A landslide-dam hazard mapping method is proposed so as to provide the necessary information to countermeasures against earthquake induced landslide disaster chain. The procedures of the method are introduced together with newly developed slope identification technique and new slope stability analysis GIS module. A practical application is presented to show the practical usefulness of the hazard mapping system.

**Keywords:** earthquake, landslide-dam, hazard mapping, GIS, slope stability analysis

1. INTRODUCTION

A strong earthquake can induce a large number of landslides, and an extensive landslide can create a landslide-dam when debris flows into and stops a river. The water impounded by a landslide dam can create a dam reservoir, which may raise the surrounding groundwater and cause back-flooding (upstream flooding). Because of its loose nature and absence of a controlled spillway, a landslide-dam can easily fail catastrophically and lead to debris flows or downstream flooding. Many reports show that the earthquake-induced landslide disaster chain (Fig.1) can cause very serious damage.

For example, the 2008 Wenchuan Earthquake (Ms8.0) induced approximately 60,000 landslides and created 828 landslide-dams. More than one-third of the total loss (both property and life) from the earthquake damage was due to the disaster chain according to a related report (Chen et al., 2012).

The disaster chain can be broken by countermeasures in two stages: before and after an earthquake. Reinforcement of a landslide prone slope is one of effective countermeasures before an earthquake. Making a drainage canal in a landslide-dam timely is another effective countermeasure after an earthquake.

For example, a landslide-dam was formed at Tangjiashan, called the Tangjiashan landslide-dam, due to the 2008 Wenchuan Earthquake. It was so large that its reservoir volume reached about $3.16 \times 10^8 \text{ m}^3$. A big city with population of about 1.3 million people in the downstream area is in risk. It was estimated that half of the population would meet with the disaster of debris flow and flooding if the landslide-dam collapsed due to the full of water. Fortunately the catastrophe was avoided because the dam was detected so early that there is enough time for taking countermeasure of making drainage canals before the water level arose.

Effective countermeasures rely on accurate information about landslide-dam prone slopes. An accurate landslide-dam hazard map can provides useful information for these countermeasures. For example, we can determine which slope needs to be reinforced based on the hazard map before earthquake. Also, it would be easy for us to detect landslide-dams immediately after an earthquake if we know the potential places from an accurate landslide-dam hazard map.

However, there have been very few studies on landslide-dam hazard map up to now. Thus, it is important and essential to develop landslide-dam hazard mapping system.

In this paper, we present a hazard mapping method for landslide-dam induced by earthquake together with some newly developed techniques necessary in the realization of the hazard mapping system, including (1) a new approach for slope unit identification; (2) a high accurate 2D slope stability analysis tool for attract landslide prone slopes; (3) several filters for eliminating slopes that are impossible to reach a river or block a river. The mapping system is developed based on
graphic information system (GIS). Also, we present a practical application to show the effectiveness and usefulness of the new hazard mapping system.

2 HAZARD MAPPING METHOD

A landslide-dam hazard map shows slopes that have high possibility of collapsing and blocking a river. Such a slope is called a landslide-dam prone slope (LDPS) in this paper. A LDPS should meet with the following conditions: (1) it will be unstable due to a strong earthquake; (2) its debris will reach a river; (3) the volume of reached debris is large enough to block the river.

In order to identify all the LDPSs in a wide area, we need (1) to identify all the slopes in the area; (2) to find unstable slopes; (3) to judge whether its debris can reach a river and is enough to block a river. Thus, we propose the following procedures for hazard mapping:

Step 1: Identify all the slope units in the study area
Step 2: Extract the slopes near a river in the area
Step 3: Eliminate the slopes that are unable to move to a river even if they collapse
Step 4: Eliminate the slopes that are stable enough
Step 5: Eliminate the slopes which failure volumes are not enough to block a river
Step 6: Eliminate the slopes which debris are not enough to block a river
Step 7: Numerical simulation of landslide-dam formation.

Since the page limitation, only two of the key issues are discussed in this paper: (1) how to identify the slopes effectively; (2) how to assess the slope stability accurately.

3 SLOPE IDENTIFICATION USING GIS

The first and essential step of hazard mapping is to identify all the slopes in a wide area since mapping units affect uncertainties in the input data, the fitness of the assessment model, and the reliability of the obtained susceptibility zonation.

A GIS based ArcHydro tool provides an effective means to extract catchments and drainage lines from DEM. Using this tool, Xie et al., (2002) proposed a slope units identify method using ridge lines and valley lines. However, the existing identification method has some limitations and problems such as (1) inaccurate division at hill top areas, (2) mismatched valley lines and ridge lines, and (3) undetected multiple possible slide directions.

For this reason, we propose a new method of identifying slope units to improve the accuracy of identification. Stream lines are used instead of valley lines to conjoin ridge lines.

The method consists of three steps: (1) preparing a topography map with ensured delineations of basins and streams; (2) using Arc Hydro tools to detect stream lines instead of valley lines; (3) extracting catchments based on the previous process; (4) identifying slope units by cutting catchment areas with stream lines.

In general, a contour map is available for topography. The polylines are the direct description of the terrain but cannot be used directly in slope stability assessment because they do not intersect and cannot form slope faces. It is necessary to transform the polygon files into a triangulated irregular network (TIN) map using the TIN tool feature of GIS, and then, transform TIN into a raster type (DEM) by using the TIN to Raster tool.

The detection of stream lines requires the combination work of GIS-based hydrologic analysis tools, including flow direction, flow accumulation, stream definition, stream definition and raster to polyline procedures.

To determine the steepest gradient direction (aspect) of a certain cell, the difference in elevations among the surrounding cells to eight altitudes is calculated with the inclination angle. By linking the direction of each cell, the flow paths of a digital terrain can be derived. For each cell in the input flow direction grid, a flow accumulation grid is then computed to contain the accumulated number of cells upstream of the cell.

By connecting the center points of cells according to the direction and accumulation results of the water flow, it is possible to extract the drainage line. Because there are a variety of streams at different levels in mountainous area, it is necessary to determine the number of cells to be included, which indicates the stream level obtained. In other words, the minimum number of cells to be included in a stream is represented as the minimum aggregate value of the flow in the drainage line origin.

The detection of catchments needs a combination of GIS-based hydrologic analysis tools, including stream segmentation, catchment grid delineation, and raster to polygon procedures.

When the conjoint point of stream lines is detected, the stream link is divided into stream segments. Two branch streams flow together into one mother stream at a conjoint point. The stream link is then divided by the number of conjoint points and each segment is assigned an index number. Finally, raster data are created to store the stream segments using its indexes. Each segment indicates the pooling of a watershed area.

According to the flow direction data, the map is divided into catchment using stream segments. Within one catchment, all the cells flow towards one stream segment, and each cell carries an index value indicating to which catchment the cell belongs. The value corresponds to the index carried by the stream segment that drains this catchment. Finally, raster data are created to store the catchment using its indexes.

The raster to polygon procedure changes the raster data of catchments into vector data of polygon. Thus, the vector data of catchments are ready to be used. The attributes of each feature in the vector data record an
assigned index number and neighbor relations.

4 SLOPE STABILITY ANALYSIS WITH GIS

Identification of a landslide prone slope (LPS) is also one of the key points. Slope stability analysis (SSA) is necessary and important. However, since SSA should be automatically carried out for a large number of slopes in a wide area, there is no commercial software available. As the most researchers, we developed a GIS module of SSA based on an infinite plane slip model (IPSM) just because it can be easily implemented and managed in grid mapping units.

Although SSA can be easily performed by using the module in GIS to calculate the safety factor of each individual pixel or cell in grid cell division, there are following major problems to be solved. (1) The failure depth should be assumed in advance. It is very difficult to determine the failure depth since it varies from place to place and its value affects the calculated results very much. (2) The scale of a landslide with slip surface and volume information cannot be obtained but they are necessary in predicting LDPS. (3) IPSM assumes that the slope is extended infinitely in all directions and slide occurs along a plane parallel to the face of the slope. In practice, most failure slip surfaces are not planes. Thus, the SSA based on a circular slip mode (CSM) is more popular than IPSM in geotechnical engineering.

For this reason, we develop a GIS module for 2D SSA based on CSM for identifying unstable slopes and develop a 3D SSA GIS module based on a semi-ellipsoid slip model for estimating the failure size and volume. However, the 3D SSA GIS module will be introduced in a separated paper.

In order to develop the 2D SSA GIS module, we apply the well-known Swedish Method to the 2D limit equilibrium analysis. Firstly, a method for automatic extraction of the cross section of a slope is proposed. And then, the searching method is proposed for the critical surface. A GIS module for evaluating slope safety factors based on the Swedish Method is developed using C# computer language. Finally, an application has been made to show that the accuracy of new SSA GIS module.

(1) Extraction of a slope cross section from a slope

A possible landslide is assumed to have a relatively large scale compared to the slope unit and can offer enough mass rushing down through the drainage. Therefore, the tendency of a landslide is to go along the flow line, from the top to the bottom.

The longest drainage line that can be derived within a slope unit is a link between the highest point and lowest point. A sample 2D slope model can be extracted from the Digital Elevation Model (DEM) along the longest drainage line. By recording the positions of the highest point and lowest point, the cross line is created by using the GIS module developed in this study.

The cross section is extended by 10% and 20% of the total projected length at the top and bottom respectively so as to include plenty of topography features (Fig.2(a)).

The Interpolate function of GIS is used to extract the elevation data into the cross line in a 1m-interval. Each point of the path line stores an elevation data. The elevations of the points are arranged within an array to obtain the cross section of a possible landslide.

Fig. 2. (a) Extracted cross section from a slope unit; (b) One case of slip surfaces.

(2) Searching for the critical slip surface

The slope surface is split into two equal parts. 10 head points of A are distributed from the upper part and 10 toe points of B from the lower part through a simple enumeration algorithm. For each pair of A and B, radii R takes 10 different values (Fig. 2(b)). By means of permutation and a combination of their sample groups, 1,000 different slip surfaces are analyzed for critical slip surface searching.

A GIS module is developed so that slope stability analysis can be easily carried out.

(3) Accuracy verification

To verify the computing results of 2D SSA GIS module, a slope with 45° as shown in Fig. 3 is used. The parameters are taken as follows: \( \gamma=24\text{kN/m}^3 \), c=24kN/m², \( \phi=35^\circ \).

Fig. 3. Comparing results between the 2D SSA GIS module (left) and SLOPE/W (right).

The calculated safety factor is 1.71. Meanwhile, it has been calculated by SLOPE/W, a commercial software. The safety factor from SLOPE/W is 1.78.

It can be seen that the results are in agreement with
each other although safety factor from the developed GIS module seems a little bit smaller than that from SLOPE/W. Therefore, the developed GIS module is reliable and can be used in practice.

5 PRACTICAL APPLICATION

The new hazard mapping method is applied to an area of the 2008 Wenchuan earthquake where five large-scale landslide-dams were formed, including the Tangjiashan Dam. The basic data used in this study consist of a DEM with resolution of 10 m and a satellite image with resolution of 2.5 m.

The following procedures are performed.

1) Identify all the slopes in the study area. We applied our newly developed slope identification tool to attract out 10,186 slopes in the area.

2) Attract slopes near the target river. As we know, if a slope is far from a river, it will not be a LDPS. We use the buffer function of ArcGIS to attract 3,996 slopes along the Tongkou river. Fig. 4(a) shows the slopes in the whole area by blue lines and the slopes within 2 km along the river by red lines.

3) Eliminate the non LDPS by the aspect filter. If the aspect of a slope is not toward the river, the slope should not be a LDPS since the debris cannot reach the river. We developed the so-called aspect filter to eliminate non LDPS. As a result, 2,400 slopes are eliminated from the remained 3,996 slopes in step (2), and 1,596 slopes remained in this step.

4) Eliminate the non LDPS by the blockage filter. If there is another slope between a target slope and the river, the target slope will be eliminated since the debris could be blocked by the midway slope. We developed the so-called blockage filter for this purpose. 460 slopes are eliminated and 1,136 slopes remained in this step (Fig. 4(b)).

5) Eliminate the non LDPS by slope stability analysis. 524 slopes are eliminated according to the safety factors calculated by the newly developed 2D SSA tool and 612 slopes remained in this step.

6) Eliminate the non LDPS based on the volume filter. The failure volume is estimated by 3D SSA, and the volume of debris moves to river is estimated by an empirical formula together with numerical analysis. As a result, 28 slopes are eliminated and 584 slopes are determined as the LDPSs (Fig. 5).

Fig. 5 shows the landslide hazard map. The five landslide-dams due to the Wenchuan earthquake are also shown by the yellow areas. It can be seen that the results are quite reasonable.

6 CONCLUSION

A strong earthquake can induce landslide-dam disaster chain which may cause more serious damage than earthquake direct damage. A landslide-dam hazard map can provide necessary and essential information to effective countermeasures against the disaster chain since it shows the location, possibility and dangerousness of potential landslides and landslide dams.

In this paper, we have proposed a hazard mapping method for landslide-dam induced by earthquake according to the slope stability analysis, possible slide volumes, together with topography data and river conditions. In order to realize the hazard mapping system, we have also made the following achievements: (1) A new approach of slope unit identification has been proposed; 2) A 2D slope stability analysis GIS module has been developed for calculating safety factors with high accuracy; 3) A 3D slope stability analysis GIS module has been developed for estimating failure volumes; 4) An aspect filter and a blockage filter have been developed to exclude non landslide-dam prone slopes using the geographical data.

It has been shown by an application example that the new hazard mapping method is of practical use in mitigation of earthquake induced landslide-dam chain disasters.

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