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HAZARD ASSESSMENT OF DEBRIS FLOWS BASED ON THE CATASTROPHE PROGRESSION METHOD: A CASE STUDY FROM THE WUDONGDE DAM SITE

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ABSTRACT

Debris flows are complex fluid movements, in which water-laden masses of soil and fragmented rock rush down mountainsides, funneled into stream channels. The occurrence of debris flows in the Wudongde Dam site threatens human lives and structures. Hazard assessment of debris flow is important for natural disaster prevention and reduction. In this paper, 3S (Geographic Information System, Global Positioning System, and Remote Sensing) technologies were applied to determine the characteristics of debris flows. Nine factors of influence were acquired through 3S technologies. The catastrophe progression method was used to conduct hazard assessments of 27 debris flow catchments. The results show that the hazard levels for one of the debris flow catchments was high, twelve were moderate, three were low, and eleven were very low. The quantitative assessments made, based on nonlinear methods, are consistent with field investigations.

Keywords: Debris flow, Hazard assessment, Catastrophe progression method, 3S technologies.

1. INTRODUCTION

Debris flow is one of the most common and dangerous natural disasters that occur in mountainous regions. It transports large amounts of water and loose material from source areas and creates serious loss of lives and structures. In recent years, debris flow hazards have gained much attention all over the world [1] [2] [3].

Hazard assessment represents an important criterion for engineers to understand the overall situation of a debris flow catchment. Several assessment methods have been proposed in the past decades [4] [5]. Among these models, physical-based and statistical-based approaches are the most used methods. Physical approaches are used to investigate the influence of geotechnical characteristics on susceptibility analysis [6]. However, data for the factors used in these approaches cannot be obtained for large-scale debris flows [7]. Statistical models are based on the analysis of relationships between environmental factors and observed debris flow events. Discriminant analysis is used widely as a statistical tool in hazard assessment. However, the availability of data should be ascertained before carrying out such an approach, since such data are difficult to obtain for most of China. Debris flow is a natural disaster that occurs suddenly under a set of specific geological conditions, topographical conditions, and excitation conditions. Thus, it is appropriate to use catastrophe theory to study debris flow hazards. This paper aims to determine debris flow hazard levels using the catastrophe progression method, based on geological, topographical, and excitation factors of influence. A geographic information system (GIS), a global positioning system (GPS) and remote sensing (RS), collectively known as the '3S technologies', were used to determine factors for analysis [8].

2. STUDY AREA

The Wudongde Hydropower Station is located in the Jinsha River (Fig. 1). In total, 27 large-scale debris flow catchments were investigated, on both sides of the Jinsha River. Given that loose material from the debris flow catchments could affect the stability of the dam site, it was critical to carry out a hazard assessment for this area. Through a hazard assessment of debris flow, it was possible to identify which of the debris flow catchments were most hazardous.

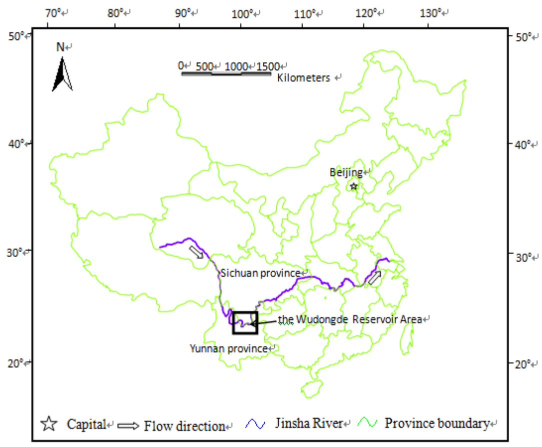

Figure 1. The position of the Wudongde dam site

Based on field investigation, four main types of sediment supply to drainage systems were observed: the Longjie fine sand layer (Fig.2), formed during the Late Pleistocene; the Madianhe layer (Fig.3), formed during the Holocene; red-bed soft rocks (Fig.4), formed between the Triassic Period (T) and the Cretaceous Period (K); and metamorphic rocks (slate, schist, and phyllite), formed during the Proterozoic era. The Longjie fine sand layer mainly comprises clayey silt, silt, and sand, in which horizontal beddings have developed. The Madianhe layer, which is composed of silt and gravel, is the most representative type of loose material with the widest distribution. Both of these sediment types have high dry-length values. Therefore, slope angles are always much steeper. Red-bed soft rocks are prone to physical weathering. The surface layer of soft rocks is completely weathered. Metamorphic rocks, such as slate, schist, and phyllite, have been significantly weathered in this area. During the survey, many kinds of loose solid material deposits were found, including landslides and collapse deposits. All loose solid material deposits in each catchment were inventoried, including information on material thickness, lateral extent, and elevation.

Figure 2. Longjie fine sand layer in Xiushuihe catchment

Figure 3. Madianhe layer in Xiabaitan catchment

3. CATASTROPHE PROGRESSION METHOD

Catastrophe theory is a mathematical technique developed principally by French mathematician Thom (1972) for modeling natural phenomena, which contain discontinuous data in the values of one or more parameters [9]. Catastrophe theory both studies and classifies phenomena that are characterized by sudden shifts in behavior arising from small changes in circumstances. It has been applied in many fields, including that of geological disasters [10]. It can be used, for example, to investigate the unpredictable timing and magnitude of a debris flow.

Catastrophe theory analyses degenerate critical points of the potential function — points where not just the first derivative, but one or more higher derivatives of the potential function are also zero. The degeneracy of these critical points can be unfolded by expanding the potential function, as a Taylor series, in small perturbations of the parameters. If the potential function depends on one active variable, and four or fewer active parameters, then there are only four generic structures for these bifurcation geometries. Each then has a corresponding standard form, into which the Taylor series around the catastrophe germs can be transformed by diffeomorphism.

The catastrophe progression method shows great potential in multi-objective evaluation when objectives of different importance are considered. First, an overall evaluation index is established, which is then broken down into sub-indices. All indices, hierarchical and mutually exclusive, are then grouped, in accordance with the purpose of the evaluation. Indices in each hierarchy form a different catastrophe system. Four common catastrophe types are fold catastrophes, cusp catastrophes, swallowtail catastrophes and butterfly catastrophes. Their potential functions are shown in Table 1.

Figure 4. Red-bed soft rocks in shenyuhe catchment

A catastrophe evaluation index system is divided into hierarchical sub-systems, each consisting of several evaluation indices, so that the indices are more specific and easily quantified. The system for the hazard assessment of debris flows can be broken down in the manner shown in Figure 5. The lack of proportionality of the indices is eliminated by using a standard transformation method, so that the evaluation indices are dimensionless [11]. The normalization formulas of cusp catastrophes, swallowtail catastrophes, and butterfly catastrophes are shown, respectively, as formulas (1), (2), and (3).

$$x_u = \sqrt{u}\ ,\ x_v = \sqrt[3]{v} \tag{1}$$

$$x_u = \sqrt{u}\ ,\ x_v = \sqrt[3]{v}\ ,\ x_w = \sqrt[4]{w} \tag{2}$$

$$x_u = \sqrt{u}\ ,\ x_v = \sqrt[3]{v}\ ,\ x_w = \sqrt[4]{w}\ ,\ x_t = \sqrt[5]{t} \tag{3}$$

Table 1. The potential function of four fundamental catastrophe types

fundamental type	active parameter	active variable	potential function
Fold catastrophe	1	1	$F(x) = x^3 + ux$
Cusp catastrophe	2	1	$F(x) = x^4 + ux^2 + vx$
Swallowtail catastrophe	3	1	$F(x) = x^5 + ux^3 + vx^2 + wx$
Butterfly catastrophe	4	1	$F(x) = x^6 + ux^4 + vx^3 + wx^2 + tx$

F(*x*) is the potential function of the active variable *x* and *u*, *v*, *w* and *t* are the active parameters.

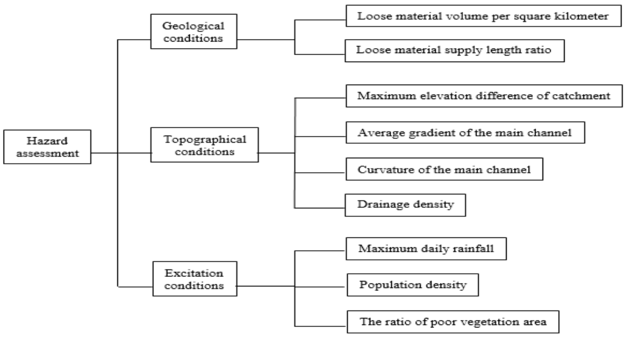

Figure 5. Factors that affect hazard assessment of debris flow

The catastrophe progression of each active variable can be computed from the initial fuzzy subordinate function, based on normalization formulas. In the research carried out for this paper, the active variables cannot offset each other. Therefore, the non-complementary principle has been followed. This means that, when looking for the value of the state variable x using the normalization formulas, the smallest of the state variable values corresponding to the active variable is chosen as the state variable value of the system [11].

Table 2. Boundaries of the major factors for hazard classes

	Very low	Low	Moderate	High
*C*1	0-30	30-100	100-1000	1000-2295
*C*2	0-0.1	0.1-0.3	0.3-0.6	0.6-1
*C*3	0-0.2	0.2-0.5	0.5-1	1-3
*C*4	0-0.1	0.1-0.2	0.2-0.35	0.35-0.85
*C*5	0-1.1	1.1-1.25	1.25-1.4	1.4-1.7
*C*6	0-5	5-10	10-20	20-30
*C*7	0-25	25-50	50-100	100-150
*C*8	0-50	50-150	150-250	250-350
*C*9	0-15	15-30	30-60	60-100

*C*1 ($\times 10^4 m^3/km^2$) is loose material volume per square kilometer; *C*2 is loose material supply length ratio; *C*3 (km) is maximum elevation difference of catchment; *C*4 is average gradient of the main channel; *C*5 is curvature of the main channel; *C*6 (km/km^2) is drainage density; *C*7 (mm) is maximum daily rainfall; *C*8 (number of people/km^2) is population density; *C*9 (%) is the ratio of poor vegetation area

Hazard assessment of debris flows is a multi-objective evaluation problem. The main feature of the catastrophe progression method is not that the evaluation weights of indices are used, but that their relative importance is considered. This means that it is possible to avoid subjective bias in determining factor weight.

4. HAZARD ASSESSMENT OF DEBRIS FLOWS

According to previous research [12][13], nine factors for a hazard assessment, including geological, topographical and meteorological factors, as well as factors relating to vegetation conditions and human activity, were selected. These factors are: loose material volume per square kilometer (*C*1); loose material supply length ratio (*C*2); maximum elevation difference of catchment (*C*3); average gradient of the main channel (*C*4); curvature of the main channel (*C*5); drainage density (*C*6); maximum daily rainfall (*C*7); population density (*C*8); and the ratio of poor vegetation area (*C*9). Data for each of these factors was acquired through 3S technologies. Hazard assessment of the debris flow catchments was carried out using the catastrophe progression method. After Zhang et al. [12], the boundaries of the major factors for each hazard class are shown in Table 2. The classification of debris flow hazards and the catastrophe progression are shown in Table 3. The classification found for the 27 debris flow catchments is shown in Table 4.

Table 3. The classification of debris flow hazards and the catastrophe progression

classification	V- low	Low	Moderate	High
progression	0-0.338	0.338-0.457	0.457-0.812	0.812-1

Table 4. The catastrophe progression and hazard classification of each catchment

Catchment	*XBT*	*SBT*	*ZGD*	*YDG*	*SYH*	*XSH*	*MGG*	*JCH*	*FJG*
Progression	0.784	0	0.616	0.363	0	0.355	0.579	0.760	0.693
Classification	*M*	*V*	*M*	*L*	*V*	*L*	*M*	*M*	*M*
Catchment	*ABG*	*ZZH*	*HZ*	*YSJ*	*NZC*	*LLK*	*ZMH*	*HP*	*JPG*
Progression	0.866	0	0.161	0	0.760	0.474	0.562	0.317	0.518
Classification	*H*	*V*	*V*	*V*	*M*	*M*	*M*	*V*	*M*
Catchment	*TFH*	*ZLG*	*YJD*	*PDC*	*FSG*	*DQG*	*MGH*	*FPG*	*DQG*
Progression	0.726	0.430	0	0.469	0.464	0	0.271	0.238	0.296
Classification	*M*	*L*	*V*	*M*	*M*	*V*	*V*	*V*	*V*

Note: *XBT, SBT, ZGD, YDG, SYH, XSH, MGG, JCH, FJG, ABG, ZZH, HZ, YSJ, NZC, LLK, ZMH, HP, JPG, TFH, ZLG, YJD, PDC, FSG, DQG, MGH, FPG, DQG* are the abbreviations for, respectively: Xiabaitan; Shangbaitan; Zhugongdi; Yindigou; Shenyuhe; Xiushuihe; Menggugou; Jiachehe; Fujiagou; Aibagou; Zhuzhahe; Heizhe; Yanshuijing; Nuozhacun; Lalakuang; Zhangmuhe; Hepiao; Jiaopinghou; Tianfanghe; Zhiligou; Yajiede; Pingdicun; Fangshanguo; Daqiangou; Mengguohe; Fapagou; Daqinggou. *H, M, L, V* are the abbreviations of, respectively: high, moderate, low and very low.

5. DISCUSSION AND CONCLUSIONS

In total, large-scale debris flow catchments, located in the lower reaches of the Jinsha River, were investigated. Using 3S technologies (GIS, GPS, and RS), it was possible to determine nine factors of influence in the debris flow catchments. These factors reflect various geological, topographical, and excitation conditions of the catchments, namely: loose material volume per square kilometer; loose material supply length ratio; maximum elevation difference of catchment; average gradient of the main channel; curvature of the main channel, drainage density; maximum daily rainfall; population density; and the ratio of poor vegetation area.

A hazard assessment for debris flows was carried out using a catastrophe progression method. Debris flow is a natural disaster that occurs suddenly under a specific set of geological, topographical, and excitation conditions. Thus, it is appropriate to use a catastrophe progression method to determine debris flow hazard levels. The results showed that the debris flow hazard of the Aibagou catchment was high, twelve catchments had moderate hazard levels, the hazard of the Yindigou, Xiushuihe, Zhiligou catchments was low, and the other eleven catchments had very low hazard values. Hazard assessment represents an important criterion for investigators to understand the overall situation of a debris flow catchment. Adopting prevention projects for debris flow catchments with higher hazard possibility as a priority is an effective way to avoid economic loss and fatalities.

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