Quantification of the Geomorphic and Hydrologic Roles of the Tunnel Systems in a Semi-arid Watershed of the Loess Plateau in China

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Abstract: Quantifying geomorphic and hydrologic roles of piping or tunnel systems remains a priority in piping study. In the present study, the sediment concentrations and waterflow discharges of tunnel flows in a semi-arid watershed of the Loess Plateau were monitored through the period of 1989 and 1990. The tunnel development was surveyed in the field over a 12-year period (1989—2001). The purpose of tunnel flow monitoring was to characterize the patterns of sediment concentrations and flow discharges of tunnel flows while the survey of tunnel development was to identify the geomorphic processes and their spatial variability which are, in turn, responsible for the patterns observed.

A total of fifteen storms were monitored from four major tunnel systems in the watershed. It was found that both waterflow discharges and sediment concentrations were highly erratic in some tunnel flow events. The survey of tunnel systems over the 12-year period indicated that the instability of tunnel systems was largely responsible for the erratic relations between tunnel flow discharges and rainfall parameters, and between the waterflow discharges and sediment concentrations. Most of the new tunnel inlets initiated in very few catastrophic storm events and the rest of the storms play an important role in tunnel enlargement through mass wasting and water erosion.

Overall, the total tunnel flow contribution to basin outflow was 43% and 57% of basin sediment production was delivered by the tunnel systems.

Keywords: piping, tunnel erosion, gullying, soil erosion, loess Plateau, china

1 Introduction

The surficial erosional processes have received much more attention than the subsurface erosional processes such as piping or tunnel erosion, despite the number of studies on piping has been increased recently (i.e. Jones, 1981,1987; Gilman and Newson, 1980;Bryan and Harvey, 1985; Uchida *et al*., 1999). Quantifying the geomorphic and hydrologic roles of piping or tunnel systems remains a high priority in piping study, especially in semi-arid areas (Bryan and Jones, 1997).

The Loess Plateau of China, where the present study is located, is one of the most severely eroded regions in the world. Some of the earliest studies on piping or tunnel erosion were, in fact, carried out in this region (Richthofen, 1877; Fuller, 1922; Thorp, 1936). The formation and development and, the factors controlling tunnel erosion in this region were also investigated by Zhu (1958), Chen (1958), and Wang (1989). Nevertheless, no attempts have been made to monitor the tunnel flow processes. Since 1989, we carried out a field study program here aimed at investigating the geomorphic and hydrological processes of tunnel flows and, the development of tunnel systems in a small catchment.

2 Study site and methods

The study site, Yangdaogou catchment, is located about 4 km north of Lish town of Shanxi Province. It is a first-order sub-basin and has a drainage area of 0.203 km^2. The climate is semi-arid warm temperate with annual precipitation of 500 mm or so, among which over 70% falls in the summer from May to September. Local deposits mainly comprise Quaternary loesses and Tertiary clayey red earth.

The tunnel systems in the catchment were first investigated in 1989. Three parts of a tunnel system were surveyed in the field: inlet, conduit and outlet. Most of the tunnel inlets show the circular and well-like nature, so we chose to measure their diameter and depth to represent their general morphometry. With respect to the inlets of irregular plan forms, several measurements were taken and averaged. Tunnel conduits refer to the sloping sections connecting inlets and outlet. Cross sections at both ends of a conduit were often measured. Details of the long profiles of the tunnel conduits are very difficult to obtain. However, we did manage to enter some conduits and measure the longitudinal and cross-sectional features. Smoke bombs were used in the field to identify the tunnel connectivity. The cross sections of tunnel outlets were sketched in the field with scales ranging from 1:20 to 1:50. The locations of tunnel inlets, conduits and outlets were indicated in a 1:1 000 contour map. In addition, soil samples were taken from various locations of the tunnel systems for physical and chemical analyses.

Six tunnel systems were selected to monitor tunnel flows from late July of 1989 and throughout the rainy season of 1990 throughout using weirs or flow dividers. At the exit of the experimental catchment, a concrete flume was constructed to check the outflow. In addition, for the purpose of comparison between overland flow and tunnel flow. Several surface plots were set up. During each runoff-generation storm of the monitoring period, stage readings were taken every minute throughout the runoff event and sediment samples were taken every three minutes during the first half hour and every six minutes during the second half hour and every twelve minutes thereafter. The annual precipitation was 340 mm in 1989 and 623 mm in 1990, which represents dry and wet years with return periods of 5 years to 10 years, respectively.

To detect the development of tunnel systems, we revisited the catchment in 1999 and 2001. The newly initiated tunnel inlets and outlets in the catchment since 1989 were measured. The changes of old outlet were surveyed.

To estimate the net tunnel erosion, existing plot data, collected by the Shanxi Institute of Soil and Water Conservation (SISWC, 1982), were combined with the tunnel flow data to establish regressional models.

3 The mophometry of tunnel systems

There were 77.30, and 67 tunnel inlets initiated in the pre-1989, 1989—1999, and 1999—2001, respectively. The diameters and depths of tunnels are given in Figure 1. Overall, these dimensions represent some of the largest inlets in non-karst regions in the world. Majority of the tunnel inlets developed in few catastrophic storm events. For example, almost all the 67 newly increased inlets over the period of 1999 to 2001 initiated in one single storm occurred in July of 2000, with event precipitation of 110 mm. Over the 12-year period, only three inlets were destroyed due to roof collapses and 8 inlets on the terraces and one on the road were filled by the farmers. Enlargement of tunnel inlets was mainly caused by the earth falls, which could occur either during the storm periods or inter-storm periods.

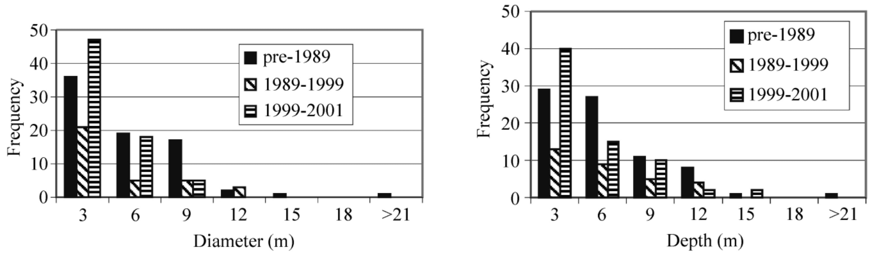

Fig. 1 Frequency distribution of tunnel inlet size

The minimum length of tunnel paths was 674 m in 1989, and increased by 97 m and 173 m in the 1989—1999 and 1999—2001 periods, respectively. Accordingly, the minimum tunnel drainage density is 4.58 km/km^2 in 2001, in comparison with the surface stream network density of 4.51 km/km^2 in the catchment.

The numbers of tunnel outlets are 7.9 and 14 in the periods of pre-1989, 1989—1999, and 1999—2001, respectively. The changes of cross sectional areas of outlet over the 12-year period are widely varied. Most of the outlets developed on the contact between the loess and red earth.

The soil samples taken from upslope of the tunnel inlets, tunnel roofs, walls, floors, as well as downslope of the tunnel outlet have no significant difference in the concentration of dissolved salts. Hence, the tunnel erosion is dominated by mechanical erosion of tunnel flows and mass wasting.

4 Hydrological and sediment processes of tunnel flow

Over the monitoring seasons of 1989 and 1990, tunnel flows occurred in 12 of 15 monitored storms. Overall, no distinctive difference exists between tunnel flow start times and overland flow start times. Tunnel flow responses to rainfall were very fast, with the start times ranging from 1 min to 67 min after the onset of rainfalls. Virtually, all tunnel flow was derived from overland flow generated from the tunnel catchments and no soil throughflow or ground water was involved. Nevertheless, tunnel flow processes do not simply mirror overland flow processes. They can be significantly disturbed by frequent blockages of tunnels, which can be reopened in the subsequent events, and by the abrupt opening of new inlets. In addition, tunnel flows are significantly reduced by the collapse of dry debris and materials surrounding the tunnel conduits at the beginning of rainy season.

Regressional analyses show that a good correlation exists between runoff discharge and rainfall with an intensity of more than 12 mm/h for the surface plots. But for tunnel systems, such a good correlation could only be found for one of the tunnel system (Table 1).

Table 1 R^2 values in linear regression analyses between runoff discharge and effective rainfall (I > 0.20 mm/min)

Overland Flow		Tunnel Flow		
Plot No.	R^2 (including all events)	Tunnel No.	R^2 (including all events)	R^2 (discarding events affected by instability)
S-1 (Zone 1)	0.642 (30)	T1	0.075 (12)	0.622 (10)
S-2 (Zones 1 and 2)	0.535 (34)	T3	0.691 (12)	0.713 (11)
S-3 (Zones 1, 2 and 3)	0.617 (40)	T4	0.257 (11)	0.542 (9)
		T6	0.125 (13)	0.301 (11)

Note: Values in parentheses represent the number of events.

Observed sediment concentration of tunnel flows ranges from 8.2 g/l to 893.2 g/l. The peak sediment concentrations in tunnel flows are not distinctively higher than those in channel flows but considerably higher than those measured from untunnelling sideslope plots. No significant correlation exists between water discharges and sediment concentrations in most of the tunnel flow events (Table 2).

Table 2 Correlation coefficients between flow discharges and sediment concentrations

Date	T1	T3	T4	T6	Sub-basin
6/8/1989	+0.247	+0.355			+0.576*
15/8/1989	+0.428	+0.446			+0.769*
7/7/1990	+0.593				+0.509
11/7/1990	+0.151	+0.652**	+0.405	–0.164	+0.542*
13/7/1990	+0.265	+0.671**	+0.636*	–0.218	+0.596*
22/7/1990	–0.219		–0.319	+0.441	+0.695**
26/7/1990	+0.491*	+0.385	+0.232	–0.242	+0.254
30/7/1990		+0.018	–0.334	+0.316	+0.796**
11/8/1990	+0.594	+0.822**	+0.442	+0.454	+0.407
13/8/1990		+0.828**	–0.268	–0.215	
28/8/1990		+0.591*	–0.014	–0.512	+0.216

Numbers with ** are significant at $\alpha < 0.05$ level, those with * between $0.05<\alpha<0.1$ level. Plus sign (+) refers to positive correlation and minus sign (–) to negative correlation.

The erratic correlation between tunnel flow discharges and rainfall and, between sediment yield and runoff suggests that the significant impact of tunnel instability on tunnel flow processes.

5 Hydrological and geomorphic significance of tunnel flows

Due to the equipment failures, tunnel flow discharge data were collected only from four of the six monitored tunnel systems, but they account for about 90% of the catchment area of all tunnel systems in the basin during the monitoring period. The overall contributions of tunnel flow to basin outflow are 43% in runoff and 57% in sediments (Table 3).

Table 3 Contributions of water discharge and sediments from tunnel systems to the experimental catchment

Date	Rainfall (mm)	Tunnel flow discharge (m^3)	Tunnel flow sediment yield (kg)	Catchment Outflow (m^3)	Catchment sediment yield (kg)	Tunnel flow discharge Contributions (%)	Sediment contribution from tunnels (%)	Net tunnel erosion contributions (%)
8/6/89	24.8	142.2	1 141 126	280.7	242 961	50.7	47	16.4
8/10/89	13.1	0	0	36.6	383	0	0	00
8/15/89	28.7	194.7	93 685	330.7	116 902	58.9	80.1	49.7
8/16/89	29.1	0	0	57.3	2 825	0	0	0
7/6/90	21	0	0	120.5	537	0	0	0
7/7/90	9.5	6.1	7 400	85.6	54 454	7.2	13.6	–4.5
7/11/90	39.7	190.0	236 577	940.6	424 620	20.2	55.7	22.1
7/13/90	28.5	141.1	88 482	283.5	133 119	49.8	66.5	45.9
7/22/90	18.2	64.3	30 106	164.5	61 328	39.1	49.1	36.2
7/26A/90	33.3	147.5	81 571	360.4	130 260	40.9	62.6	17.7
7/26B/90	19.8	N/A	N/A	332.8	N/A	N/A	N/A	N/A
7/30/90	15.8	80.6	53 202	104.5	69 146	77.1	76.9	59.1
8/11/90	20.2	20.0	13 742	79.8	22 035	25.0	62.4	35.1
8/13/90	35.4	353.8	135 689	/	N/A	/	N/A	N/A
8/28/90	53	189.9	87 504	389.2	155 749	48.8	56.2	10.8
Total	390.1	1 530.2	1 414 319	3 566.7	1 414 319	42.9	57	25.5

In a tunnel system, net tunnel erosion (S_{net}) is the difference between the sediment output measured at the tunnel outlet (S_{out}) and the sediment inputs to the tunnel system from tunnel contributing areas via tunnel inlets (S_{in}). It can be simply expressed as

$$S_{net} = S_{out} - S_{in} \tag{1}$$

In equation (1), as S_{out} was measured in the field and S_{in} was the only unknown independent variable. Because the contributing areas of tunnel inlets are widely varied in topographic features such as slope, slope length and drainage area, S_{in} may be very different between tunnel inlets. However, it is not practical to set up surface plots to monitor tunnel inflows at all tunnel inlets. Here, we use a regression equation to estimate sediment inputs to tunnel systems via tunnel inlets. Data for development of the regression equation was collected by Shanxi Institute of Soil and Water Conservation (SISWC) in Yangdaogou and its neighboring catchments during the earlier period (1956—1970) (SISWC, 1982). The data set include 9 surface plots which cover a wide range of drainage area (200 m^2—4167 m^2), slope (4° — 36°), and slope length (40 m—185 m). A total of 290 plot flow-event were used to established the following regression equation :

$$Ss = 95.7 * Rs^{1.04} L^{0.373} J^{1.02} \qquad (R^2 = 0.94,\ n=290) \tag{2}$$

Where Ss is sediment yield [kg/km^2]; Rs is runoff depth [mm], L is slope length [m], and J is slope [tangent].

Here, we use the equation (2) to estimate sediment inputs to tunnel systems from tunnel flow contributing area. It is assumed that all tunnel outflow was derived from tunnel contributing areas via tunnel inlets and runoff reduction inside tunnel systems was negligible. Accordingly, Rs in equation (2) can be estimated from water discharges measured at tunnel outlet. L and J are derived from the topographic map. Ss is therefore equal to $S_{in.}$

Overall, about 25% of the sediments might be contributed by net tunnel erosion.

6 Conclusions

Tunnel inlets in this catchment were mainly developed in catastrophic storm events, and enlarged by earthfalls and slumps thereafter, which, in turn, provides materials for tunnel flows to transport in subsequent storm events. Though tunnel flows are solely derived from tunnel catchments via inlet, they do not simply mirror overland flow. Instead, an erratic correlation exists between tunnel flow discharges and rainfall and, tunnel flow discharges and sediment yields, which are caused by tunnel instability. Tunnel flows contribute catchment outflow about 43% in runoff and 57% in sediments. Net tunnel erosion accounts for at least 25% of the sediment production in this catchment.

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