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Risk Assessment of the Chaancun Debris Flow Gully and Mitigative Measures in Dalian City, China

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Abstract: The Chaancun debris flow gully is located on the mountain slope of the crown of the Chaancun landslide. The hiking corridor, leisure square, Lvshun middle road, and Wangjiadian reservoir are situated below the debris flow track. The Chaancun debris flow gully poses a serious threat to the safety of this site and to the development of tourist attractions. First, an appropriate recognition of the debris flow gully is required by a field investigation. This gully is steep and straight. The weathered and denuded rocks coming from the fault zone are the debris source. In addition, concentrated rainfall occurs in this area. Therefore, the debris flow gully has the forming conditions of a debris flow. Many factors affect the formation and assessment of a debris flow, and they result in uncertainty, randomness, and fuzziness. Therefore, the fuzzy mathematics method is suitable for the risk assessment of debris flow. To improve the reliability of the risk assessment of the Chaancun debris flow gully, primary fuzzy assessment and secondary fuzzy assessment considering hierarchical analysis were undertaken for quantitative risk assessment. This gully was categorized as “extremely hazardous;” thus, appropriate mitigations such as building a concrete dam and planting in bare areas were designed and implemented.

Keywords: *debris flow, risk assessment, fuzzy mathematics, mitigative measures*

1. Introduction

Chaancun debris flow gully is located on the mountain slope of the crown of Chaancun landslide, shown in Figure1. Lvshun middle road and Wangjiadian reservoir at the toe of Chaancun landslide are situated below the debris flow track. Chaancun Landslide is the second largest landslide has occurred in northeast China (Zhang et al., 2015; Xu et al., 2011). Now, it was mitigated as a park for tour and leisure. Hiking corridors distribute on the slope and leisure square is sited at the toe of slop. Beautiful landscapes of this site attract many tourists. However Chaancun debris flow gully forms a serious threat to the safety of this site and development of tourist attraction. So an appropriate recognition of the debris flow gully is required by field investigation, then risk assessment of debris flow need to be undertaken, providing scientific evidence to determine whether or not applying protective mitigations.

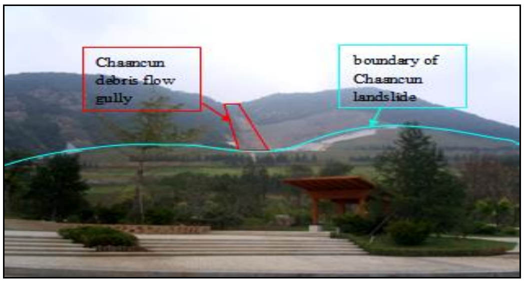

Figure 1: *Chaancun landslide was mitigated as a park for leisure and tour. Hiking corridors distribute on the slope and leisure square is constructed at the toe of slope*

2. Field investigation of Chaancun debris flow gully

Debris flow as a kind of sudden geological disaster needs three conditions including favorable topography, rich loose material and rainfall. Slope gradient of longitudinal gully of Chaancun gully is 322‰ and bend coefficient is 1.2. Average slope angle on the left and right flank of the gully is 32° and 31° respectively. The gully is steep and straight. Longitudinal section of Chaancun debris flow gully is shown in Figure2. Topography of this gully is favorable to the occurrence of debris flow.

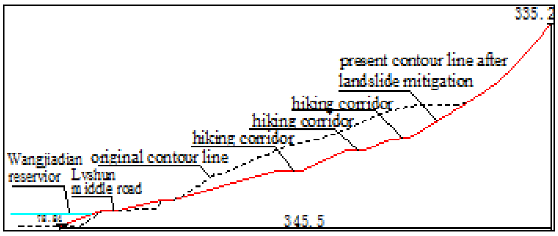

Figure 2: *Longitudinal section of Chaancun debris flow gully (unit: m)*

Bedrock are alternating layers of thick layer of slate and laminated quartzite and the overlying quaternary diluvium are gravel and silty clay containing gravel. According to geophysical prospecting of resistivity survey and seismic survey, there are three faults in the study area, as shown in figure3. F_1 is reverse fault with strike of NE18° and inclination angle of 20°.The outcropping length is about 600 m. Meanwhile, there was another fault called F_2 truncated by F_1.Strike of F_2 is NW310° and inclination angle is

70~80°.Outcropping length is about 800m.The third fault called F_3 close to the NS strike and outcropping length is about 600m.

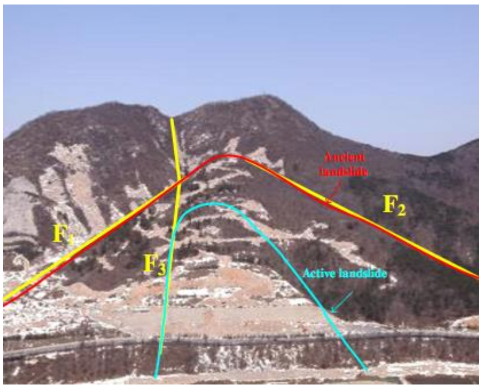

Figure 3: *Faults in the study area*

Chaancun debris flow gully is located along the fault fracture zone of F_3. Fault fracture zone is weak and vegetation is rare. Therefore bare rock in natural condition easily weathered and denuded, generating a lot of loose debris accumulating in the gully. Rich loose material about 730m^{3}of this gully is favorable to forming debris flow.

Rainfall is excitation condition of debris flow. This study area is located in Dalian city and belongs to the northern hemisphere warm temperate semi-humid monsoon climate zone. Rainfall mainly concentrated in July and August, average annual precipitation of 662mm, maximum precipitation per hour of 68 mm, maximum precipitation within 24 hour of 149.4 mm. Large and concentrated rainfall provides a rich source of water for debris flow and hydrodynamic conditions.

Table 1: *Rainfall statistics in the study area*

Precipitation	Value
average annual precipitation	662.0mm
largest precipitation within 10min	20.5mm
maximum precipitation within 1 hour	68.0mm
maximum precipitation within 24 hour	149.4mm
maximum precipitation of continuous rain	178.6mm

Based on investigation of topography, loose material and rainfall, Chaancun debris flow gully has occurrence conditions of debris flow. Once debris flow occurring, it will bring serious hazard to person and public facilities. Therefore, before the disaster occurring, risk assessment of debris flow need to be undertaken, providing scientific evidence to determine whether or not applying protective mitigations, which is important for reducing loss of life and property due to debris flow.

3. Risk assessment of fuzzy mathematical method

Debris flow risk can quantitatively describe the degree of debris flow hazard, expressed by probability value rang [0%˜ 100%], as expression of the debris flow warning level. Many factors affect the formation and assessment of debris flow, which result in debris flow risk having character of uncertainty, randomness and fuzziness. Hence fuzzy mathematics method is very suitable for use in debris flow risk assessment (Lin et al,2012). In order to improve the reliability of risk assessment to Chaancun debris flow gully, primary fuzzy assessment and the secondary fuzzy assessment considering hierarchical analysis were undertaken.

3.1 Determination of assessment factor set

Consulting the related literature published in recent, volume of loose material, catchment area, longitudinal slope gradient, rainfall intensity, daily precipitation, cumulative precipitation, vegetation coverage, soil and rock type, bend coefficient of gully were frequently applied in debris flow risk assessment, that illustrates the importance of these factors in debris flow risk assessment(Liu et al 2009; Lin et al 2002; Ohlmacher et al 2003;Lan et al 2004; Catani et al 2005; Chang et al 2006,2007; Lu et al 2007;Tiranti et al 2008; Tunusluoglu et al 2008).According to field investigation of the Chaancun debris flow gully, seven factors were selected related to topography, loose material and rainfall.

Assessment factor set $U=(u_1, u_2, u_3, u_4, u_5, u_6, u_7)$ were established. Seven assessment factors from u_1 to u_7 are respectively volume of loose material, catchment area, slope gradient of longitudinal gully, maximum precipitation within 24 hour, bend coefficient of gully, vegetation coverage, soil and rock type, values obtained by investigation as shown in table 2.

Table 2: *Value of assessment factor obtained by investigation*

u_1/10^{4}m^3	u_2/km^2	u_3/ ă	u_4 /mm	u_5	u_6/ %	u_7
0.073	2.1	322	149.4	1.2	39	strong weathered rocks and denuded rocks

3.2 Determination of assessment set

Risk degree of debris flow is divided into four levels, it is shown by assessment set $V=(v_1,v_2,v_3,v_4)$ =(slightly hazardous, moderately hazardous, very hazardous, extremely hazardous). According to actual conditions by field investigation and in line with the suggestions of experts, standard values of assessment factors were determined, as shown in Table 3.

Table 3: *Standard values of assessment factors relative to risk degree*

	v_1 slightly hazardous	v_2 moderately hazardous	v_3 very hazardous	v_4 extremely hazardous
$u_1/10^4m^3$	1	5	10	50
u_2/km^2	0.20	0.5	2	5

u_3/%	10	20	25	30
u_4/mm	50	75	100	125
u_5	1.1	1.25	1.4	1.5
u_6/%	70	50	30	10
u_7	hard rock	strong weathered and joints developed rock	Soft and hard interlayer rock	Soil and soft rock

3.3 Weight vector of assessment factor

For fuzzy assessment of debris flow risk degree, the first is to consider the weight of assessment factors selected, and correctness of risk assessment depends on the rationality of weight assignment. At present, weighting method of experts'experience combine with mathematical method was widely used. Therefore, according to actual conditions of Chaancun debris flowgully, judgment matrix A was given by expert scoring, and then weight vector W was obtained by calculation.

a_{ij} in judgment matrix A is defined that considering seven assessment factors relative to the final risk degree , the different importance of one assessment factor relative to another factor, represented by nine natural number of 1-9 and eight fraction of 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9.

***Table 4:** Explanation of a_{ij} in judgment matrix A*

Value	Explanation
1	Indicates that two factors are of equal importance.
3	Indicates that i factor is a little more important than J factor
5	Indicates that i factor is obviously more important than j factor
7	Indicates that i factor is significantly important than j factor
9	Indicates that the i factor is extremely important than the j factor
2,4,6,8	Indicates that the intermediate value of the adjacency judgment

a_{ij} in judgment matrix of A is as follows: $a_{ij}>1$, $a_{ii}=1$, $a_{ij}=1/a_{ji}$

Scoring the seven assessment factors of Chanancun debris flow gully by experts, judgment matrix A was given as shown below.

$$A=\begin{bmatrix} 1 & 7 & 3 & 3 & 5 & 6 & 3 \\ 1/7 & 1 & 1/6 & 1/4 & 1 & 1/2 & 1/2 \\ 1/3 & 6 & 1 & 3 & 5 & 5 & 4 \\ 1/5 & 4 & 1/3 & 1 & 5 & 4 & 4 \\ 1/5 & 1 & 1/5 & 1/5 & 1 & 1/2 & 1/2 \\ 1/6 & 2 & 1/5 & 1/4 & 2 & 1 & 1 \\ 1/3 & 2 & 1/4 & 1/4 & 2 & 1 & 1 \end{bmatrix}$$

Maximum eigenvalue and corresponding eigenvectors after normalization of judgment matrix A are calculated, and then making consistency check. When meeting the consistency check, the corresponding eigenvector after normalization can be as weight vector $W=(w_1,w_2,w_3,w_4w_5,w_6,w_7)^T$, w_i is the weight of each factor, otherwise establishing new judgment matrix.

First, calculate maximum eigenvalue λ_{max} and corresp-onding eigenvector of judgment matrix A. Eigenvectors $\overline{W}$ is calculated by formula below.

$$\overline{w}_i=\sqrt[7]{\prod_{j=1}^{7} a_{ij}} \quad i=1,2,\cdots,7 \tag{1}$$

$$\overline{W}=(3.437,\ 0.395,\ 2.494,\ 1.666,\ 0.412,\ 0.615,\ 0.701)^T$$

Normalizing $\overline{W}$, eigenvector after normalization W is calculated by formula as follow:

$$w_i=\frac{\overline{w}_i}{\sum_{i=1}^{7}\overline{w}_i} \quad i=1,2,\cdots,7 \tag{2}$$

$W=(0.345,\ 0.041,\ 0.257,\ 0.171,\ 0.042,\ 0.063,\ 0.072)^T$,where w_i is weight of each factor.

Maximum eigenvalue is calculated by formula below.

$$\lambda_{max}=\sum_{i=1}^{7}\frac{(Aw)_i}{7w_i} \tag{3}$$

$$\lambda_{max}=7.376$$

Then, consistency check of judgment matrix A is divided into the following three steps. First step the consistency index CI is calculated, where n is matrix order of A in the following formula.

$$CI=\frac{1}{n-1}(\lambda_{max}-n) \tag{4}$$

Second step, according to Table 5 and matrix order n of judgment matrix A, the mean random index RI is determined. Third step, consistency of matrix A is judged by the value of consistency ratio CR.

***Table 5:** The mean random consistency index RI*

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54

$$CR=CI/RI \tag{5}$$

If $CR<0.1$ judgment matrix meets consistency check. If $CR\geq 0.1$, judgment matrix needs to be adjusted until meeting consistency check.

Based on the above process, for Chaancun debris flow, n=7,CI =0.059, RI=1.32, while CR=0.045 < 0.1, The judgment matrix A meets consistency check. So vector W can be as the weight vector of assessment factor.

3.4 Determination of membership degree

Assessment factor set of Chaancun debris flow was established as $U=(u_1\ u_2\ u_3\ u_4\ u_5\ \ u_6\ u_7)$; Risk degree of debris flow was divided into four levels $V=(v_1\ v_2\ v_3\ v_4)$; Matrix R was used to show the fuzzy relationship between U and V.

$$R=\begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ \ldots & \ldots & \ldots & \ldots \\ r_{71} & r_{72} & r_{73} & r_{74} \end{bmatrix} \quad (6)$$

In the above formula where $r_{ij}=\mu(u_i,v_j)(0\le r_{ij}\le 1)$ is the possibility of assessment factor u_i evaluated as level v_j, or r_{ij} also can be interpreted as the probabilities of assessment factor u_i belong to level v_j, namely membership degree.

Membership degree was defined by L.A.Zadeh (1965). There is a $F(x)$, $F(x)\in[0,1]$, and x belongs to U. If $F(x)$ corresponding to each x , namely $F(x)$ is a function of x, in this case F is fuzzy set for U, $F(x)$ was membership degree of x relate to F. For Chaancun debris flow, weight values of seven factors had already been given, so the membership degree can be determined by a linear function as shown in formula(7)-(10) below.

$$u_1(x)=\begin{cases} 1 & x\le x_1 \\ \dfrac{x_2-x}{x_2-x_1} & x_1<x<x_2 \\ 0 & x\ge x_2 \end{cases} \quad (7)$$

$$u_2(x)=\begin{cases} 0 & x\le x_1 \text{ or } x\ge x_3 \\ \dfrac{x-x_1}{x_2-x_1} & x_1<x\le x_2 \\ \dfrac{x_3-x}{x_3-x_2} & x_2<x<x_3 \end{cases} \quad (8)$$

$$u_3(x)=\begin{cases} 0 & x\le x_2 \text{ or } x\ge x_4 \\ \dfrac{x-x_2}{x_3-x_2} & x_2<x\le x_3 \\ \dfrac{x_4-x}{x_4-x_3} & x_3<x<x_4 \end{cases} \quad (9)$$

$$u_4(x)=\begin{cases} 0 & x\le x_3 \\ \dfrac{x-x_3}{x_4-x_3} & x_3<x<x_4 \\ 1 & x\ge x_4 \end{cases} \quad (10)$$

$u_1(x)$, $u_2(x)$, $u_3(x)$, $u_4(x)$ is the membership degree of an assessment factor belongs to risk degree v_1, v_2, v_3, v_4 respectively. x_1,x_2,x_3,x_4 is the standard values of this assessment factor relative to risk degree in Table 3 respectively and x is value of this assessment factor obtained by investigation shown in Table 2.

Membership degrees of seven assessment factors were summarized in membership degree set R as follow.

$$R=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0.967 & 0.033 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0.33 & 0.67 & 0 & 0 \\ 0 & 0.75 & 0.25 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

3.5 The result of primary fuzzy assessment

In membership degree set R, r_{ij} is the membership degree of assessment factor u_i belongs to risk degree v_j. The row of i shows membership degree of assessment factor u_i relative to each risk degree, $r_{i1}+r_{i2}+r_{i3}+r_{i4}=1$. However, each factor has a large or small importance in risk assessment , w_i is the weight of assessment factor u_i relative to target risk, $w_1+w_2+w_3+\cdots+w_7=1$, $0\le w_i\le 1$; $W=\{w_1,w_2,w_3,\cdots,w_7\}$ as the weight of assessment factor.

The comprehensive membership degree is associated of w_i and r_{ij} with formula below $s_j=\sum_{i=1}^{7} w_i r_{ij}$. The fuzzy set $S=(s_1,s_2,s_3,s_4)(0\le s_j\le 1)$ is obtained by formula $S=W\circ R$. s_1 s_2 s_3 s_4 shows the probability of risk degree v_1, v_2, v_3,v_4, respectively, $s_{i_0}=\max_{1\le i\le 4}\{s_j\}$, v_{i_0} is target risk degree.

For Chancun debris flow gully, $S=W\circ R=$[0.368 0.148 0.055 0.429], 0.429 is the largest probability shown in Table 6, so risk degree of Chaancun debris flow gully is categorized as 'extremely hazardous' by primary fuzzy assessment.

Table 6: *Comprehensive membership degree of debris flow*

Risk degree	v_1 Slightly hazardous	v_2 Moderately hazardous	v_3 Very hazardous	v_4 Extremely hazardous
Membership degree	0.368	0.148	0.055	0.429

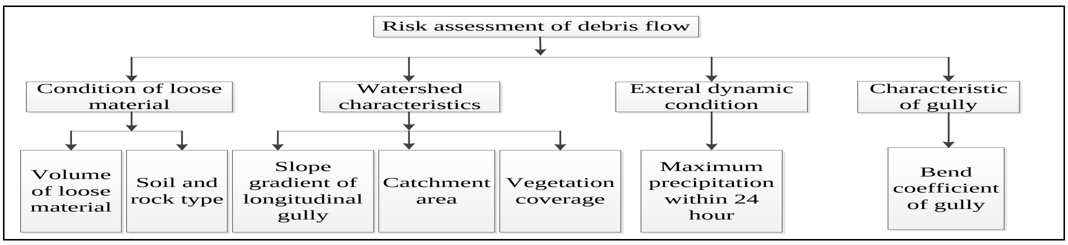

Figure 4: *Flow chart of AHP in secondary fuzzy assessment*

3.6 The secondary fuzzy assessment considering hierarchical analysis

Analytic hierarchy process (AHP) is widely used in many fields of engineering geology, According to thesimilar attributes, seven assessment factors are divided into four categories, illustrated in the Figure4. First, make primary assessment in each category, and then make secondary assessment of four categories again, finally risk degree of debris flow is obtained. The framework is as follows:

$$U=\{U_1,U_2,U_3,U_4\}$$

$$U_1=\{u_1,u_7\};\quad U_2=\{u_2,u_3,u_6\};\quad U_3=\{u_4\};\quad U_4=\{u_5\}$$

Table 7: *The explanation of four categories*

U_1	U_2	U_3	U_4
Condition of loose material	Watershed Characteristics	External dynamic condition	Characteristic of gully

The result of secondary assessment is shown in Table 8. The probability of v_4 was the highest one which was 0.408, so risk degree of debris flow of Chaancun gully is extremely hazardous.

According to result of primary fuzzy assessment and secondary fuzzy assessment considering hierarchical analysis, risk degree of Chanancun debris flow gully is extremely hazardous. Secondary fuzzy assessment considering hierarchical analysis was recommended for risk assessment of debris flow, due to that evaluation factors divided by attribute and it is better to avoiding error because of relevance factors compared with each together.

4. Mitigative Measures

Risk degree of Chaancun debris flow was categorized as 'extremely hazardous', so corresponding defensive measures must be taken. A concrete dam was built at start part of transition area beside the uppermost hiking corridors, perpendicular to downstream gully, shown in Figure5 and Table 9. Moreover vegetation was planted on the bare area.

Figure 5: *Mitigation with a concrete dam with length of and planting vegetation.*

Table.8: *Comprehensive membership degree of the secondary fuzzy assessment*

Risk degree	v_1 Slightly hazardous	v_2 Moderately hazardous	v_3 Very hazardous	v_4 Extremely hazardous
Membership degree	0.289	0.141	0.162	0.408

Table 9: *Size designed of concrete dam*

Length of dam base/ m	Length of dam top/ m	Height of dam / m	Width of dam top / m	Width of dam base /m	Depth of dam foundation / m
34.4	42.0	5.0	1.8	3.8	2.0

5. Conclusions

Chaancun debris flow gully is steep and straight. Weathered rocks and denuded rocks coming from tectonic fault zone provide debris source, furthermore more and concentrated rainfall. Chaancun debris flow gully has occurrence conditions of debris flow. Fuzzy mathematical method was undertaken for quantitative risk assessment, providing scientific evidence to determine whether or not applying protective mitigations. Seven factors including of volume of loose material, catchment area, slope gradient of longitudinal gully, maximum precipitation within 24 hour, bend coefficient of gully, vegetation coverage, soil and rock type were selected related to topography, loose material and rainfall. Based on the primary fuzzy assessment and the secondary fuzzy assessment considering hierarchical analysis, this gully was categorized as 'extremely hazardous'.

Risk degree of Chaancun debris flow was categorized as 'extremely hazardous', so corresponding defensive measures must be taken. A concrete dam was built at start part of transition area, moreover planting on the bare slope, in order to avoid debris flow hazards that may occur in the future.

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