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Susceptibility Zonation of Earthquake induced Landslide-dams at the Catchment of Tongkou River, China

by

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Abstract

Significant hazards may occur due to large landslide-dams formed by earthquake induced landslides. Those landslide-dams present serious threats to both life and property from possible upstream flooding when the impounded lake water level rises, and possible dam failure and downstream flooding with rapid release of impounded water.

In order to prevent those secondary disasters, we made an assumption that the landslide-dams are only formed when a large amount of landslide deposits directly rush into a river with moderate or high-velocities. Then a practical prediction method is presented to extract the dangerous slopes which are thought as the sources of earthquake induced landslide-dams. The prediction procedure consists of the following steps: (1) identification of all the slopes using spatial statistics; (2) the extraction of potential slopes according to our assumption using three spatial relation filters; (3) stability analysis to determine landslide prone slopes and volume estimation of potential landslide deposits using Limit Equilibrium Analysis. (4) susceptibility mapping by ranking the exact slopes.

This method has been used to extract slopes those are potential to collapse and form landslide-dams in the catchment of Tongkou river after the 2008 Wenchuan earthquake, China. Results show that the proposed method is effective and efficient.

Keywords: Landslide-dam, Wenchuan earthquake, Susceptibility analysis, GIS, Stability analysis, Limit Equilibrium Analysis, Spatial filters

1. Introduction

Recently, amount of landslides were triggered by large-scale earthquake and then formed a number of landslide-dams, such as the ChiChi Earthquake in Taiwan (M7.6, 1999) [1)], the

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Niigataken Chuetsu-oki Earthquake in Japan (M6.8, 2004) [2)], the Hindukush Earthquake in Pakistan (M7.6, 2005) [3)], the Iwate-Miyagi Nairiku Earthquake in Japan (M7.2, 2008) [4)] and the Wenchuan Earthquake in China (M8.0, 2008) [5)]. Take the Wenchuan Earthquake as an example, the earthquake induced more than 50,000 landslides in Sichuan Province, China. Consequently, some large landslides blocked many rivers and created more than 34 large-scale landslide-dams. While the dam is being filled, the surrounding water level rises and causes upstream flooding. Moreover, because the loose characteristic of the debris and absence of controlled spillway, a landslide dam can easily collapse catastrophically and lead to debris flow or downstream flooding. In order to prevent these secondary disasters, it is necessary to establish an efficient warning and evacuation system in emergency. Therefore, this study attempts to develop a practical method to predict earthquake induced landslide-dams.

In the previous studies on earthquake induced landslide-dams, researches focused on the prediction method for the flood flow at the time of collapse[6)] and numerical simulations [7)]. However, researches on prediction method to extract dangerous slopes which whether form landslide-dams or not after a large scale earthquake are very scarce.

In this paper, we propose a new prediction method to extract dangerous slopes as sources of landslide-dam, based on Geography Information System (GIS) combining spatial statistics and Limit Equilibrium Analysis (LEA). In addition, we assume that a landslide dam is only formed when a large amount of landslide deposits directly rush into a river with moderate or high-velocities. The proposed method adopts the following procedures (**Fig.1**).

i). Identification of Slope Units. All the slopes are identified based on slope unit tool in GIS, which has been developed by us, for the target area.

ii). Slope Units identification. The slopes with potential to form a dam are extracted through three filters in spatial relations.

  a) Buffer filter. The slopes along a stream are extracted for a certain distance from the river banks.

  b) Aspect filter. A slope that could not reach to the river is excluded according to its direction to the river.

  c) Blockage filter. A slope that could not reach to the river is excluded according to the blockage height along the way to the river.

iii). Stability analysis and volume estimation. The slopes with low susceptibility are excluded by the index of safety factor calculated from the Two/Three-dimensional Limit Equilibrium Analysis. The volume of slide mass calculated from Limit Equilibrium analysis is also considered.

iv). Production of the susceptibility map.

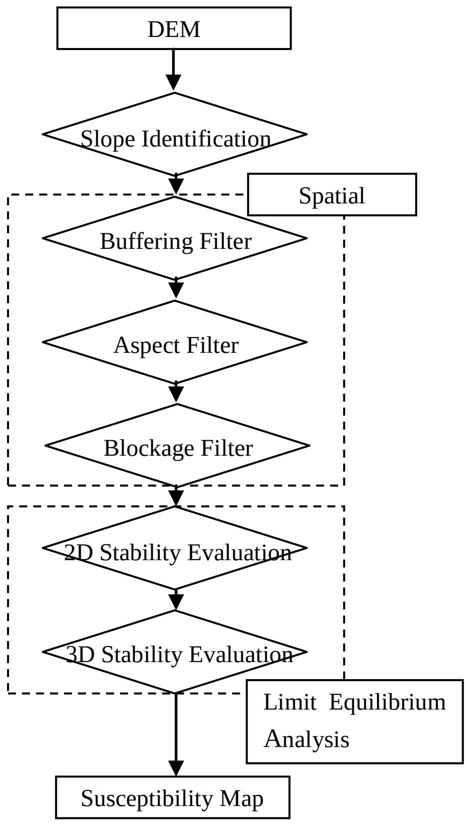

Fig. 1 The framework of this study.

This method is used to extract potential collapse slopes which may form landslide-dams after the

Wenchuan earthquake in the catchment of Tongkou river. Results show that the proposed method is very effective and efficient.

2. Study Area and Data Source

Out study area is located in Beichuan County, 180 km away from the northern part of Chengdu and northeast of the earthquake's epicenter, with eastern longitude of 103°44′ to 104°42′, and northern latitude of 31°14′ to 32°14′. As it is situated in the transitional belt between the Sichuan Basin and the Western Sichuan Plateau, most parts of this area are mountains. The tectonics and strata system are very complex, a wide variety of sedimentary, metamorphic rock, unconsolidated sedimentary deposits and exposes strata of Cambrian, Silurian, Devonian, Carboniferous, Triassic, Jurassic age and Quaternary loose deposits are wildly outcropped. Yingxiu-Beichuan fault goes through this area, which belongs to the Longmenshan middle fracture zone. The geological structure and rock strata show the same orientation, mainly north-east orientation.

Besides, this area has abundant rainfall each year. The average annual rainfall is 1,399 mm, the maximum annual rainfall is 2,340 mm (1967), the daily maximum rainfall is 101 mm, and the hourly maximum rainfall is 32 mm. In the same year, the rainfall concentrated from June to September, accounting for 71~76%, the maximum record reaches to 90% (1981) among the annual rainfall.

The Tongkou (Jinxing) River is a tributary of PeiJiang River, which originates from northwest mountains, and runs through the county territory. It is with a full-length of 47.9 km and a drainage area of 455.80 km^2 in Beichuan County. The river head is 203 m, average slope is 4.2%, average annual runoff is 102.7 m^3/s, average annual runoff volume is 3,257 billion m^3, average annual sediment runoff is 40~50 million T, and basin average annual erosion modulus is 7072, 61T / km^2 • a.

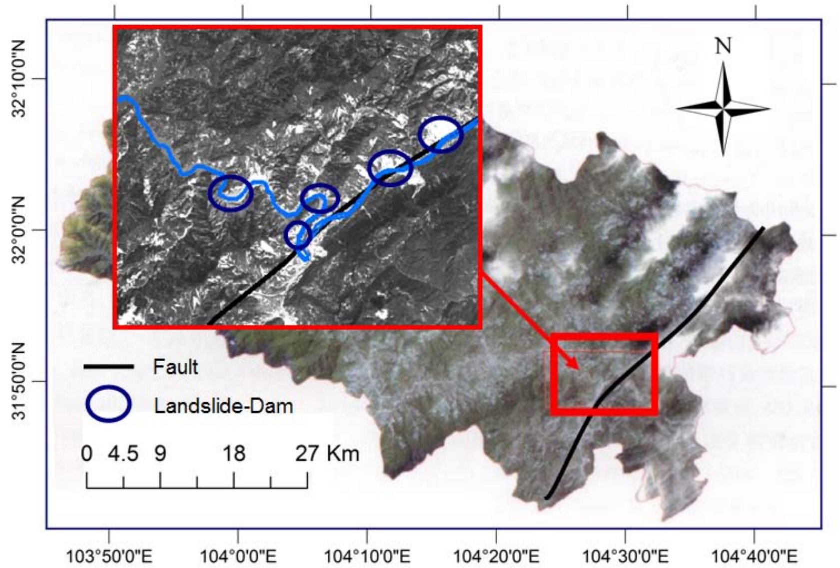

Fig. 2 Spatial relation between landslide-dam and Longmenshan middle fracture zone.

Our target catchment area is a 12×12 km^2 square field over the basin of Tongkou river. A large number of the Wenchuan Earthquake-induced landslides could be observed from satellite image. And also five large-scale landslide-dams were reported in this area, including the Tangjiashan Dam, the largest dam with a volume of 20.37 million m^3 (**Fig.2**). The basic data utilized in this study included a digital elevation model (DEM) with resolution of 10 meters, and a satellite image with resolution of 2.5 meters.

3. Methodologies, Results and Discussion

3.1 Slope Identification

For slope stability analysis in a wide area, the key problem is to define the mapping units . Each mapping unit, the portion of land surface that contains maximum internal homogeneity differing from adjacent units, should have relative similar topographic and geological characteristics respectively. Some researchers carried out their analysis based on tectonics and strata division, soil and vegetation division, administrative and climate division, etc. The pixel (or grid) division was widely used because it can be easily obtained and managed.

In this study, in order to divide slides, a SlopeUnit division is used here, which means a slope shows similar aspect trend. Thus, the SlopeUnit can be considered to be slide toward one aspect. Two kinds of methods have been proposed to make SlopeUnit divisions; both of them employed a GIS-based hydrologic analysis tool [8] and identified Slope Units by ridge lines and valley lines (**Fig.3**).

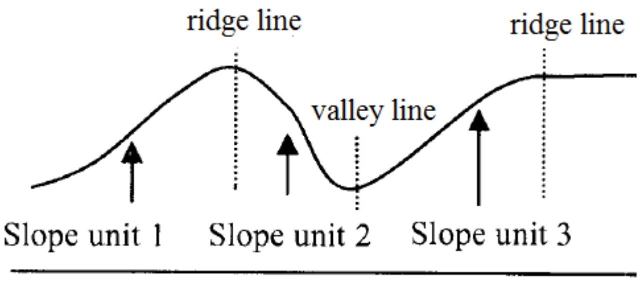

Fig. 3 SlopeUnit identification.

By using Arc Hydro tool [8], a suite of tools which facilitate the creation, manipulation, and display of Arc Hydro features and objects within the ArcMap environment, the catchment polygons and the stream lines of a study area can be obtained easily from the DEM. Topologically, the outlines of a catchment polygon can be considered as the ridge lines. The two methods adopted the same approach to obtain the valley lines. Their difference is the way to determine the ridge lines.

Assuming that water always flows downhill along the path of the steepest descent, the stream lines calculated from flow accumulation, can be considered as the valley lines in a mountainous area. However, based on a flow accumulation grid, streams are defined through the use of a threshold drainage value, which means that only the areas with flow accumulation values greater than the threshold value can be considered as streams. While the ridge lines are defined by the accumulation close to 0. Consequently, the ridge lines are impossible to conjoin to the stream lines.

The first method [9] assumes that the valley line can be derived from the reversed topography. Thus, the catchment of this reversed terrain is generated to generate valley lines.

The second method[10] traces back to the origination of each tributary flow to obtain the longest flow path, which conjoin the ridge lines.

However, a problem is existed to divide the flow origination (flow origin) area into two parts. Head flow, also determined as first-degree flow, is usually being an unchanneled valley, where the headward erosion is taking place. It means that the landslide occurred in this area will run through the flow channel. So it would be better to keep the whole catchment of first-degree flow as one SlopeUnit. Consequently, there is no need to divide the catchment of first-degree flow, otherwise the landslide direction will be scattered (**Fig.4**).

For this reason, this research uses stream lines only as valley lines to conjoin ridge lines. An example of SlopeUnit division by stream lines is shown in **Fig.5**. By using the union tool within GIS, the catchments corresponding to the first-degree flows (marked with ①, ②, ③) were left as Slope Units, and the catchments corresponding to the subsequence-degree flows (marked with ④, ⑤) were split by stream flows, and saved as Slope Units pairs.

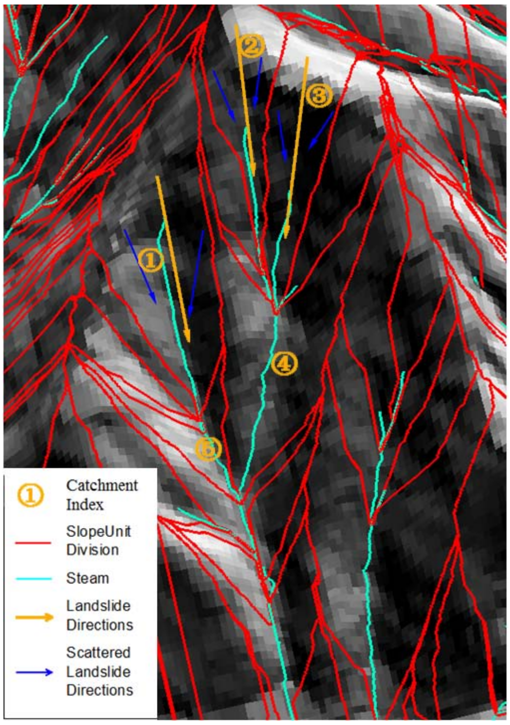

Fig. 4 Unchanneled valleys with landslide directions.

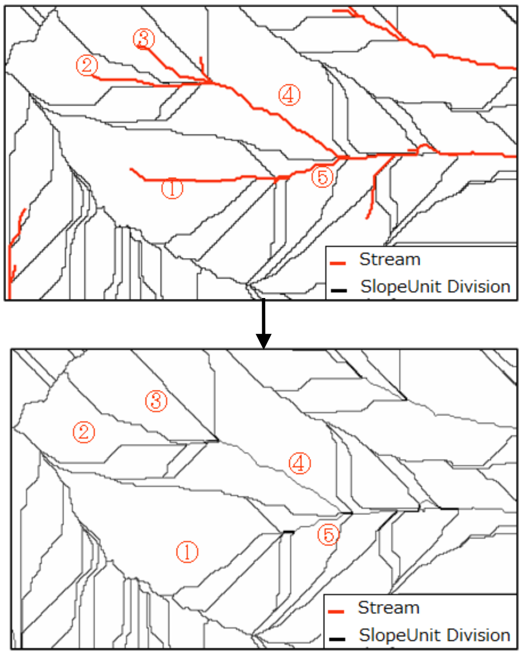

Fig. 5 Stream line division example.

The appropriate size of a slope unit depends on the average size of the landslide bodies in the study. Based on the landslides observed from satellite image, we controlled the size through adjusting threshold drainage value to identify the slopes when they are in good agreement with landslides area. A number of drainage values were tested and the best fit result was chosen. Finally, 10,186 SlopeUnits were indentified in total.

3.2 Spatial Filters

Earthquake induced landslide-dams are related to certain geomorphological conditions. In addition, according to our assumption, a landslide dam can be created only when a large amount of material with moderate or high-velocities directly rush into a river. Therefore, the following spatial filters are proposed.

3.2.1 Buffer Filter

To form a landslide-dam, the collapsed SlopeUnit should be close to the river channel. According to the filed investigation at the seismic area after the Wenchuan Earthquake, the longest runout distance is about 4.5 km observed from the Daguangbao landslide, in which about 2.5 km is running through the river bed. Therefore, the buffer distance from the center of slide slope to the potential blocked channel was set as a constant distance 2 km. Thus, using buffer filter, the slopes along Tongkou River were extracted. As a result, 3,996 Slope Units were extracted as potential risk area from the total 10,186 Slope Units (**Fig.6**)

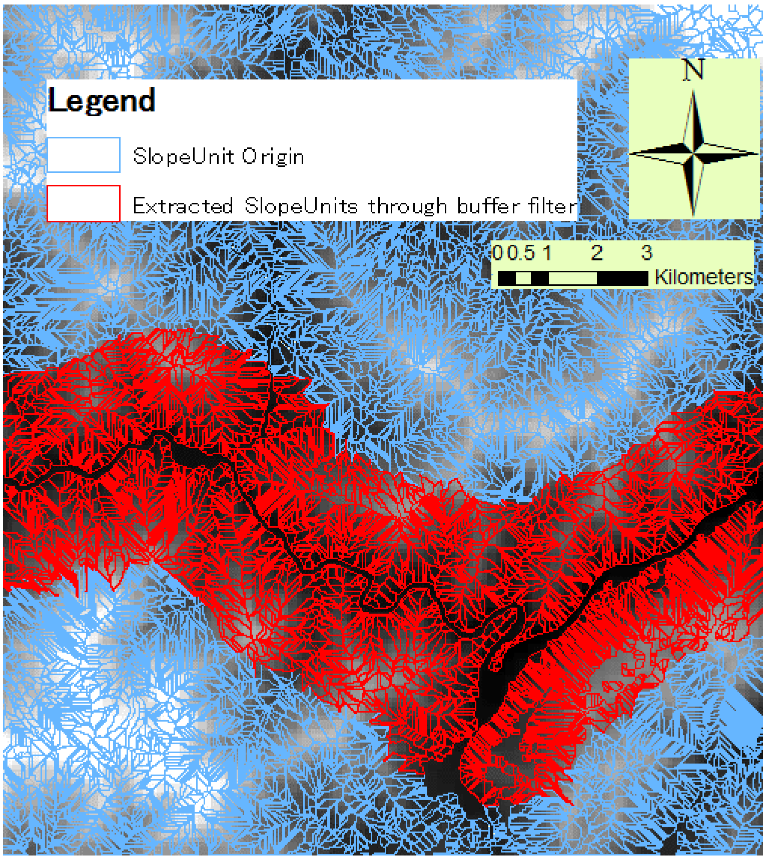

Fig. 6 Extracted Slope Units through buffer filter.

3.2.2 Aspect Filter

To extract dangerous landslide-dams, whether the slide runouts reached the valley or not should be considered. It could be solved by extending a runout path towards slide direction and then checking if it is conjoin with stream lines (**Fig.7**). In this research, the highest point was linked to the lowest point in each SlopeUnit to obtain the approach runout path and direction. And then, runout paths were extended 2 km towards downhill side. Spatial join tool of GIS was used here to obtain the spatial relationship between extended lines and stream lines. Thus, using the second filter, we excluded the slopes that could not reach to the river.

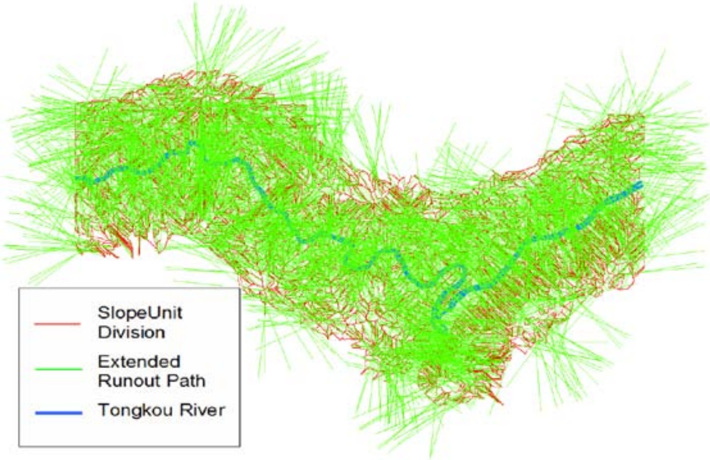

Fig. 7 Spatial relationship between extended lines and Tongkou River.

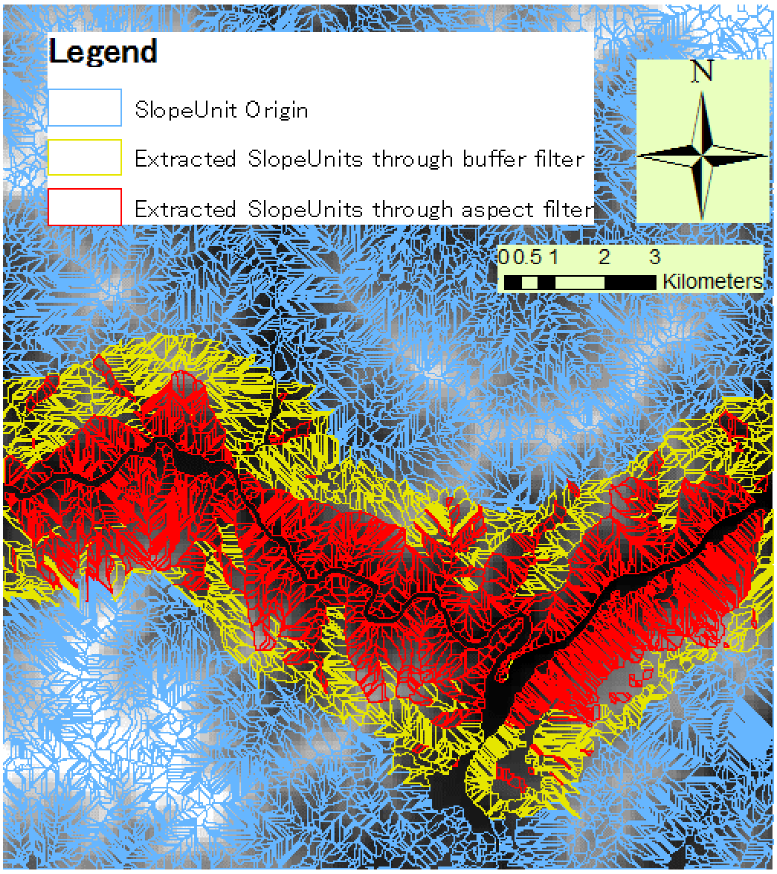

Fig. 8 Extracted Slope Units through aspect filter.

As a result, 1,596 Slope Units were extracted as potential risk area from the remaining 3,996 Slope Units (**Fig.8**).

3.2.3 Blockage Filter

The last spatial filter is the blockage height along the runout path towards river. The blockage is a risen topography on the runout path. If it is high enough, we considered it as a hill along the runout path and the landslide deposits would be blocked. In another words, the target SlopeUnit is not a riverside slope. So in this research, the extended runout paths obtained above were cut off by the two side lines of river region by using the intersect tool within GIS. Then the elevations were extracted along cut lines as a cross section shown in **Fig.9**.

The blockage height of each runout path was counted from top towards downhill direction by SlopeWalker tool, which was developed by us. Basically, 5 m is considered to be high enough to hold back most landslide deposits along the path, so 5m is used as the threshold value. Thus, using the third filter, slopes that could not reach to the river were excluded according to the block height along the way to the river. As a result, 1,136 Slope Units were extracted as potential risk area from the remaining 1,596 Slope Units (**Fig.10**).

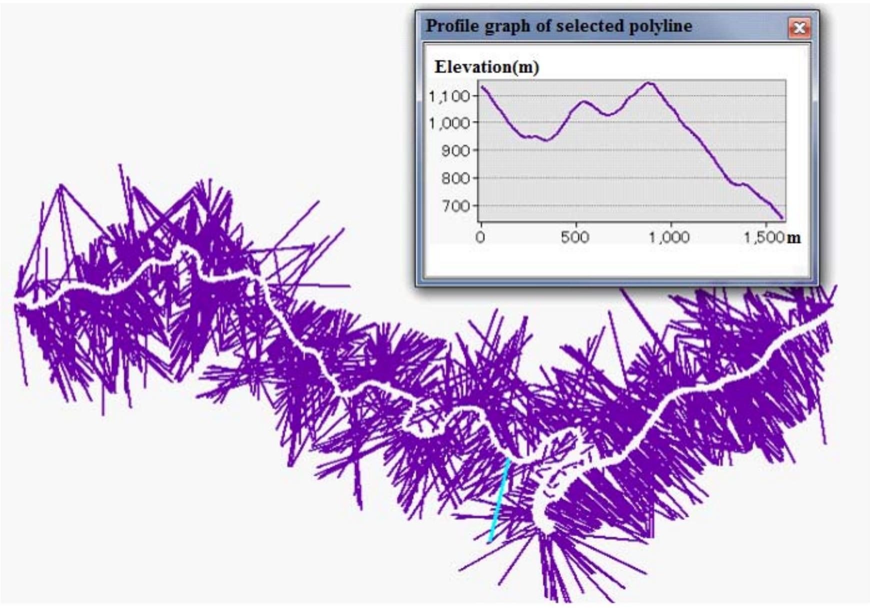

Fig. 9 Cut lines of each runout paths and its cross section.

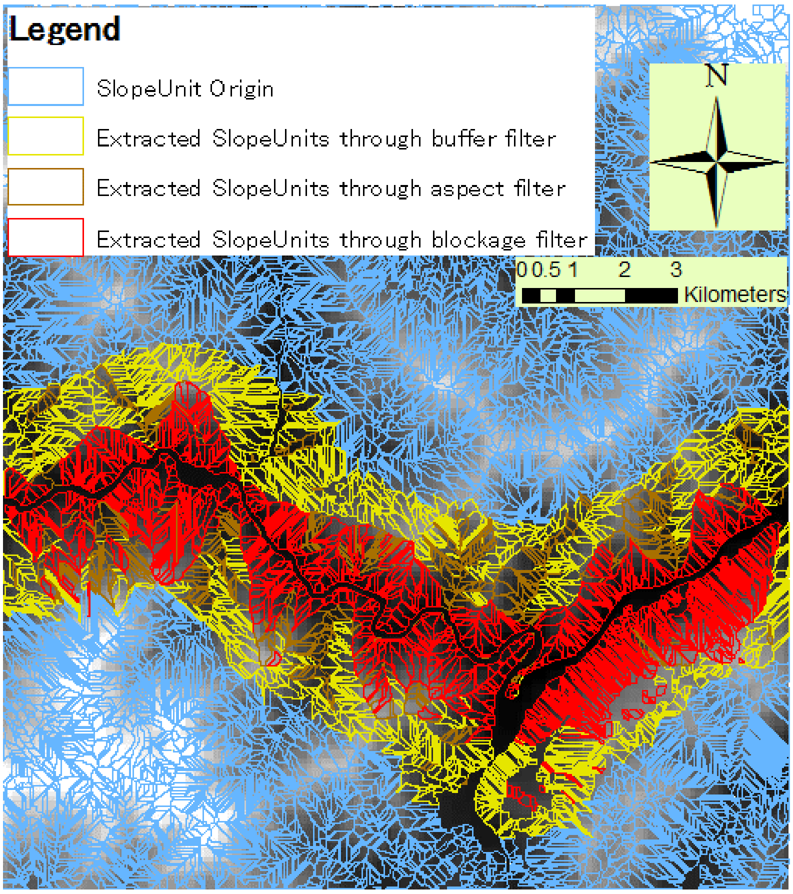

Fig. 10 Extracted Slope Units through blockage filter.

3.3 Limit Equilibrium Analysis

The deterministic limit equilibrium formulation, is widely employed in geotechnical engineering and engineering geology and has been applied to landslide hazard assessment and mapping [11]. The index of stability is the well known, mainly adopts the safety factor of strength reserve concept.

3.3.1 2D Stability Evaluation

Among all the limit equilibrium methods, two dimensional (2D) models are the most widely used for engineered slopes. And in wide area assessment, the two dimensional (2D) models is simple to calculate and easy to manage. In this research, a safety factor calculation tool has been developed based on GIS, using Bishop's simplified Method [12] and taking no account of water pressure. The enumeration algorithm was performed to get a series of trial slip surfaces with various centres of rotation, O and radii, R. And then, the minimum factor SF_{2D} can be derived according to Eq. 1:

$$SF_{2D} = \frac{\sum (W \cos\alpha \tan\phi) + \sum cL}{\sum W \sin\alpha} \qquad (1)$$

Where, c is the cohesion, ϕ is the internal frictional angle, W is the weight of each slice, α is the angle of inclination of the sliding surface of each slice and L is the length of the sliding surface of each slice.

Before the process of safety factor calculation, some pretreatment should be done. It is due to the sliding area that may go beyond a SlopeUnit region, (**Fig.11**), and the safety factor calculation which take place base on the cross sections lines of each Slope Units. Thus, each cross sections line was extend 10% and 20% of the total projected length at its top and bottom respectively.

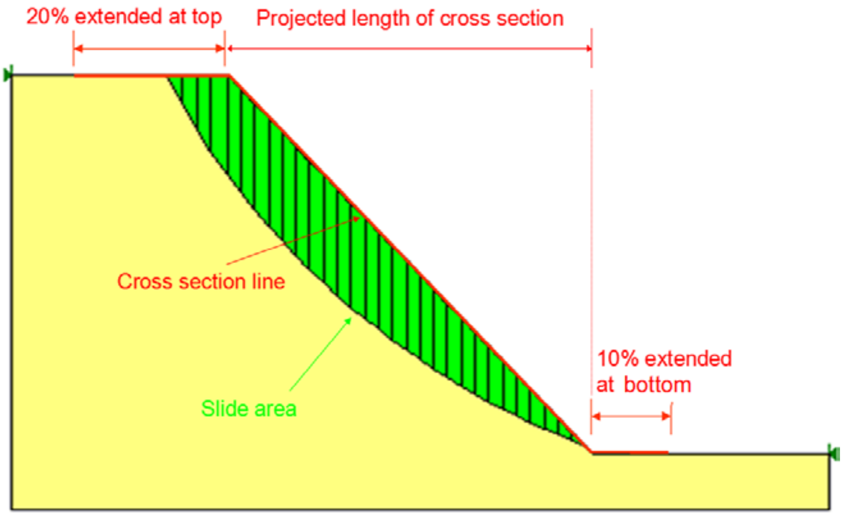

Fig. 11 Slide area and extended cross section line in cross section view.

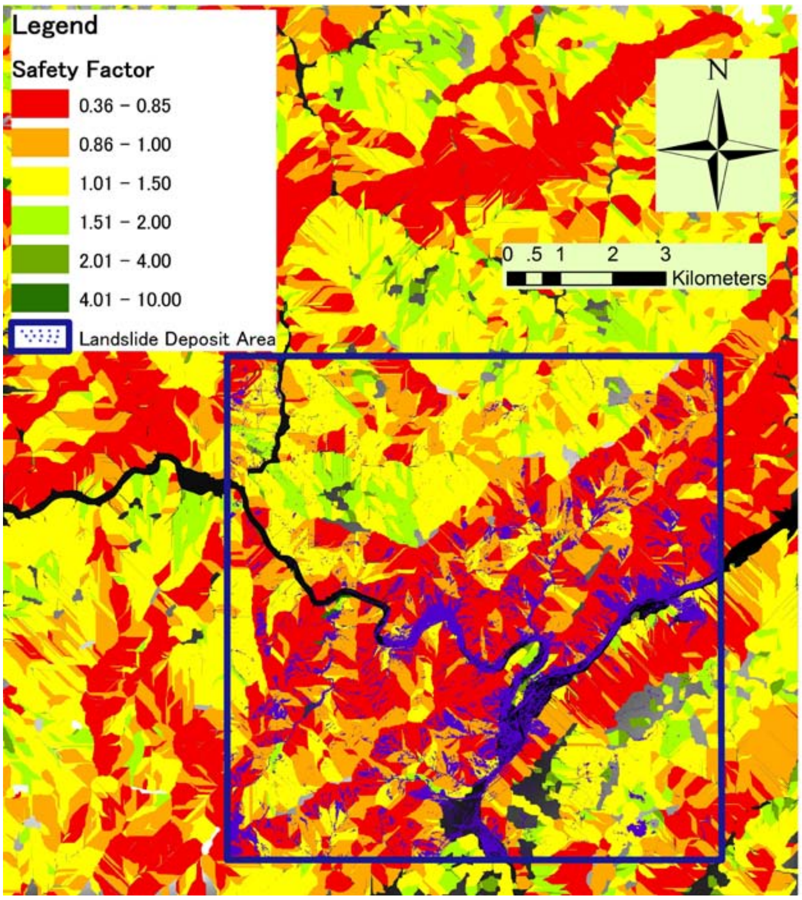

Fig. 12 Safety factors distribution covered with satellite image (landslide deposit area in purple).

According to the field investigation at Tangjiashan landslide, the following parameters, which are the averages of weathered rock remained, were performed in the safety factor calculation: the soil unit weight is γ=22kN/m^3, the cohesion strength of slope material is c=20kN/m^2 and the internal friction angle of slope material is ϕ=32°. The result is shown in **Fig.12**.

It should be noted that the used soil material is predicted under an ideal assumption (the soils are homogeneous using parameters of weathered rock). Comparing to satellite image, it could be concluded that most landslide deposit areas shown in satellite image are within the Slope Units whose safety factor are less than 1. So the Slope Units with a safety factor more than 1 are excluded. As a result, 694 Slope Units were extracted as potential risk area from the remaining 1,136 ones (**Fig.13**).

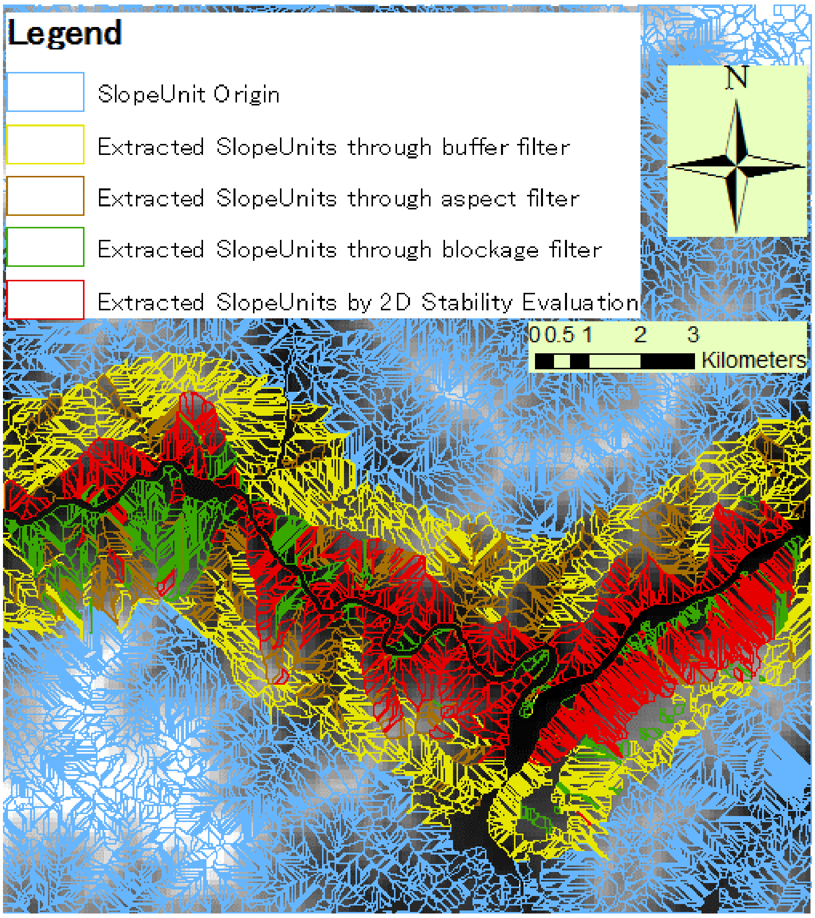

Fig. 13 Extracted Slope Units by 2D Stability Evaluation (in red region).

3.3.2 3D Stability Evaluation

For natural slopes, especially in mountainous areas, section-line based 2D methods cannot replicate the three dimensional (3D) geological structures of natural slopes. Therefore, 3D models are preferred for natural slope stability assessments, because they consider the shear resistance along the two sides of slide mass. In addition, using 3D stability evaluation, a total volume of landslide mass can be obtained.

In this research, a column-based 3D limit equilibrium model, revised Hovland model [13)], was used to calculate the safety factor of each SlopeUnit through the safety factor calculation tool developed by us. The shear outlet of slip mass and the position of the center of slip surface circle were inherited from 2D safety factor calculation extracted UnitSlopes. And then, the enumeration algorithm was performed to search a suitable width of assumed ellipsoid slip mass. The 3D safety factor (SF_{3D}) can be derived according to Eq. 2:

$$SF_{3D} = \frac{\sum_j \sum_i (cA + W\cos\theta\tan\phi)\cos\theta_{Avr}}{\sum_j \sum_i W\sin\theta_{Avr}\cos\theta_{Avr}} \tag{2}$$

where j and i are the numbers of row and column of the grid in the range of slope failure, W is the weight of one column, 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 slip surface) and θ_{Avr} is the apparent dip in the main inclination direction of the slip surface.

The risk of landslide-dam is closely associated with the volume of runouts materials. The volumes of materials are calculated from the 3D stability analysis. Through searching the sliding surface, the one with the smallest safety factor was selected as the most dangerous sliding surface, and then the volume of each landslide can be determined. The ranked risk Slope Units according to size of critical slide body from the result of 3D Stability Evaluation are shown in **Fig.14**.

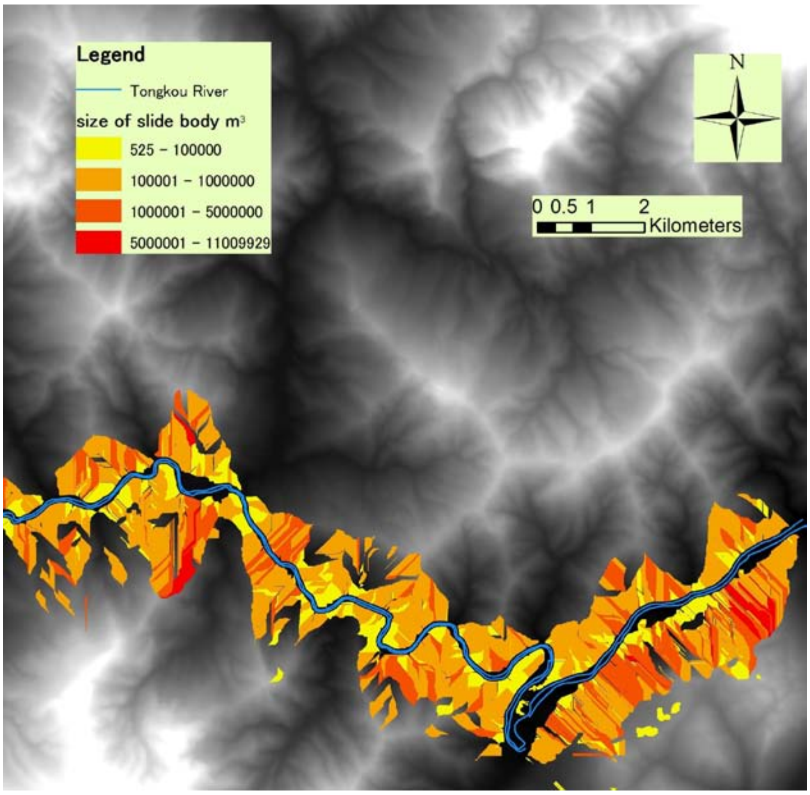

Fig. 14 Susceptibility Map ranked by slide body size.

4. Conclusions and Discussions

In this paper, we proposed a method aiming at predicting the dangerous slopes as the sources of landslide-dams in case of strong earthquake over wide area. This method has been applied to identify the dangerous slopes in the catchment of Tongkou river after the Wenchuan Earthquake. The results shown in susceptibility map succeed in extracting five large-scale landslide-dams actually occurred in this area, with safety factors ranged from 0.57 to 0.8 and slide body size ranged from 200,000 to 5,000,000 m^3. The other extracted unit slopes are also show good agreement with the landslide generating area observed from satellite image (**Fig.12**), which are supposed to contribute runouts materials into the target river. However, some more assignment and exploration need to be done as follows.

(i) For Slope Units Identification, the division size is changed with threshold drainage value. A certain size mapping for landslide is not suitable for other sizes. How to cope with landslides with different sizes is a perplexing problem.
(ii) For Spatial Filters, some artificial constructions and vegetations could be considered to remove the safe slopes and more filters could be used to extract dangerous UnitSlopes.
(iii) For Limit Equilibrium Analysis, it is a challenge to balance the efficiency and the accuracy of critical slip surface searching in both 2D and 3D geological structures. And as it is triggered by earthquake, the influence of accelerate should be enclosed in equilibrium equation.
(iv) For Susceptibility Map, the relationship between risk of landslide dam formation and the runouts distance and volume is needed. And regression analysis could be carried out to rank risk levels with those factors.

Acknowledgements

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