slope unit. If the failure probability is more than 70%, the slope unit is distinguished as 'unstable' from other slope units and the landslide hazard can be mapped for the whole study area.

Key words: GIS, landslide hazard, slope-unit, Failure Probability

1. INTRODUCTION

Landslides are the major natural disasters that frequently occur in the hilly and mountainous terrains. The assessment of landslide hazard and risk has become a topic of major interest for both geoscientists and engineering professionals as well as for local communities and administrations in many parts of the world (Burton et al., 1978; Rezig et al., 1996; Guzzetti et al., 1999; Aleotti and Chowdhury, 1999; Wang et al., 2006). The susceptibility of a given large area to landslides can be determined and depicted using hazard zonation. Assessing relative landslide hazard is the objective of the method described in this study.

The City of Zagreb is located in northwest Croatia in the western part of the Pannonian Basin. The urbanized area is located below the forest region of Mt. Medvednica to the north and extends to the flood plain of the Sava River in the south. Approximately 40% of the urban area is located in hilly areas in which landslides are the main geological hazard. Landslides in the hilly area of Zagreb are mostly small and shallow movements of superficial deposits along contacts with fresh deposits of soil (Mihalić and Arbanas 2013). Despite this, landslides cause significant economic losses by damaging houses and the urban infrastructure. Therefore, it is necessary to predict the potential landslides and to enhance landslide inventory for hazard mitigation and security management of local society in this area.

The hilly area of Mt. Medvednica, which covers about 180km^2, is the pilot area of Japanese-Croatian scientific joint-research project 'Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia' which was launched in 2008 when it was selected for the Science and Technology Research Partnership for Sustainable Development (SATREPS). One of the main research activities is the landslide hazard assessment for the hilly area of Mt. Medvednica in Zagreb City. Veliki potok catchment, which is approximate size of 45 km^2, is selected as the representative area in the hilly area of Mt. Medvednica. **Figure 1** shows the location and the digital elevation model of the study area. In this study, a GIS-based three-dimensional deterministic model and probabilistic method is combined to assess potential landslide zones including their locations, size and sliding surfaces in Veliki potok catchment.

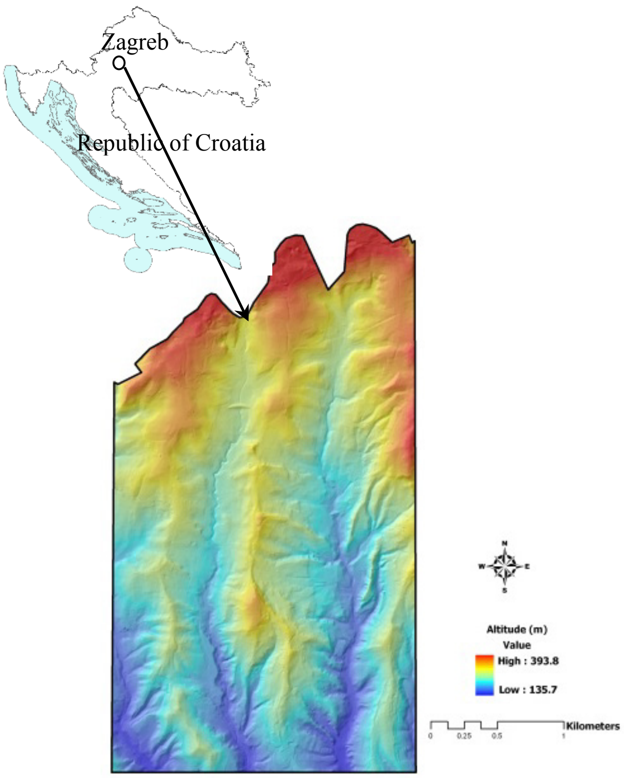

Fig. 1 The study area in Croatia

2. SLOPE UNIT DIVISION FOR LARGE SCALE AREA

The methods of landslide hazard assessment can be summarized to the four approaches, namely: statistical analysis, probabilistic analysis, heuristic analysis and deterministic analysis. All these methods are considered valid in certain contexts. The first three approaches are often used for large-scale landslide hazard assessment. For use of deterministic analysis in a large-scale area, the problem is how to divide large-scale area into small terrain units that can be as study objects for the deterministic approach. The terrain units are also called slope units. It is defined as the portion of land surface that contains maximum internal homogeneity differing from the adjacent units, has relatively similar topographic and geological characteristics. In recent years, many authors have proposed several methods of slope unit division (Carrara 1983; Hansen 1984; Carrara et al. 1995; Xie et al. 2003). Among them, the methods which is based on Hydrological ananlysis in ArcGIS and presented by Xie et al. (2003) can effectively divide slope units in a mountainous area with high topographic relief. Slope units can be basically divided by geomorphological, geological and hydraulic conditions, but mainly by topological breaks, because the topological breaks have implicit relationship with materials and geological and hydraulic conditions. A watershed is a subclass of the drainage area. (**Fig.2a**). A slope unit can be considered as the left or right part of a watershed. Topologically, it can be identified by a ridge line and a valley line of a watershed (**Fig. 2b**) which can be extracted by the hydrology analysis tool in ArcGIS.

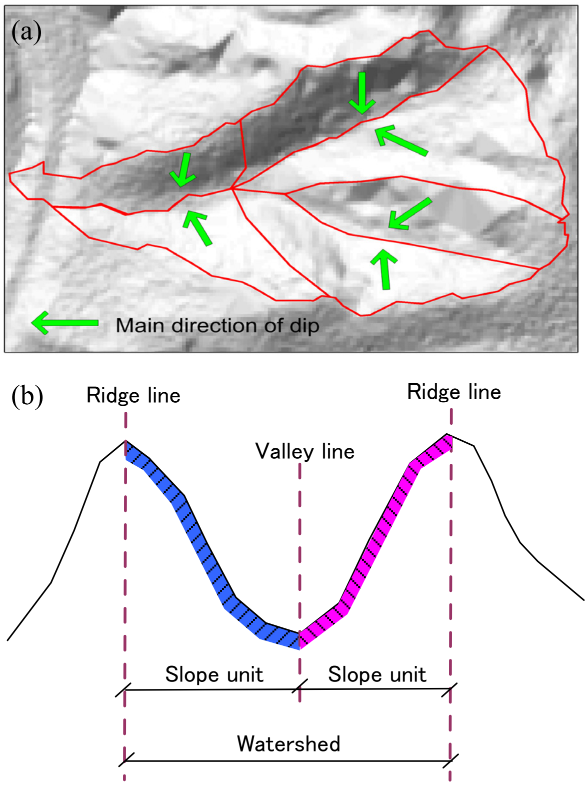

Fig.2 Conceptual illustration of slope unit division ((a) planar view of slope units in a watershed; (b) profile of slope unit.

The appropriate size of slope unit should be dependent on the grid-cell size and the average size of the study object, for example, the average size of landslide bodies present 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.

The detailed method of how to divide large-scale area into slope units is introduced by Xie et al. (2003). In this study, a slope unit tool developed by Modelbuilder tool in ArcGIS Version 10 is developed to extract slope units automatically (**Fig. 3**). **Fig. 4** shows the results of the slope units in the study area.

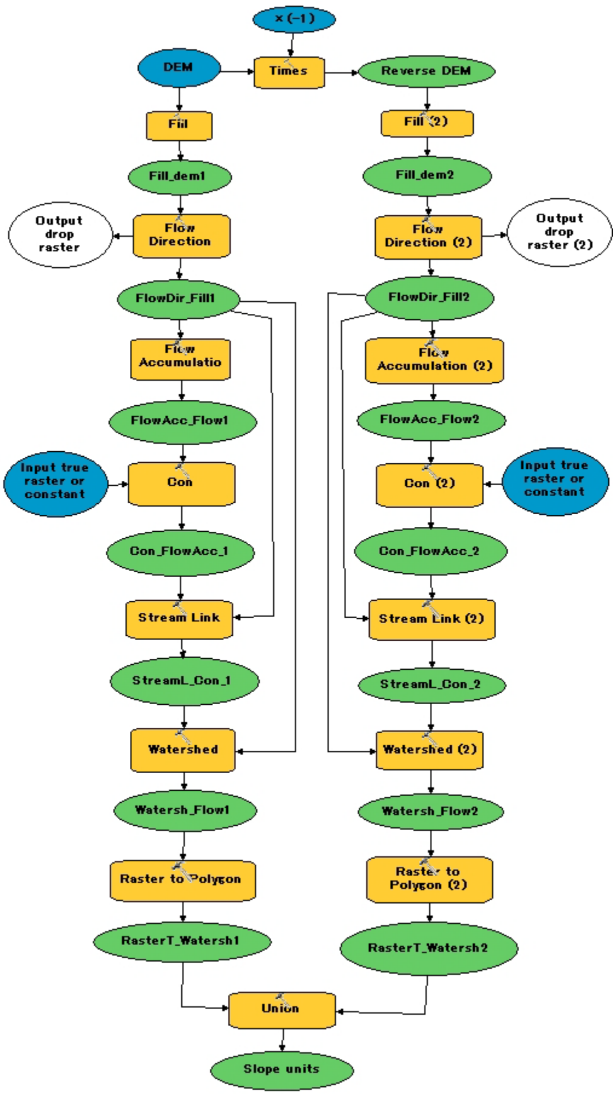

Fig.3 a slope unit tool developed by Modelbuilder in

3. GIS-BASED 3D LANDSLIDE HAZARD ASSESSMENT

When evaluating the landslide susceptibility of

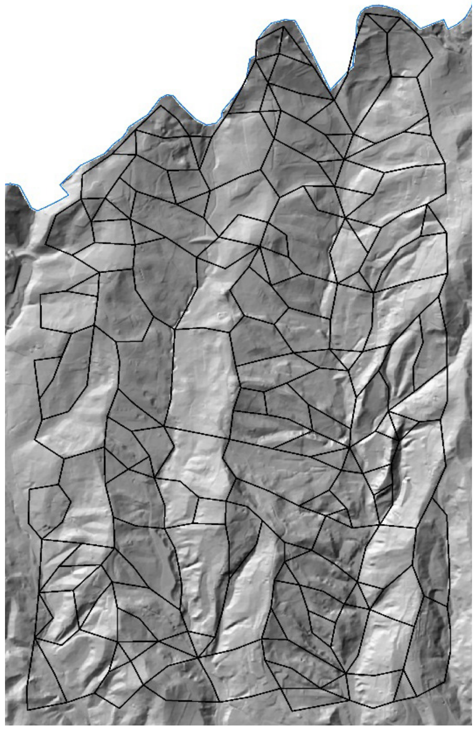

Fig.4 the slope units for the study area

regional area, processing large amounts of spatial data and identifying the potential instability zones would be arduous works. Recently, Geographical Information System, with its excellent data structures and spatial data processing capacity, has attracted great attention in landslide disaster assessment. The collection, manipulation and analysis of the geological and environmental data on region-scale landslide hazard can be accomplished much more efficiently and cost effectively. In this study, the GIS-based modified 3D Hovland's method for slope stability analysis (Xie et al. 2003, 2006) is used to identify the sliding surface and to calculate the corresponding 3D safety factor for each slope unit. **Fig. 5** shows the conceptual model of this method. The spatial data of ground surface, strata, underground water, and slip surface can be obtained from the grid-based layers. The modified Hovland model is defined by Eq. (1).

$$SF_{3D} = \frac{\sum_J \sum_I (cA + [(Z_{ji} - z_{ji})\gamma \cos\theta - u_{ji}]\tan\phi)\cos\theta_{Avr}}{\sum_J \sum_I (Z_{ji} - z_{ji})\gamma \sin\theta_{Avr} \cos\theta_{Avr}} \qquad (1)$$

Where SF_{3D} is the 3D slope safety factor; j and i are the row and column numbers of the grid in the range of slope failure; Z_{ji} and z_{ji} are elevations of ground surface and slip surface respectively; u_{ji} is the pore-water pressure acting on the slip surface of each column; γ is unit weight; A is the area of the slip surface; c is the cohesion; ϕ is the friction angle: θ is the dip (the normal angle of the slip surface); θ_{Avr} is the apparent dip in the main inclination direction of the slip surface.

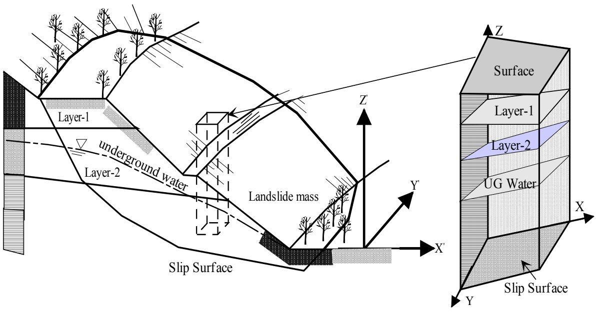

Fig.5 a 3D sliding mass and its GIS concept.

The slip surface is assumed to be the lower part of an ellipsoid. The direction of inclination of the ellipsoid is considered to be the same as the main dip direction of the slope unit. The center point of the ellipsoid is randomly set to the center point of a grid cell in the slope unit. The geometrical parameters (a,b,c) of the ellipsoid are randomly set from a certain range that is set as in Equ. (2):

$$\begin{aligned} &\mathrm{a} \in (a_{min,} a_{max}), \\ &\mathrm{b} \in (b_{min,} b_{max}), \\ &\mathrm{c} \in (c_{min,} c_{max}) \end{aligned} \quad (2)$$

Here, a_{min} and b_{min} are equal to the grid-cell length, a_{max} is equal to the nearest distance from the central point to the slope unit polygon (border), $b_{max} = r * \mathrm{a}_{\mathrm{max}}$, c_{min} is greater than 0, c_{max} is the maximum depth of the slip surface, r is greater than 1, r and c_{max} can be set by the user. Assuming that a, b, c are uniform distribution, their values are calculated by Monte Carlo method. In this study, the identifying method of slip surface presented by Xie et al. (2003) is revised. The intersection of the ellipsoid and the ground surface should be within a slope unit (**Fig. 6**). The distance of one point within a slope unit to the boundary of the slope unit (as shown in **Fig. 6**) should be satisfied with Equ. (3) in order to make the boundary located within the slope unit.

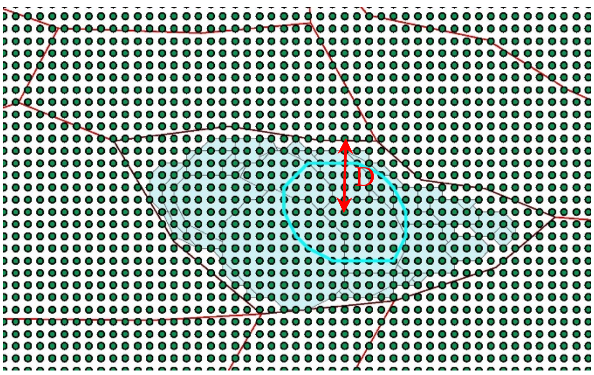

Fig. 6 illustration of how to calculate the distance from one point to boundary of a slope unit

$$\textit{Grid-cell size} < D < a_{max} \quad (3)$$

Based on the engineering geological report of this area, the physical and geomechanical parameters for the surface stratum are proposed as c (cohesion), φ (friction angle), and γ (unit weight) are 22 kN/m^2, 25°, and 20.3 kN/m^3, respectively. Because there is no field groundwater level monitoring, the influence of the groundwater on slope stability was ignored in this study.

As shown in **Fig. 7**, taking one point in the range of the target slope unit as the center point of the trial ellipsoid, a large number of slip surfaces with various spatial shapes can be simulated. After sufficient trial calculations for the safety factor of simulated slip surfaces, the values of 3D safety factors can be obtained. These values are then assigned and recorded to the attribution table of the point data. The shape of the light blue polygon in **Fig.7** is the contact boundary of the ellipsoid and the ground surface.

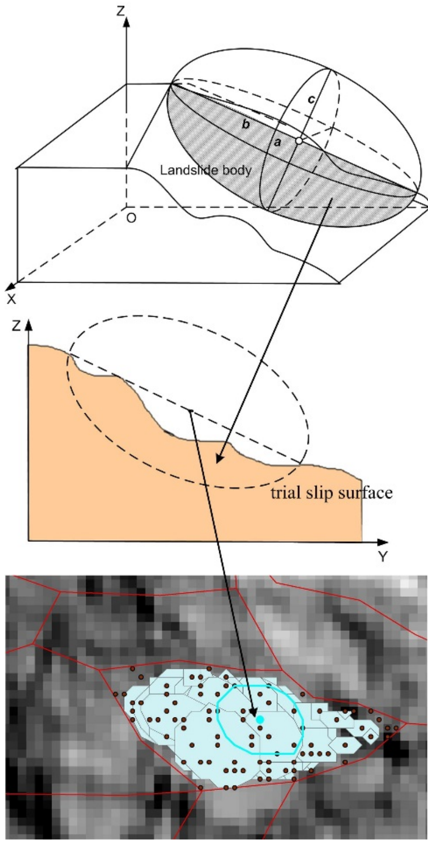

Fig. 7 searching for the potential instability zone in a slope unit

Since a single value of safety factor is insufficient to evaluate the slope stability of a slope unit, the ratio of the number of calculation cases in which the three-dimensional safety factor values less than 1.0 to the total number of trial calculation is defined as the failure probability of the slope unit (Equ. 4). **Fig. 8** shows the flowchart of the calculation procedure. If the failure probability is more than 70%, the slope unit is distinguished as 'unstable' from other slope units and the landslide hazard can be mapped for the whole study area. **Fig. 9** shows the result of failure probability of slope units in Veliki potok catchment.

$$\text{Failure probability} = \frac{\mathit{Calculation\ times\ of\ SF_{3D}}<1.0}{\mathit{Total\ times\ of\ calculation}} \tag{4}$$

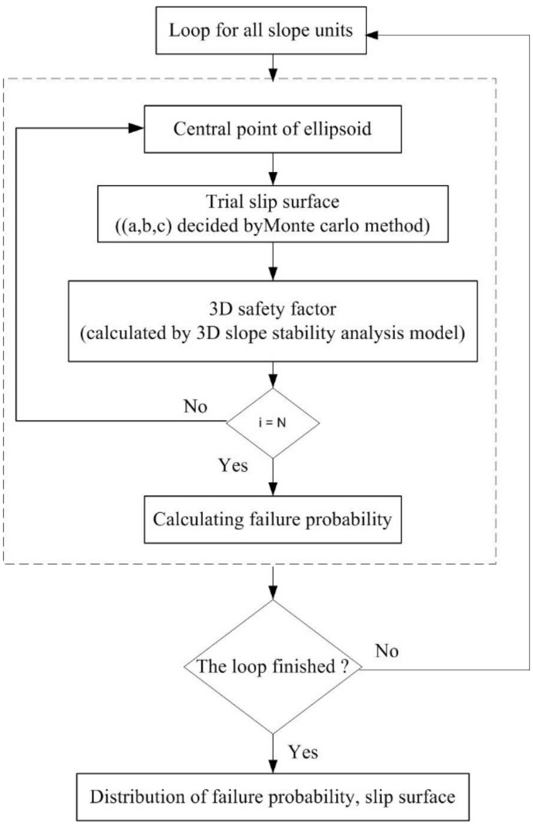

Fig. 8 flowchart for the probabilistic calculation

4. CONCLUSION AND DISCUSSION

Landslide hazard assessment in a regional-scale or large area is an important step towards landslide hazard and risk management. Although there are several methods of landslide hazard assessment, e.g., statistical analysis, probabilistic analysis, heuristic analysis and deterministic analysis, no one method is accepted universally for effective assessment of landslide hazards. This paper presented an approach coupling deterministic analysis and probabilistic analysis. For use of deterministic analysis, the study area is divided into slope units as study objects. A useful Modelbuilder tool is developed for dividing slope units in ArcGIS version 10 environment. For

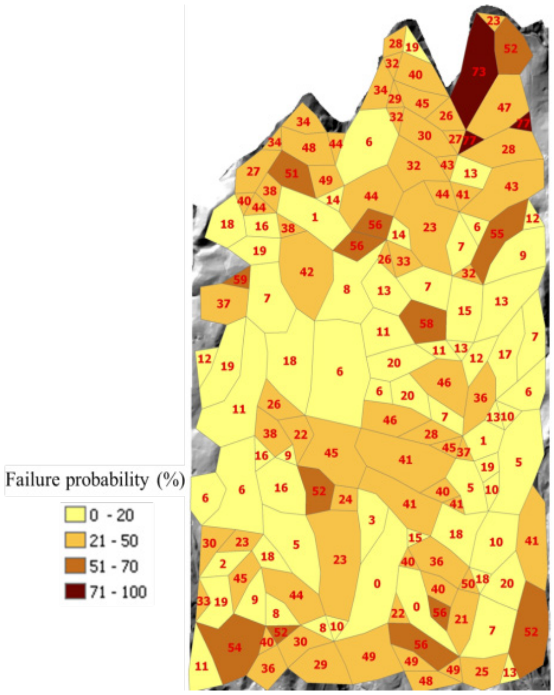

Fig. 9 failure probability of slope units in Veliki potok

the procedure of searching the slip surface within a slope unit, the GIS-based 3D slope stability model developed by Xie et al. (2003) is revised in this study. The revised approach was applied to Veliki potok catchment, Zagreb Ctiy, Croatia and the probability of natural slope failure has been determined.

For assessing a regional-scale landslide hazard, the deterministic analysis using a safety factor in geotechnical engineering will be biased due to the uncertainty of the input data, the probabilistic analysis approach provides a better alternative. In this study, the uncertainty of the location of slip surface was considered using Monte Carlo method. The uncertainties of geomaterial properties and groundwater level are also important for assessing landslide hazard. It will be worthy to consider those factors for further implementation.

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