Characteristics and risk assessment of debris flow in northeast tibetan plateau

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Abstract. Debris flow disasters frequently occur in northeast Tibetan plateau, especially, along section of the G-213 line from Ceke to Mohan highway in Longwu Gorge. This area is prone to debris flow disasters due to its special geological environment. In present study, we investigated the characteristics of 11 typical debris flow gullies and calculated the risk assessment by matter-element extension method. The matter-element model of debris flow hazard assessment was constructed and ten assessment factors were selected to evaluate the debris flow hazard. The results showed that the matter-element extension method was highly accurate for the risk assessment of debris flow gullies, which was in good agreement with the result of expert assessment. This method has obvious superiority, the risk assessment of debris flow gully was based on the grade, corresponding to the maximum of the comprehensive correlation degree.

1. Introduction
Due to the special topography and fragile ecological environment, Qinghai Province is one of the provinces with serious impact of debris flow disasters, especially in the eastern part of Qinghai Province. In this region, the rainfall is mainly short-term rainstorm along topography and the permeability of surface layer is poor. In recent years, due to extreme weather, heavy rainfall frequently occurred in Huangnan Tibetan Autonomous Prefecture of Qinghai Province, which resulted in frequent mudslides in Longwu Gorge section of the G-213 line from Ceke to Mohan Highway. Rainstorm results in many subgrade and watercourses being washed away that endangers traffic safety. Based on the survey of several debris flow ditches in this section, the topography, lithology, physical source, frequency and meteorological conditions of debris flow were analyzed. The results of present study can provide significant guidance to reduce the environmental risk for for highway construction and maintenance in Longwu Gorge area (Figure 1).

2. Study region
The study region is located in the southeast side of Jianza county, Huangnan Tibetan Autonomous Prefecture, southeast of Qinghai province, the lower section of the Longwu river, the north of the Xiqing mountain range, the Ameid Hulong mountain and the Amexia Qiongyan mountain, which is extend from south to north, belong to the middle and high mountain area (Figure 1). The surface elevation is 2020~3500 m, the relative height difference is 300~1500 m.. The Longwu gorge is about 26 km long, the G-213 line runs through the valley. Longwu valley has deep cut, the slope of both sides of the mountain is 35°-65°. The dendritic valley is relatively developed, the gully slope is very steep, its shape is narrow "V" type and the bottom of valley is also narrow. Vegetation on surface of
mountain is very poor, bedrocks are exposed due to strong weathering, therefore, debris flow highly
developed along the both sides of gorge (Figure 2).

There are eleven accountabilities in the canyon area that have a great influence on the G-213 line
Cek to Mohan Highway (Figure 2), all of those intersect with the line at a large angle with a width of
50~200 m. Under the influence of strong destructive changes, the gully in the canyon is dense, the
rock mass is broken, and the loose solid material is formed, which is also the main reasons for the
dense development of debris flow in this area.

The stratigraphic rock mass in Longwuhe gorge is mainly composed of Permian limestone,
gravelly limestone intercalated with calcareous sandstone, silty clayey slate, lower to upper triassic
sandstone, slate and cretaceous volcanic rocks, with a monolayer thickness of 2-15 m. Gully and base
of slope has thick quaternary alluvial deposits, which are composed of stone block, gravel and sandy
clay.

The climate in the study region is a typical semiarid continental climate with cold and dry seasons,
frequent full sunshine, precipitation and other characteristics. This region receives annual precipitation
about 350-496 mm, which is concentrated in May to September. Especially, precipitation in June to
August accounts for about 60% of annual precipitation.

3. Characteristics of debris flow in the study region

Table 1. Statistical tables of debris flow morphological elements in the study region.

| Position | Catchment area (km²) | Channel length (km) | Relative elevation (km) | Average channel gradient (%) | Type of debris flow |
|----------|----------------------|---------------------|------------------------|----------------------------|---------------------|
| K65+350  | 0.64                 | 1.635               | 526                    | 322                        | Slope type          |
| K65+600  | 4.65                 | 3.45                | 1091                   | 316                        | Trench valley type  |
| K66+000  | 3.25                 | 4.39                | 1183                   | 270                        | Trench valley type  |
| K66+107  | 0.65                 | 1.78                | 720                    | 405                        | Slope type          |
| K66+500  | 0.27                 | 0.91                | 350                    | 385                        | Slope type          |
| K68+550  | 0.4                  | 1.17                | 698                    | 596                        | Slope type          |
| K69+430  | 3.69                 | 3.4                 | 1171                   | 344                        | Trench valley type  |
| K70+245  | 0.73                 | 1.2                 | 887                    | 739                        | Slope type          |
| K71+100  | 0.91                 | 2.2                 | 905                    | 411                        | Slope type          |
| K72+810  | 4.1                  | 4.37                | 1326                   | 303                        | Trench valley type  |
| K73+200  | 0.41                 | 1.78                | 1038                   | 583                        | Slope type          |
Debris flow gully usually has noticeable forming area, circulation area and accumulation area, but debris flow developed in groups in Longwu Gorge, most debris flow gully forming area and flow through area are mixed together. The debris flow often outbreaks on the G-213 line Cake-Mohan highway. Among eleven debris flows investigated, seven were slope type, accounting for 63.6% of total debris flow. The Characteristics of debris flow in the study region are shown in Table 1.

4. Calculation of debris flow parameters

The flow rate of clear water in debris flow gully in the study region was calculated according to the latest results of the Revision and Application Research of Qinghai Highway Bridge and culvert Water Subarea (2012). This study region belongs to area II of the Yellow River. Therefore, the flow discharge was calculated by Eq. (1):

$$Q_{2\%}=3.5351F^{0.6064}$$  \hspace{1cm} (1)

where $Q_{2\%}$ is the flood peak discharge once in 50 years, $m^3/s$; $F$ is the watershed area of the debris flow gully, $km^2$. The calculated results of the flood peak discharge once in 50 years in the study region are shown in Table 2.

| Position | Catchment area ($km^2$) | Blockage Coefficient | T(s) | $\gamma_c$(m$^3$/s) | $Q_{2\%}$(m$^3$/s) | $Q_{0\%}$(m$^3$/s) | $Q(10^4m^3)$ |
|----------|------------------------|----------------------|------|---------------------|---------------------|---------------------|---------------|
| K65+350  | 0.64                   | 1.8                  | 960  | 1.658               | 2.697               | 8.074               | 0.16          |
| K65+600  | 4.65                   | 1.6                  | 1200 | 1.684               | 8.977               | 24.534              | 0.59          |
| K66+000  | 3.25                   | 1.7                  | 1200 | 1.658               | 7.224               | 20.428              | 0.50          |
| K66+107  | 0.65                   | 1.5                  | 900  | 1.651               | 2.722               | 6.745               | 0.12          |
| K66+500  | 0.27                   | 1.5                  | 720  | 1.643               | 1.598               | 3.928               | 0.06          |
| K68+550  | 0.4                    | 1.2                  | 780  | 1.660               | 2.028               | 4.056               | 0.06          |
| K69+430  | 3.69                   | 1.6                  | 1200 | 1.596               | 7.803               | 19.544              | 0.47          |
| K70+245  | 0.73                   | 1.3                  | 960  | 1.724               | 2.921               | 6.766               | 0.13          |
| K71+100  | 0.91                   | 1.2                  | 720  | 1.652               | 3.339               | 6.624               | 0.10          |
| K72+810  | 4.1                    | 1.3                  | 1200 | 1.658               | 8.318               | 17.985              | 0.44          |
| K73+200  | 0.41                   | 1.2                  | 780  | 1.658               | 2.059               | 4.109               | 0.06          |

Because of the same frequency and synchronous occurrence of debris flow and rainstorm the design flow of rainstorm flood in the calculated section is all transformed into the discharge of debris flow[1]. The discharge of the gully debris flow with P frequency was calculated by Eq. (2):

$$Q_c=(1+\phi_c)Q_p\cdot D_c$$  \hspace{1cm} (2)

where $D_c$ is the blockage coefficient in the debris flow gully and its value is based on the channel characteristic obtained from the field investigation[2]. In this study, the debris flow gully blockage coefficient was obtained by field investigation and the value are shown in Table 2. $\phi$ is the amplification coefficient of the debris flow peak discharge, which can be calculated from Eq. (3).

$$\phi = (\gamma_c - \gamma_s)/(\gamma_H - \gamma_c)$$  \hspace{1cm} (3)

where, $\gamma_H$ is the specific gravity of the soil, g/cm$^3$, and the value is 2.65 g/cm$^3$. $\gamma_s$ is the unit weight of water, $\gamma_s=1$ g/cm$^3$; $\gamma_c$ is the unit weight of the debris flow (g/cm$^3$) and the values are shown in Table 2.

The total runoff of a single debris flow was calculated by applying the empirical Eq. (4).

$$Q=K\cdot T\cdot Q_c$$  \hspace{1cm} (4)

Where, $Q$ is total runoff of a single debris flow (m$^3$); $Q_c$ is peak discharge of debris flow (m$^3$/s) ; $K$ is the correlation coefficient about basin area,$K=0.202$; $T$ is the duration of debris flow (s) and the values are shown in Table 3. The calculated results of total runoff of debris once in 50 years flow are shown in Table 2.
5. Risk analysis of debris flow

5.1. Methods

In this research, the matter-element extension model was used. The matter is named as N and its value of feature C is v. The basic elements of the matter, which were shortly titled as matter-element, are described with triple order ‘matter, feature, value’, while, R = (N, C, v) [3]. If a matter has n features C1, C2, ..., Cn and corresponding values v1, v2, ..., vn, R is called n dimensions matter-element, it is also denoted by R = (N,C,v):

\[
R(t) = \begin{bmatrix}
N_1, c_1, v_1 \\
c_2, v_2 \\
... \\
c_n, v_n
\end{bmatrix} = \begin{bmatrix}
N(t), c_1, <a_1(t), b_1(t) > \\
c_2, <a_2(t), b_2(t) > \\
... \\
c_n, <a_n(t), b_n(t) >
\end{bmatrix}
\]

(5)

Classical domain is

\[
R_i = \begin{bmatrix}
N_i, c_{i1}, x_{i1} \\
c_{i2}, x_{i2} \\
... \\
c_{in}, x_{in}
\end{bmatrix} = \begin{bmatrix}
N(t), c_i, <a_{i1}, b_{i1} > \\
c_i, <a_{i2}, b_{i2} > \\
... \\
c_i, <a_{in}, b_{in} >
\end{bmatrix}, \quad i = 1,2,? , m.
\]

(6)

where Ni is the i-th elevation level (i=1, 2, ..., m); ci is the ith evaluation indicator; xi is the ith-level value range of ci, that is the classical domain. The range of xi is interval [ai, bi] (i=1, 2, ..., n).

According to the classical domain, the section domain (Ri) is

\[
R_f = (N, C, X) = \begin{bmatrix}
N_1, c_{11}, x_{11} \\
c_{21}, x_{21} \\
... \\
c_{n1}, x_{n1}
\end{bmatrix} = \begin{bmatrix}
N_1, c_{11}, [a_{p1}, b_{p1}] \\
c_{21}, [a_{p2}, b_{p2}] \\
... \\
c_{n1}, [a_{pn}, b_{pn}]
\end{bmatrix}
\]

(7)

Where, N is the whole evaluation levels, and the xpi is the value range of ci. All that is the N section domain, which can be recorded as xpi = [api, bpi], i=1, 2, ..., n. api is the lower limit of a grade, bpi the upper limit of a grade.

The matter-element of evaluation object can be expressed as:

\[
R_a = (P, C, X) = \begin{bmatrix}
P, c_1, v_1 \\
c_2, v_2 \\
M M \\
c_n, v_n
\end{bmatrix}
\]

(8)

The equation is called evaluation matter-element of P, vi is the specific value of indicator ci of the evaluation object.

The correlation degree (Ki (vi)) between evaluation index and evaluation level is calculated based on the classical domain and section domain [3].

\[
K_i(x_j) = \frac{\rho(x_j, x_{i1})}{|x_{i1}|}, \quad x_j \in x_{i1},
\]

(9)

where \(\rho(x_j, x_{i1})=|x_j-0.5(a_{i1}+b_{i1})|-0.5(b_{i1}-a_{i1}); |x_{i1}|=|a_{i1}-b_{i1}|, (i =1, 2, ..., n; j =1, 2, ..., m), \rho(x_j, x_{i1})=|x_j-0.5(a_{i1}+b_{i1})|-0.5(b_{i1}-a_{i1}).\rho(x_j, x_{i1}), \rho(x_j, x_{i1}) are respectively, the distances between vi, classical domain xij and section domain xpi.

The correlation degree (Kj(P)) of evaluation object and its corresponding grade was calculated by following equation[4]:

\[
K_j(p) = \sum_{i=1}^{n}a_iK_i(x_j)
\]

(10)

Where \(a_i\) is the weight of the corresponding index ci. \(K_j (P)\) is the combined value of the correlation degree when considering the importance of indexes, and it expresses the correlation degree between evaluation object P and its corresponding grade j. If \(K_j (P) = \max K_j (P), j \in (1, 2, ..., m), P\) belongs to level j.
5.2. Case study

5.2.1. Selection of evaluation indexes and their weights. According to the characteristics of debris flow in northeast Tibetan plateau, the main 10 factors were selected as the evaluation indexes including, S1 (Q), S2 (Catchment area), S3 (Channel length), S4 (Average channel gradient), S5 (Loose solid matter), S6 (Maximum daily rainfall), S7 (Cutting density), S8 (Bending factor), S9 (Frequency) and S10 (Vegetation coverage). The value of evaluation indexes are shown in Table 3. We used AHP method to give their weights, the evaluation factors’ weights are shown in Table 4.

Table 3. The Value of evaluation indexes.

| Position   | S1  | S2  | S3  | S4  | S5  | S6  | S7  | S8  | S9  | S10 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| K65+350    | 0.16| 0.64| 1.635| 0.526| 3.69| 133 | 2.55| 1.09| 50  | 5   |
| K65+600    | 0.59| 4.65| 3.45| 1.091| 3.33| 75  | 1.63| 1.01| 40  | 35  |
| K66+000    | 0.50| 3.25| 4.39| 1.135| 18.75| 133 | 1.35| 1.07| 10  | 50  |
| K66+107    | 0.12| 0.65| 1.78| 0.720| 3.75| 133 | 2.55| 1.09| 50  | 5   |
| K66+500    | 0.06| 0.27| 0.91| 0.350| 1.56| 133 | 3.37| 1.03| 50  | 40  |
| K68+550    | 0.06| 0.41| 1.17| 0.698| 2.31| 133 | 2.95| 1.07| 100 | 50  |
| K69+430    | 0.47| 3.69| 3.4| 1.171| 21.29| 133 | 0.921| 1.06| 30  | 25  |
| K70+245    | 0.13| 0.73| 1.2| 0.887| 4.21| 133 | 1.644| 1.03| 100 | 3   |
| K71+100    | 0.10| 0.91| 2.2| 0.905| 5.25| 133 | 2.42| 1.257| 50  | 40  |
| K72+810    | 0.44| 4.1| 4.37| 1.326| 23.66| 133 | 1.38| 1.187| 30  | 50  |
| K73+200    | 0.06| 0.41| 1.78| 1.038| 2.37| 133 | 4.34| 1.00| 100 | 80  |

Table 4. The evaluation factors’ weights.

| evaluation indexes | S1  | S2  | S3  | S4  | S5  | S6  | S7  | S8  | S9  | S10 |
|--------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| weights            | 0.1989| 0.0814| 0.0363| 0.0525| 0.1945| 0.0964| 0.0814| 0.0458| 0.1945| 0.0183|

According to the classification standard of the 2018 (Debris flow disaster prevention and control engineering exploration code) and the research results of Xilin Liu et al., (1993), the debris flow hazard grade is divided into four grades[5], as shown in Table 5.

Table 5. Debris flow risk assessment index.

| Factors | Low risk | Moderate risk | High risk | Very high risk |
|---------|----------|---------------|-----------|----------------|
| S1      | 0~10     | 10~100        | 100~1000  | 1000~1200      |
| S2      | 0~0.5    | 0.5~10        | 10~35~    | 35~50          |
| S3      | 0~1      | 1~5           | 5~10      | 10~15          |
| S4      | 0~0.2    | 0.2~0.5       | 0.5~1     | 1~1.5          |
| S5      | 0~10     | 10~100        | 100~1000  | 1000~4000      |
| S6      | 0~25     | 25~50         | 50~100    | 100~120        |
| S7      | 0~1      | 1~5           | 5~10      | 10~15          |
| S8      | 0~1.1    | 1.1~1.25      | 1.25~1.4  | 1.4~1.6        |
| S9      | 0~10     | 10~50         | 50~100    | 100~120        |
| S10     | 100~60   | 60~40         | 40~20     | 20~0           |

5.2.2. Evaluation results. The evaluation results were obtained by input of specific data of evaluation object matter-element to equations (9) and (10). Taking the debris flow gully in K65+350 as an example, the calculation results are shown in Table 6. The integrated correlation degrees between all indicators and each grade were calculated by the weighted sum[6], the correlation degree between various indicators, each grade and the corresponding weight (Table 6) were input data for Equation
The results are as follow: $K_1(P_1) = -0.1978$, $K_2(P_1) = -0.5226$, $K_3(P_1) = -0.7972$, $K_4(P_1) = -0.6888$. Based on the criteria of evaluation, $K_1(P_1) = \max K_j(P_1)$, $j \in (1, 2, 3, 4)$.

Table 6. The correlation degree results in K65+350.

| Factors | Low risk | Moderate risk | High risk | Very high risk |
|---------|----------|---------------|-----------|----------------|
| S1      | 0.0160   | -0.9840       | -0.9984   | -0.9998        |
| S2      | -0.1795  | 0.0147        | -0.9360   | -0.9817        |
| S3      | -0.2797  | 0.1588        | -0.6730   | -0.8365        |
| S4      | -0.3826  | -0.0471       | 0.0520    | -0.4740        |
| S5      | 0.3690   | -0.6310       | -0.9631   | -0.9963        |
| S6      | -0.9789  | -0.9714       | -0.9000   | 0.1000         |
| S7      | -0.3780  | 0.3875        | -0.4900   | -0.7450        |
| S8      | 0.0091   | -0.0192       | -0.2388   | -0.3780        |
| S9      | -0.4444  | -0.6667       | -0.8333   | -0.5000        |
| S10     | -0.9167  | -0.8750       | -0.7500   | 0.2500         |
| Integrated relevance | -0.1978 | -0.5226 | -0.7972 | -0.6888 |

Calculated results of the hazard grade of 11 debris flow ditches in Longwu gorge section of the G-213 line from Ceke to Mohan highway are shown in Table 7. Results showed that the degree of risk of debris flow ditch in the study region was very high and the overall agreement degree of the expert evaluation result was 90.9%. The moderate risk debris flow ditches were all Trench valley type, which were 100% consistent with the result of expert evaluation. It shows that when the physical element extension method evaluated the dangerous degree of debris flow gully, the accuracy of debris flow gully was high, and the slope debris flow gully was slightly deviated.

Table 7. Integrated relevance degree and grade of debris flow gully risk index in study region.

| Position | Low risk | Moderate risk | High risk | Very high risk | Grade evaluation | Expert assessment |
|----------|----------|---------------|-----------|----------------|-----------------|------------------|
| K65+350  | -0.1978  | -0.5226       | -0.7972   | -0.6888        | Low             | Low              |
| K65+600  | -0.3722  | -0.1934       | -0.6659   | -2.0310        | Medium          | Medium           |
| K66+000  | -0.3563  | -0.2287       | -0.8233   | -2.0841        | Medium          | Medium           |
| K66+107  | -0.2260  | -0.3510       | -0.7984   | -2.0400        | Low             | Low              |
| K66+500  | -0.1763  | -0.4047       | -0.8719   | -2.0659        | Low             | Low              |
| K68+550  | -0.2670  | -0.5805       | -0.8366   | -2.0500        | Low             | Low              |
| K69+430  | -0.3400  | -0.1920       | -0.7426   | -2.0484        | Medium          | Medium           |
| K70+245  | -0.2741  | -0.5875       | -0.7959   | -2.0814        | Low             | Medium           |
| K71+100  | -0.2188  | -0.5383       | -0.7596   | -2.0353        | Low             | Low              |
| K72+810  | -0.3778  | -0.1484       | -0.7382   | -2.0411        | Medium          | Medium           |
| K73+200  | -0.2738  | -0.6374       | -0.7674   | -2.0631        | Low             | Low              |

6. Conclusions
It can be concluded that the frequent occurrence of debris flow in Longwu gorge section of Cek-Mahan highway on line G-213 is mainly due to the strong cutting under the Longwu valley, narrow valley bottom, steep bank slope, large height, broken rock mass, abundant loose material and the extreme weather. The main types of debris flow gully which frequently harms highway in Longwu gorge section are slope type, which accounts for 63.6%.

According to the theory of extension, the risk degree of debris flow gully was evaluated by establishing a material element model. The results showed that 7 debris flow ditches were low risk and 4 debris flow ditches were medium risk. The material element extension method showed a high accuracy for evaluating debris flow gully, which was 100% consistent with the result of expert evaluation.
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