Did the 2008 Wenchuan Earthquake Lead to a Net Volume Loss?

Chong Xu, Xiwei Xu, Tolga Gorum, Cees J. van Westen, and Xuanmei Fan

Abstract

The topographic evolution of mountain landscapes is a coupling process of tectonic rock uplift, landslide erosion, and valley incision etc. A widely accepted notion is that an earthquake will build up the mountainous topography, whereas some researchers suggest that the 2008 Wenchuan earthquake tumbled down the mountain because the wasting mass volume due to landsliding is two to six times larger than the gain volume caused by rock uplift. The purpose of this paper is to compare the wasting mass volume due to seismic landsliding with the gain volume caused by rock uplift related to the 2008 Wenchuan event based on a new detailed landslide inventory prepared by visual interpretation of aerial photos and satellite images of high resolutions. The results show that about 5.9 km^3 materials, generated by nearly 200,000 landslides triggered by the Wenchuan earthquake, are distributed in the landslide intensity area. Although the landslides volume is larger than the published volume of tectonic rock uplift (2.6 ± 1.2 km^3), it is rather smaller than that from the previous study. We think it is not enough only to account for the co-seismic landslide volume and uplifted volume in the study of landscape evolution of the Longmenshan mountain area where the Wenchuan event took place. Orogenic evolution is affected by a variety of factors, such as co-seismic and interseismic crustal uplift, and isostatic compensation of mass removed from the surface of the earth which leads to orogenic growth, whereas co-seismic landslides and river erosion can destroy mountainous topography.

Keywords

Landslide • 2008 Wenchuan earthquake • Tectonic rock uplift • River erosion

Introduction

A detailed and accurate landslide inventory is an essential part of assessment of co-seismic landslides hazard. Harp et al. (2011) considered an ideal inventory would cover the entire area affected by an earthquake and include all of the landslides that are possible to detect down to size of 1–5 m in length, and the landslides must also be located accurately and mapped as polygons depicting their true shapes. Such inventories can then be used to perform seismic landslide hazard analysis (e.g. Xu et al. 2012a, b), regional landslide volume calculation (Xu and Xu 2013a, b), and other

C. Xu (✉) • X. Xu
Key Laboratory of Active Tectonics and Volcano, Institute of Geology, China Earthquake Administration, Qijiahuozi, Deshengmenwai, P.O. Box 9803, Beijing 100029, China
e-mail: xc11111111@126.com; xuchong@ies.ac.cn; xiweixu@vip.sina.com

T. Gorum • C.J. van Westen • X. Fan
Faculty for Geo-Information Science and Earth Observation, University of Twente, Enschede, The Netherlands
e-mail: gorum@itc.nl; westen@itc.nl; fanxuanmei@gmail.com

quantitative analyses (Dai et al. 2011; Gorum et al. 2011; Xu et al. 2013a).

The topographic evolution of mountain landscapes is a coupling process of tectonic rock uplift, landslide erosion, and valley incision, etc. A widely accepted notion is that an earthquake will build up the mountainous topography, whereas Parker et al. (2011) found the Wenchuan earthquake tumbled down the mountain because the wasting mass volume due to landsliding is two to six times larger than the gain volume caused by rock uplift. However, we question their landslide volume estimation to be overestimate of the co-seismic landslide volume due to two limitations in their landslide inventory: (1) the incompleteness of the inventory; and (2) the generalization of landslide mapping (delineating several landslides as one landslide). They have contrary effect on the landslide volume calculation. Which aspect plays a more important role? Only a detailed and complete landslide inventory could answer this question. Further, it will affect judging of the correlation between the wasting mass volume due to seismic landsliding and the gain volume caused by rock uplift related to the 2008 Wenchuan earthquake.

In this work, a detailed and objective inventory of landslides triggered by the 2008 Wenchuan earthquake was prepared by using visual interpretation of aerial photos and satellite images in high resolutions. Then, the wasting mass volume due to seismic landsliding was calculated by landslide "area-volume" formulas. In our opinions, the landscape evolution of the earthquake area is affected by various factors, such as co-seismic and interseismic crustal uplift, isostatic compensation of mass removed from the surface of the earth, co-seismic landslides, and river erosion. The conclusion that the 2008 Wenchuan earthquake led to a net volume loss (Parker et al. 2011) seems too hastily.

Two Important Limitations of the Landslide Inventory Constructed by Parker et al. (2011)

The fact that various factors may affect the quality of landslide inventories (Guzzetti et al. 2012) commonly result in many landslide inventories of poor quality. In our opinion, there are two important limitations in the landslide inventory for the 2008 Wenchuan earthquake constructed by Parker et al. (2011). One relates to the incompleteness of the inventory which might lead to an underestimation of the regional landslide volume, and the other is associated with the grouping of individual small landslides into larger units. The second limitation is more important than the first one, leading to an overestimation of the total landslide volume. These limitations were already acknowledged by Parker et al. (2011) in their supplementary data, but cannot be quantified due to the lack of a complete landslide inventory.

Incomplete Landslides Inventory

Parker et al. (2011) did not use of image visual interpretation for constructing landslide inventory, instead employed a semi-automated detection algorithm and EO-1 and SPOT 5 imagery for the mapping of individual landslides. Their inventory contained 73,367 landslide features across an area of 13,800 km^2, which is substantially smaller than the entire earthquake affected area. They did not make a comparison between their inventory and the available one of Dai et al. (2011) which contained 56,847 landslides mapped across an area of 41,750 km^2. When compared with our landslide inventory map, the inventory map of Parker et al. (2011) lacks information on tens of thousands of landslides that occurred in areas in the N, NW, W, and SW direction of the epicenter, as well as in the NE section of the main co-seismic surface rupture.

Overestimation of Individual Landslide Areas

Parker et al. (2011) obtained landslide polygons based on a semi-automated detection algorithm and EO-1 and SPOT 5 imagery, using only post-earthquake images. Although such automatic detection methods can provide a first indication in a short time, the resulting inventory maps tend to be extremely general and include numerous errors when compared with detailed landslide inventory maps prepared by image experts through visual interpretation (Harp et al. 2011). In addition, Parker et al. (2011) did not exclude pre-existing landslides since only the post-earthquake images were used. Considering these factors, there is very possible that bare-rocky areas were mapped as landslides. This can significantly change the results they present in Fig. 2 in their main manuscript, which compares "Net volume changes" of co-seismic uplift and landslides within a swath profile with a width of 1-km in the along-strike distance from the epicenter. The automated image classification method used by Parker et al. (2011) also resulted in the grouping of many single landslide events into larger ones, leading to an exaggeration of the landslide area. This can be observed from the example resented in Fig. 1, from Beichuan County, where they combined the Beichuan Middle-school rock-avalanche with several other rock falls in the neighbouring slope into a single landslide (Fig. 1a). This overestimation of individual landslide areas can change the volumetric calculations considerably. When using the exact area of each landslide (Fig. 1b) and using the conversion to volume indicated in their supplementary data, the area of the individual landslides varies between 1,531 m^2 (L4) and 123,329 m^2 (L1) and the volumes range between 2,793 m^3 and 1,235,048 m^3, using the area-volume conversion formula of $V_{ls} = 0.106 \times A_{ls}{}^{1.388}$ (Parker et al. 2011). The total

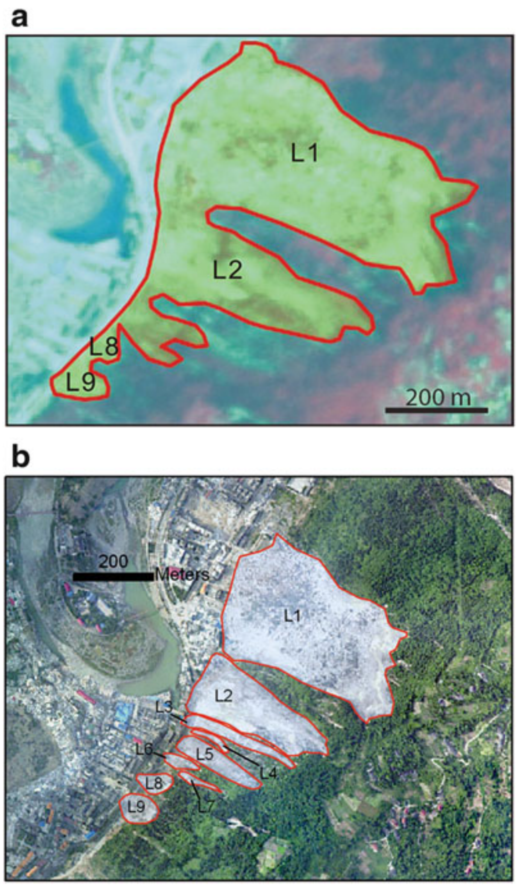

Fig. 1 Comparison of landslide interpretation: (**a**) an image classification by Parker et al. (2011); (**b**) for a test area in Beichuan County. Nine individual landslides can be observed clearly in (**b**), whereas only some of them can be distinguished in (**a**)

area of the nine landslides (L1–L9) is 192,935 m^2, and the total volume is 1,612,466 m^3. When following Parker et al.'s image classification result (Fig. 1a) the area of the combined landslide is 192,935 m^2 and the corresponding volume is $0.106 \times 192{,}935^{1.388} = 2{,}379{,}382$ (m^3), which is an overestimation of $2{,}379{,}382/1{,}612{,}466 \times 100\ \% = 147.6\ \%$ with respect to the reality.

Data and Methods

Our initial landslide distribution data, as cited by Parker et al. (2011), showed more than 56,000 landslides (Dai et al. 2011; Gorum et al. 2011) triggered by the 2008 Wenchuan earthquake. These landslides were delineated by visual interpretation of high-resolution aerial photos and satellite images over a broad area, using mainly post-earthquake images. Although the inventory contains a large number of landslides, some of the earthquake affected areas still lacked high- resolution post-earthquake remote sensing images, resulted in an incomplete landslide inventory map.

Images Used for Landslides Visual Interpretation

We manually mapped landslides in polygons based on the visual interpretation of pre- and post- earthquake remote sensing images. These images of post-earthquake include aerial photos of 1 m, 2 m, 2.4 m and 5 m resolutions, SPOT 5 of 2.5 m resolution, CBERS02B of 19.5 m resolution, IKONOS of 1 m resolution, ASTER of 15 m resolution, IRS-P5 of 2.5 m resolution, QuickBird of 0.6 m and 2.4 m resolutions, and ALOS of 2.5 m resolution. The images of pre-earthquake consist of SPOT 5 of 2.5 m resolution covering part of the landslides distribution area and ETM + of 15 m resolution throughout the whole landslide area. In addition, a few hundreds of landslides occurred in areas lacking clear images were delineated from visual interpretation of images on Google Earth platform.

Inventory of Landslides Triggered by the Earthquake

An inventory of landslides triggered by the 2008 Wenchuan earthquake was prepared using visual interpretation on a GIS platform, resulting in a total of 197,481 landslides delineated as individual solid polygons (Fig. 2; Xu 2012; Xu and Xu 2012; Xu et al. 2013b), with a total area of about 1,160 km^2, occurring over an area of about 110,000 km^2. This landslide distribution map is more detailed than previous ones (e.g. Dai et al. 2011; Gorum et al. 2011; Chigira et al. 2010; Yin et al. 2010; Qi et al. 2010; Huang and Li 2009).

The distribution of the co-seismic landslides triggered by the Wenchuan earthquake (Fig. 2) shows several features as follows: (1) Most of the landslides are concentrated around the Yingxiu-Beichuan co-seismic surface rupture, indicative of a control on the spatial distribution patterns of the landslides. (2) Most of the landslides occurred northeast of the epicentre, consistent with the earthquake rupture mechanism. (3) Most of the landslides occurred on the hanging wall of the seismogenic fault, especially the southwest segment of the fault dominated by thrusting. (4) In the areas of hanging wall of the seismogenic fault but far away from the fault, some co-seismic landslides were also present and mainly distributed along rivers. (5) The area between the two main surface-ruptures also registered high density landslides, but less than the hanging wall area. (6) The landslides in areas northeast to the Beichuan County were distributed in clusters around the surface rupture.

Results

Based on our landslide inventory, we recalculated the landslide volume in the same manner as Parker et al. (2011)

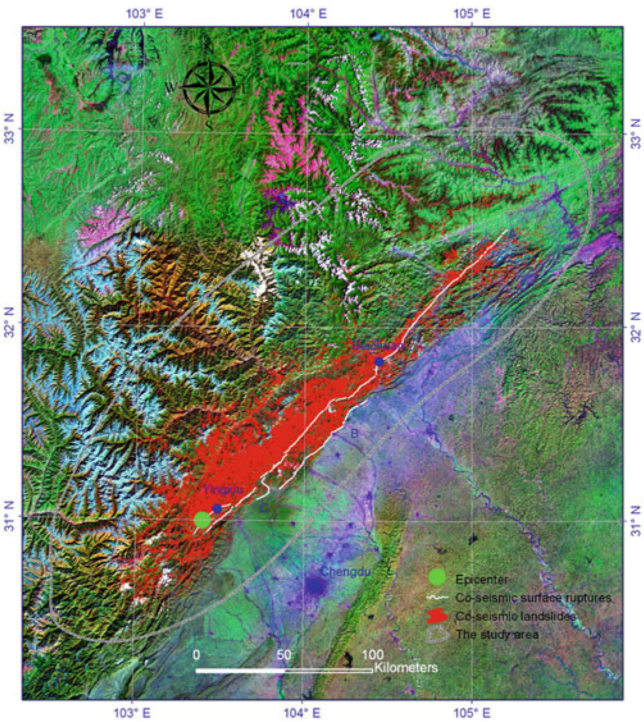

Fig. 2 Distribution of co-seismic surface ruptures (*white lines*) and earthquake triggered landslides (*red polygons*). (**a**) The Yingxiu-Beichuan co-seismic surface rupture; (**b**) The Guanxian-Jiangyou co-seismic surface rupture; (**c**) The Xiaoyudong co-seismic surface rupture. The co-seismic surface rupture is revised from Xu et al. (2009)

(Table 1), resulting in volume estimations that are between 49 and 86 % of their results. The volume of the Wenchuan earthquake triggered landslides is about 5.9 km^3 based on the "volume-area" power-law from Parker et al. (2011). Furthermore, a large part of the landslide materials is not likely to be eroded away within a short period of time, as many landslides occurred as rockfalls or large rockslides (Hovius et al. 2011; Fan et al. 2012), e.g. the Daguangbao landslide. Fan et al. (2012) concluded that over 80 % of the co-seismic landslide materials are still suspended on the hillslopes inside the mountain system about 3 years after the earthquake, and the time needed to transport them outside the mountain system largely depends on the stream power, long-term rock uplift as well as the regional climate change. Therefore, the maximum volume loss due to landslides is only 20 % of 5.9 km^3, which is about 1.2 km^3, evidently less than the uplifted volume of 2.6 $\pm$ 1.2 km^3 (Parker et al. 2011; de Michele et al. 2010). The uplifted volume of 2.6 $\pm$ 1.2 km^3 from InSAR (de Michele et al. 2010) was the most credible result currently due to the rare GPS vertical data (Shen et al. 2009; Wang et al. 2011) for the Wenchuan earthquake struck area.

The two limitations mentioned above have an opposite effect on the estimation of the total landslide volume calculation. We calculated the total landslide volume in a landslide density area of about 13,800 km^2 based on our own inventory in the same manner as Parker et al. (2011). The results are shown in Table 1. The resulting total landslide volume is much larger than our results, even though their inventory lacked data for some landslide density areas. For some of the area-volume relations, our results are less than 50 % of their results. In our opinion, using the same empirical relationships between area and volume the total landslide volume was between ~4 and 8 km^3, which is much less than the range of ~5–15 km^3 reported by Parker et al. (2011).

Table 1 Comparison of landslide volumes based on our results, as compared with those of Parker et al. (2011)

RS	MidV (%)	MaxV (%)	MinV (%)
L1	4.49/5.73 (78)	4.73/6.14 (77)	4.26/5.35 (80)
L2	6.92/9.36 (74)	7.69/10.75 (72)	6.22/8.15 (76)
L3	10.63/14.9 (71)	11.82/17.1 (69)	9.56/13 (74)
G	8.09/15.2 (53)	8.93/17.2 (52)	7.33/13.4 (55)
FM	5.91/9.08 (65)	15.27/31.28 (49)	2.35/2.73 (86)

"RS" represents several published relationships between individual landslide area and volume. "MidV (%)", "MaxV (%)", and "MinV (%)" mean the middle, maximum, and minimum volume values (reference to Parker et al. 2011) of total landslides triggered by the earthquake in "km^3" from this study and from Parker et al. (2011), data in the double brackets mean the percentage ratio of them. "L1", "L2", "L3" (Parker et al. 2011) respectively mean all landslides, all bedrock landslides, mixed Himalayan landslides from Larsen et al. (2010). "G" (Parker et al. 2011) represents all landslides from Guzzetti et al. (2009). "FM" means using the landslide "area-volume" relationship from field measurements by Parker et al. (2011)

In order to conveniently observe spatial distribution patterns of materials generated by the co-seismic landslides, we divided the study area into 44,041 square cells of size 1 km^2. Because the area of some giant landslides is larger than 1 km^2, it is inappropriate to consider such giant landslides as a point to calculate landslide material thickness in an 1 km^2 cell. In this study, we select 20 m as sampling intervals to extract landslide material thickness in co-seismic landslide areas. The nearly 200 thousands co-seismic landslides cover about 1,150.622 km^2 and 2,875,676 points were extracted in 20 m interval. Based on the area-volume conversion formula of $V_{ls} = 0.106 \times A_{ls}{}^{1.388}$ (Parker et al. 2011), landslide material volume can be obtained and each average thickness of the 2,875,676 points were assigned. Then, landslide erosion material average thickness of every 1 km^2 cell were calculated based on the following formula:

$$\mathrm{Thick}_{\mathrm{Average}} = \sum_{1}^{2500} \mathrm{Thick}_i \times 400/10^6 \qquad (1)$$

where $\mathrm{Thick}_{\mathrm{Average}}$ represents the landslide material thickness of certain 1 km^2 square cell, and every 1 km^2 square area contains 2,500 points in 20 m intervals; i ($1 \leq i \leq 2{,}500$) means the i point of the 2,500 points in the 1 km^2

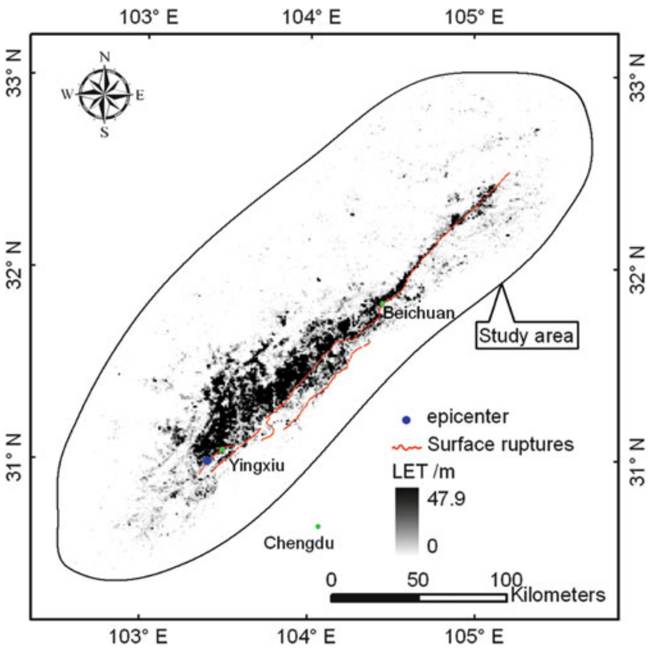

Fig. 3 Distribution map of landslide erosion thickness based on 1 km^2 cells. *LET* landslide erosion thickness

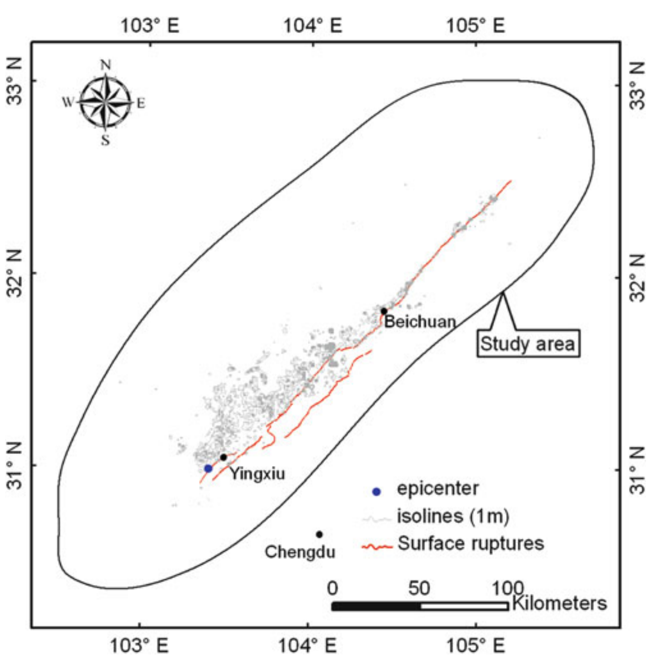

Fig. 4 Isolines of landslide erosion thickness related to the Wenchuan earthquake

cell; and Thick$_i$ is landslide erosion thickness of the i point (area of 20 m × 20 m) with unit meter. Then, a distribution map of landslide erosion thickness based on 1 km^2 cells (Fig. 3) were constructed. Subsequently, landslide erosion thickness isolines (Fig. 4) were constructed by the Fig. 3 based on 1 m intervals. It can be observed landslide erosion thickness (LET) values of the most study area are less than 1 m. Most LET values larger than 1 m are located in the hanging wall of the southwest segment (between Beichuan County and the Yingxiu County) of the Yingxiu-Beichuan co-seismic surface rupture. This indicates high density of the co-seismic landslides occurrence on the hanging wall of the southwest segment of the fault dominated by thrusting.

Conclusions

After the 2008 Wenchuan earthquake, a detailed inventory map of the earthquake-triggered landslides was prepared. This inventory map contains 197,481 individual landslides mapped as individual polygons, with a total area of about 1,160 km^2. These landslides are distributed over an area of more than 110,000 km^2. About 5.9 km^3 materials were generated by the landslides. Our results show that Parker et al. (2011) overestimated the volume of landslides triggered by the 2008 Wenchuan earthquake, and therefore their conclusion that such major earthquakes led to a net material deficit seems not supported by the data. It is not enough only to account for co-seismic landslide volume and uplifted volume in the study of landscape evolution of the Longmenshan mountain area where the 2008 Wenchuan event took place. Orogenic evolution is affected by a variety of factors, such as co-seismic and interseimic crustal uplift, and isostatic compensation of mass removed from the surface of the earth (Molnar 2012) which can lead to orogenic growth, whereas co-seismic landslides and river erosion can destroy mountainous topography.

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