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FORMATION CONDITIONS AND RISK EVALUATION OF GLACIAL DEBRIS FLOW DISASTERS ALONG INTERNATIONAL KARAKORUM HIGHWAY (KKH)

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ABSTRACT

The area of International Karakorum Highway (KKH), a mountain highway connecting northern Pakistan with northwestward China, is an area with dense and frequent glacial debris flow disasters due to the special glacial geology and landform. In this area the three basic conditions inducing glacial debris flow have developed,namely the widely distributed glacial till and ice-snow colluvium, which arise from collapse and landslide, provide the main solid sources of glacial debris flow; the very high and steep slopes, take the landform of steps with a very big gradient, to provide the moving way for glacial debris flow; and the ice-snow melt water from high-mountain, the melt water of glacier avalanche and glacial lake outburst flood provide glacial debris flow for the force to move. The valley-type debris flow is the main type of glacial debris flow occurred in the area, and it can be classified into further three sub-types according to the water source, namely glacierablation type debris flow, glacier-avalanche type debris flow and glacial-lake-outburst-flood type debris flow. Based on in situ investigation and analysis of seven controlling variables of glacial debris flow, such as occurrence frequency, catchment areas, volumes of alluvial fan, estimated outflow of every time,vegetation coverage, slope and altitude,to evaluate the risk degree of 8 chosen representative glacier debris flows along KKH. The comprehensive fuzzy evaluation method is applied to evaluate the risk degree of glacier debris flow and then the evaluation result shows a good correspond with the practical situation, i.e. this method has a valuable application foreground.

Key words: glacial debris flow, International Karakorum Highway (KKH), risk evaluation, the comprehensive fuzzy evaluation method

INTRODUCTION

The International Karakorum Highway (KKH) is the highest international road in the world, which locates in Pamirs plateau hinterland. It connects Kashgar in the north, a city in the Xinjiang province of China, through the Karakorum Mountain Range, Hindu Kush Mountains, Pamirs Plateau and west of Himalayas, south to Thakot, a city of northern Pakistan (Figg.1-3). KKH runs approximately 1036 km with a section of 616 km in Pakistan and 420 km in China. Due to its great achievements in engineering and the incredible difficulties in construction, it is also admired as the"the eighth man-made miracle of the world."

The unique geology and geomorphology make the KKH as the very complicated geo-hazard collection site. The geological background is determined by special high-mountain glaciers geological environment, so glacial debris flow is as a key geological disaster along KKH,especially the section from Raikot to Khunjerab pass. The glacial debris flow disasters dominated the International Karakorum Highway after it was built, so some roads, bridges and constructions along KKH often are destroyed or damaged. What is more serious, traffic conditions usually result in the tragedy of car destroyed and person died.

FORMATION CONDITION OF GLACIER DEBRISFLOW DISASTERS ALONG KKH

As an outcome of the co-action of geology,atmosphere and landform etc, three basic conditions control the formation of debris flow, namely high and steep mount landform, the sufficient loose solid material and sudden and heavy water source, which are all provided in the area of International Karakorum Highway.

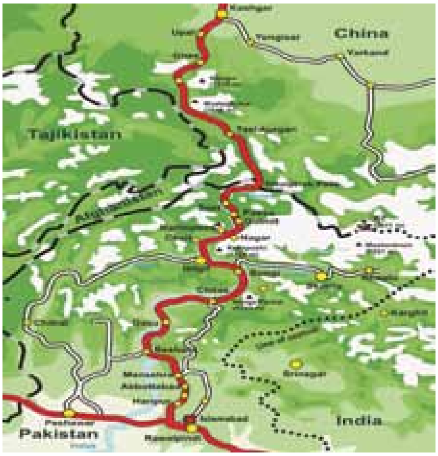

Fig. 1 .-Karakorum Highway route map

Fig. 2. - Karakorum Highway in China

Fig.3 - Karakorum Highway in Pakistan

International Karakorum Highway goes through four mountains which are so-called "bow wave" in the Indian geology---the Karakorum Mountain Range, Hindu Kush Mountains, Pamirs Plateau and Himalayas, which are at high altitudes and also larger relative height. With regard to the area of International Karakorum Highway, not only the altitude considerably change from 4733 meters (Khunjerab pass) to 460 meters (Thakot), but also the average altitude is over 3000m (Zhao, 2009).Therefore,the towering mountains and high and steep slope provide a movement condition for the glacial debris flow in the area. Geologic structure and crustal movement in the area are very available for the formation of sufficient loose solid material,beacuse International Karakorum Highway not only locates on the high intensity earthquake zone,which belongs to Mediterranean- Himalayan seismic zone, one of three seismic zones in the world, but also lies on the subduction zone,interacted by the Indian Ocean plate,the Eurasia plate and Arab plate.On the one hand,the weathering, the erosion, the denudation and downcutting along KKH ,including cold aspic weathering, Chemical weathering, rivers erosion, freeze-thaw erosion and block movement and so on, have formed loose texture,which becomes the origin material of accumulation of falling directly and in another way fail to support upper hard rocks and inducing them in the state of easy sliding.On the other hand, the developed and developing original joints in the hard rock cut its body into broken lump and the nearly horizontal the gently declining joint and weak plane are also very easy to bring about landslide and collapse, so the stratum and structure assembly of frequently alternate weak and hard layers in the area can afford the condition to the destruction of rock body. It can be seen that the above provided a very abundant solid material sources for the glacier debris flow along KKH. The special water source condition provide glacial debris flows for the force to move in the area.Glaciers,which are distributed

widely along Karakorum Highway, such as Batura glacier, Pasu glacier, Gulmit glacier, Ghulkin glaciers and Momhil glaciers etc, supply rich water source inducing glacial debris flows ,i.e., the icesnow melt water from high-mountain, the melt water of glacier ava-

Fig. 4 - Glacial-ablation type debris flow (K676+450, 10- 20-2010, taken photograph by Dr. Zhu Ying Yan)

Fig. 5 - Glacier-avalanche type debris flow (K653+900, 6- 27-2009 , taken photograph by Dr. Zhu Ying Yan)

Fig. 6 - Glacial-lake-outburst-flood type debris flow (K687+440,1- 6-2008 , taken photograph by Khan)

lanche and glacial lake outburst flood.So the above provide plenty of heavy and sudden water source condition for the formation of glacier flow.

THE DISTRIBUTION AND TYPES OF GLACIER DEBRIS FLOW DISASTERS ALONG KKH

The area along KKH distribute mostly the glacial debris flow disasters between Hasnabar (K623) and Gosghil (K796). According to the landform of movement, the debris flow along KKH, can be categorized into two types, i.e. valley-type glacial debris flow and mount-slope type glacial debris flow.

Valley-type glacial debris flow is the main type occurring, whereas,mount-slope type glacial debris flow happens comparatively rarely along KKH. Valley-type glacial debris flow can be classified into further three sub-types according to the water source of ice-snow melt water, namely glacier-ablation type debris flow (Figs.4) glacier-avalanche type debris flow (Fig.5) and glacial-lake-outburst-flood type debris flow (Fig. 6).

RISK DEGREE EVALUATION OF GLACIER DEBRIS FLOW DISASTERS ALONG KKH

Two aspects need to analyze,which are the risk historically happened and the potential risk,whenwe evaluate debris flow risk in a certain area (Liu & Tang, 1995). In the paper the study is made on evaluate the risk of potential glacial debris flow at the base of the current formation conditions of glacial debris flow. The follows describe the evaluation process of 8 chosen representative glacialdebris flow along KKH, which are represented by number 1 to 8.

THEORY AND MODEL OF RISK DEGREE EVALUATION

The debris-flow potential risk evaluation, which is focused on physical attributes of debris flow disaster, is used to evaluate the probability of debris flow occurrence in the region concerned in the future by comprehensively analyzing some disaster-inducing activity and formation variables of debris-flow disaster. The comprehensive fuzzy evaluation method provides a suitable disposal measures to some complicated problem due to the multifactor in the course of formation of debris flow (Luo & Chen, 2000; Han & Liu, 2007), so now it is often used in a potential risk evaluation,

which is generally expressed as following:

$$R_p = \sum_{i=1}^{n} w_i x_i \qquad (1)$$

where: $\boldsymbol{R_p}$ is the potential risk index to debris flow (0–1 or 0%– 100%); i_x is activity and formation variables of debris-flow disaster; i_w is weighting coefficient for the corresponding variable.

Classifying potential risk of debris flow disaster in terms of their threat is the first thing to proceed to the classification of risk. At present, a reasonable and recognized criterion for measuring risk degree of debris flow does not reliable. Anyone has separate rule to define degree between the value ranges of the potential risk .In most cases, the traditional equidistant value classification method makes potential risk values ranged from 0 to 1and suggested equidistantly classified into the following five degrees: very low (0-0.2), low (0.2-0.4), moderate(0.4-0.6), high (0.6-0.8), and very high (0.8-1), which is still widely used (Liu, 2002).

DETERMINATION OF VARIABLES AND OBJECTIVE TO STUDY

To choose the variables that bring about the potential risk of glacial debris flow directly or importantly into analysis and discard other unimportant or subordinated variables.By means of in situ investigation,7 main variables,such as occurrence frequency (average times/year, x_1), catchment areas (km x_2), volumes of alluvial fan (m^3, x_3), estimated outflow of every time (m^3, x_4), vegetation overage rate (%, x_5), slope (°, x_6), altitude (m, x_7),etc, are chosen, and the observed original data of 8 chosen representative glacier debris flows along KKH for analysis are shown in the table 1.Risk degree of glacier debris flows is calculated in index-weight model (each variable times its weight and then plus together),the formula(1) is as follows:

$$R_p = \sum_{i=1}^{7} w_i x_i = \omega_1 x_1 + \omega_2 x_2 + \omega_3 x_3 + \omega_4 x_4 + \omega_5 x_5 + \omega_6 x_6 + \omega_7 x_7$$

DETERMINE WEIGHTED COEFFICIENTS FOR THE CORRESPONDING EVALUATING VARIABLE

The weighted coefficients reflect the contributions of these variables to the potential risk. The basis for the determination of the weighted coefficients is the relative degrees of these variables (Liu & Yue, 2002).

In order to determine the significances of the auxiliary variables based on their parallel degrees to the leading variable(s) of debrisflow disaster along KKH, we adopt the theoretical principle for determining the relative degree is a comparison of the geometric curves of the sample sequences between the leading variable(s) and auxiliary variables in this paper (Liu & Yue, 2002).Give an example, there are four variables Y_a ,Y_b , Y_c and Y_d , then polt a map of the four corresponding curves, if the Y_a and Y_b are least parallel, there is the worst relationship between Y_a and Y_b, and their relative degree Rab is the smallest; while if the Y_a and Y_d are most parallel, the correlation of Y_a and Y_d is the best, and their relative degree Rad is the largest. According to the above analysis, the relative degree order $R_{aa}=1>R_{ad}>R_{ac}>R_{ab}>0$ can be determined, thus we may select those most contributive variables for the comprehensive fuzzy evaluation model under an assigned significance level.

In the study, as stated above we choose estimated outflow of every time (x_4) of the glacier debris flow considered to be the leading variable,thus the other 6 suggested variables (x_1 - x_3 , x_5 - x_7) are considered to be auxiliary variables. The detailed mathematical procedures to calculate the relative degree R have been described in a Liu's paper (Liu, 1992).In terms of calculating the relative degrees (R), the relative order of 7 chosen variables is shown in formula (3).

$$Rx_4 = 1 > Rx_3 > Rx_5 > Rx_1 > Rx_6 > Rx_7 > Rx_2 > 0 \quad (3)$$

We adopt an arithmetical and geometrical incorporation way to decide the weighted coefficients of the evaluating variables in the study (Liu, 1996),the weighted numbers and their weighted coefficients of these variables could be shown in the table 2.

Using the suggested weighted coefficients, equation (2) could be given as:

$$R_p = 0.12x_1 + 0.03x_2 + 0.18x_3 + 0.36x_4 + 0.15x_5 + 0.10x_6 + 0.06x_7 \quad (4)$$

DETERMINE TRANSFORMATION FUNCTIONS FOR THE EVALUATING VARIABLES

Because the dimensions of selected evaluating variables are different, it is not appropriate to directly use their observed original datas to calculate the risk degree of glacier debris flow, so to build transformed values of the evaluating variables is necessary in the process of evaluating the risk degree of the glacier debris flow along KKH. The method is that having determined the upper limit value and the mean value for each variable, the variable can be transformed by taking the upper limit value, the mean value, and the zero value as the

Number	Pipe number of Highway mileage	Observed original data of 8 chosen representative glacier debris flows *along KKH*						
		x_1	x_2	x_3	x_4	x_5	x_6	x_7
1	K653+900	1.2	5	12×10^4	6000	0	45°	2355
2	K673+300	1.2	6	15×10^4	2000	30%	8°	2442
3	K674+985	0.2	12	6×10^4	5000	25%	20°	2431
4	K676+450	2.5	5	45×10^4	10000	0	30°	2445
5	K676+660	0.4	7	10×10^4	5000	15%	25°	2456
6	K687+440	1.5	2	7×10^4	4000	6%	10°	2514
7	K763+750	1.6	10	8×10^4	6000	0	35°	3344
8	K765+200	2	8	40×10^4	9000	0	24°	3455

Tab. 1 - Observed original datas of evaluating variables of 8 chosen representative glacier debris flows along KKH

evaluating variables	x_1	x_2	x_3	x_4	x_5	x_6	x_7
Weighted coefficients	0.12	0.03	0.18	0.36	0.15	0.10	0.06

Tab. 2 - Weighedt coefficients of evaluating variables of 8 chosen representative glacier debris flow along KKH

control points, which are transformed to 1, 0.5, and 0, respectively; It is assumed that the transformed variables vary linearly between the control points, Therefore, each variable can be represented by linear or bilinear model (Liu, 1996). Based on the observed original data of glacier debris flow along KKH and relevant literatures (Liu, 1996; Liu, 2002), the upper limit value is estimated,and the mean value for each variable.Then the transformation functions for the evaluating variables might be as follows:

$$X_1 = \begin{bmatrix} x_1, x_1 < 1 \\ 1, x_1 \geq 1 \end{bmatrix} \quad (5)$$

X_1 is the transformed value of occurrence frequency of glacier debris flow along KKH.

$$X_2 = \begin{bmatrix} x_2/14, x_2 \leq 7 \\ \frac{x_2}{86} + \frac{18}{43}, 7 < x_2 < 50 \\ 1, x_2 \geq 50 \end{bmatrix} \quad (6)$$

X_2 is the transformed value of catchment areas of glacier debris flow along KKH.

$$X_3 = \begin{bmatrix} x_3/(4\times10^5), x_3 \leq 2\times10^5 \\ \frac{x_3}{16\times10^5} + \frac{3}{8}, 2\times10^5 < x_3 < 10\times10^5 \\ 1, x_3 \geq 10\times10^5 \end{bmatrix} \quad (7)$$

X_3 is the transformed value of volumes of alluvial fan of glacier debris flow along KKH

$$X_4 = \begin{bmatrix} x_4/12000, x_4 \leq 6000 \\ \frac{x_4}{8000} - \frac{1}{4}, 6000 < x_4 < 10000 \\ 1, x_4 \geq 10000 \end{bmatrix} \quad (8)$$

X_4 is the transformed value of estimated outflow of every time of glacier debris flow along KKH.

$$X_5 = \begin{bmatrix} -5x_5 + 1, x_5 \leq 10\% \\ -\frac{5x_5}{7} + \frac{4}{7}, 10\% < x_5 < 80\% \\ 0, x_5 \geq 80\% \end{bmatrix} \quad (9)$$

X_5 is the transformed value of vegetation coverage rate of glacier debris flow along KKH

$$X_6 = \begin{bmatrix} x_6/50, x_6 \leq 25° \\ \frac{x_6}{70} + \frac{1}{7}, 25° < x_6 < 60° \\ 1, x_6 \geq 60° \end{bmatrix} \quad (10)$$

X_6 is the transformed value of slope of glacier debris flow along KKH.

$$X_7 = \begin{bmatrix} x_7/1000 - 2, 2000 \le x_7 \le 2500 \\ \dfrac{x_7}{4000} - \dfrac{1}{8}, 2500 < x_7 < 4500 \\ 1, x_7 \ge 4500 \end{bmatrix} \quad (11)$$

X_7 is the transformed value of altitude of glacier debris flow along KKH

The transformed values of evaluating variables for 8 chosen representative glacier debris flow along KKH can be get by equations (5-11),which are given in the table 3.

EVALUATION OF RISK DEGREE

Based on equation (4) and table3, the risk degree of 8 chosen representative glacier debris flow along KKH are obtained as in the table 4.

From table 4, it can be seen that the risk degree of both no. 4 of K676+450 and no. 8 of K765+200 glacier debris flow along KKH is very high, belonging to extremely serious debris flow. The judgment got by means of comprehensive fuzzy method evaluation results shows that the calculation correspond excellently to the practical situation and then provide a effective analysis method for prevention of the risk of glacier debris flow at near situation.

CONCLUSION

- In the area of International Karakorum Highway three basic conditions control the formation of glacier debris flow are all serious, that is, high and steep mount landform, the sufficient loose solid material and rich water source. The development of glacier debris flow influence the safe property of International Karakorum Highway.
- The estimated outflow of every time of the glacier debris flow is the most controlling variable to determine the development and distribution regularity of glacier debris flow in the area of International Karakorum Highway.Valley-type glacial debris flow is the main type occurring and it can be classified in further three sub-types according to the water source of meltwate of ice-snow, namely glacier-ablation type debris flow, glacier-avalanche type debris flow and glacial-lake-outburstflood type debris flow.

Number	Pipe number of Highway mileage	*Transformed values of evaluating variables for 8 chosen representative glaciers debris flow along KKH*						
		X_1	X_2	X_3	X_4	X_5	X_6	X_7
1	K653+900	1.00	0.36	0.30	0.50	1.00	0.79	0.36
2	K673+300	1.00	0.43	0.38	0.17	0.38	0.16	0.44
3	K674+985	0.20	0.56	0.15	0.42	0.39	0.40	0.43
4	K676+450	1.00	0.36	0.66	1.00	1.00	0.57	0.45
5	K676+660	0.40	0.50	0.25	0.42	0.46	0.50	0.46
6	K687+440	1.00	0.14	0.18	0.33	0.70	0.20	0.50
7	K763+750	1.00	0.53	0.20	0.50	1.00	0.64	0.71
8	K765+200	1.00	0.52	0.63	0.88	1.00	0.48	0.74

EVALUATION OF RISK DEGREE

Tab. 3 - Transformed values of evaluating variables for 8 chosen representative glaciers debris flow along KKH

Number	Pipe number of highway mileage	evaluation results	risk degree
1	K653+900	0.62	High
2	K673+300	0.36	Low
3	K674+985	0.34	Low
4	K676+450	0.84	Very high
5	K676+660	0.41	Moderate
6	K687+440	0.43	Moderate
7	K763+750	0.61	High
8	K765+200	0.81	Very high

Tab. 4 - The evaluation results and the risk degree of 8 chosen representative glacier debris flow along KKH

The comprehensive fuzzy evaluation method are applied to evaluate the risk degree of glacier debris flow in the area of International Karakorum Highway and then the evaluation result shows a good correspond with the practical situation, i.e. this method has a valuable application foreground, based on in situ investigation and analysis of seven controlling variables of glacial debris flow along KKH.

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