Statistics of Landslide Sizes to Determine Landslide Mobilization Rates and to Ascertain Landslide Hazard and Risk

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Abstract

Knowing the number, area and volume of landslides in an area is important to evaluate the long-term evolution of landscapes dominated by mass-wasting processes, to determine landslide susceptibility and hazard, and to ascertain landslide risk. In this talk, I summarize work conducted chiefly in the last decade to determine the statistics of landslide sizes, primarily landslide area, A_L, and landslide volume, V_L.

Fujii (1969) was probably the first to investigate the statistics of landslide size. Studying an inventory of 800 landslides caused by heavy rainfall in Japan, he obtained cumulative number-area and number-volume distributions that correlated with two distinct power-law relations. More recent work has shown that the probability density $p(A_L)$ of landslide area, A_L, exhibits a typical distribution (Stark and Hovius, 2001, Guzzetti et al., 2002, Malamud et al., 2004). When plotted in log-log coordinates, the probability density increases with increasing landslide size (A_L) up to a maximum value (A_{Lmax}), after which the probability density decreases rapidly with increasing landslide area, following a power law. For most datasets, the scaling exponent of the power law tail of the distribution is $\alpha = 2.5\pm0.5$. For incomplete (and inaccurate) landslide inventories the "rollover" in the probability density is an artifact due to incompleteness in the landslide catalogue for small and very small slope failures (mapping resolution). For high quality landslide inventories, the "rollover" in the probability density is real (i.e., physical) and not influenced by censoring of the landslide inventory (Guzzetti et al., 2002).

Pelletier et al. (1997) attributed to the "rollover" typically shown by the probability density of landslide area, $p(A_L)$, to a transition from a resistance controlled chiefly by friction (for large landslides) to a resistance controlled by cohesion (for small landslides). Katz and Aharonov (2006) conducted experiments in a vibrating box, and postulated that the presence of heterogeneities in the soil and rock controls the size distribution of the landslide inventories. Stark and Guzzetti (2009) showed that the primary control on the shape of the probability density $p(A_L)$ is the relative importance of cohesion over friction in setting slope stability; the scaling of smaller, shallower failures, and the size of the most common landslide volumes, are the result of the low cohesion of soil and regolith, whereas the negative power-law-tail scaling for larger failures is tied to the greater cohesion of bedrock.

Determining the volume of a landslide is a difficult task that requires information on the surface and sub-surface geometry of the slope failure. This information is difficult to collect, and explains the paucity of information on landslide volume, compared to landslide area. Brunetti et al. (2009) examined 19 datasets with measurements of landslide volume, V_L, for sub-aerial, submarine, and extraterrestrial mass movements. The individual datasets covered different landslide types, including rock fall, rock slide, rock avalanche, soil slide, slide, and

debris flow, with individual landslide volumes ranging over $10-4$ m3 $\leq$ VL $\leq$ 1013 m3. The scaling behavior of p(VL) for the ensemble of the 19 datasets was over 17 orders of magnitude, and was independent of lithological characteristics, morphological settings, triggering mechanisms, length of period and extent of the area covered by the datasets, presence or lack of water in the failed materials, and magnitude of gravitational fields. Brunetti et al. (2009) argued that the statistics of landslide volume is conditioned primarily on the geometrical properties of the slope or rock mass where failures occur. Due to disparity in the mechanics of rock falls and slides, rock falls exhibit a smaller scaling exponent $(1.1 \leq \alpha \leq 1.4)$ than slides and soil slides $(1.5 \leq \alpha \leq 1.9)$.

Estimating the volume of individual slope failures for a large population of landslides (hundreds to several thousand failures) in an area is an even more challenging task, that can be achieved only by adopting empirical relationships to link the volume of individual landslides, VL, to geometrical measurements of the failures, chiefly landslide area, AL. Guzzetti et al. (2009) compiled a catalogue of 677 landslides of the slide type for which measurements of landslide area (AL) and volume (VL) were available. The measurements were used to establish an empirical relationship to link AL (in m2) to VL (in m3). The relationship takes the form of a power law with a scaling exponent $\alpha = 1.450$, covers 8 orders of magnitude of AL and 12 orders of magnitude of VL, and is in general agreement with existing relationships published in the literature.

The new relationship was used to determine the volume of individual landslides of the slide type in the Collazzone area, central Italy, a 78.9 km2 area for which a multi-temporal landslide inventory covering the 69-year period from 1937 to 2005 is available (Guzzetti et al., 2006). In the observation period, the total volume of landslide material was VLT = 4.78×107 m3, corresponding to an average rate of landslide mobilization $\varphi L = 8.8$ mm·yr-1. Exploiting the temporal information in the landslide inventory, the volume of material produced during different periods by new and reactivated landslides was singled out. A wet period from 1937 to 1941 was recognized as an episode of accelerated landslide production. During this 5-year period, approximately 45% of the total landslide material inventoried in the Collazzone area was produced, corresponding to an average rate of landslide mobilization $\varphi L = 54$ mm·yr-1, six times higher than the long term rate. The volume of landslide material in an event or period was used as a proxy for the magnitude of the event or period, defined as the logarithm of the total landslide volume produced during the event, or period. With this respect, the new relationship to link AL and VL is a starting point for the adoption of a quantitative, process based landslide magnitude scale for landslide events.

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