Semi-automatic terrain slope unit division method based on human–computer interaction

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Abstract. A slope is the fundamental element of a landslide. Conducting a high-precision geohazard survey and a slope-based evaluation is important for geohazard prevention and mitigation and useful for governments in terms of improving the precision and the efficiency of geohazard management. The efficient and accurate division of slope units is the precondition of improving the accuracy and automation of a slope-based geohazard evaluation. This study introduces a semi-automatic slope unit division method that mainly includes automatic division using the geographic information system technology, followed by the revision and refinement of results by experienced professionals. Three major steps are involved in this method: 1) searching and eliminating the disturbing effect areas that could result from the disturbance of the micro-landform during the automatic division process; 2) determining the slope unit density by disclosing the relationship between the valley length and the threshold by fitting the trend with the power function; and 3) experienced professionals would perform the revision and refinement of the results generated from the previous steps to ensure that the slope unit division results meet the requirements of the slope-based evaluation. The field verification indicates that the slope units generated by the presented method are sufficient to support a slope-based evaluation on a scale of 1:10,000. The method can save considerable time and effort, which could, otherwise, be consumed during the conventional slope unit division process.

Key words: Geohazards; terrain slope units division; human–computer interaction; DEM data analysis; hydrological analysis

1. Introduction

As one of the most devastating natural hazards, geohazard has caused significant human and economic loss in history. The Lon Lake landslide in Norway in 1905 resulted to 61 deaths⁰¹, while the Vajont landslide in Italy in 1963 caused approximately 3000 deaths⁰². In China, the Ministry of Natural Resources, PRC (2011 and 2016) stated that 85,000 landslides have occurred since 2011, causing more than 2800 deaths and an economic loss of more than 60 billion USD⁰³⁰⁴.

With the advancements of numerical modeling and information technologies over the past decade, studies on geohazard mitigation and prevention have developed toward becoming more quantified, precise, and automated⁰⁵. For a highly populated region threatened by geohazard, the precision of the field survey and mapping must be improved to better protect vulnerable elements. Conducting slope-based geohazard survey and evaluation and providing appropriate risk reduction measures slope-by-slope are important in improving the mitigation efficiency for highly populated regions. The slope-based
geohazard survey and evaluation can guide the optimization and refinement of remediation efforts depending on the actual condition of each slope unit.

Conducting a slope-based geohazard evaluation has been a great concern for the international community of geohazard research. Guzzetti mentioned that the mapping unit of a regional geohazard risk evaluation can be classified into five categories: grid cell unit; geographic unit; specific condition unit; slope units; and topographic unit. Among the various types of mapping units, considering the entire slope as one mapping unit could better incorporate the slope features into the evaluation and mapping process. Governments can also more efficiently and directly apply slope-based mapping results to the geohazard prevention and mitigation process. Wu et al. (2013) conducted a slope-based geohazard susceptibility analysis. The parameter set established by considering all major influencing factors potentially improved the accuracy and the precision of the mapping results otherwise generated based on the grid unit. Meanwhile, Xu et al. (2015) conducted slope-based geohazard susceptibility for a densely populated region. Their results indicated that the slope-based mapping results could fit the actual topographic features and present the spatial distribution of geohazard better than grid unit-based mapping.

Therefore, conducting slope-based geohazard evaluation and mapping can improve the result accuracy, advance the evaluation from using semi-quantitative models to using deterministic or quantitative models, and better improve one’s understanding of the geohazard triggering conditions. A slope-based mapping method is also important for discovering the relations between the geohazard spatial distribution and other geological triggering conditions and increasing the accuracy of the statistical analysis results. Considering the basic needs and challenges in geohazard prevention and mitigation management, the slope-based mapping results can be better used to create slope-by-slope guidance and mitigation measures, such that the slope can be classified into various treatment levels based on its own risk level. Thus, mitigation efforts could be optimized and improved.

The basis of conducting geohazard survey and evaluation is to obtain the slope units of an acceptable accuracy and human effort consumption. Two types of division methods are generally used: 1) the manual division method based on professional technology and experiences and 2) the automatic division method based on the processing tools provided by geographic information system (GIS) software. The manual division method can be applied to small mapping areas with acceptable accuracy and time efficiency, but not applicable to large areas because of its non-standardization and hardly repeatable results. Meanwhile, the automatic method based on GIS software is mainly based on the principle of hydrological analysis, extraction of mountain ridge and valley lines based on digital elevation model (DEM), and obtainment of the slope unit boundary through superposition analysis. Philip et al. (1998) introduced a slope unit division method based on remote sensing images and topographic condition. Xie et al. (2004) presented a GIS-based tool for a hydrological analysis method based on the automatic identification of a three-dimensional terrain. Moreover, Romstad and Etzelmüller (2009 and 2012) presented a slope unit division method by overlaying the boundary of the concave and convex slopes.

The previously proposed slope division methods required significant professional experiences and/or high-resolution DEM data, and considerations on topographic, geological boundary, and vulnerable elements are insufficient. The existing method could also divide the approximate horizontal area without collapse, landslide, debris flow, and other geohazards and the small- and medium-sized area of micro-landform into slope units, resulting in a phenomenon in which a single vulnerable element could be threatened by more than one slope unit. This would directly provide inappropriate slope unit division results to the following field investigation and evaluation.

By taking advantage of experts’ professional technology, this study presents a semi-automatic slope unit division method based on the human–computer interaction at a 1:10,000 scale, which includes three major steps. The field verification of the proposed slope division results show that the presented method can well complete the slope unit
division based on DEM with better efficiency and accuracy compared to the conventional method. Furthermore, the method can meet the needs of geohazard prevention and provide slope-by-slope mitigation measures.

2. General framework of the slope unit division

The basic principle of the slope unit division is to obtain preliminary slope unit division results using the GIS technology by performing a surface hydrological analysis based on DEM data that meet the accuracy and quality requirements. The preliminary slope unit division results would then be refined to obtain the final results through a human–computer interaction. Figure 1 illustrates the major process involved with the following steps:

1. Step 1 (Preliminary slope unit division using the GIS tool): The accuracy and the integrity of the DEM data are analyzed. The disturbing effect of the micro-landform in the slope is identified and eliminated. The density degree of the slope division is determined. The preliminary results of the slope unit division are obtained.

2. Step 2 (Refinement of the preliminary slope unit division results based on the human–computer interaction): The major task of Step 2 is to improve the slope unit division results from Step 1 and eliminate terrain flat areas and slope units with very low or zero probability of geohazards. The final result is obtained to make it more suitable for the needs of geohazard risk assessment and management.

3. Semi-automatic method of slope unit division based on GIS

3.1. Analysis based on DEM

DEM data are the basis of the slope unit division, and their accuracy is directly related to the quality of the geohazard risk assessment. To meet the requirements of the 1:10,000-scale geohazard risk survey and evaluation, the DEM data used for the slope unit division should be able to reflect the fourth-level valley and slope boundary of the study area, and the mapping scale should not be less than 1:10,000. The DEM data of the 2 m resolution of the
study area were collected. Quality was then analyzed depending on the data accuracy and integrity.

3.1.1 Data accuracy analysis
The resolution of the remote sensing data must satisfy the basic requirements of the data resolution for the slope unit division. According to the mathematical correlation between the mapping scale and the resolution of the remote sensing images \( (e \times m \times 10^{-3} = C \times R) \), coefficient “e” is the visual resolution of approximately 0.2 mm; “m” is the denominator of the mapping scales; “C” is the coefficient of the image registration that is approximately 0.9 to 1.0; and “R” is the resolution of remote sensing images\(^{14}\). The minimum resolution of remote sensing images should not be less than 2 m for the mapping scale of 1:10,000. Therefore, the data resolution satisfies the requirements. That is, the collected DEM data match well with the DLG data. Overall, the DEM accuracy satisfies the requirements of the following process (Figure 2).

3.1.2 Data integrity analysis
The identification and correction of the major topological errors of the DEM data are important for the following analysis. The DEM should comprehensively cover the whole studied region without existing “No data” problems. After confirming the two issues, the DEM data can now be used for the slope unit division process.

3.2 Elimination of the disturbing effect caused by micro-geomorphology
Conducting a surface hydrologic analysis is an important step for extracting the ridge and valley lines from the DEM. In this analysis, the network boundary formed by the fusion of the ridge and valley lines is regarded as the slope unit boundary. Meanwhile, the field survey indicated that low-lying areas existed in most of the slope body. According to the conventional surface hydrological analysis, the slope of these areas would automatically be divided and result in a slope in slope land forms. This problem is referred to as the “disturbing effect.”\(^{15}\)\(^{16}\) The slope classification results based on the automated surface hydrological analysis are not consistent with the actual terrain as in the field and could lead to an increase of efforts in the geohazard field survey and a decrease of the accuracy of the geohazard risk assessment. Therefore, this study uses the hydrological analysis principle to eliminate the disturbing effect in the slope body from two aspects: identification and
elimination of the micro-geomorphology.

3.2.1 Automatic identification of the micro-geomorphological disturbing effect area

In the DEM data, the elevation value of the micro-geomorphological disturbing effect region was smaller than that of the surrounding grid data. The water pond was identified and extracted to find the areas in the study area with a micro-geomorphological disturbing effect. The flow direction of each grid cell in the DEM data was analyzed. Moreover, the grid cells with an uncertain water flow direction were extracted to obtain the grid data of the sink in the study area. The grid data of the identified sinks were the potential micro-geomorphological disturbing effect areas. The statistical analysis results showed that the area with the disturbing effect measured 0.078 km². Figures 3 and 4 depict the searching process and results.

![Flow Direction](image1.png)

Input: DEM; Output: flow direction raster

![Sink](image2.png)

Input: flow direction raster; Output: sink area

Figure 3. Extraction process of the disturbing effect

![Area of the disturbing effect observed in the field](image3.png)

Figure 4. Area of the disturbing effect observed in the field

3.2.2 Elimination of the micro-geomorphological disturbing effect

The field survey results found no karst landform. Therefore, all disturbing effects were determined to be caused by the micro-landform on the slope body. Eliminating the disturbing effect of the micro-landform was actually eliminating the sink or filling the
depression. First, the water flow contribution area of all sinks was statistically calculated using the hydrological analysis module in GIS software. Second, the lowest elevation of each contribution area was calculated by partition. Third, the water outlet elevation (minimum elevation of the region boundary) of each contribution area was calculated by region filling. Finally, the outlet elevation was reduced to the lowest elevation to calculate the real depression depth and determine the filling threshold \((Z)\) to fill the depression. Figure 5 presents the elimination process.

![Input: flow direction raster](image1)

- Input: flow direction raster
- Input: sink area
- Output: watershed

![Input: watershed](image2)

- Input: watershed
- Input: DEM
- Output: minimum elevation of catchment area

![Input: watershed](image3)

- Input: watershed
- Input: DEM
- Output: maximum elevation of catchment area

"Maximum elevation of catchment area" − "Maximum elevation of catchment area"

Figure 5. Elimination process of the disturbing effect

The maximum depth of the depression in the study area was calculated as 2.4 m based on the abovementioned principle. A comparison of the field survey results and the actual topographic maps showed that to fill up all depressions, the threshold for filling the depressions must be greater than the maximum depression depth to eliminate the convergence point of the DEM data. Therefore, the threshold of depression filling was set as 2.5 m herein. In addition, the DEM data after the depression filling were used for the hydrological analysis to ensure that the gully network extraction is consistent with the actual terrain.

3.3 Slope boundary determination

According to the local government department of geohazard prevention and mitigation, 67 geohazard events, including collapses and landslides, have occurred in the study area since 1950. The analysis on the local triggering conditions and geohazard failure mechanism showed that the geohazard deformation and failure are controlled by the combination of topographic and rock characteristics. The geohazard boundaries also do not cross the valley.
lines (Figure 6). Therefore, when identifying the slope units in the field investigation, evaluation, and risk control work with slope units, the slope units should not be divided along the ridge line. The focus should be on the extraction of the areas enclosed by the valley line.

Figure 6. Deformation and failure characteristics of the geological hazards in the study area

The accuracy and the density degree of the slope unit classification depend on the quality and resolution of the valley line generated from the hydrological analysis. Improving the accuracy of the valley line description would improve the accuracy of the slope unit division. Consequently, improving the valley line density would improve the precision of slope unit division[17][18]. Based on the abovementioned principles, the method of extracting the catchment area boundary in the GIS hydrologic analysis was used herein to characterize the valley line to determine the slope unit boundary.

However, to meet the geohazard survey and risk assessment requirements of the 1:10,000 scale, the slope unit division results should reflect the distribution of the fourth-level gully. Therefore, the reasonable catchment area threshold should be selected to control the density of the slope unit division. For the size of the watershed area threshold (i.e., flow grid pixel value in the hydrological analysis process), a larger pixel value would lead to a larger watershed area, while a sparser valley line distribution would lead to a larger slope unit area and a small number of the slope unit. This study used the data fitting method to select the fixed target and obtain the actual terrain to ensure that the slope unit division meets the mapping requirements. Under different grid pixel values, the automatically computed total length of the valley lines in the target area was used as the sample data to fit the grid pixel values as a function of the valley line. Professional experts would then draw the target zone valley line formed by the slope units to determine a reasonable border pixel threshold.

3.3.1 Selection of the standard target area for the slope unit division and determination of the valley line

According to the previous geohazard zoning maps, the topography information can be shown based on the DEM elevation data and the high-resolution remote sensing image. The research area was selected based on the field investigation because of the higher elevation in the southwest portion of the working area and the obvious relief in the rectangular area. Therefore, experienced professionals could draw the valley line represented by the slope unit boundary (Figure 7).
3.3.2 Relationship between the valley line length and the flow raster pixel value

According to the range of the flow raster pixel values, different pixel values were selected to extract the valley line. The relationship between different pixel values and the valley line length was then statistically analyzed (Table 1). The power function curve between the two was fitted (Figure 8) based on the statistical analysis, and the function expression 2-1 was obtained:

\[ y = 11897.44 \times x^{-0.66} \]

Eq. (1)

- \( y \) — valley length;
- \( x \) — grid cell value.

The fitting coefficient was calculated as 0.990. The results showed that the valley line length was closely related to the fitting of the flow raster pixel value. The flow raster pixel value corresponding to the valley line length was calculated using formula 2-1.

Figure 7. Valley line chart drawn by an expert in the standard target area

Figure 8. Fitting correlation between the valley length and the pixel value
Table 1. Valley length vs. threshold of the pixel value of the slope unit

| Threshold of the pixel value | Valley length (km) | Threshold of the pixel value | Valley length (km) |
|-----------------------------|--------------------|-----------------------------|--------------------|
| 3000                        | 60.15              | 6500                        | 35.25              |
| 3500                        | 54.14              | 7000                        | 33.15              |
| 4000                        | 50.06              | 7500                        | 32.11              |
| 4500                        | 47.01              | 8000                        | 31.35              |
| 5000                        | 44.44              | 8500                        | 30.82              |
| 5500                        | 41.01              | 9000                        | 30.51              |
| 6000                        | 38.51              | -                           | -                  |

3.3.3 Flow raster pixel threshold
Statistics showed that the valley line length outlined in the expert standard target area was 34.3 km. Using formula 2-1, the flow raster pixel value corresponding to the valley line in the standard target area was calculated as 7058. Accordingly, the flow raster pixel threshold divided by the slope units in the whole area was determined as 7058.

3.3.4 Slope unit boundary division
The boundary of the upper slope units was automatically divided by the GIS based on the calculated flow raster pixel threshold. A comparison of the mountain shadow generated by the DEM and the high-resolution remote sensing image showed that the slope unit boundary line in most areas was in a good agreement with the terrain (Figure 9). The local areas still need to be further corrected.

Figure 9. Slope unit pre-division results

4. Result refinement through human–computer interaction
In the slope unit division process, if only the GIS software is used to automate the division, the result could contradict the actual terrain because of the disturbing effect mentioned earlier. The three following principles should be followed to improve the accuracy of the slope unit division results, support geohazard investigation and evaluation, optimize the field investigation, improve the risk assessment accuracy, and enhance the disaster risk
control system:
① The flat terrain area without geohazards should not be considered in the slope unit division.
② If the area of certain slope units significantly differs from the actual slope area, then the slope unit division results should be adjusted appropriately.
③ Each vulnerable element should be attached to only one slope unit.

The man–machine interaction method is used to repair and perfect the unreasonable slope unit based on the abovementioned principles.

4.1 Comparison of a DOM remote sensing image, a 2 m contour line, and a mountain shadow map to eliminate the flat terrain and lake and river regions

The topographical conditions were presented by overlying on the remote sensing images of the 1:10,000 scale and the 2 m resolution of DEM. The flat area along the river valley and the line between the actual slope units can then be deleted to extract the regions of very low geohazard probability or flat area (Figures 10(a) and (b)). This can effectively improve the working efficiency of the field investigation and the indoor geohazard risk assessment work precision.

4.2 Slope unit rationalization

The GIS technology was used to automatically divide the slope units. Some units have a very small area and are not consistent with the geohazard investigation, evaluation, and management. Through the mathematical statistical analysis of the initial generated slope element area, 1% of the average slope element area in the study area was set as the threshold. The slope element with an area less than this threshold was manually incorporated into the adjacent slope element. In the natural state, two kinds of threats exist between the disaster-bearing body and the slope: 1) the single vulnerable element is threatened by the single slope; and 2) the single vulnerable element is threatened by multiple slopes. To facilitate the geohazard risk assessment and control work, the slope and the position relationship between the geohazard-affected body should follow a hazard-affected body that should only belong to the principle of a slope unit, and, therefore, should be combined with field investigation results to adjust the distribution of wild unreasonable slope unit boundaries, making everything belong to the single slope units of the hazard-affected bodies. Figures 10(c) and (d) show the adjusted result.

4.3 Overall inspection of the slope unit morphology and fine-tuning of the slope unit

The slope unit boundary automatically divided by the GIS has sharp angles and serrated shapes. The slope units in the key investigation area divided by the GIS are inspected and fine-tuned based on the geohazard risk zoning map previously divided by the research area.

(a) Before elimination  (b) After elimination
Figure 10. Comparison of the slope unit division results before and after the disturbing effect elimination

5. Slope unit division results

5.1. Results
The research area was divided into 802 individual slope units by establishing the slope unit division through the interaction process (Figure 11). The slope unit area ranged from 0.0013 to 0.4462 km². The average slope unit area was 0.072 km². The superimposed comparison between the resulting slope units and the mountain shadow map generated by the DEM showed that the slope unit boundary can match well with the valley line in the mountain shadow map. This result indicates that the slope unit division is reasonable and can meet the requirements of high-precision geohazard investigation, evaluation, and risk management.

Figure 11. Results of the slope unit division

5.2. Summary of the slope unit division method
The classification method of the slope units using the GIS technology and the human–computer interaction mainly included two steps: automatic calculation and result refinement by experienced professionals. An effective classification method of the slope units can be established through the human–computer interaction. This method combines the advantages and the characteristics of the former two methods proposed in the previous studies. Meanwhile, the slope units obtained by the established method can meet the needs of the geohazard evaluation with a scale accuracy above 1:2000.

The following results are considered:
(1) In preparing the DEM data analysis, qualitative and quantitative methods are adopted to analyze the accuracy and completeness of data and ensure the scientific and reasonable division of slope units.
(2) Using the hydrologic analysis tools built in the GIS software, the disturbing effect of the micro-landform to the slope unit division can be quantitatively, visually, and efficiently eliminated.

(3) The slope unit division accuracy of the slope element can be calculated based on the relation between the pixel threshold (flow grid pixel value) of the slope element in the expert target area and the length of the valley line. Moreover, the problem of insufficient accuracy and low precision in the previous GIS or manual division can be solved.

(4) A further improvement of the classification results of the slope units through the human–computer interaction would ensure that the requirements of the risk assessment and control in the later stage are satisfied.

6. Conclusion
This study proposed a slope unit division method based on GIS and human–computer interaction that can solve problems, such as the disturbing effect of a micro-landform in a slope body, especially the difficulty of determining the density degree of slope division and the inappropriate shape of slope units if only the computer automatic division was applied. The following conclusion and suggestions are obtained:

(1) The DEM data used for the slope unit division should meet the basic requirements of data accuracy and integrity; otherwise, the accuracy of the slope unit division cannot meet the requirements of large-scale geohazard investigation, evaluation, and risk management.

(2) With the help of the working principle of extracting the water source and sink in the hydrological analysis of GIS, the method can accurately remove the micro-landform disturbing effect area and provide DEM data without depression for the subsequent hydrological analysis to obtain the valley line.

(3) The standardized target area is established. The functional relationship between the valley line length and the threshold (flow grid pixel value) in the target area is fit. The valley line length drawn by the expert in the target area is used to determine the required flow grid pixel value when dividing the slope units in the whole area. This method can effectively determine the density degree of slope unit division and obtain the slope units that can meet the actual terrain and work requirements.

By combining a DOM remote sensing image, 2 m elevation contour lines, and a hillshade map, experienced professionals could remove areas with low geohazard probability or a flat terrain without identified geohazards. By adjusting the slope unit boundary, the slope units are finally in line with the actual terrain, thereby meeting the needs of the 1:10,000-scale geohazard risk investigation, evaluation, and management.

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