Sediment Dynamics for a Changing Future (Proceedings of the ICCE symposium held at Warsaw University of Life Sciences - SGGW, Poland, 14–18 June 2010). IAHS Publ. 337, 2010.

Grain erosion – an intense form of rock erosion

ZHAOYIN WANG, DANDAN LIU & WENJING SHI
State Key Laboratory of Hydroscience and Engineering, Tsinghua University, 100084, Beijing, China
zywang@tsinghua.edu.cn

Abstract Grain erosion is defined as the phenomenon of physically breaking down bare rocks. Bare rocks are caused by avalanches, landslides and human activities. Grain erosion causes flying stones that can injure humans, and results in numerous slope debris flows. The process of grain erosion is studied by field investigations and experiments. The rocks are broken down to grains under the action of insolation and temperature change. Then, wind detaches the grains from the bare rock, the grains flow downslope under the action of gravity, and the grains accumulate at the toe of the hillslope forming a depositional fan. The most serious grain erosion occurs in spring and early summer when it is very hot and dry. Experimental results showed that the number of grains blown by wind, per area of rock surface per unit time, is proportional to the fourth power of the wind speed; however, the size of the grains increases linearly with the wind speed.

Keywords erosion; Wenchuan earthquake, China; bare rocks; debris flow; wind

INTRODUCTION

Erosion can be defined as the detachment and removal of solid particles from their original place. Erosion is distinguished from weathering, which is defined as the chemical or physical breakdown of the minerals in the rocks, although the two processes may occur concurrently (Halsey *et al.*, 1998; Wikipedia, 2009). Various types of erosion are classified according to the main agents causing it, including water erosion, wind erosion, gravity erosion and ice erosion (Goldman *et al.*, 1986; Korup & Schlunegger, 2009). Gravity plays an important role in all forms of erosion. Landslides, avalanches, slumping, and surface creep are all forms of gravity erosion that move material from higher to lower elevations (Wang *et al.*, 2007a,b,c).

Grain erosion of bare rocks is much more intensive than shattering erosion (Harris & Prick, 2000; Saas & Krautblatter, 2007). Rock falls, bank failures, avalanches, and landslides cause bare rocks in mountainous areas, especially in mountainous areas experiencing riverbed incision (Matsuoka, 1990, 2008). Human activities, such as highway construction and mining, also cause bare rocks (Sass, 2005). Mass movements triggered by the Wenchuan earthquake, which occurred on 12 May 2008 in the Sichuan Province of China, have left a huge area of bare rocks (Chen & Hayes, 2008). Erosion has been occurring in the form of grain detachment and movement. The erosion is intense. A surface layer of 3–50 cm of bare rocks has been eroded already, only one year after the earthquake. The bare rocks have been broken into quite uniform grains, which deposit at the base of hillsides and form grain fans.

Grain erosion caused many problems in the earthquake area: destroying and burying vegetation, causing slope debris flows, and generating flying stones which caused damage to cars and injured humans (Huang, 2008; Wang *et al*., 2009). The highways in the earthquake area often are closed because of flying stones. Grain erosion also occurred before the Wenchuan earthquake, in dry valleys with poor vegetation. Dry valleys have two unique features which may be used as diagnostic characteristics: (a) deeply incised valleys on a plateau; and (b) significantly higher temperatures and evaporation, and lower precipitation rates than the surrounding areas on the plateau (Shen *et al*., 2001; Moseley & Tang, 2006). The Jinsha River valley (upper Yangtze River), the upper Minjiang River valley, and the Xiaojiang River valley are dry valleys. The Xiaojiang River is a small tributary of the Jinsha River in Yunnan Province, which is about 560 km to the southwest of the epicentre of the Wenchuan earthquake. Rockfalls, avalanches, slope slumps, small-scale landslides, and human activities result in bare rocks on the slopes in the dry valleys.

Eight investigations dealing with grain erosion were conducted in the earthquake area, with emphasis on the Minjiang and Mianyuan rivers, from May 2008 to August 2009 (Carter & Viles, 2003, 2005). Three field investigations were conducted during the same period in the Xiaojiang Valley for comparison with the intense grain erosion in the earthquake area. Two experiments were conducted in the Mianyuan and Xiaojiang rivers to study the rate of grain erosion. This paper reports the results of those studies.

PHENOMENON OF GRAIN EROSION

Figure 1 shows the monitored grain erosion sites on the Minjiang and Mianyuan rivers in the earthquake area in Sichuan, and the grain erosion sites in the Xiaojiang River basin in Yunnan. Grain erosion on the Minjiang and Mianyuan rivers started after the Wenchuan earthquake in May 2008, whereas grain erosion in the Xiaojiang River basin has been occurring for decades.

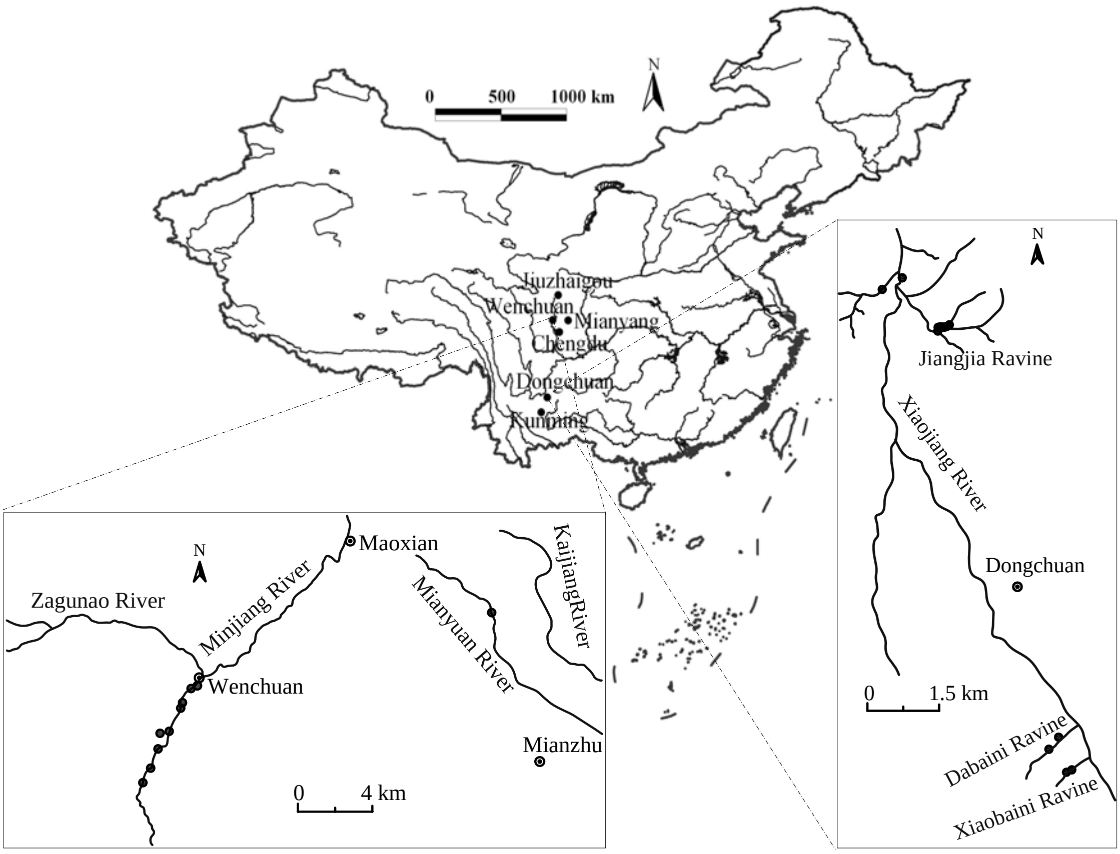

Fig. 1 Location of research area and grain erosion sites.

In general, a grain erosion site consists of three sections: a top where surface grain erosion occurs; a middle where grain flow occurs; and a bottom where depositional fans form at the toe of the slope (Fig. 2). The rock surface where grain erosion occurs has a slope angle in the range of 45°–60°. Typically, there is no vegetation on the erosion surface. The detached particles roll or flow through a section, which has a slope angle of about 40°. The deposit fan has an angle of about 35°, which is equal to the angle of repose for the granular material.

Figure 3(a) shows a grain erosion site on the Xiaojiang River. The grain erosion rock surface is larger than the surface of the deposit fan, although it looks small from the picture. The grain flow section is about 40 m long. Figure 3(b) shows several grain erosion sites on the Minjiang River near Wenchuan. Avalanches induced by the Wenchuan earthquake have left many bare rocks. Intensive grain erosion has been occurring, especially in the dry season from March to June, 2009. The grains are much finer than the avalanche deposit. A part of the grain erosion deposit has been carried away by river flow.

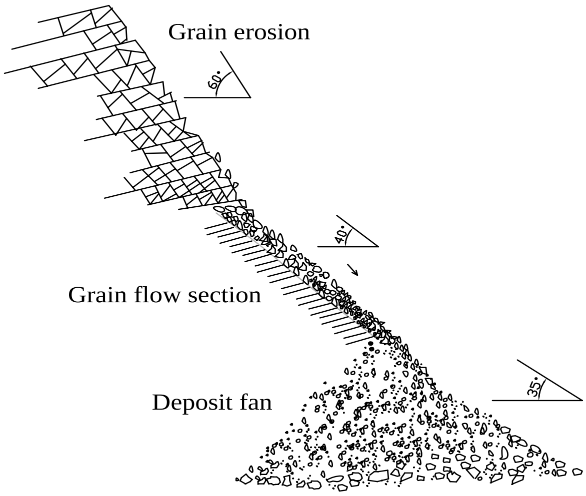

Fig. 2 Schematic diagram of a grain erosion site.

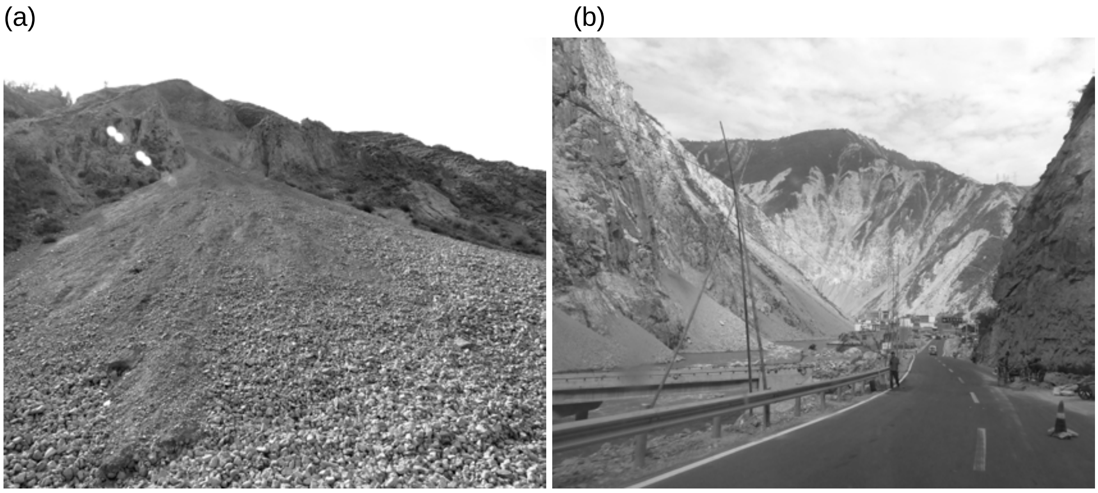

Fig. 3(a) A grain erosion site on the Xiaojiang River. (b) Several grain erosion sites.

Most of the highways in west Sichuan are constructed along rivers. People have repaired or reconstructed the highways that were damaged or destroyed by the earthquake. All highways were re-opened less than one year after the Wenchuan earthquake. However, a potential danger for cars and humans continues as a result of the grain erosion of particles, with diameters ranging from 1 to 20 cm, that roll and saltate downslope. Grain erosion provides plenty of solid materials for mass movements. The deposit fans consist of uniform and loose solid materials, and have high slope angles. Rainfall, with an intensity of more than 20 mm/day can trigger mass movements of the grains. These mass movements behave like debris flows, but the distance travelled is much shorter than for normal debris flows; in general, they travel only several tens to hundreds of metres. Water in the particle interstices acts as a lubricant, and facilitates the downslope movement of the grains to streams or highways. Such a mass movement is called a slope debris flow. Slope debris flows carry a lot of grains into rivers, or deposit the grains on highways, causing highway blockages or local riverbed sedimentation.

MECHANISM OF GRAIN EROSION

Grain erosion occurs as a result of expansion and contraction due to temperature changes and the subsequent breakdown of rocks under the action of sunshine. New bare rocks are very vulnerable to erosion. Without vegetative cover, or a layer of soil on their surface, bare rocks are subjected to solar radiation and marked temperature changes. Insolation weathering, and the cycle of expansion during the day, and contraction during the night, causes fissures and the breakdown of the rocks. Figure 4(a) shows the cracking of bare limestone due to insolation and temperature change along the Mianyuan River. The limestone is fragile, and a 10-cm thick surface layer was broken. The surface layer of the rock was further broken down into grains. Wind or tremors caused the grains to roll down the slope. Figure 4(b) shows a grain erosion deposit covering an avalanche deposit fan along the Minjiang River near Wenchuan. The grain erosion occurred on granite rock and the grains are generally finer than the grains in limestone areas. The grains are very uniform in size, with a median diameter of about 1 cm. As a comparison, the avalanche deposit beneath the grain layer is much more heterogeneous, consisting of material ranging in size from several metres to less than 1 mm. Because the grains from grain erosion are uniform in size and regular in shape, they have been mined for building materials at some sites where transportation facilities are available.

(a) (b)

Fig. 4 (a) Bare limestone is cracked and broken down due to insolation and temperature change. (b) A grain erosion depositional layer covering an avalanche deposit fan on the Minjiang River near Wenchuan.

Grain erosion mainly occurs in granite, limestone, and metamorphic rocks. The grains produced in limestone areas are relatively coarse, with diameters between 10 and 200 mm, grains in granite areas are finer, with diameters between 5 and 30 mm; while in metamorphic areas, grain diameters range from 0.1 to 300 mm. Figure 5 (GE represents grain erosion) shows the size distributions of particles resulting from grain erosion from the Minjiang River (granite rock), Jiuzhaigou Creek (limestone), and the Xiaojiang River (phyllite rocks). Minjiang 1 and Minjiang 2 are two grain erosion sites on the Minjiang River near Wenchuan, whereas the Jiangjia and Dabaini ravines are two tributaries of the Xiaojiang River. As a comparison, the size distributions of landslides on the Shiting and Qingzhu rivers are shown in Fig. 5 as well; they are not far from Mianyang. The two landslides were triggered by the Wenchuan earthquake and caused thousands of casualties. The range of size distributions of solid particles in the landslide deposits covers six orders of magnitude from 0.01 mm to 10 m, whereas the grain erosion deposit has diameters within two orders of magnitude for granite and limestone (5 to 50 mm for the former and 5 to 200 mm for the latter), and three orders of magnitude for metamorphic rocks (from 3 to 300 mm).

The rocks along the Minjiang River became bare after a series of avalanches on 12 May 2008 that were triggered by the earthquake. Until early March 2009, grain erosion along the Minjiang River occurred only at a few sites with limited areas. From March to June, relative to the rest of

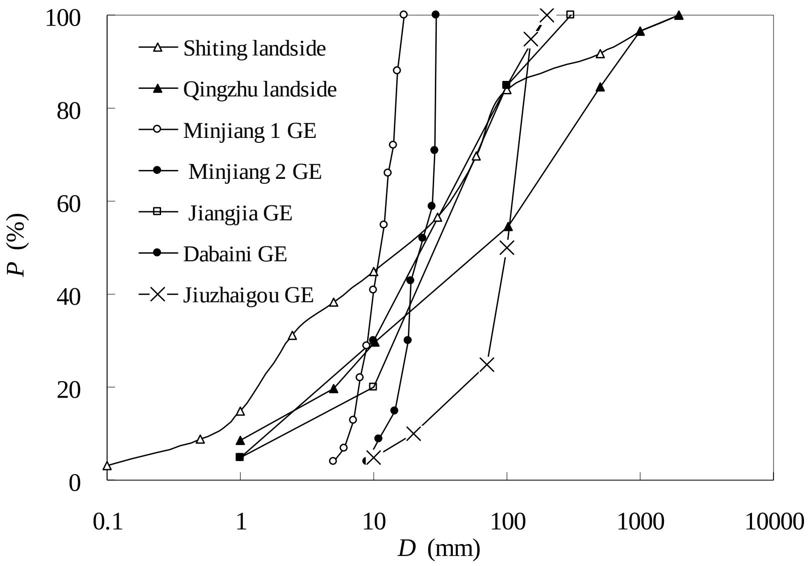

Fig. 5 Size distributions of grain erosion deposits (GE represents grain erosion).

the year, the Minjiang River experienced the strongest insolation and driest period. During this time grain erosion developed very quickly, and the occurrence area almost doubled. In general, grain erosion on the south-facing banks of rivers is more intense than that on the north-facing bank. Figure 6 shows grain erosion on the south-facing bank, and rill erosion (water erosion) on the north-facing bank of the Chaqing Gully along the Xiaojiang River. The lithology (phyllite) and rainfall on the two banks are the same, but insolation on the north-facing bank is much weaker than on the south-facing bank; therefore, grain erosion occurs on the south-facing bank, and water erosion occurs on the north-facing bank.

The amount and size of the grains removed by wind is a function of wind speed. An experiment was conducted to study the relation of the amount and size of grains blown down with wind speed. The lithology at the experimental sites is metamorphic, mainly phyllite. The particles resulting from the grain erosion of a surface layer of rocks were blown down with a battery-powered bellows, which had been transported to the mountain of the Chaqing Gully by donkey. Wind speed was measured with a rotational wind velocity meter that had a 10×10 cm^2 square nozzle. The bellows created a “wind blast” with a maximum speed of 20 m s^{-1}. It acted on the bare

(a) (b)

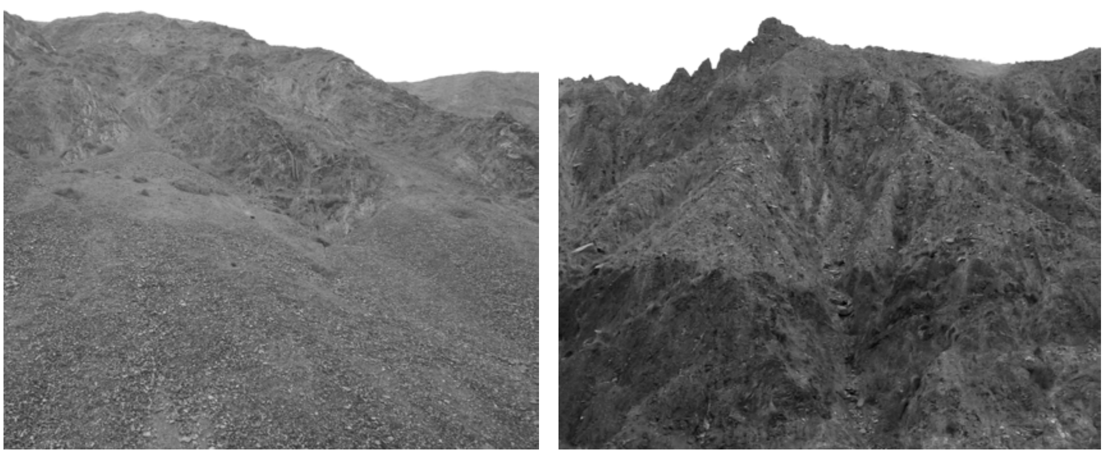

Fig. 6 Grain erosion occurs on the south-facing bank (left) while rill erosion (water erosion) occurs on the north-facing bank (right) of a small stream.

rock surface, and the grains blown by the bellows were collected with a bag and weighed on a balance. For each experiment, an area of 1 m^2 of bare rock surface was acted on by the "wind", at a given speed for 10 min. As shown in Fig. 7(a), the amount of grains blown down by the wind in the four experiments had the same relation to, and was proportional to the fourth power of wind speed. The size of the largest grain blown from the bare rock was proportional to the wind speed. We have:

$$E_b = 0.00625V^4 \quad (1)$$

$$D_m = V \quad (2)$$

where V is the wind speed in (m s^{-1}), E_b is the amount of grains blown down by the wind per time per square metre of bare rocks in (g min^{-1} m^{-2}); and D_m is the diameter of the largest grain blown down by the wind (mm).

A wind with a speed of 20 m s^{-1} blew 1 kg of grains per minute away from 1 m^2 of bare rock, with a maximum grain size of 20 mm.

The rate of grains blown by the wind per area, per time (Fig. 7) represents a high instantaneous rate of grain erosion. The annual rate of grain erosion depends on the frequency of high wind speeds, the rate of insolation weathering, and the action of temperature change. In general, bare rock may be eroded by several to several tens of cm^2 $year^{-1}$, depending on the lithology, location, local weather, and wind strength.

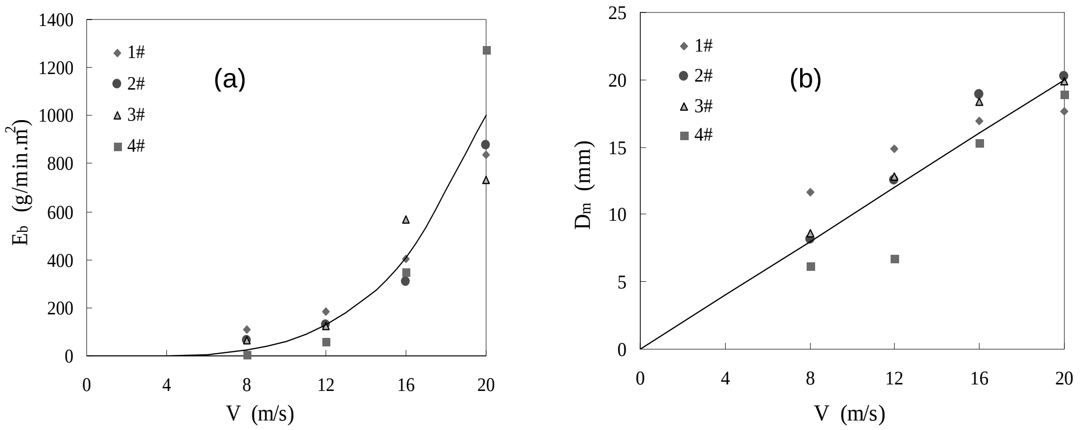

Fig. 7 (a) Amount of grains blown by wind from 1 m^2 of rock surface per time as a function of the wind speed. (b) The largest grain size blown by wind as a function of wind speed.

Table 1 lists the rate of grain erosion in the earthquake area, and in the Xiaojiang River basin, which was measured in June and July 2009. As shown in Fig. 4(b), the depth of grain erosion deposits on the avalanche deposit fan, which could easily be identified by their uniform size, was measured at two or three locations. The average depth of grain erosion deposits, multiplied by the surface area of the fan, represents the volume of grains eroded from each erosion site in the past year. The area of grain erosion on the bare rock surface was measured with laser range meters, which have a maximum error of 1 m. The bare rock surfaces generally were larger than 100 m in length and width; therefore, the maximum relative error was less than 1%. The rate of grain erosion was obtained by dividing the volume of grains by the surface area of bare rock. The same measurements were also performed for nine other grain erosion sites in the Xiaojiang River basin.

The rate of bare rock grain erosion along the Minjiang River was between 3 and 53 cm $year^{-1}$, with an average rate of about 17 cm $year^{-1}$. The rate of grain erosion in the Xiaojiang River Basin was only 1.1–4.6 cm $year^{-1}$, with an average rate of about 2.8 cm $year^{-1}$. The rate of grain erosion in the earthquake area was much higher than in the Xiaojiang River Basin because the bare rocks in the former were fresh. The rate of grain erosion gradually will decline, even if no control strategies are implemented.

Table 1 Characteristics and rate of grain erosion in the Wenchuan earthquake area and the Xiaojiang River basin.

River		Location (GPS)	Slope (degree)			Rate of grain erosion (cm/year)
			Grain erosion surface	Grain flow section	Deposit fan	
Minjiang River from Caopo to Wenchuan		N31°20'08.5", E103°29'16.1" 1221 m	45°		36°	13.9
		N31°18'42.1", E103°28'20.8" 1172 m	49°	40°	34°	52.8
		N31°25'40.1", E103°32'25.8" 1300 m	52°	39°	35°	15.9
		N31°23'36.7", E103°30'59.4" 1267 m	57°		35°	11.0
		N31°21'53.2",E103°30'02.4" 1236 m	48°	39°	34°	7.5
		N31°23'31.0",E103°31'12.9" 1280 m	49°		31°	2.6
		N31°26'04.8", E103°32'40.5" 1310 m	53°		25°	5.3
		N31°27'38.0", E103°33'57.1" 1330 m	47°		34°	11.8
		N31°27'26.5",E 103°33'30.1" 1307 m	48°		39°	33.0
Xiaojiang River basin	Dabaini Ravine	N25°59’59",E103°12′21" 1480m	61°	42°	36°	1.5
		N25°59’59",E103°12′21" 1460m	55°	37°	35°	1.1
	Xiaobaini Ravine	N25°58′45″,E103°12′53″ 1489m	54°		35°	2.7
	Xiaojiang River	N26°16′30″,E103°05′51″ 1091 m	60°		34°	2.5
		N26°16′51″, E103°06′49″ 1025m	60°		35°	4.6
	Jiangjia Ravine	N26°14′55″,E103°08′02″ 1051m		43°	32°	
		N26°15′03″, E 103°08′03″ 1045m	57°		35°	2.5
	Chaqing Gully	N26°15′03″, E103°08′03″ 1357m	63°		37°	3.4
		N26°15′03″, E103°08′12″ 1420m	55°		31°	3.4

CONCLUSIONS

Grain erosion is defined as the breakdown of bare rocks under the action of insolation and temperature changes, the flow of grains downslope under the action of gravity, and accumulation at the toe of the mountain forming a deposit fan. Grain erosion occurred on the bare rocks in the Wenchuan earthquake area, and in the Xiaojiang River basin. Grain erosion caused flying stones that injured humans, and resulted in slope debris flows. The most intensive grain erosion occurred in March, April, May and June because intense insolation occurs during that period. The amount of grains blown by wind from the bare rocks, per area, per unit time, is proportional to the fourth power of wind speed, whereas the size of the grains increases linearly with wind speed. The annual rate of grain erosion in the earthquake area was about 17 cm year^{-1}, whereas it is only 2.7 cm year^{-1} in the Xiaojiang River basin.

Acknowledgements The study is supported by the Ministry of Science and Technology of China (2008CB425803) and the Ministry of Water Resources of China (2007SHZ0901034).

REFERENCES

Carter, N. E. A. & Viles, H. A. (2003) Experimental investigations into the interactions between moisture, rock surface temperatures and an epilithic lichen cover in the bioprotection of limestone. *Building and Environment* **38**(9–10), 1225–1234.

Carter, N. E. A. & Viles, H. A. (2005) Bioprotection explored: the story of a little known earth surface process. *Geomorphology* **67**(3–4), 273–281.

Chen, Ji & Hayes, G. (2008) Finite fault model of the May 12, 2008 Mw 7.9 Eastern Sichuan, China, Earthquake. US Geological Survey National Earthquake Information Center.

Goldman, S. J., Jackson, K. & Bursztynske, T. A. (1986) *Erosion and Sediment Control Handbook.* McGraw-Hill Book Company, New York, USA.

Korup, O. & Schulunegger, F. (2009) Rock-type control on erosion-induced uplift, eastern Swiss Alps. *Earth Planet. Sci. Lett*. **278**(3–4), 278–285.

Halsey, D. P., Mitchell, D. J., *et al*. (1998) Influence of climatically induced cycles in physical weathering. *Quart. J. Engng Geol. Hydrogeol*. **31**, 359–367.

Harris, S. A. & Prick, A. (2000) Conditions of formation of stratified screes, Slims River valley, Yukon Territory: A possible analogue with some deposits from Belgium. *Earth Surf. Processes Landf*. **25**(5), 463–481.

Huang, Runqiu (2008) Analysis on the distribution of secondary geological hazards induced by the Wenchuan earthquake and its impacts on reconstruction. Symposium on Earthquake Induced Mountainous Hazards and Disaster Reduction (Chengdu Research Institute of Mountain Hazard Reduction and Environment, August 2008 (in Chinese).

Matsuoka, N. (1990) The rate of bedrock weathering by frost action – field-measurement and a predictive model. *Earth Surf. Processes Landf*. **15**(1), 73–90.

Matsuoka, N. (2008) Frost weathering and rockwall erosion in the southeastern Swiss Alps: Long-term (1994–2006) observations. *Geomorphology.* **99**(1-4), 353–368.

Moseley, R. K. & Tang Ya (2006) Vegetation dynamics in the dry valleys of Yunnan, China, during the last 150 years: implications for ecological restoration. *J. Plant Ecol* **30**(5), 713–722

Sass, O. (2005) Temporal variability of rockfall in the Bavarian Alps, Germany. *Arctic Antarctic and Alpine Research* **37**(4), 564–573.

Saas, O. & Krautblatter, M. (2007) Debris flow-dominated and rockfall-dominated talus slopes: Genetic models derived from GPR measurements. *Geomorphology*. **86**(1-2), 176–192.

Shen, You-xin, Zhang, Yan-Dong, Zhang, Ping & Liu, Wen-Yao (2001) Effects of disturbance type on soil seed banks in a debris-flow prone dry valley of northern Yunnan. *J. Plant Ecol.* **25**(5), 623–629.

Wang, C., Que, Y., Li, X. & Zhang, X. (2007a) Movement characteristics and Dynamical numerical analysis of sand-sliding slope composed by granular clastics: Part II of sand-sliding slope series. *Rock and Soil Mechanics*. **28**(2), 219–223 (in Chinese).

Wang, C., Que, Y., Xu, J. & Li, X. (2007b) Equation of motion and soil pressure for sand-sliding slope composed by granular clast: Part III of sand-sliding slope series. *Rock and Soil Mechanics.* **28**(7), 1299–1303 (in Chinese).

Wang, C., Zhang, X., Que, Y. & He, S. (2007c) Formation and basic characteristics of sand-sliding clastslope composed of granular clasts: Part I of sand-sliding slope series. *Rock and Soil Mechanics* **28**(1), 29–35 (in Chinese).

Wang, Zhaoyin, Cui, Peng & Wang, Ruiyu (2009) Mass movements triggered by the Wenchuan Earthquake and management strategies of quake lakes. *Int. J. River Basin Manage.* **7**(1), 1–12.

Wikepedia (2009) http://en.wikipedia.org/wiki/Erosion.