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EFFECTS OF DEBRIS FLOWS ON CHANNEL MORPHOLOGY AT JIANGJIA RAVINE, YUNNAN PROVINCE, CHINA

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ABSTRACT

Debris flows, widespread in mountainous areas of China, transport large amounts of sediment in small intervals of time. To investigate the effects of debris flows on channel morphology, we chose 10 cross-sections to monitor periodic series of multiple debris flows triggered by summer rainstorms at Jiangjia ravine, Yunnan province, southwestern China. The 10 sections were distributed in the upper, middle, and lower sections of the trunk drainage to record erosion and deposition. Based on the observation data from 1999 to 2006, the effects of debris flows on channel morphology in the upper, middle and lower channel were analyzed respectively. It can be found that the channel morphology evolvement in upper, middle and lower channel were not uniform, as the erosion or deposition of a specific section depends on the local conditions of the section and scale of the debris flow. The analysis shows sediment discharge, maximum velocity of debris flow and channel gradient are three key factors in erosion/deposition volume calculation in channel. Based on the erosion/deposition characters of Jiangjia ravine, a simple computational model is presented to calculate the erosion or deposition of the debris flow channel.

Key words: *debris flow, sediment transportation, erosion and deposition, channel morphology*

INTRODUCTION

Debris flows, widespread in mountainous areas, are characterized by high capacity of sediment transport, catastrophic occurrence, high-concentrated sediment, wide range of grain size, high velocity and short period of movement (Wu *et alii*, 1990; Wu *et alii*, 1993; IMDE, 2000). When thousands million tons of debris are transported from upper to lower channel, strong erosion or deposition always occurs and dramatically changes the channel morphology and threats people's lives and property along the channel.

At present, some scholars have studied the influence of debris flows on channel morphology and gained some achievements. Several scholars considered that the erosion in upper channel is related to soil erosion in upper stream and they provided several computational methods to quantify channel erosion or deposition (Caine, 1976; Dietrich & Dunne, 1978; Benda, 1990). Others found that the erosion or deposition in debris flow channel had relation to the scale of debris flow (Cenderelli & Kite, 1998; Rickenmann *et alii*, 2003). With the development of 3S technology and mathematical theory, new analytical and numerical simulation methods are attracting increasing attention (Formann *et alii*, 2007; Danie & Kelly, 2008). However, many present studies are based on some specific single debris flow events or laboratory tests data, and the available research data are not continuous and systematic. Therefore, the conclusions gained from these studies may not match with the fact. To investigate the effects of debris flows on channel morphology, we set 33 cross-sections to monitor periodic series of multiple debris flows triggered by summer rainstorms in Jiangjia ravine. The drainage is the site of the renowned Dongchuan Debris Flow Observation and Research Station (DFORS). Analyzing the observation data, some scholars get the following conclusions: the debris flow channel morphology will dramatically evolve along with debris flow events; the channel morphology evolvement in upper, middle and lower channel are not entirely consistent even in the same debris flow event (FENG *et alii*, 2005; CUI *et alii*, 2006; CHEN & HE, 2006).

In this work, 10 cross sections, distributed in upper, middle and lower channel, were chosen to monitor debris flow in Jiangjia Ravine. Based on the data of field observations from 1999 to 2006 in Jiangjia Ravine, the channel morphology evolvement in upper, middle and lower channel was analyzed combined with debris flow events in the 8 years respectively. As the erosion or deposition of a specific section depends on the local conditions of the section and debris flow characteristics, we found the sediment discharge of debris flow, the maximum velocity of debris flow and channel gradient were the three key factors. Combined with the erosion or deposition characteristics of Jiangjia Ravine, a simple computational model is presented to calculate the eroded/deposited volume in debris flow channel.

THE STUDY AREA

Jiangjia Ravine is at Dongchuan section of Yunnan Province and at the right bank of the Xiaojiang River, which is a tributary of Jinsha River. The area of watershed is 48.6 square kilometers and the length of mainstream is 13.9 kilometers with three main lateral channels - Menqian Gully, Duozhao Gully and Dawazi Gully.

As the whole valley is located in the east side of Xiaojiang fault zone, the stratum is strongly draped and broken. Therefore, a large number of landslides and collapses distribute in the area, which can provide about $1.23 \times 10^{10} m^3$ of loose sediments. In addition, the terrain in Jiangjia Ravine is very steep. The longitudinal gradient reaches to more than 0.35 in upper channel while about 0.06~0.09 in lower channel. The gradients at both sides of the valley are also very steep and the average gradient is up to 43°. Based on the differences of morphologic characteristics, the main debris flow channel can be divided into three sections: the erosion section, the debris flow transport section and the deposition section (CUI *et alii*, 2005). The main rock types in Jiangjia watershed are grey black slate and sandstone, and they are susceptible to be weathered into clod and sheet. Weathered rock and Neozoic deposits formed the thick gravel soil layer in the watershed, often 30-80 m thick mantling on bedrock. What's more, as Jiangjia Ravine is at the west side of Wumeng Mountain and is influenced by the warm and humid airflow from Indian Ocean, the climate in this area can be divided into dry season and rainy season. The rainy season is from May to October and the precipitation is up to 500~1000 mm, which accounts for more than 85% of the annual precipitation in this area.

Jiangjia ravine becomes the ravine with the most frequent occurrence of debris flow in Xiaojiang alley for the abundant of loose sediment, steep stream slopes and plentiful precipitation.

CHARACTERS OF DEBRIS FLOW SEDIMENT TRANSPORTATION

Jiangjia Ravine is one of the most famous debris flow ravine in China. Dongchuan Debris Flow Observation and Research Station (DFORS) was set up in the mid-60s of last century, and some researchers began to observe and record debris flow events since then. Based on the continuous and systematic observation data of nearly 50 years at DFORS, Figure 1 shows the annual debris flow discharge in Jiangjia Ravine. By analyzing the observation data of debris flow discharge in the 50 years, we can conclude as follows:

1) Debris flow events occur at Jiangjia ravine every year, which transport a large number of sediment into Xiaojiang River. According to statistics, there were 465 debris flow events in Jiangjia

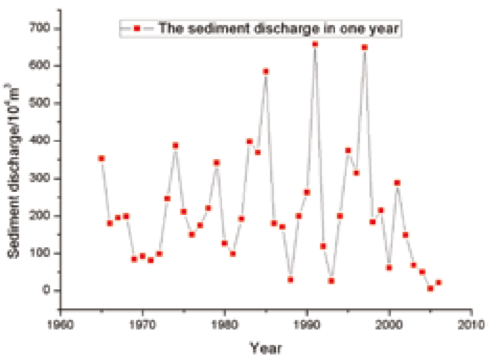
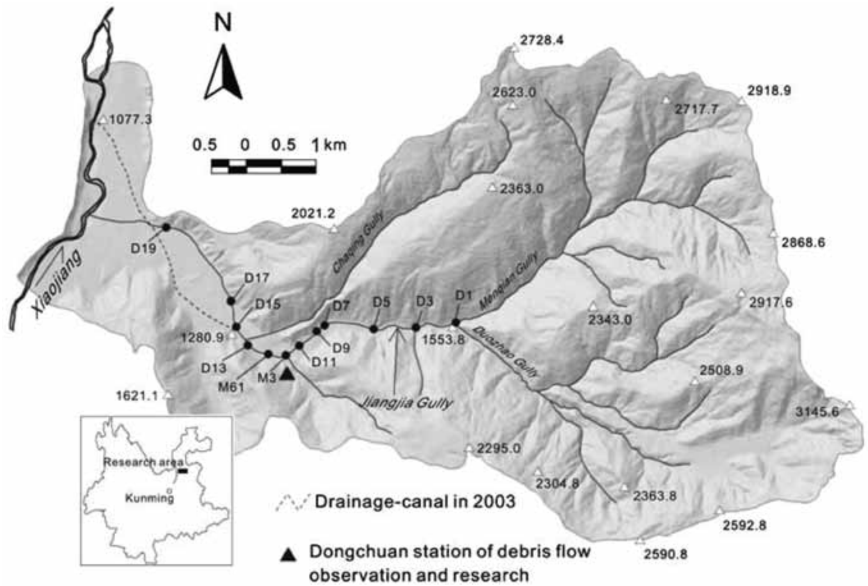


Fig. 1 - The annual sediment discharge in Jiangjia Ravine



(D11 was used from 2000 to 2006, D17 and D19 were used from 1999 to 2002, and others were used from 1999 to 2006)

Fig. 2 - The distribution of observation cross-sections in Jiangjia Ravine

Ravine from 1965 to 2006. The most frequent year is 1965 with 28 times while the less frequent year is 1993 with 2 times.

2) There are differences and periodicity about the interannual variation of sediment discharge. The amount of sediment transportation in Jiangjia Ravine is very huge and the average sediment transportation through DFORS is 6.91×10^6t each year. However, the annual discharge shows differences and periodicity with a period of 5 to 9 years.
3) Debris flow mainly occurs in rainy season, especially from June to September.

Debris flow can transport large quantities of sediments from upper channel to lower channel, which dramatically changes the channel morphology. Therefore, analyzing the sediment transport in Jiangjia Ravine will contribute to the study of channel morphology evolvement.

THE STUDY OF CHANNEL MORPHOLOGY EVOLVEMENT IN JIANGJIA RAVINE

METHODS

To study the effects of debris flows on channel morphology in detail, we have monitored the debris flow activities at 33 cross-sections in Jiangjia Ravine since 1999. In each cross section, a fixed point on the left channel is selected for the measuring instrument and another point on the right of the channel is marked for surveying reference.

In this work, the observation data of 10 cross sections are used to analyze the characters of channel morphology evolvement. Figure 2 shows the distribution of related observation cross sections in Jiangjia Ravine. As drainage canal was built in 2003 and channel was diverted subsequently, there were only 4 years observation data of D17 and D19 from 1999 to 2002. The data about D11 was from 2000 to 2006 and the field observation data of the rest 6 cross sections are from 1999 to 2006. M3 and M61 are arranged to monitor the erosion and deposition changes in curved channel in detail, which is not analyzed in this work.

As the interval between two debris flow events is too short sometimes, a survey could not be done right after each debris flow event. Therefore, only 40 surveys were carried out even there were 67 debris flows events in Jiangjia Ravine in the 8 years.

THE ANALYZING METHOD OF OBSERVATION DATA

The erosion or deposition always changes the elevation of lowest point and area of cross section. By pointing the observation data in Cartesian coordinate (The X axis represents width in cross direction while Y axis represents height), the erosion or deposition of a cross section can be reflected in this coordinate. The changes of the lowest point elevation and cross section area can reflect channel morphology evolvement to a certain extent.

In addition, we define channel erosion as negative changes and deposition as positive changes. In analyzing process, A_i is defined as the changes of cross-section i, D_i as the horizontal distance between adjacent sections and V_i as the quantity of erosion-sedimentation between adjacent section. V_i can be calculated as follow equations:

$$V_i = D_i(A_{i+1} + A_i + \sqrt{A_{i+1}A_i})/3 \qquad (1)$$

$$V_i = D_i(A_{i+1} + A_i - \sqrt{A_{i+1}A_i})/3 \qquad (2)$$

where A_{i+1} is the area changes of the cross sections i+1. If the sum of A_i and A_{i+1} is above zero, we use Eq.1 to calculate the eroded volume; otherwise Eq.2 is used. Accumulate the eroded or deposited volume of each corresponding channel, the eroded or deposited volume of Jiangjia Ravine can be calculated.

CHARACTERS OF EROSION AND DEPOSITION IN UPPER, MIDDLE AND LOWER CHANNEL

As the complexity of debris flow deposition and erosion, the channel morphology evolvement is notably different in upper, middle and lower channel even in the same debris flow event (Chen *et alii*, 2006). Therefore, the channel morphology evolvements in upper, middle and lower channel are analyzed along with debris flow events in the 8 years respectively.

In this work, 10 cross-sections are chosen to record the channel morphology evolvement. In these 10 cross-sections, D1, D3, D5, D7 are chosen as to reflect the channel morphology evolvement in upper reaches. Likewise, D9, D11, D13 and D15 are chosen to reflect the evolvement in middle reaches while D17 and D19 are chosen in lower reaches.

CHARACTERS OF EROSION AND DEPOSITION IN UPPER CHANNEL

D1, D3, D5 and D7 are chosen to reflect the upper channel morphology evolvement. Figure 3 shows the elevation changes of cross-section D5 from the early 1999 to the end of 2006. The elevation changes can reflect morphology evolvement of upper channel in these 8 years to a certain extent.

As we can see from figure 3, the channel elevation had been lift 18m since 1999. Moreover, the cross-section was obviously eroded in 2001 and quickly elevated by almost 10m in 2002. In the rest other years, the elevation of this section was mainly slow in general, but erosion in several local areas. In figure 1, it can be seen that the debris flow was relatively active in 2001 and sediment discharge was up to $2.88\times10^6m^3$, which was the largest scale in these 8 years. The sediment discharge was $1.49\times10^6m^3$ in 2002 and declined quickly since 2002. Therefore, it can be concluded as follows: 1) the channel morphology in upper channel changes along with the changes of debris flow sediment discharge; 2) there is a limit value of debris flow scale in channel morphology evolvement. The channel may be scoured when the sediment discharge reach or exceed this limit value, otherwise the channel may be lift by sediment deposition; 3) the limit value of sediment discharge in Jiangjia Ravine is between $1.49\times10^6m^3$ and $2.88\times10^6m^3$.

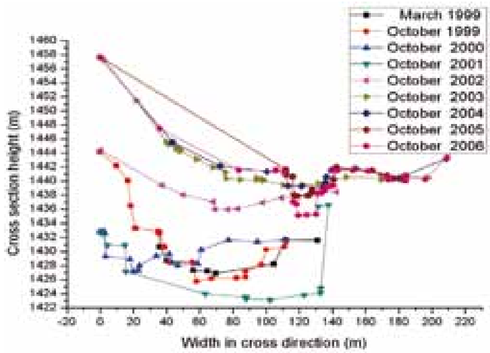


Fig. 3 - The erosion and deposition changes of D5 from 1999 to 2006

CHARACTERS OF EROSION AND DEPOSIIION IN MIDDLE CHANNEL

D9, D11, D13 and D15 are chosen to reflect the middle channel morphology evolvement. In this work, the cross section D11 is taken as an example to analyze the characters of middle channel morphology evolvement in the 7 years.

Comparing the elevation curve of 2006 with the curve of 2000 in figure 4, it can be found that the channel elevation was lift in the 7 years in general with the maximum lifting height of 15.3m. However, the erosion occurred in several local areas for some years. In figure 1, it can be seen that the scale of sediment discharge was up to $2.88\times10^6m^3$, but the elevation of middle channel was lift slightly in 2001 which was different from upper channel. Compared with the morphology evolvement of upper channel, the characters of erosion and deposition in middle channel are shown as follows: 1) the extent of erosion and deposition was larger in middle channel than that in upper channel

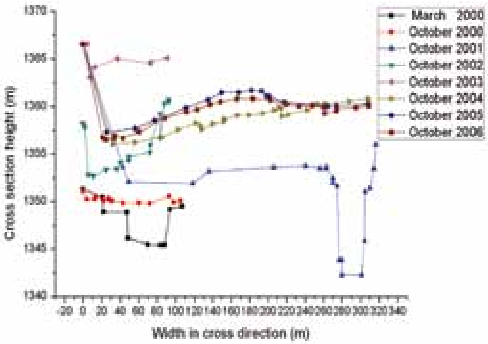


Fig. 4 - The erosion and deposition changes of D11 from 1999 to 2006

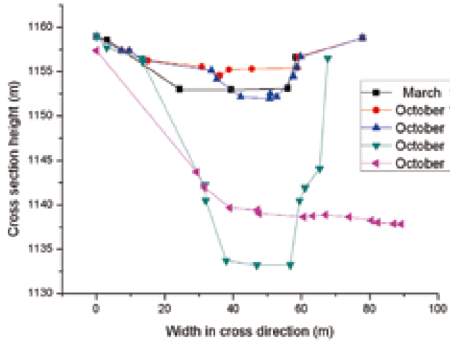


Fig. 5 - The erosion and deposition changes of D19 from 1999 to 2002

even in the same debris flow event. The cumulate deposited volume of D11 was about 31.2% larger than that of D5 and the cumulate amount of erosion of D11 was 27.4% larger than that of D5. 2) The middle channel was lift slightly in these 7 years in general, which was different from upper channel.

CHARACTERS OF EROSION AND DEPOSITION IN LOWER CHANNEL

In this work, D17 and D19 are chosen to reflect the lower channel morphology evolvement. As drainage canal was built in 2003 leading channel diversion subsequently. Therefore, the observation data of D17 and D19 was only 4 years from 1999 to 2002. Figure 5 shows the elevation changes of cross-section D19 from the early 1999 to the end of 2002.

As we can see from figure 5, the elevation cross-section D19 was lift in 1999 with an average lifting height of 3.6m. Meanwhile, the lower channel was diverted in 1999, which lead the gradient of lower channel up to 13%. As the debris flow activity was not active in 2000, the channel was eroded slightly in 2000. However, the debris flow was relatively active in 2001 and the channel was eroded about 16.7m. He Y.P. (2003) once introduced channel gradient balance to analyze the erosion and deposition changes of D19. The channel gradient balance means that the channel slope has a capacity of self-adjustment by the erosion and deposition of the partial or whole channel. Based on this analysis, we hold these following points: 1) the equilibrium condition will be broken as the change of gradient in lower channel and the channel will re-adjust the gradient by eroding or depositing to achieve new equilibrium condition; 2) the process of the self-adjustment will feed back from lower channel to upper channel until new equilibrium condition is realized.

THE COMPUTATION MODULE OF CHANNEL EROSION AND DEPOSITION

As the characters of erosion or deposition in upper, middle and lower channel are not uniform even in the same debris flow event, whether a specific channel will erode or deposit depends on debris flow characters and the channel characters. Therefore, a range of factors related to erosion and deposition should be considered, such as debris flow characters (density, viscosity, composition, flow depth, and speed) and channel characters (composition of banks, mobility of components, and shape). However, we just chose three key factors including the sediment discharge of debris flow, the maximum velocity of debris flow and channel gradient.

From field observations, deposition quantity in the channel increased with the sediment discharge in a certain range. If the debris flow discharge is high enough, the channel will be eroded. In other words, there is a limit value of debris flow scale between erosion and deposition in channel morphology evolvement. The channel may be soured when the sediment discharge reach or exceed this limit value, otherwise the sediment may deposit in channel. The maximum velocity of debris flow, which is the typical dynamic parameters, has a feeble positive correlation with quantity of erosion or deposition sediment in channel. There is a paving process in the channel during the early stage of debris flow. A residual layer remained afterwards which contributed to protection of the channel bed (Wang *et alii*, 2001). If the speed of debris flow increased to a level sufficient to break the protection of the residual layer, erosion happened. The effects of a debris flow on the upper channel and the lower channel may not be the same, therefore eroded/deposited volume may differ.

Some cross sections were eroded while the others were deposited. At the same time, erosion and deposition will adjust the overall channel gradient.

By analyzing the relationship among quantities of erosion or deposition sediment, scale of debris flow, debris flow velocity and channel gradient, the computation module can be expressed as equation 3:

$$\Delta V_j = F(D(V_T, v), C(J)) \begin{cases} < 0 & V_T < V^*_T \\ = 0 & V_T = V^*_T \\ > 0 & V_T > V^*_T \end{cases} \quad (3)$$

where ΔV_j is the quantity of erosion-sedimentation, D is the eigenfunction of debris flow, C is the eigenfunction of channel conditions, V_T is the quantity of sediment discharge, V_T* is the limit value of debris flow scale, v is the velocity of debris flow, J is the channel gradient.

CONCLUSIONS AND DISCUSSIONS

In this work, we have analyzed the characters of channel morphology evolvement in upper, middle and lower channel based on observation data from 1999 to 2006. The conclusions can be drawn as follows: 1) the eroded/deposited volume is closely related to the scale of debris flows. 2) The characters of erosion or deposition in upper, middle and lower channel are not uniform. The extent of erosion and deposition was larger in middle channel than that in upper channel. 3) The gradient may change with the variation of the base level of erosion, which will break the equilibrium condition. Erosion and deposition will adjust the channel gradient to achieve new equilibrium condition. What's more, the process of the adjustment always feed back from lower to upper channel.

By analyzing the relationship between quantity of erosion or deposition sediment, scale of debris flow, debris flow velocity and channel gradient, the computation module of channel erosion can be expressed as follow:

$\Delta V_j = F(D(V_T, v), C(J))$

In future work, the following aspects need to be considered in the study of channel morphology evolvement:

1) Based on the observation data and model experiments, quantifying the relationship among the sediment discharge, the maximum velocity of debris flow and the gradient of debris flow channel. Subsequently, the explicit mathematical expression of equation 3 can be educed to calculate the quantity of erosion or deposition.
2) As we can see from the characters of erosion and deposition in upper, middle and lower channel, the upper channel is eroded while the lower channel is lift in general. In other words, there must be a channel segment or cross-section which keeps deposition-erosion equilibrium. The local conditions of channel and the related debris flows characters are the boundary conditions and solutions of equation 3, which can be used to verify the explicit mathematical expression of equation 3.
3) There are many other factors affecting channel morphology evolvement, such as debris flow characters (density, viscosity, composition, flow depth) and channel characters (composition of banks, mobility of components, and shape). These factors should be appropriately considered in the study of channel morphology evolvement.
4) The channel morphology evolvement registers as self-adjustment of channel gradient under the influence of debris flow. In the view of dynamics, the self-adjustment of channel gradient is sediment transportation from upper channel to lower channel based on principle of minimum potential energy. Therefore, the kinematics and kinetic theory should be used to analyze it.

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