Erosion, Debris Flows and Environment in Mountain Regions (Proceedings of the Chengdu Symposium, July 1992). IAHS Publ. no. 209, 1992.

An index system for delineating landslide regions

WANG CHENGHUA & TAN WANPEI
Institute of Mountain Disasters and Environment, Chinese Academy of Sciences, PO Box 417, Chengdu, Sichuan 610015, China

Abstract The forecasting of landslide regions is very complicated. Fuzzy mathematics is applied in this article to form a fuzzy set of landslide regional forecast according to six factors: geomorphological conditions, lithologic characteristics, fracture structure, rainfall, earthquake and freeze-thaw action, which are chosen from many factors. To use functional exponents to show the functional extent of each factor on the landslide and decide the boundary of their subset critical values, an index system for forecasting landslide regions is set up. Landslides are not due to a single factor, but the combined effects of many factors. The forecasting of landslide regions expresses the integrated effect of fuzzy field using general mathematical formula.

ANALYSIS OF THE ENVIRONMENTAL CONDITIONS OF LANDSLIDES

Landslides form only in particular environments. The formation conditions are a combination of natural and manmade conditions.

Natural conditions

The natural conditions consists of internal and external conditions.

Internal conditions These are the basic factors of the slope. Forecasting of landslides depends on:

(a) *Geomorphological conditions*. Based on statistical analysis, the lowest gradient for landslide formation is 10°-20°, the relative height difference is 50 m; the best gradient is 20°-35°. The top of the fracture wall at the landslide trail is 100-400 m higher than the gully-bed, but is less than 900 m (Fig. 1).

(b) *Lithology of strata*. Even if the geomorphological conditions are suitable, the landslides will not occur over the whole region. Landslides are mainly concentrated in regions of slip strata (Table 1).

(c) *Structure of the slope*. That is the discontinuous structure plane controlling the landslide edge which includes the bedding plane and

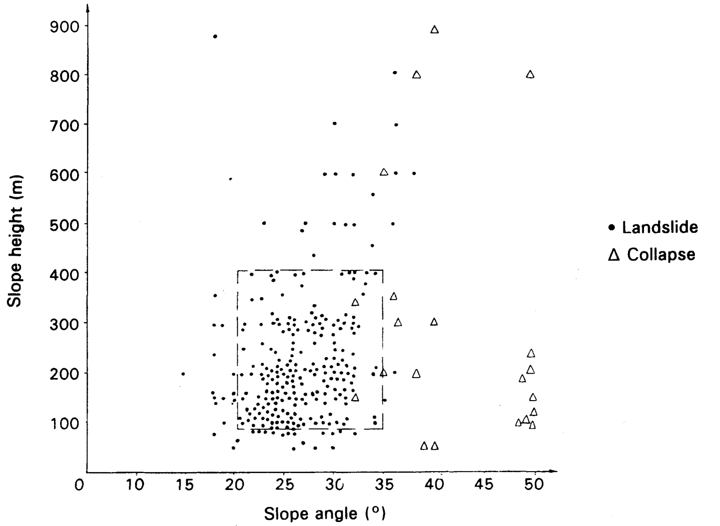

Fig. 1 The distribution of landslides in seven counties of Liangshan.

various joints. A bedding plane of consequent slope with a slope angle larger than that of the bedding plane, combined with more than two groups of steep joints through the slope body will make the structure slide easily. The distributed region of the fracturing structure can coincide with these structural forms. Therefore, the fracturing structure instead of the slope is chosen to delineate the landslide regions.

External conditions The complexity of mountain environments makes the external conditions which affect the development of landslide even more complicated. These are erosion, softening, dissolving by rainfall and groundwater, hydrostatic or hydrodynamic pressure, earthquakes, scouring and washing by water, freeze-thaw action, and natural deposition on slopes. Distribution of rainfall, earthquakes and freeze-thaw are particularly significant and can be used to delineate landslide regions.

Manmade factors

Manmade activities such as digging at the slope foot, shattering and serious vibration from large machinery, loading by deposition on slopes and leaking water can assist the formation of landslides. All those can accelerate the shape-evolution of a slope and decrease its stability.

The internal conditions (geomorphological conditions, stratum lithological characteristics and the slope structure) are the basic conditions for landslides and all must be present. The external conditions if present, can only speed up the formation of landslides. For example, rainfall lasting a long time, heavy rain and rainstorms can all make a slide happen just because of the rainfall

Table 1 The main slip strata in China.

Lithology	Slip strata	Region	Development of landslides
Clayed soil	Chengdu clay	Chengdu Plain	concentrated
	Xiashu clay	Middle and lower reaches of the Changjiang River	slight
	Red clay	Provinces in south-central China, west Shanxi, north Shanxi, Henan, etc.	slight concentrated
	Black clay	Provinces in northeast China	slight
	Yellow soil	The upper and middle reaches of the Huanghe River, provinces in north China	concentrated
	Gonghe group	Qinghai Province	concentrated
Semi-diagenetic strata	Xigeda group	Southwest Sichuan	extra concentrated
	Mottled clay rock	Shanxi province	a little
	Red mud-rock, sand, shale	Provinces in southwest China, Shanxi	concentrated
	Sandstone, coal-bearing shale	West Sichuan, north Guizhou, west Yunnan	concentrated extra concentrated
Diagenetic strata	Phyllites	West Sichuan, south Ganshu, south Shannxi	extra concentrated
	Sandy slate	Xizang, Sichuan, Hubei, Hunan, Yunnan, etc.	extra concentrated-concentrated
	Magmatic rock	Fujian	slight concentrated
Special strata	Frozen-soil	The north of northeast China, west Sichuan, the Qinghai-Xizang Plateau, and mountains	slight

process; earthquakes can make a slope which is at the equilibrium limit, slide or collapse; digging at the foot of a slope can make the slope slide. Nevertheless, if contributing external conditions and manmade factors are absent, a slope does not necessarily slide even if the internal conditions are suitable; furthermore, a slope which might slide may just collapse due to weathering exfoliation, as seen in the Kunlun Mountains of Qinghai-Xizang Plateau. Therefore, the acceleration effect of external conditions and manmade factors must not be ignored.

THE SELECTION OF FORECASTING FACTORS

The natural environment in which a landslide occurs is very complicated. The formation factors are in fact a fuzzy set:

$$A = \{A_1, A_2, \ldots, A_n\} \tag{1}$$

If containing the 14 factors stated in formula (1), the fuzzy set A will be a general set A_λ:

$$A_\lambda = \{a_1, a_2, \ldots, a_{14}\} \tag{2}$$

As stated previously, the landform, lithological character of strata and fracture structure are the basis of landslide formation. The distribution of the rainfall, earthquakes and freeze-thaw has some regularity as shown by an investigation and analysis of the data. Therefore, a rainfall isopleth map, an earthquake intensity map, and a map of the distribution of seasonal frozen-soil should all be drawn and used in forecasting landslide regions. The distribution of other external conditions and manmade factors changes, so they are not useful for forecasting landslides regions. The distribution of groundwater can be obtained, but deep water has no effect on the formation of landslides, and while perched water on the upper layer and the infiltrated water are controlled by rainfall which is not considered as a forecasting factor in this article.

The factors which are important to forecast landslide regions are geomorphological conditions (*t*), lithology of the strata (*s*), fracturing structure (*f*), precipitation (*p*), earthquake (*e*) and freeze-thaw (*fm*). The fuzzy set of landslide factors changes then into the general factor set for forecast landslide regions:

$$V = \{t, s, f, p, e, fm\} \tag{3}$$

THE FUNCTIONAL EXPONENTS AND THE COMPREHENSIVE EFFECTS

The functional exponents

Because the functional extent of the landslide factors is different in the development of landslide, so it is shown as a functional exponent and the total of the upper limits of the six functional exponents is considered as 150. According to the functional extent that each factor has on landslides, the factors are divided as follows:

Internal conditions The internal conditions are foundational factors which are geomorphology, strata lithology and fracture structure as mentioned above. They are necessary conditions for landsliding. The total of their functional exponents is chosen as 100: that for geomorphology is 50; and that for strata lithology is 30 and that for the fracture structure is 20.

External conditions The important external conditions are precipitation, earthquake and freeze-thaw. Whether the landslide will happen or not is to some extent decided by the functions of rainfall and earthquake. But their functional exponents cannot be bigger than that for the inner conditions. The upper limit of the functional exponents of these three external conditions is taken to be 50: that of precipitation is 20 while that for earthquake is 20, and that for freeze-thaw is 10.

The characteristics of the factors and the classification of the functional extent

Factors of geomorphology The geomorphological condition of landsliding is decided by the mean slope angle. According to an analysis of almost 1000 slope angles where landslide happened in Liangshan, Sichuan Province, the geomorphic conditions of the slope can be divided into three types:

(a) When the slope angle is between 0° and 10° landslides do not occur. The functional exponent is 0.

(b) When the slope angles are between 11°-20° and 35°, a few landslides happen. Their functional exponent is 10-20 in which that for the slopes where slope angles are 11°-15° are 10 while that for the slopes where the slope angles are 16°-20° or 35° are 20.

(c) When the slope angles are 21°-35° a lot of landslides happen. The functional exponent is 40-50: for slopes where slope angles are 21°-25° or 31°-35° it is taken as 40; while for slope where slope angles are 26°-30° it is taken as 50.

Landslides do not occur over the whole slope. According to investigations the front shear mouths of the sliding bed are often near the gully bed, the back top of the cracked wall is mostly 100-400 m higher than the gully bed, sometimes it is higher than 600 m, but never more than 900 m. The back tops of new landslides are all no higher than 600 m. Therefore, the relative height difference adopted as the back fringe for landslide region forecast is 600 m.

Factors of strata lithology These are divided into four types:

(a) Stable strata where landslides rarely occur are mainly thick sandstone layers, thick gravel layers, extra thick sandstone layers, limestone layers and Quaternary magmatic strata with course grains, dense structure and shear strength high enough to hinder the landslide. But landslides still might happen under particular conditions. Therefore, the functional exponent of such strata is decided as 5.

(b) Strata where sliding occasionally occurs are mainly sandstone, limestone, conglomerate, shale and magmatic rock. These strata are almost the same as those in (a) but their strength is less because they have mud or shale layers. Nevertheless, the strata are very difficult to slide, so the functional exponent is decided as 10-15.

(c) Easy to slide strata are mainly sandstone, mudstone, shale, argillaceous, metamorphic limestone, slate and phyllite, dolomite, dolomitic limestone and tuff etc. Because hard and soft strata alternate, the shear strength is low, and these strata slide easily. Therefore, the functional exponent is decided as 20-25.

(d) Strata that slide extra easily are mainly shale, calciferous shale and phyllite with mudstone-sandstone, fine sandstone and slate. The strata of Tertiary lake facies, yellow soil, Chengdu clay, Xiashu soil and depositional cracked soil on a Quaternary slope are also strata extra easy to slide. These strata have low shear strength. The functional exponent is decided as 30.

Factors of fracture structure The structures are divided into three types according to the weakening effect of fracturing:

(a) There is no effect in sandstone and gravel layers of the Quaternary. The functional exponent is 0.

(b) There is a slight effect in strata whose joints and cracks are developed by fracturing and folding. Most of the mountain regions in China are of this type. The functional exponent is 5-10.

(c) There is a serious effect in crushed sections formed by fracturing. Because the rock is crushed and weathered, its sear strength is extra low, so the functional exponent is 15-20.

Factors of precipitation According to statistical analysis, 70-80% of landslides occur in rainy seasons. Thus, the rainfall affects the formation of landslide to some extent. this extent is divided into four degrees:

(a) In dry regions with mean annual rainfall less than 200 mm there are no functional exponents, so the functional exponent is 0.

(b) In slightly rainy regions where the mean annual rainfall is 200-400 mm there are occasional landslides; the functional exponent is 1-5.

(c) In very rainy regions where the mean annual rainfall is 400-800 mm there are a lot of landslides. So the functional exponent is 10-15; regions which have heavy rain are 15.

(d) In extremely wet regions where the mean annual rainfall is more than 800 mm there are many landslides. The functional exponent is 20.

Earthquake factors According to investigation on earthquake regions in west China, the lower limit of intensity that induced landslides is magnitude six, and the destruction of slopes increases doubly with the intensity of earthquake. If the functional exponent in a six-magnitude region is 4, then the exponent in regions more than six can be computed by:

$$e = 4(n-5) \ , \ n \geq 6 \tag{4}$$

where n is the intensity of earthquake. The upper limit of the functional factors is 20.

Freeze-thaw function This mainly happens in cold mountains and is

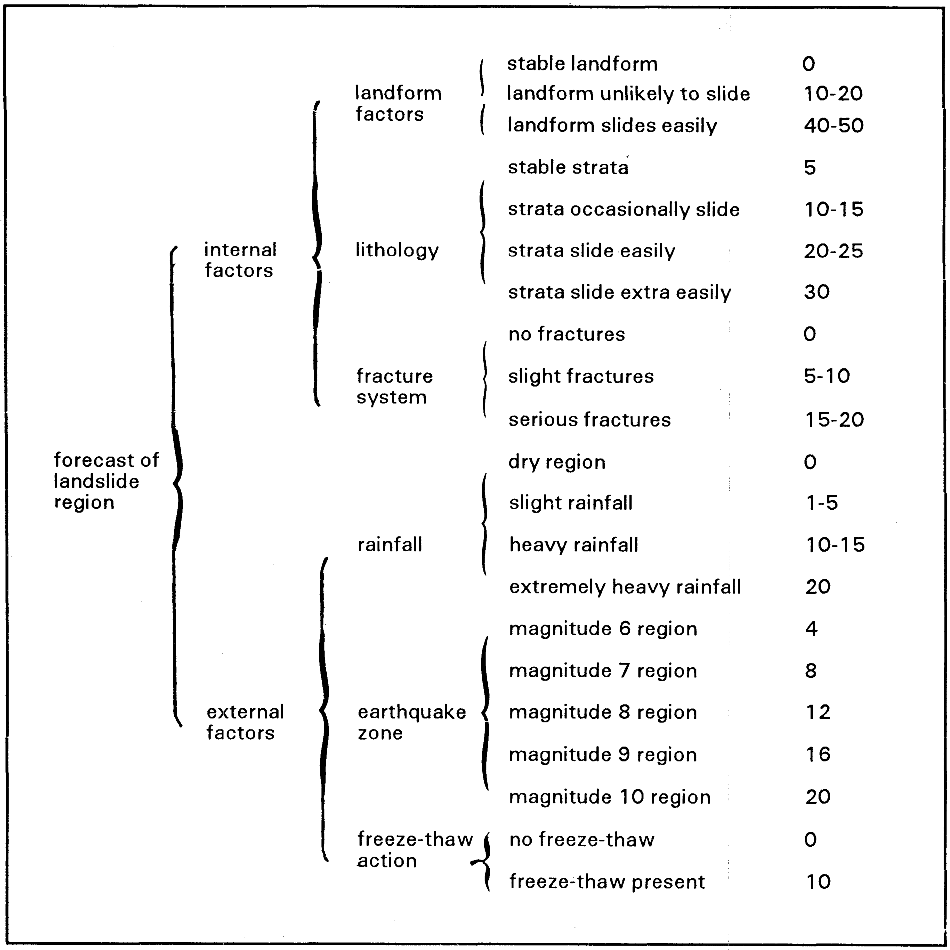

Fig. 2 The index system for forecasting landslide regions.

divided into two types:

(a) In regions with no freeze-thaw action, the functional exponent is 0.

(b) In regions with freeze-thaw action, the functional exponent is 10.

The index system for forecasting landslide regions can now be formed (Fig. 2).

COMPREHENSIVE FUNCTIONAL EFFECT

The comprehensive functional effect is shown by R:

$$R_i = \frac{\sum_{n=1}^{n} Ain}{\sum_{n=1}^{n} An} \tag{5}$$

where *Ain* is the functional exponent of the formation factors in region *i*, while *An* is the upper limit of *Ain* in the region studied, R_i is the comprehensive functional effect of the factors in region *i*.

If using the index system, formula (5) will be:

$$R_i = \frac{t_i + S_i + f_i + p_i + e_i + fm_i}{t + s + f + p + e + fm} \qquad (6)$$

The comprehensive functional effect of formation factors can be applied to forecast the occurrence of landslides in a given region. If computing the comprehensive functional effect of many points and connecting those points with the same comprehensive functional effect in a given region, the isopleth map of the comprehensive functional effect results. This can be used to forecast landslide regions and hazard regions.

CONCLUSION

According to the investigation, the main source of debris flow solid material is landslides (including collapse). The distribution of landslides generally coincides with that of debris flow. Therefore, the form of the index system for debris flow regional forecasting is similar to that of the index studies in this article.