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I－3 Development of GIS-based spatial three-dimensional slope stability analysis system: 3DSlopeGIS

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Abstract: Based on a new IT technology-Geographic Information System (GIS), this paper presents a new slope analysis approach which can be used to identify the possible slope failure bodies from complicated topography. In a system, all slope-related spatial information (vector or raster dataset) are integrated; the study area is divided into Slope Unit which possesses approximate inclination; assuming the initial slip to be the lower part of an ellipsoid, the 3-D critical slip surface in the 3-D slope stability analysis is located by minimizing the 3-D safety factor using the Monte Carlo random simulation.

The system 3DSlopeGIS has been validated based on the results of three cases study. Based on numerous times Monte Carlo simulation (30 millions per 1km^2 range), the possible slope failure bodies have been identified which is impossible by using transitional slope stability analyses.

Keywords : GIS, slope stability, slope disaster, spatial three-dimensional, slope unit, natural slope, GUI

抄録：本論文は，最新の IT 技術である GIS を用い，自然の複雑な地形の中から崩壊の可能性のあるすべり体の位置と規模を抽出することのできる新しい斜面解析の技術開発について述べた。すなわち，斜面崩壊に関する様々な空間情報のベクトル及びラスターデータの準備と統合；複雑な自然斜面地形を同一傾斜方向が有する領域に区分する Slope Unit の概念と区分の手順；区分した Slope Unit 毎に，楕円体の下半分の形状と仮定したすべり体から安全率を求める計算方法およびモンテカルロシミュレーションにより最も不安定となるすべり体の位置と規模を推定する計算手順；さらに，これらの計算過程を GUI によってビジュアルに表示しなから実行するシステムの開発を行った。

この開発したシステム 3DSlopeGIS を三つの現場に対して適用性を確認した。その結果，山地 1km^2 当り約 3000 万回の繰り返し試行により，従来の斜面安定解析で不可能であった、不安定なすべり体の位置と規模の抽出が実現できた。

1. Introduction

Slope stability is widely evaluated in various development planning and slope disaster decreasing, in planning linear projects such as roads, railways and transmission lines. The probability of a landslide event is the likelihood that a mass movement (or slope failure) will occur. It can be expressed in relative (qualitative) terms or probabilistic (quantitative) terms. Probability can refer to the probability of occurrence within a certain period, or to the probability caused by the uncertainty of geomechanical parameters or geotechnical models, or the frequency, intensity and duration of triggering agents [1)]. This paper aims to predict where slope failures are most likely to occur. Mass movement events, according to movement type, are commonly classified into five main groups [2)]: falls, topples, slides, spreads and flows. In this paper, slope failure means a slide of weathered rock of nature slope.

There are three methods of zoning slope failure probability: qualitative, statistical methodologies and geotechnical model based methodologies.

Generally, qualitative approaches are based entirely on the judgment of those conducting the susceptibility or hazard assessment [3,4,5)]. The input data are usually derived from assessment during field visits, possibly supported by aerial photo interpretation. Because of the lack of a concrete physical concept with slope failure, qualitative approaches are seldom used as a guide for large-scale areas. The statistical approach is an indirect method in which either a predictive function or index is derived from a combination of weighted factors. The relative contribution of each factor is obtained by means of statistical analyses (bivariate and multivariate). Deterministic, or physically based, models are based on the physical laws of conservation of mass, energy and momentum. The parameters used in these models can be determined in the field or in the laboratory.

The geotechnical model, which is deterministic or probabilistic, has been widely employed in civil engineering and engineering geology for slope stability analysis. A deterministic approach was traditionally considered sufficient for both homogenous and non-homogenous slopes. Unfortunately, there has been an

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increasing tendency to adopt an "infinite slope" model, which is well known as a "one-dimensional model" that represents the potential failure of long natural slopes along the slip surface parallel to the ground surface [5,6,7]. This model may be valid for shallow slope failure.

Two-dimensional (2-D) deterministic analysis models for slope stability analysis are widely used in civil engineering design and evaluation. Various 2-D methods have been developed and have employed for practice use. Since an area consists of many "slopes" in the 2-D concept, the use of 2-D models to obtain the spatial distribution of safety factors is almost impossible as "each slope" has to be analyzed separately, and "each slope" means "each random profile".

All slope failures have a three-dimensional (3-D) geometry, which varies in space even along a short distance. Therefore, it is reasonable to use a 3-D model to analyze slope stability. Since the mid 1970s, increasing attention has been directed toward the developing and applying 3-D slope stability models. Several 3-D methods of analysis have been proposed in geotechnical literature [8,9,10,11,12,13]. Most of these methods have used a column-based approach. Because of the complicated spatial data, managing a 3D problem is still a difficult problem.

GIS, as a computer-based system for data capture, input, manipulation, transformation, visualization, combination, query, analysis, modeling and output, with its excellent spatial data processing capacity, has attracted significant attention in natural disaster assessment [14]. For the past 20 years, GIS has been widely used in landslide hazard assessment [6,15,16,17], but little researcher had implemented a slope stability deterministic model.

For a 3D slope problem, the stability analysis is related to the complicated topography, strata, shear strength, and/or pore-water pressure condition, all these information cannot been easily managed in the ordinary 3D stability analysis software, but GIS can provides a ease way and a common platform to manage all these complicated slope-related information. Most of 3D methods for slope stability mentioned above have used a column-based method. Because the entire slope related data could be changed to the grid-based data in GIS, it is possible that these column-based 3D models can be used for the 3D stability calculation by using the GIS grid-based data.

In fact, the 3-D landslide stability calculation results in only an average 3-D safety factor. The problem is that any variability (introduced by error and uncertainty) in the input parameters is not accounted for in this result of the 3-D safety factor. Thus, there has been an increase in the development and use of the probability technique. Ground condition and properties vary from one location to another, even within homogeneous layers. This variability is caused by factors such as variation in mineralogical composition, conditions during deposition, stress history, and physical and mechanical decomposition processes [18].

This study takes effective cohesion c and effective friction angle ϕ of the ground properties as the major source of uncertainty, and assuming variables of c, ϕ, and the 3-D factor of safety to be in the normal distribution, the 3-D probability of the landslide is calculated by an approximate method that uses a probability in the range of $\mu \pm 3\sigma$; the 99.75% of precision in this range is sufficient for slope failure assessment.

Many researchers assume the pixel (or grid) to be the study object [5,16,17,19] 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. However, the grid cell does not bear any relation to the mechanism of slope failure or even to geological, geomorphologic and other environmental boundaries, so the results obtained by this approach are relatively unacceptable in physical terms.

Landslide is intrinsically related to the geological and geomorphologic aspects of the study area when no activity is recorded in the mass movement. This study takes the slope unit as the mapping unit. The slope unit, that is, the portion of land surface with a set of ground conditions that differ from the adjacent units, has an explicit topographical (break line, stream, aspect and slope) and geological form. Slope units are divided by geomorphological, geological and hydraulic conditions. Since it is virtually impossible to draw consistent dividing lines on topographic maps covering large regions, an automatic computer procedure is required. This study develops a GIS-based hydrologic analysis and modeling tool to automatically identify the slope unit.

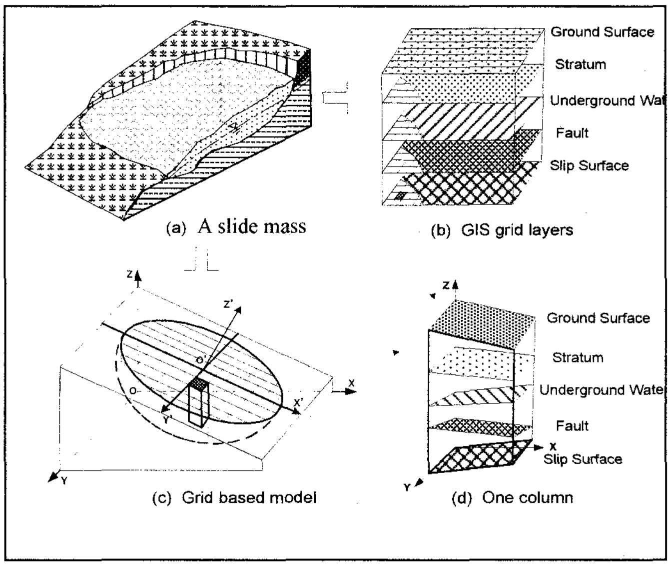
Combining GIS grid-based data with a column-based 3-D slope stability-analysis model [8], this study uses a new GIS grid-based 3-D deterministic model [23] for calculating the safety factor. To detect 3-D critical slip, the search is performed by minimizing the 3-D safety factor using the Monte Carlo random simulation method. The basic slip surface is assumed to be the lower part of an ellipsoid slip, and the critical slip will be changed according to different strengths of strata and conditions of the discontinuous surface. This improved approach [23] is more effective to detect the critical slip surface because it uses more random variables than former one [23].

2. Development of 3D slope model based on GIS and Monte Carlo simulation

2.1 Slope-related GIS database implementation

Representation models try to describe the landslide-related objects such as stratum, fault, groundwater, sliding surface and ground. The way of representation models created in GIS is through a set of data layers. These data layers will be either raster or vector data. Vector GIS comprise three different geometry data types: point, line and polygon. Each element can be described by many additional characteristics archived in the database comprising all GIS data. Raster GIS are formed by raster layers where each layer represents certain information whose value forms the pixel value and is visualized as a color of the pixel. All attributes are visualized in forms of raster layers. Raster layers are represented by a rectangular mesh or grid.

Using the functions of GIS spatial analysis, all slope-related data (such as elevation, inclination, slope, groundwater, strata, slip surface and mechanical parameters) for the safety factor calculation are available with respect to each grid pixel, while all slope-related data are grid-based. Fig. 1 shows a real slope mass and its abstracting GIS layers. In GIS, the reality of a landslide is abstracted to GIS layers for each topographic and geological theme, each layer of which represents each theme: ground surface, strata, weak discontinuities, groundwater and slip surface, respectively. By inputting these data into a deterministic model of slope stability, a safety factor value is calculated.


(a) A slide mass

(b) GIS grid layers

(c) Grid based model

(d) One column

Fig. 1 A sliding mass and its abstracting GIS layers

2.2 3D model of slope stability analysis[21)]

Based on the Mohr-Coulomb criterion, the 3D safety factor of a landslide body can be calculated by the available resistant force and the sliding force:

$$SF_{3D} = \frac{Available\_force}{Sliding\_force} \tag{1}$$

the equation (1) can be mathematically calculated by an integration formula:

$$SF_{3D} = \frac{\iint f_R(x,y)dxdy}{\iint f_S(x,y)dxdy} \tag{2}$$

where, $f_R(x,y)$ is the resistant force function and $f_S(x,y)$ is the sliding force function along slip. Because the functions of sliding force, normal stress and even the water pore pressure along on the slip surface cannot be clearly obtained, this integration formula is always approximately calculated by a differentiation formula which is the standard approach in the finite element method analysis:

$$SF_{3D} = \frac{\sum_x \sum_y f_R(x_i, y_i)}{\sum_x \sum_y f_S(x_i, y_i)} \tag{3}$$

As we known, the slope-related data can be expressed by the grid-based data (raster data form), so, a grid-based 3D model for the slope safety factor calculation is possible if a column-based 3D model is used.

For a real slope failure mass as shown in Fig. 1, using the functions of GIS spatial analysis, all input data (such as the elevation, the inclination, the slope, the groundwater, the strata, the slip surface and even the mechanical parameters) for the 3D safety factor calculation can be available for each grid cell, 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. Actually, as shown in Fig. 1, a 3D grid-column, which is correspondent to each grid cell, is used to represent all the strata data, ground surface and slip surface, all geomorphologic and engineering geological information are included in each 3D grid-column unit.

By now, all slope-related data are modeled by the grid dataset in GIS using the spatial analyst function. Then all the column-based models can be adopted for analyzing.

Based on Hovland's [8,20,21)] model, a more effective [23)] GIS-based 3-D model in which pore groundwater pressure is considered based on effective stress analysis, and in which all input data can be easily presented in a grid-based form, is used to calculate the safety factor.

3-D slope safety factor SF_{3D} can be calculated by Equations (4)-(7), which are deduced from Hovland's [8,20,21] model (Fig. 1),

$$SF_{3D} = \frac{\sum_J \sum_I (cA + [(Z_{ji} - z_{ji})\gamma' \cos\theta - u_{ji}] \tan(\phi)) \cos\theta_{Avr}}{\sum_J \sum_I (Z_{ji} - z_{ji})\gamma' \sin\theta_{Avr} \cos(\theta_{Avr})} \tag{4}$$

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

$$\tan\theta_{yz} = \tan\theta\cos(Asp), \tan\theta_{xz} = \tan\theta\sin(Asp) \tag{5}$$

the area of slip surface of one grid column is

$$A = cellsize^2 \left[\frac{\sqrt{(1 - \sin^2\theta_{xz} \sin^2\theta_{yz})}}{\cos\theta_{xz} \cos\theta_{yz}} \right] \tag{6}$$

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

$$\tan\theta_{Avr} = \tan\theta \left|\cos(Asp - AvrAsp)\right| \tag{7}$$

where, for each grid, Z_{ji}, z_{ji} = the ground surface elevation and the slip surface; u_{ji} = 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 the 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.

Here, the probability of a landslide failure is calculated using an approximate method. Two main variables c and ϕ are considered in the calculation of probability, and variables c, ϕ and probability function $P = f(c, \phi)$ are assumed to be in normal distribution. From the characteristic of the normal distribution, in the range of $\mu \pm 3\sigma$ (μ is the mean and σ is the standard deviation), the probability is 99.75%, so the range of $\mu \pm 3\sigma$ can be taken approximately as the highest and lowest limits of the variable. Then the range of parameters c, ϕ and probability can approximately equal $\mu \pm 3\sigma$.

In fact, if parameters c, ϕ are taken as random variables in the probability calculation, a range of value such as $[Min, Max]$ is always suggested by the engineer, and standard deviation σ can be evaluated by the range of $[\mu - 3\sigma, \mu + 3\sigma]$. With reference to Fig. 2, the mean of SF_{3D} is calculated by Equation (1), and the minimum ($\mu - 3\sigma$) and the maximum ($\mu + 3\sigma$) of SF_{3D} can be calculated by the process shown in Fig. 2. Finally, with reference to Fig. 3, the probability of slope failure can be calculated by Equation (8):

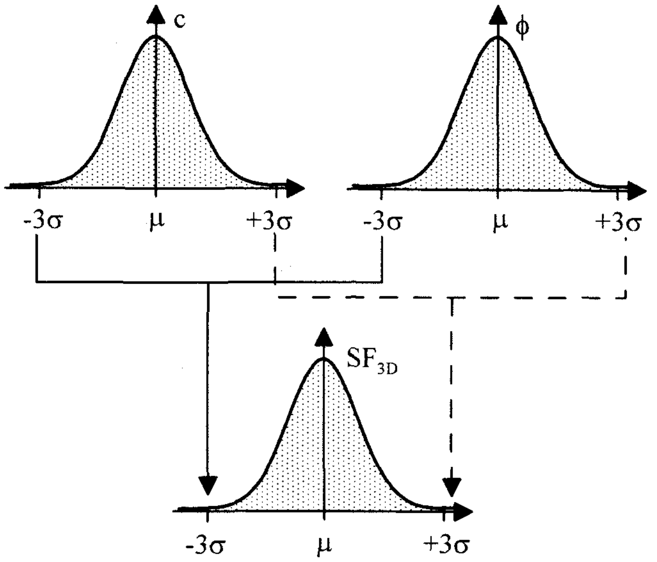


Fig. 2 Minimum and maximum 3-D safety factor

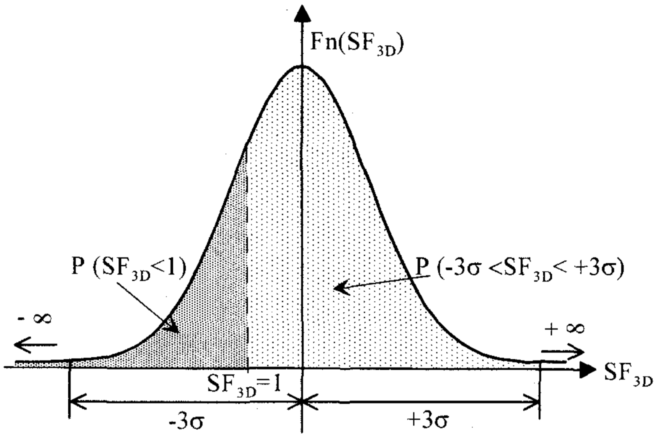


Fig. 3 Failure probability calculation.

$$P(SF_{3D} \le 1) = \int_{-\infty}^{1} \frac{1}{\sqrt{2\pi\sigma}} e^{(\frac{x-\mu}{\sigma})^{\frac{1}{2}}} dx \cong \int_{-3\sigma}^{1} \frac{1}{\sqrt{2\pi\sigma}} e^{(\frac{x-\mu}{\sigma})^{\frac{1}{2}}} dx \tag{8}$$

Without GIS, a 3D safety factor calculation based on this column-based model would be a tedious and time-consuming task, and the data renewal or a multi-case study would also be impossible by conventional numerical analysis approach. But in the GIS system, by using the GIS spatial analysis function, the slope stability related data of the whole study area can also be represented as the GIS vector layers as shown in Fig. 1. For each 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.

For calculating the 3D safety factor of slope by equation (4), the following equations are necessary:

W is the weight of each grid-column, which can be calculated:

$$W = d^2 \sum_{i=1}^{n} h_i \gamma_i \tag{9}$$

where, d is the grid size of grid-column, $i = 1,\dots,n$ is stratum number, h_i, γ_i is the height and the unit weight of each stratum.

P is the vertical force acting on each column, which can be calculated by vertical stress p, the vertical load produced by exterior load can be considered in P,

$$P = d^2 p \tag{10}$$

U is the pore pressure acting on the slip surface of each column, which is calculated by the pore stress u along the slip surface:

$$U = Au \tag{11}$$

by now, it is clear that just using the slope-related GIS grid layers and the cohesion and the friction angle of the slip surface (these two parameters can be represented by the grid layers too, in which, the spatial distribution of the parameters uncertainty can be addressed), the 3D safety factor can be calculated by equation (4).

2.3 Locating critical slip surface

The determination of the slip surface can be obtained by the detailed geotechnical investigation, because of the high cost of geological surveying, the detail of a slip surface is always uncertain, therefore, it is important, for the slope stability 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 [23] (which is calculated by Eq. (4) using the Monte Carlo random simulation method. The initial slip surface is assumed as the lower part of an ellipsoid slip and the slip surface will change according to differing layer strengths and conditions of discontinuous surface. Finally, the critical slip surface will be obtained and consequently a relative minimization of the 3D safety factor can be achieved.

The initial slip surface is assumed as the lower part of an ellipsoid; the direction of inclination of the ellipsoid is set the same as the main direction of inclination (dip) of the study area. The inclination angle of the ellipsoid is basically set as the main inclination angle of the study area with changes in certain fluctuations. The main inclination direction α and the main inclination angle β are determined by the main value of all grid pixels in the slope failure area. Assuming the direction of inclination and the angle are in normal distribution, the main inclination direction α and the angle β are set to be the mode of their distributions. Let,

$$s_1 = \sin\alpha, c_1 = \cos\alpha, s_2 = \sin\beta, c_2 = \cos\beta \tag{12}$$

then the coordinate conversion can be performed by Eq. (13) and (14).

$$\begin{Bmatrix} x''' \\ y''' \\ z''' \end{Bmatrix} = B_3 \cdot B_2 \cdot B_1 \left(\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} + \begin{Bmatrix} -x_0 \\ -y_0 \\ -z_0 \end{Bmatrix} \right) = \begin{bmatrix} c_1c_2 & -s_1c_2 & -s_2 \\ s_1 & c_1 & 0 \\ c_1s_2 & -s_1s_2 & c_2 \end{bmatrix} \cdot \begin{Bmatrix} x-x_0 \\ y-y_0 \\ z-z_0 \end{Bmatrix} \tag{13}$$

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \begin{bmatrix} c_1c_2 & s_1 & c_1s_2 \\ -s_1c_2 & c_1 & -s_1s_2 \\ -s_2 & 0 & c_2 \end{bmatrix} \begin{Bmatrix} x''' \\ y''' \\ z''' \end{Bmatrix} + \begin{Bmatrix} x_0 \\ y_0 \\ z_0 \end{Bmatrix} \tag{14}$$

where x, y, z are for world coordinates, x''', y''', z''' are for local coordinates, and x_0, y_0, z_0 is the central point of the ellipsoid. Fig. 4 shows the coordinate conversion processes.

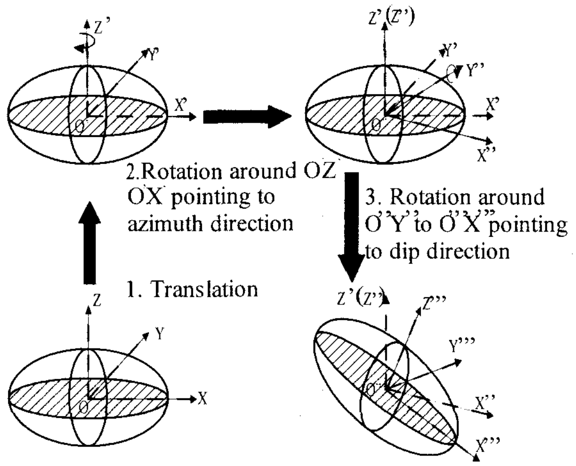


Fig. 4 The coordinate conversion

The Z value (elevation) of point "B" of the slip surface is determined by the result of equations of line AB and ellipsoid as in Eq. (12) (see Fig. 5)

$$\left.\begin{aligned} &\frac{x - x_0}{\sin(Slope)} = \frac{z - z_0}{\cos(Slope)} \\ &y = y_0 \\ &\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \end{aligned}\right\} \tag{15}$$

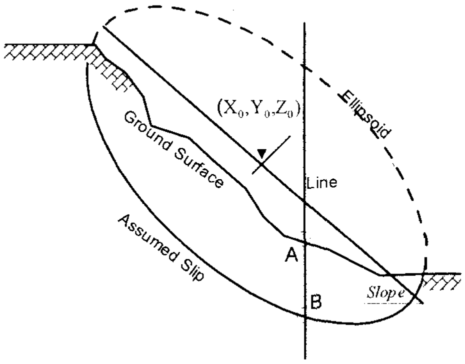


Fig. 5 For calculating elevation of slip surface

For critical slip surface identification, the Monte Carlo simulation is used to choose the variables for the 3D slope stability analysis. These variables are the central point, the geometrical parameters and the inclination angle of the ellipsoid (Fig. 6). The central point of the ellipsoid is first set as the central point of the study area, and then randomly chosen within a certain range.

The geometrical parameters a,b,c of the ellipsoid are randomly set from a certain range that is set by the user as the following Eq. (16):

$$\begin{aligned} a &\in (a_{\min}, a_{\max}) \\ b &\in (b_{\min}, b_{\max}) \\ c &\in (c_{\min}, c_{\max}) \end{aligned} \tag{16}$$

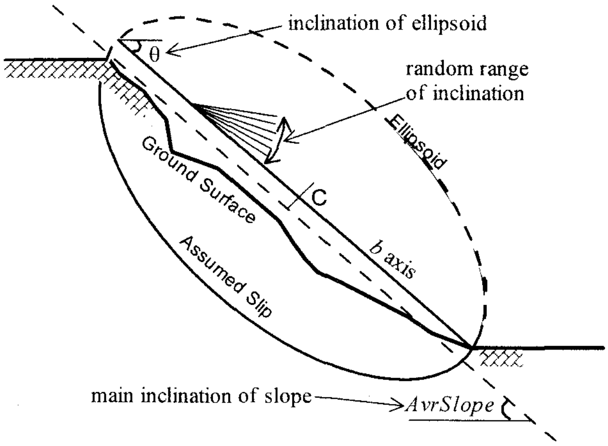


Fig. 6 The variables of Monte Carlo simulation

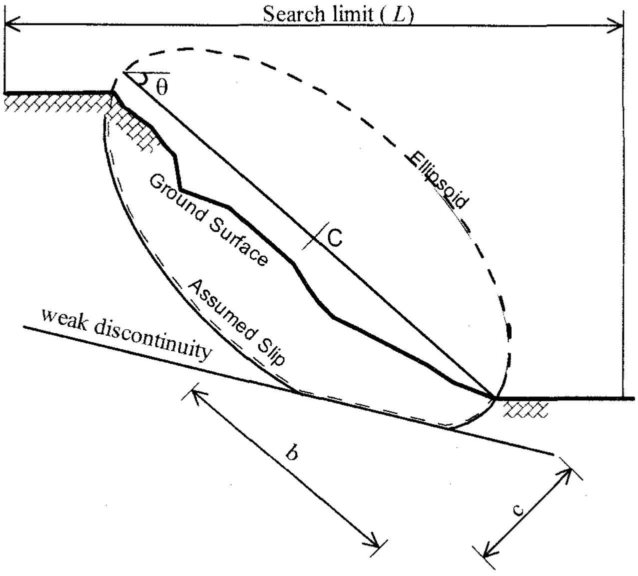


Fig .7 A composite slip surface considering discontinuity

Assuming that a,b,c are in a uniform distribution, the random variables of the Monte Carlo simulation are calculated by Eq. (17) and (18).

The random variable of uniform distribution with the range of [0,1] is obtained by the method of multiplicative congruity method:

$$\begin{aligned} y_i &= a y_{i-1} Mod(m) \\ r_i &= y_i / m \end{aligned} \tag{17}$$

where r_i = the random variable of uniform distribution on [0,1]. The random variable of uniform distribution on $[a,b]$ is then calculated by Eq. (19),

$$x_i = r_i(b-a)+a \tag{18}$$

where x_i = the random variable of uniform distribution with the range of $[a,b]$.

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.

At the same time, if a random selected slip surface is lower than the discontinuities, a part of discontinuity will be selected as a slip surface (Fig. 7).

3. Identifying slope unit

For the 3-D landslide hazard map of a certain mountain area, the critical sliding surface is identified and the minimum 3-D safety factor calculated based on each mapping unit (slope unit). A slope unit, here, is defined as one slope part, or the left/right part of a watershed. Topologically, slope units can be divided by the watershed divide and drainage line.

This study employs a GIS-based hydrologic analysis and modeling tool, Arc Hydro [22], to draw dividing lines for forming slope units automatically. Arc Hydro is an ArcGIS-based (ESRI's GIS software: ArcGIS) system geared to support water resources applications. It provides a consistent method for watershed and stream network delineation using digital elevation models (DEMs) of land-surface terrain.

The watershed feature class is a subclass of the drainage area, which contains a landscape subdivision into human-selected drainage areas, which may drain to a point on a river network, to a river segment or to a water body. It can be automatically delineated using a set of rules applied to a terrain model. The definition of watershed requires a human intervention process, where the analyst selects and edits the watershed subdivision of the landscape unit to obtain the desired arrangement.

By using Arc Hydro 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 watershed divide (ridge line). To detect the drainage line (valley line), the reverse DEM data is used. By 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 drainage line can be turned into a watershed divide. Thus, by using this reverse DEM data, the drainage line can also be obtained by watershed analysis. As shown in Fig. 8, the No.1 watershed can be obtained using the DEM data, and No.2 and No.3 watersheds can be determined using the reverse DEM data. It can be seen that No.1 watershed is divided into left and right parts, these two parts representing two slope units.

By combining the watershed by DEM and watershed by reverse DEM, the slope unit can be obtained. Fig. 9 is a flow chart to determine the slope unit from DEM. Using a hydro model, firstly filling the DEM data, secondly by obtaining 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).

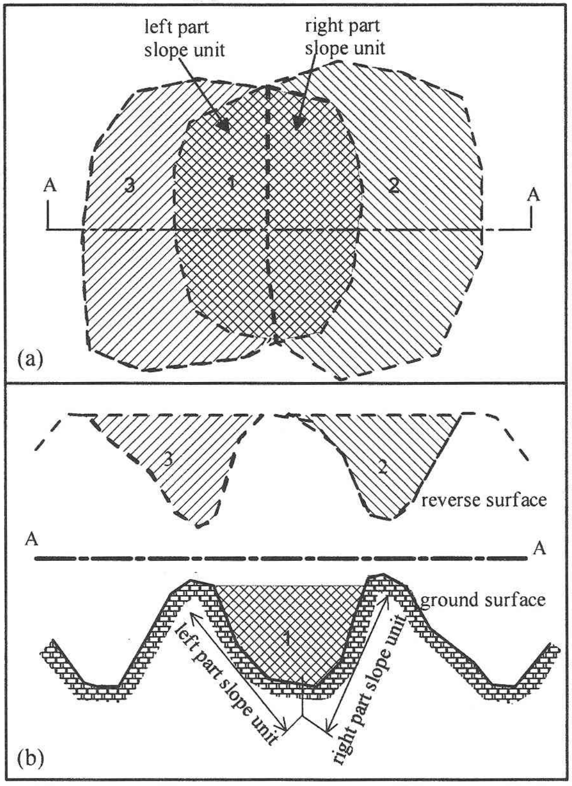


Fig. 8 Slope unit derived using a GIS-based hydrological and modeling tool

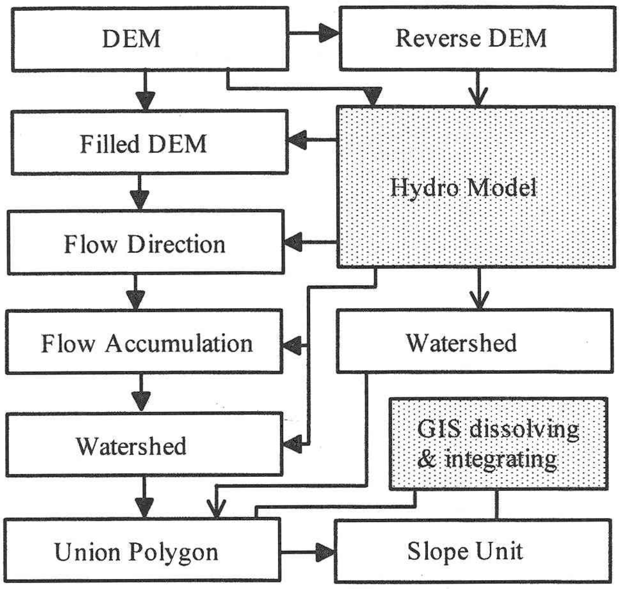


Fig. 9 Flow chart for obtaining slope unit from DEM

Fig. 10 shows the difference between the grid-based mapping unit and the slope unit-based mapping unit of an example; it can be seen that, unlike the grid-based mapping unit, each slope unit-based mapping unit corresponds to the right/left part of each slope.

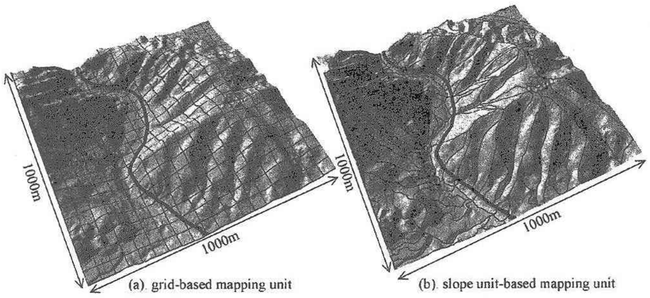


Fig. 10 Difference between the grid-based mapping unit and the slope unit-based mapping unit

4. System development and functions

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 3-D slope stability analysis, all of the above calculation procedures are programmed by Microsoft's Visual Basic (using GIS components). This program, called 3DSlopeGIS, employs Visual Basic 6.0 and ESRI's MapObjects 2.1. MapObjects as a GIS component is used for implementing GIS data management and spatial analysis, so no data export or import between GIS and the

3-D model is needed to perform the slope stability analysis. The process for calculating the minimum 3-D safety factor and for hazard mapping is illustrated in Fig. 11. In this process, the function of the data module is to obtain all slope-related geological, geomorphologic and hydraulic data and geomechanical parameters; the Monte Carlo module is used for randomly selecting each trial slip surface using the Monte Carlo simulation; the 3-D safety factor is calculated in the 3-D stability module; finally, the critical slip surface and its corresponding 3-D safety factor can be obtained by numerous (1000 times for one slope unit) trial calculations. Using this 3-D safety factor as a mean value, the failure probability of the landslide can be calculated by considering two random variables: effective cohesion c and effective friction angle ϕ. Additionally in Fig.11, it can be seen that all modules are related to a GIS spatial analysis function that is implemented by a GIS component; by implementing a GIS component in this 3DSlopeGIS system, the 3-D safety factor problem can be effectively computed. By using the slope-related GIS data, all of the related data and results can at the same time be visualized in the 3DSlopeGIS system. Fig. 12 is the interface of system of 3DSlopeGIS, the functions of system are listed in this figure too.

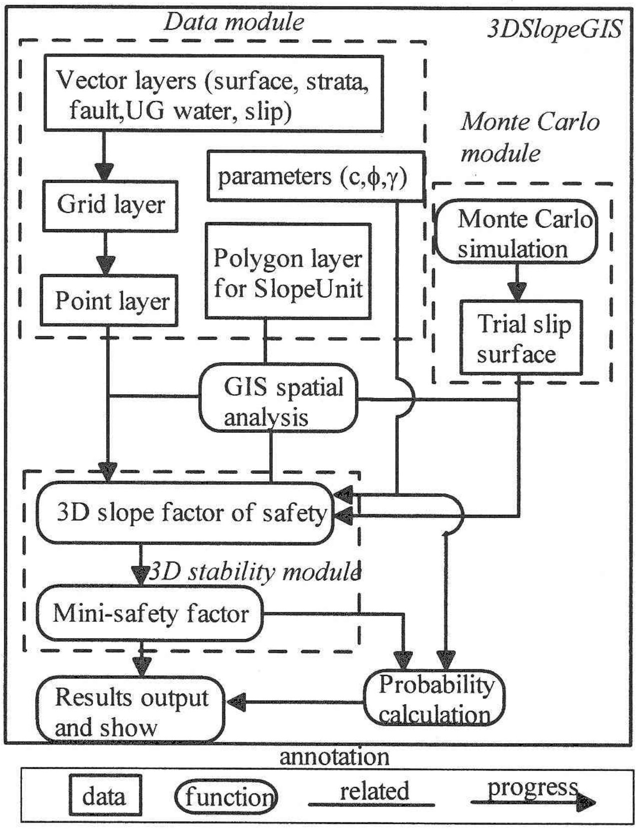


Fig. 11 Computational processes of 3DSlopeGIS

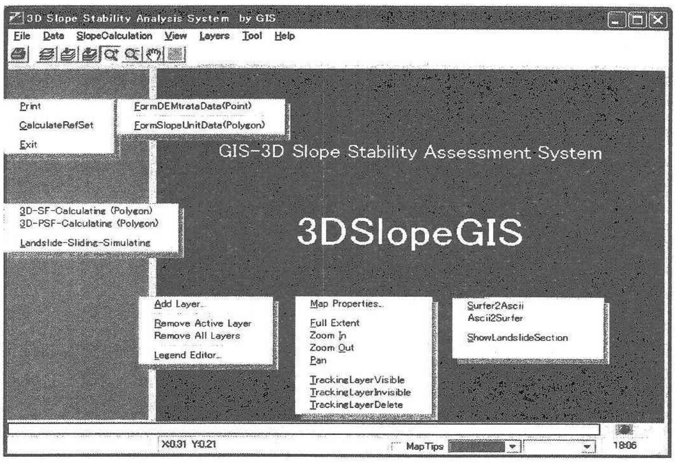


Fig. 12 The interface of system of 3DSlopeGIS

5. Applications of system

5.1 Example 1

Harabun town in the northern part of the Sasebo district, where a representative slide landslide occurred in July 1997, is selected to map landslide hazard. The case study area (Fig. 13) for the landslide hazard mapping is about 3.4 km^2 in an area located in Sasebo city.

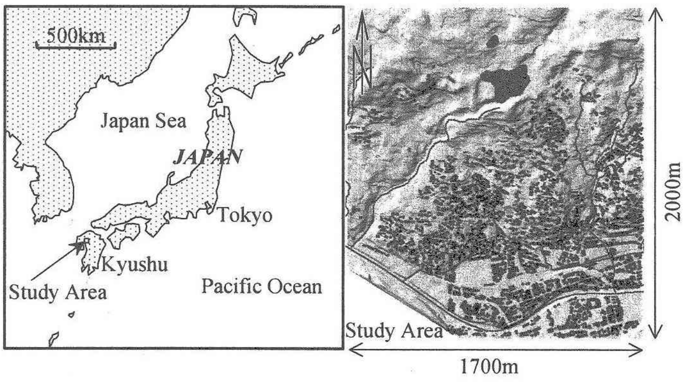


Fig. 13 The study area for mapping landslide hazard

In this area, the most frequent type of landslide is the Hokusho-type landslide. The Hokusho-type landslide, names second landslide, is a slope failure of collapsed sediment sliding along the interface between the tertiary strata and the collapsed sediment. The Kitamatsuura basalt overlies the tertiary strata. Since columnar jointing is prominent in the Kitamatsuura basalt, the basalt collapses frequently with rock fall and rock debris spreading over the hillside of the tertiary strata during rainfall. This type of landslide is usually termed the first Hokusho landslide which is no longer an active one. The collapsed sediment of the first landslide forms colluviums over the tertiary strata. The landslide, of the slide slope failure type, which occurred in the upper weathered colluvium layer (collapsed sediment), is called the second landslide. In the case of the second landslide, the sliding surface is usually along the base of the weathered collapsed colluviums, or in the top of the tertiary strata. The colluvium layer (collapsed sediment) is about 5-30 *m* thick. Landslide hazard in this example concerns the second landslide that is now the main potential hazard in this urban residential area.

The interface between the tertiary strata and the colluviums inclines gently and consists predominately of weathered materials and clay, forming a slide surface in the case of the second landslide. To map landslide, it is essential to determine the spatial distribution of the slide surface. According to field investigations, due to rainfall and long-term erosion, a complicated stream network has formed in this area; outcrops of the tertiary strata are frequently found at the bottom of the channel. In other words, the bed position of the colluviums is nearly equal to the streambed elevation along the stream network. Then, by interpolating the stream network, the interface or the bed position of colluviums can be identified. By overlaying the stream network with the DEM data, the elevation in each pixel of the stream network can be obtained. Finally, the interface can be determined using the Kriging interpolation method. The preciseness of the interpolation results is verified by comparing them with eight items of boring data, and the difference is acceptable. The digital elevation data is newly produced with the scale of 1/500 that is suitable for detailed study of the landslide, and the DEM used in this research is in grid form with a 2 *m* pixel size. The map of the distribution of buildings in the scale of 1/2500 is scanned and read in GIS as a polygon dataset. The groundwater is assumed to be 30% of the possible landslide depth, which are groundwater conditions in the rainy season. By collecting past in-situ test and laboratory test results for the interface clay, the range of properties for the clay and bedrock are decided as shown in Table 1.

Table 1 Physical and geomechanical parameters for the case study

Layer	c (kN/m^2)	ϕ (°)	γ (kN/m^3)
Collapsed sediment	5-15	5-15	16.4
Bedrock	100	35	22.6
Slip surface	5-15	5-15	/

Before mapping 3D landslide hazard, the study area is first divided into slope unit, which is the basis mapping unit. The potential landslide boundaries, with a 3D safety factor smaller than 1, show the distribution of critical landslide bodies. Fig. 14 shows the 3D view of landslide hazard map. 3D results can provide a comprehensive landslide hazard map which illustrates the 3D safety factor, the failure probability and the possible landslide boundary and body.

5.2 Example 2

The slope failure will possess the same properties within a range with the same engineering geological conditions. For landslide hazard assessment of a mountainous area, the study of past slope failure is very important for evaluating possible slope failure around the past landslide site. In July 2003, many heavy rain trigged slope disasters took place in various places of Kyushu. We selected Hogawachi Atsumari district of Minamata City in Kumamoto Prefecture is the study area. Based on the study of mechanism of a past slope failure (Fig. 15) taken place in Kumamoto of Japan, we firstly proposes the mechanical parameters for slope stability evaluating using a 3D slope stability method. For each slope unit in the study area, the critical slip surface, which gives a minimum safety factor of a slope, can be obtained. The affected streams and range of possible landslide masses are analyzed based on the damaged range of the past slope failure. Overlayered with the layers of infrastructure in GIS, this possible slope failure indicates which buildings and road sections are still in the dangerous area. As a result of this study, the locations and scales of slope failure are estimated in this area. In addition, the assessment of the influence of the slope failure induced debris flow is suggested in the research. This hazard map will be very useful for prevention of slope disasters (Fig. 16).

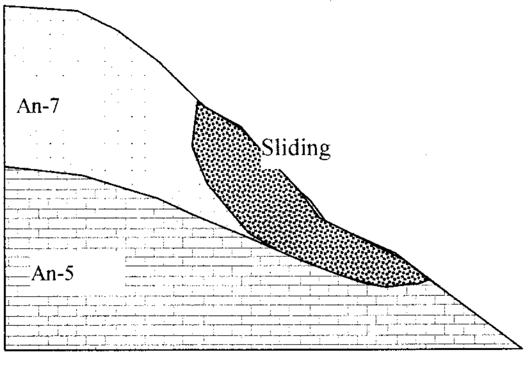


Fig.15 The schematics of landslide profile

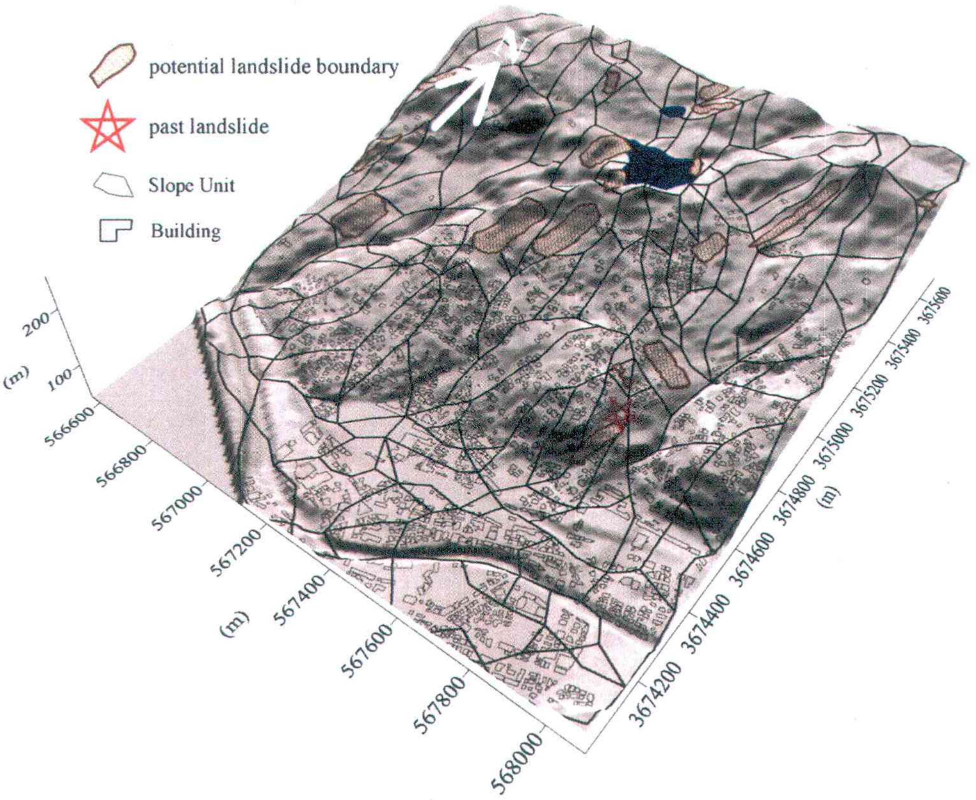


Fig. 14 The 3D landslide hazard map at Harabun town

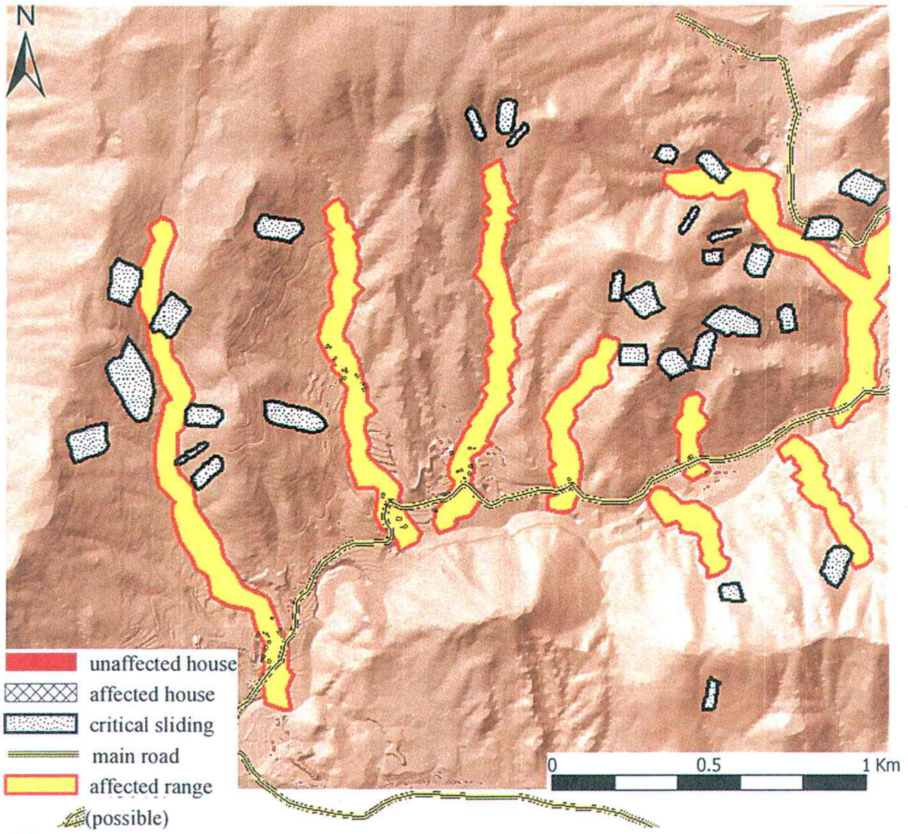


Fig. 16 Possible slide mass and possible affecting range at Hougawachi district

5.3 Example 3

Slope failure, those occurred on steep slopes beside roads, always cause traffic stagnation, even endanger the property and the life. For doing maintenance work effectively and avoiding disaster, it is essential to assess stability of road slope. After surveying and analyzing possible slope failure mode of slopes at granite weathered zone, where along the national road number 49 in Gouto area of Iwaki city(Fig. 17), the depth distribution of regolith is obtained by a simple survey method, the slope failure here is considered either along the interface of fresh granite rock and weathered surficial granite layer or inside the weathered rock (Fig. 18). By dividing the large research area to slope units, and using a random searching method to find out the critical slip surface of every slope unit, the critical slip surface with the minimum safety factor is obtained. Finally, the failure susceptibility of every slope unit is calculated and possible slope failure degree of the study area is evaluated quantitatively (Fig. 19).

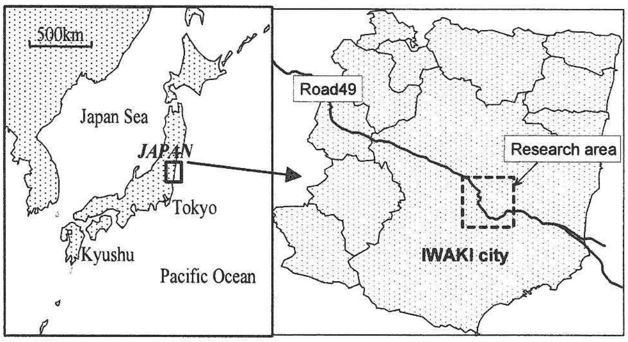


Fig.17 Location of study area

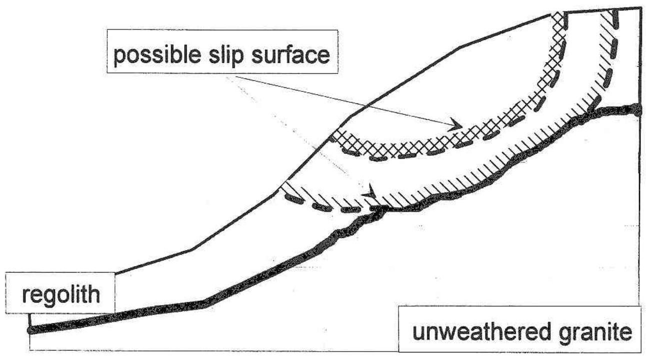


Fig.18 Possible mode of slip surfaces of weathered granite area

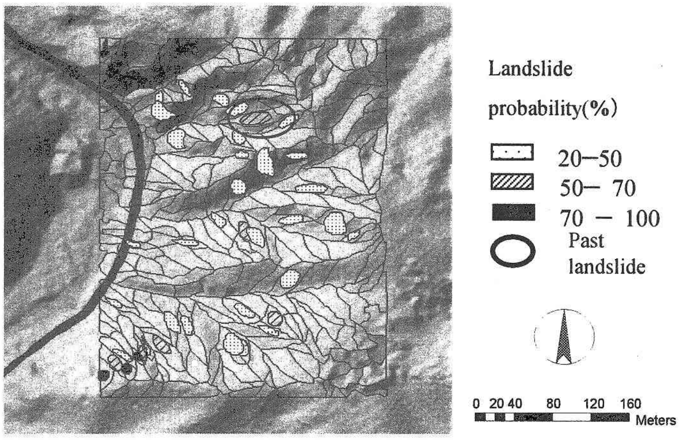


Fig. 19 Landslide hazard map of Gouto area

6. Conclusions

A GIS-based system of 3DSlopeGIS has been developed for evaluate the possible slope failure of a hilly area. A new Geographic Information Systems (GIS) grid-based 3-D deterministic model has been used to zone possible slope failure using the index of the 3-D safety factor of slope.

1. Unlike most research that has taken the rectangular pixel as the mapping unit, in this study, the slope unit, which has a fixed relationship with the landslide, has been used for the mapping unit. Using a hydrologic analysis and modeling tool for the watershed analysis, an automatic process has been developed for identifying the slope unit.
2. Assuming the initial slip to be the lower part of an ellipsoid, the 3-D critical slip surface in the 3-D slope stability analysis is performed by minimizing the 3-D safety factor using the Monte Carlo random simulation in which three parameters, a, b, c, and the central point of an ellipsoid are taken as random variables. The failure probability of the landslide is calculated using an approximate method in which effective cohesion c, effective friction angle ϕ and 3-D safety factor are assumed to be in normal distribution.
3. A computational program called 3DSlopeGIS, in which a GIS component is used to fulfill the GIS spatial analysis function and effective data management, has been developed to implement all the calculations of the 3-D slope problem. By using the spatial analysis functions, the data management and the visualization of GIS for processing the complicated slope-related data, the 3-D slope stability problem is easier to study by a friendly

visual graphical user interface.

4. The developed system had been used in some Sabo projects. Three examples listed in the paper verified the feasibility of system.

The developed system can be used for locating "where" and "how" of the critical sliding mass in a large mountain area, which is impossible by using a available slope stability approach.

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