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Frequency–size relation of shallow debris slides on cut slopes along a railroad corridor: A case study from Nilgiri hills, Southern India

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Abstract The probability of landslide volume, V_L, is a key parameter in the quantitative hazard analysis. Several studies have demonstrated that the non-cumulative probability density, $p(V_L)$, of landslide volumes obeys almost invariably a negative power law scaling of $p(V_L)$ for landslides exceeding a threshold volume and a roll-over of small landslides. Some researchers attributed the observed roll-over to under-sampling of data, while others relate it to a geo-morphological (physical) property of landslides. We analyzed 15 sets of a complete landslide inventory containing shallow debris slides ($2 \leq V_L \leq 3.6 \times 10^3$ m^3) with sources located on cut slopes along a 17-km-long railroad corridor. The 15 datasets belong to individual years from 1992 to 2007. We obtained the non-cumulative probability densities of landslide volumes for each dataset and analyzed the distribution pattern. The results indicate that for some datasets the probability density exhibits a negative power law distribution for all ranges of volume, while for others, the negative power scaling exists only for a volume greater than 10 m^3, with scaling exponent β varying between 0.96 and 2.4. When the spatial distribution of landslides were analyzed in relation to the terrain condition and triggering rainfall, we observed that the number of landslides and the range and the frequency of volumes vary according to the changes in local terrain condition and the amount of rainfall that trigger landslides. We conclude that the probability density distribution of landslide volumes has a dependency on the local morphology and rainfall intensity and the deviation of small landslides from power law, i.e., the roll-over is a "real effect" and not an artifact due to sampling discrepancies.

Keywords Shallow debris slide · Cut slope · Landslide volumes · Probability density distribution · Nilgiri

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1 Introduction

The understanding of size (area or volume)–frequency relationship of landslides is important as it has implications in hazard and risk analysis (Hungr et al. 1999, 2008; Guzzetti et al. 1999, 2002; Fell et al. 2008). The relationship has been used to estimate the probability of landslide size (Guzzetti et al. 2002), which is an important component of landslide hazard assessment.

Several studies have been conducted on the statistics of landslide size, and probably Fujii (1969) was the first to investigate the area/volume–frequency distribution based on an inventory of 800 landslides triggered by heavy rainfall in Japan. Other studies on size–frequency statistics were based on different types of inventories (Picarelli et al. 2005), including landslides of all ages of undefined long periods of time including palaeo landslides, landslides within a defined time interval (e.g., Dai and Lee 2001), continuous records of landslide occurrence within a region or along transportation corridors (e.g., Fell et al. 1996; Hungr et al. 1999), and landslides occurring in a very short period of time such as after a rainstorm (e.g., Malamud et al. 2004). The researchers have defined landslide size either by scarp area (Hovius et al. 1997; Stark and Hovius 2001), by total area including the deposition zone (Guzzetti et al. 2002; Malamud et al. 2004; Guthrie and Evans 2004), or by source volume (Hungr et al. 1999; Dai and Lee 2001; Hungr et al. 2008; Brunetti et al. 2009).

In many studies, the landslide size and frequency distribution was observed to exhibit a negative power-law scaling for landslides of large size and a flattening of the curve at the lower size, termed as a 'roll-over' (e.g., Stark and Hovius 2001; Dai and Lee 2001; Guzzetti et al. 2002; Guthrie and Evans 2004; Malamud et al. 2004; Brardinoni and Church 2004; Catani et al. 2005; Hungr et al. 2008). Some researchers concluded that the roll-over of the curve is a 'real effect' reflecting slope stability processes (Guthrie and Evans 2004; Malamud et al. 2004), while others attribute it to the incompleteness of the inventory (Stark and Hovius 2001; Brardinoni and Church 2004; Catani et al. 2005). Inspection of literature further reveals that the frequency distribution of landslide size, particularly volume, correlates also with a power-law relation for all range of volumes (e.g., Fujii 1969; Brunetti et al. 2009). Given the above facts, it is yet not clear whether the frequency distribution of landslide size actually follows a power-law for all range of data or a roll-over distribution pattern.

If we believe that the roll-over effect is due to the incompleteness of the inventory, as demonstrated by Brardinoni and Church (2004) who have shown an increase in the frequency of small landslides when the photo-interpreted inventory was integrated with intensive-field-based inventory, then the actual distribution of landslide size can be established whether a complete inventory is available. We define a complete inventory as one that includes all landslides that occurred in an area within the considered time period.

Inventories are often incomplete for practical reasons particularly for small landslides, which are often overlooked when the inventory is made from remote sensing (Brardinoni et al. 2003) or remains unrecorded due to smaller landslide deposits that are either removed or are not discernible (Corominas and Moya 2008). However, one possibility of obtaining a complete inventory is to prepare it shortly after the occurrence of a landslide-triggering event (Malamud et al. 2004). Some technical offices, such as road and railway maintenance units or geotechnical offices, produce such inventories, which are mostly restricted to landslides from cut slopes and fills along transportation lines (Fell et al. 1996).

For a railroad corridor in Southern India, we obtained one such complete landslide inventory based on the records provided by the railway maintenance unit of the Southern

Railway located at Coonoor. The inventory contains data on shallow debris slides for the period between 1992 and 2007 with the source of landslides located on cut slopes along the railroad. We have used this inventory to analyze the volume–frequency relation of debris slides along the railroad corridor in Nilgiri hills of Southern India.

2 Study area and landslide distribution

The study was carried out along a 17-km-long railroad corridor in the Nilgiri hills of Southern India (Fig. 1). The railroad was cut through Charnockite rocks and regolith. The thickness of regolith varies between 1 and 20 m. From east (Kallar) to west (Coonoor), the railroad traverses highly dissected deflection slopes up to Hillgrove and a moderately dissected plateau up to Coonoor (Seshagiri et al. 1982). The land use around the railroad is mainly forest reserve and tea plantations with some patches of barren (rocky) slopes and horticulture plantations.

Landslide is an annual recurring phenomenon along the railroad and mostly triggered between October and December due to the retreating monsoon. The railway maintenance unit of the Southern Railway located at Coonoor maintains records for all the landslides that affected the railroad since 1992. Prior to 1992, no systematic records were available from the railway office. The landslide maintenance record is locally called 'railway slip register' and contains information on the spatial distribution of landslide debris on the railroad, the type of material (e.g., earth mixed with boulder), the total volume of debris on the railroad, and the date of occurrence of landslides. The register is updated immediately after the occurrence of a landslide-triggering event and is used for tendering contracts for railroad clearance.

All landslides are shallow debris slides, which are individually small in size (median volume $\sim$20 m^3) and occur with high frequency. The average density is 33 landslides per kilometer length of the railroad, but in some sections, the density of slope failures is higher, exceeding 50 landslides per kilometer. The minimum density is 12 landslides per kilometer as recorded in km-12 of the railroad. Table 1 summarizes the main characteristics of landslides on cut slopes as inventoried from railway slip registers. The method used to prepare the landslide inventory from the railway slip register is discussed in detail in

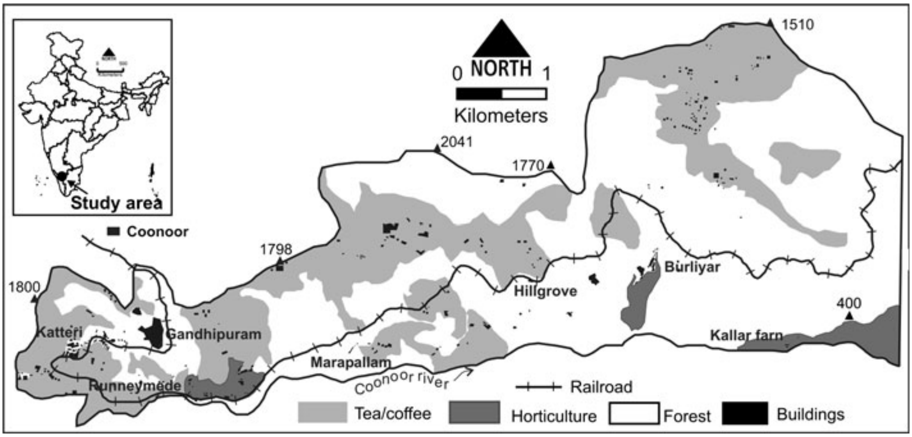

Fig. 1 Location of the railroad corridor in the Nilgiri hills. The elevations (*black triangles*) are in meter above the mean sea level

Table 1 Main characteristics of the landslide inventory along the railroad

Attribute summary	Unit	
Type of landslides	–	Debris slides
Location of landslide source	–	Cut slopes
Main landslide trigger	–	Rainfall
Total number of landslides	No.	565
Total volume of landslides	m^3	52,500
Volume of smallest landslide	m^3	2
Volume of largest landslide	m^3	3,600
Average volume of landslides	m^3	90
Median volume of landslides	m^3	20
Standard deviation of landslide volume	m^3	270
Average landslide density	No./km	33
Total number of landslide events	No.	86
Number of events per year	No.	5.3

Jaiswal et al. (2011). A total of 565 landslides were catalogued, which were triggered on 86 different dates. The number of landslides per triggering event (i.e., date on which landslide occurred) varies from 1 to 88, and the number of events per year varies from 1 to 11. Since the railway slip register is purposely meant for tendering contracts for debris clearance and is updated soon after the landslide-triggering event, therefore, it records all landslides and of all sizes triggered by an event. The presence of data on a substantial fraction of small landslides (see Table 1) and the availability of records of 86 triggering events in 16-year time (average ~5.3 triggering events/year), including events that triggered even one landslide, clearly indicate that the landslide inventory along the railroad is complete at least for the time period 1992–2007. Figure 2 shows the spatial distribution of landslides (represented as points) along the railroad in different years. In most years, the number of landslides recorded remains less than 40, except in 1992, 2001, 2004, and 2006 when more than 50 landslides were triggered along the railroad. No landslides occurred in 1995.

3 Analyzing the volume–frequency (*v*/*f*) relationship

To study the statistics of landslide sizes (area or volume), researchers have used the cumulative or the non-cumulative number–size distributions. Stark and Hovius (2001) suggested that a non-cumulative distribution is appropriate to observe any crossover from a non-power-law to a power-law scaling. In the present analysis, a non-cumulative distribution was used for obtaining probability density of landslide volumes adopting the method given by Malamud et al. (2004). At first, a frequency histogram of volume was obtained at different class intervals. The frequency density was computed by normalizing the number of landslides in each bin by its width. The probability density was then obtained by further normalizing the frequency density in each bin by the total number of landslides in the inventory. The probability density $p(V_L)$ can be expressed as:

$$p(V_L) = \frac{1}{N_{LT}} \frac{\delta N_L}{\delta V_L} \quad (1)$$

where δN_L is the number of landslides with volumes between V_L and $V_L + \delta N_L$, and N_{LT} is total number of landslides in the inventory.

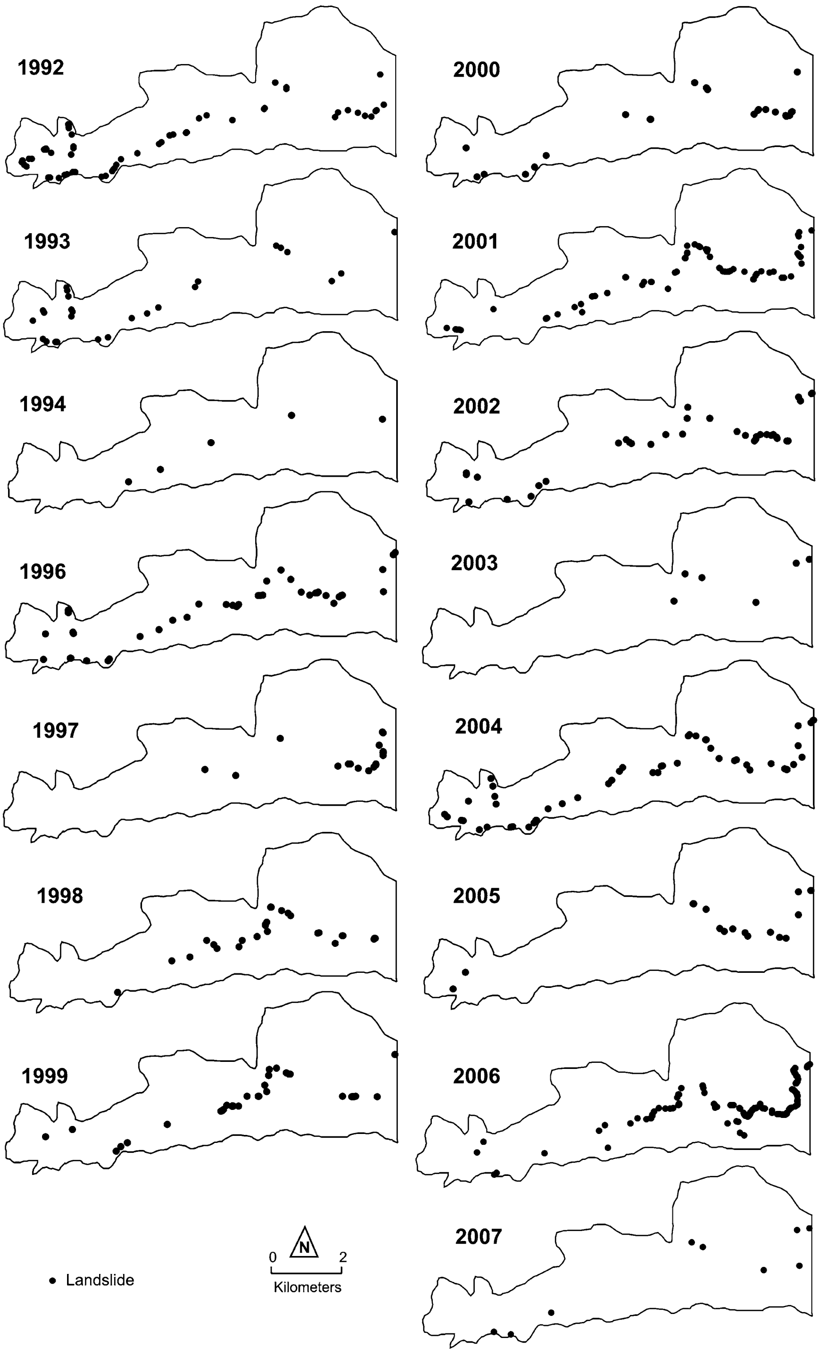

Fig. 2 Spatial distribution of landslides in different years along the railroad. Landslides are shown as *points* irrespective of their size

3.1 Probability density of landslide volumes for the period from 1992 to 2007

We first considered all landslides that occurred between 1992 and 2007 ($N_{LT} = 565$) for the probability density calculation. Figure 3 shows the probability density, $p(V_L)$, obtained using Eq. (1). The observed distribution shows a distinct roll-over for failure volumes less than 20 m^3. The linear portion of the curve with failure volumes >20 m^3 shows a negative power relationship with power-law scaling exponent β as 1.8 (determination coefficient $r^2 = 0.98$).

A distribution pattern similar to Fig. 3 was observed in many case studies, though with different values of β and the range of volumes showing power fitting. Brunetti et al. (2009) summarizes 15 case studies of the probability density distribution of landslide volumes. Out of the 15 cases, only two were for rainfall-induced debris slides, with β varying from −2.94 to −1.87, and the remaining cases were for rock failures. For the two cases of debris slides, the distribution shows roll-over for failure volumes of less than 200 m^3. Dai and Lee (2001) studied the inventory of 5,000 landslides (with 69% slides on cut slopes) belonging to the Geotechnical Engineering Office (GEO), Hong Kong, and analyzed the cumulative frequency–volume distribution using 2,811 landslides for which information on volume was available. The distribution shows roll-over for volumes less than 10 m^3 and power fit with scaling exponent, α, as −0.79 for volumes ranging between 10^1 and 10^5 m^3. For the 800 landslides studied by Fujii (1969), the cumulative number–volume distribution correlated with a negative power-law relation with $\alpha = 0.85$. It should be noted that for a non-cumulative power-law distribution with exponent $\beta > 1$, the corresponding cumulative

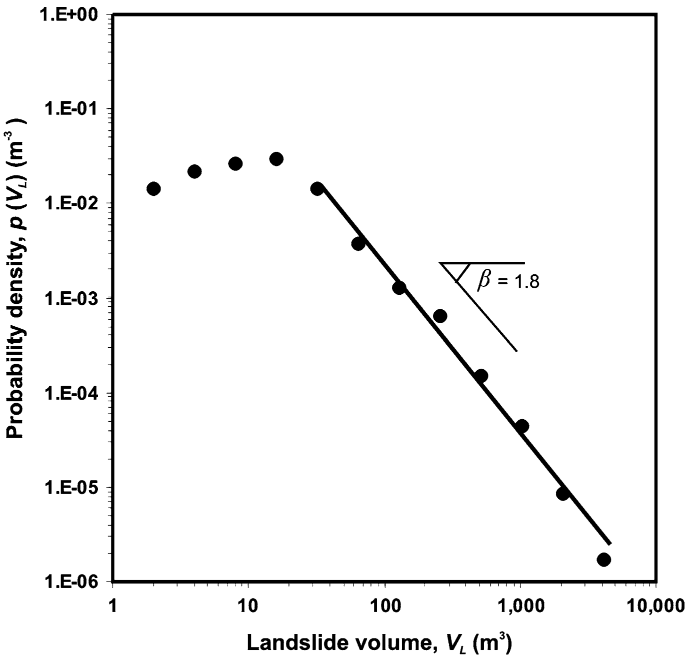

Fig. 3 Probability density of landslide volumes for the period 1992–2007. The *black line* is the fitted power trend to the linear portion of the probability density curve (β is −1.8)

distribution, obtained by integration and summation, has exponent $\alpha = \beta - 1$ (Guzzetti et al. 2002).

The probability density distribution shown in Fig. 3 thus fits well with majority of the observed volume–frequency relations studied in many locations worldwide. In this study, the availability of a substantially complete landslide inventory for individual years provides us an additional opportunity to analyze the volume–frequency relation for each year separately. This will help us in understanding the probability distribution of landslide volumes in different landslide events having different spatial distribution of landslides and different intensity of a trigger (rainfall).

3.2 Probability density distribution of landslide volumes in different years

Figure 4 shows the non-cumulative probability density, $p(V_L)$, of landslide volumes obtained based on Eq. (1) for individual year for the period from 1992 to 2007 using the landslide inventory shown in Fig. 2. Ideally, for such an analysis, different event inventories should be analyzed, but this was not possible due to lack of a sufficient number of landslides in all events (as some events contained only one landslide). Therefore, the total landslides per year were considered in the analysis. For the 15-year data (between 1992 and 2007), 15 curves were obtained (Fig. 4). Inspection of the figure reveals that not all distributions show similar curves, rather three distinct types of distribution curves are observed:

- Type-I, where the probability density distribution of volumes shows a negative power-law scaling for all range of volumes (e.g., 1993, 1994, 1997, 1998, 1999, 2001, 2002, 2003, and 2007);
- Type-II, where the distribution exhibits a distinct and sharp bend of the curve (positive slope) for volumes less than 30 m^3 (e.g., 1992, 2004, and 2005); and
- Type-III, where the distribution shows gentler flattening of the curve for volumes less than 100 m^3 (e.g., 1996, 2000, and 2006).

This indicates that the general nature of the distribution of landslide size is not similar across all landslide events of the study area. Table 2 summarizes the characteristics of the probability density distribution of landslide volumes for each year. Differences were observed in the maximum volume of landslides in each year and the negative power scaling exponent of the fitted range. The maximum volume in most of the years lies between 100 and 1,000 m^3 except in 2003 and 2005, where the maximum volume is less than 100 m^3. The power exponent β for the fit volume range varies from -0.96 to -2.4.

Although the study area is small and landslides are of the same type and triggered by the same natural phenomena under similar geo-environmental conditions, but still the number of landslides and the volume–frequency distribution in each year differ. It was expected that years with a similar spatial distribution of landslides should also show identical volume–frequency relationships. However, this is not the case, for example in 1992, 1996, 2001, and 2004. Although the spatial distribution of landslides is similar in these years (Fig. 2), the probability density distribution shows three different distribution curves (Type-I, II, and III) that differ both in the range of volume (10^1 to 9×10^2 m^3) and in the β value (1.4–2.4). Similarly, the spatial distribution of landslides in 1998, 1999, and 2002 is also comparable, and although they belong to Type-I distribution pattern, they differ in the range of volumes, showing power fit and the corresponding β value.

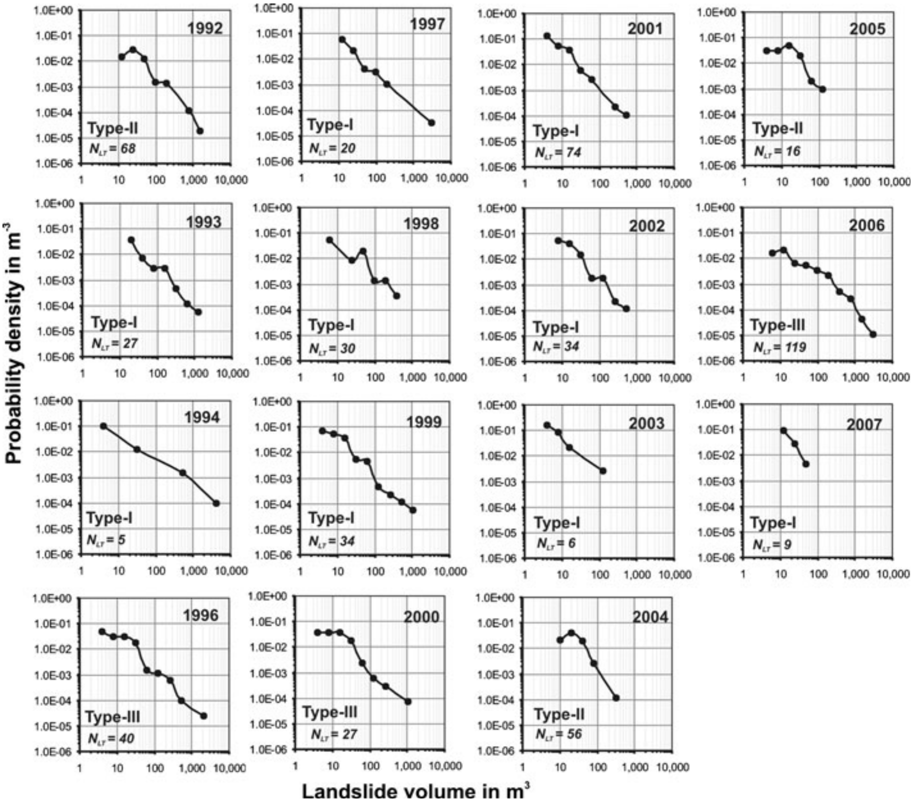

Fig. 4 Probability density of landslide volumes for different years. N_{LT} is total number of landslides in the inventory

4 Effect of terrain and rainfall on the *v*/*f* distribution

The differences in the number of landslides that occurred in a year and the volume–frequency could be due to changes in the local terrain conditions and the amount of rainfall. Similar observation was also made by Dai and Lee (2001) in a case study of Hong Kong. The authors showed landslide volume-dependency on the intensity of rainfall and indicated that the number of landslides varies according to the rainfall intensity.

To analyze the effect of the local terrain conditions on the frequency distribution of landslide volumes, the entire railroad corridor was divided into four sections (Fig. 5). A terrain profile for each section is prepared to highlight the general slope condition. In section 1, the terrain has a relief of about 400 m above the railroad before a major slope break (gentler slope). The average slope is 32° and contains regolith with a thickness from 1 to 10 m. In section II, relief above the railroad is about 350 m, and most of the steep slopes contain rock outcrops. In the other parts, the relief is less than 150 m before a major slope break. In section III, relief above the railroad is less than 100 m before a major slope break and above it the slopes are gentler and covered by tea plants. In section IV, relief above the railroad is less than 50 m before a major slope break. Above this break, the slopes are covered by tea plants and settlements. In this section, the regolith thickness

Table 2 Characteristics of the probability density distribution of volumes of rainfall-induced debris slides V_L (in m^3) for different years

Year	Number of slides	Distribution type for fit range $p(V_L) = k\ V_L^{-\beta}$	Volume range (in m^3)	Fitted range	r^2
1992	68	$\beta = 1.7$	$6–9 \times 10^2$	$2 \times 10^1–9 \times 10^2$	0.97
1993	27	$\beta = 1.5$	$1 \times 10^1–8 \times 10^2$	$1 \times 10^1–8 \times 10^2$	0.97
1994	5	$\beta = 0.96$	$2–4 \times 10^3$	$2–4 \times 10^3$	0.98
1996	40	$\beta = 1.4$	$2–2 \times 10^3$	$3 \times 10^1–2 \times 10^3$	0.95
1997	20	$\beta = 1.3$	$6–2 \times 10^3$	$6–2 \times 10^3$	0.98
1998	30	$\beta = 1.1$	$3–3 \times 10^2$	$3–3 \times 10^2$	0.87
1999	34	$\beta = 1.4$	$2–9 \times 10^2$	$2–9 \times 10^2$	0.96
2000	27	$\beta = 1.5$	$2–6 \times 10^2$	$3 \times 10^1–6 \times 10^2$	0.92
2001	74	$\beta = 1.5$	$2–5 \times 10^2$	$2–5 \times 10^2$	0.98
2002	34	$\beta = 1.5$	$4–3 \times 10^2$	$4–3 \times 10^2$	0.96
2003	6	$\beta = 1.2$	$2–8 \times 10^1$	$2 \times 10^1–8 \times 10^1$	0.98
2004	56	$\beta = 2.4$	$5–1 \times 10^2$	$4 \times 10^1–1 \times 10^2$	0.99
2005	16	$\beta = 2.0$	$2–1 \times 10^2$	$16–1 \times 10^2$	0.95
2006	119	$\beta = 1.8$	$3–3 \times 10^3$	$2 \times 10^2–3 \times 10^3$	0.98
2007	9	$\beta = 2.1$	$6–2 \times 10^2$	$6–2 \times 10^2$	0.98

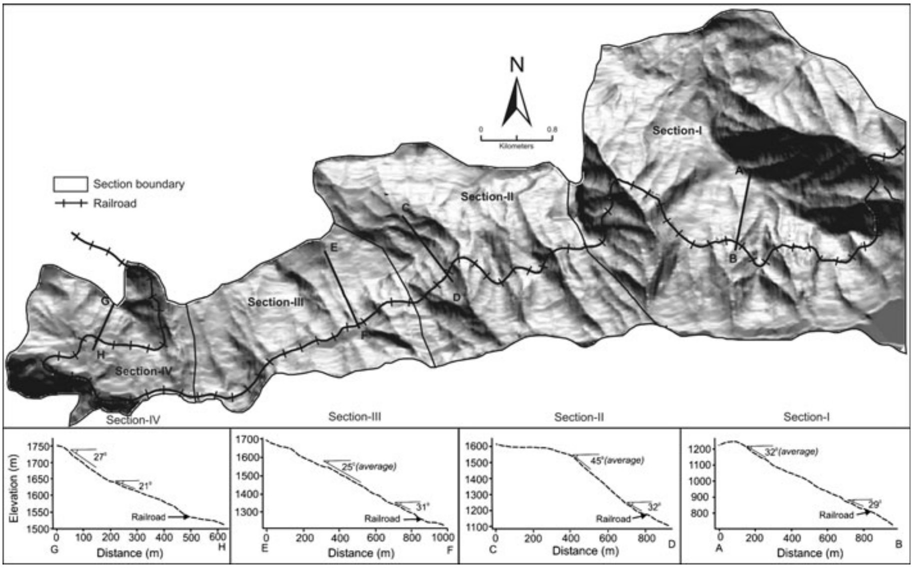

Fig. 5 Four sections (I, II, III, and IV) along the railroad corridor. And their corresponding terrain profile is shown in *boxes*. The same sections were previously used to compute threshold rainfall for landslides on cut slopes (Jaiswal and van Westen 2009)

varies from more than 5 m to a maximum of 20 m. The above sections also have different threshold value of rainfall that can trigger landslides on cut slopes (Jaiswal and van Westen 2009). The threshold value increases from section I to section IV such that section IV requires relatively large amount of rainfall to trigger landslides.

The cumulative percentage of total landslides within the four sections was calculated. The cumulative percentage distribution shows three distinct distribution patterns, for example:

(1) in 1992 and 1993, a small percentage of landslides (26%) occurred within section I and there is a rise in the landslide frequency toward section IV;
(2) in 1997 and 2005, a high percentage of landslides (>85%) occurred within section I; and
(3) in 1996 and 2004, distribution of landslides is uniform in all sections.

The effect of terrain and rainfall on the volume–frequency distribution of landslides was analyzed for the three cases. The cumulative percentage distribution of landslides in the years 1992 and 1993 shows a similar trend (Distribution Pattern 1), which means that the probability density distribution of their volume is expected to be similar as well. The 1993 distribution shows a power fit for the entire range of volumes while the one from 1992 shows roll-over for small landslides. In 1992, there is a uniform rise in the percentage of landslides from section II (20%) to section IV (30%), whereas in 1993, there was a sharp rise, i.e., from 10% in section II to 42% in section IV, indicating a sudden increase in the number of landslides in section IV. The gentler terrain with small relief in section IV probably resulted in a larger number of small landslides in 1993, thereby leading to a power distribution of landslide volumes for all range of data.

In 1997 and 2005, more than 85% of the landslides occurred within section I (Distribution Pattern 2). Though both 1997 and 2005 have a similar percentage distribution of landslides along the railroad, they differ in the range of volumes and probability density curves. In 2005, the inventory contains 16 slides with a maximum volume of 100 m^3 and a mean of 21 m^3, and in 1997, the inventory contains 20 slides (mean = 134 m^3 and maximum = 1,944 m^3). The difference in the total number of landslides and the range of volumes could be due to differences in the amount of rainfall. On November 25, 2005 rainfall occurred in all sections, but only in section I rainfall, it was more than the threshold value (daily rainfall (R_d) = 153 mm and 5 days antecedent rainfall (R_{5ad}) = 30 mm). In section III, the rainfall was below the threshold value (R_d = 139 mm and R_{5ad} = 6 mm), and in section IV, it was slightly above the threshold value (R_d = 200 mm and R_{5ad} = 54 mm) but did not trigger any landslide. The rainfall on November 27, 1997 was very high in section I with $R_{5ad} > 320$ mm and $R_d > 50$ mm. The high rainfall in 1997, which was well in excess of the required threshold value, might have resulted in landslides of relatively large volumes.

In 1996 and 2004, landslides are uniformly distributed along the railroad (Distribution Pattern 3) with a maximum recorded volume of 2,000 m^3 and a mean of 120 m^3 in 1996, and a maximum of 200 m^3 and a mean of 27 m^3 in 2004. In both years, about 49% of landslides occurred within section I but with different mean value and with different probability density curve. This difference was because the average daily (R_d = 28 mm) and antecedent rainfall (R_{5ad} = 155 mm) during the main event of 2004 was less than the main event of 1996 (R_d = 155 mm and R_{5ad} = 334 mm). Thus, if there is a continuous high rainfall of more than the threshold value then the same terrain can trigger more landslides of large volumes.

From the above study, it is evident that the number and sizes of landslides varies according to the rainfall intensity and the local terrain conditions.

5 Estimation of the probability of landslide volume

One purpose of analyzing the volume–frequency distribution of landslides is to estimate the probability of landslide volume and to use the estimate in landslide hazard analysis.

The probability of landslide size can be obtained from its probability density distribution by fitting a function to the curve (Stark and Hovius 2001; Malamud et al. 2004). But due to the large variability in the frequency of landslide volume (Fig. 4, Table 2), it is evident that a single probability density distribution is not enough to explain the probability of landslide sizes on cut slopes for all triggering events and hence any one curve cannot totally represent the entire study area. Since this difference was due to the variation in the intensity of landslide-triggering rainfall and due to the variation in the local terrain conditions; therefore, it is appropriate to estimate probability as the frequency percentage of landslide volumes separately for each landslide event.

Two sets of probabilities were calculated: for years with or without more than 100 landslides. This is because the event inventories indicate that if rainfall triggers less than 100 landslides in a year then the majority (>55%) has a volume less than 100 m^3. These are the events that occur more frequently, have low rainfall intensity, and trigger more number of small landslides. For triggering events resulting in more than 100 landslides (e.g., November 14, 2006), a larger proportion consists of landslides with volumes greater than 100 m^3. Such triggering events occur less frequently.

The frequency percentage of landslide size in different years was calculated, which was taken as the probability of occurrence of a particular landslide size on cut slopes (Table 3).

6 Discussion and conclusions

Analysis of the probability densities, $p(V_L)$, of the 15 inventories for each year between 1992 and 2007 indicates that six inventories exhibit negative power-law scaling of $p(V_L)$ for landslides exceeding a threshold volume, and nine inventories show a negative power-law distribution for all range of volumes. This observation is in accordance with the distribution pattern of landslide volumes given in Brunetti et al. (2009). The researchers have shown that irrespective of space and type of failures and their triggering mechanisms, the probability density distribution of landslide volume exhibits power-law behavior for failures exceeding a threshold volume. Inspection of other literature reveals that contrary to the above observation the size of landslides depends on local scale of the slope (slope length) and terrain geometry (Guzzetti et al. 2002; Hungr et al. 2008), and on rainfall intensity and the presence of man-made features (Dai and Lee 2001). The present findings also support to the latter theory because the analysis clearly indicates that, even within a small catchment area, the number of landslides, the volume–frequency relationship, and the range of volumes vary according to the rainfall intensity and the local terrain conditions. This study confirms that landslide volumes have a dependency on the

Table 3 Probability of landslide size on cut slopes

Landslide-triggering event	Probability of landslide of volume		
	$<10^2$ m^3	10^2–10^3 m^3	$>10^3$ m^3
<100 landslides per year	0.5–1 (avg. = 0.85)	0.01–0.33 (avg. = 0.13)	0–0.16 (avg. = 0.02)
≥100 landslides per year	0.39	0.53	0.08

local morphology and rainfall intensity, at least for cut slopes and, therefore, any attempt to use a regionally derived volume–frequency relation for estimating the probability of landslide size could lead to incorrect predictions.

Brunetti et al. (2009) studied non-cumulative distributions of landslide volumes of 19 inventories, including rock and debris slides and submarine failures. The tails of the distributions (volume $\geq 10^2$ m^3) were shown to follow negative power-laws, with $1.0 \leq \beta \leq 1.9$, average of $\beta = 1.3$, median 1.3, and standard deviation 0.3. In comparison with this, the power-law for the fit range in our study also shows variation in the β value (Table 2), with $0.96 \leq \beta \leq 2.4$, average of $\beta = 1.5$, median 1.5, and standard deviation 0.39. Most of the inventories correlated well with a power-law distribution, while some (e.g., 1992, 1996, 2000, 2004, 2005, and 2006) exhibited a roll-over of probability densities for small V_L. This is similar to the roll-over identified in the probability density distribution of the area of landslides (Stark and Hovius 2001; Guzzetti et al. 2002; Guthrie and Evans 2004; Malamud et al. 2004; Brardinoni and Church 2004; Catani et al. 2005). The researchers attributed the roll-over as a result of incompleteness of landslide inventory (Stark and Hovius 2001; Brardinoni and Church 2004; Catani et al. 2005) or a phenomenon related to slope stability processes (Guthrie and Evans 2004; Malamud et al. 2004). But, since our inventory is complete, we also attribute the roll-over as a "real effect" and not an artifact due to sampling discrepancies.

In this research, we have used a substantially complete landslide inventory for a relatively small study area. The inventory was complete in terms of all landslides and of all sizes triggered in the study area; however, it is possible that some of the "event inventories" may not be complete if they have triggered landslides outside the study area. Nevertheless, for the volume–frequency analysis, it is important that the inventory must record all landslides within the modeled area because the ultimate goal is to obtain the probability of landslide size for a certain study area and not for the triggers.

The landslides in the study area are relatively small in size in comparison with the known mass movements in the Nilgiri hills, such as those shown in Seshagiri et al. (1982). Some landslides are of volume less than 5 m^3. One could argue that small slides are actually local slips, which may not be of much significance. This could be true if such slides are on natural slopes but along a railroad even small slips can result in train accident. The inventory suggests that most (92%) of the landslides are of volume less than 500 m^3. Small landslides in fact constitute most part of landslide inventories containing cut slope failures. For example, out of the 2,811 landslides reported in the GEO database of Hong Kong for the period from 1992 to 1997, about 90% are of volume less than 50 m^3 (Dai and Lee 2001).

The probability values derived in this study are based on an inventory of a limited time period (1992–2007) containing less than 600 landslides. The probability density curves show different distribution patterns for the total inventory (Fig. 3) and for the individual years (Fig. 4). It is expected that the curve would be different for an inventory covering the entire Nilgiri hills. Thus, for a better understanding of the volume–frequency relationship, we require to study more event inventories containing large number of landslides and covering a larger study area. Based on the present study, we conclude that: (1) the frequency distribution of landslide volumes is related to the location in the study area and to the magnitude of the triggering event; (2) for rainfall-induced landslides, the number of landslides and the range of volumes depend on the variation in the local terrain and rainfall conditions; (3) the probability density distribution of landslide volumes can either show a negative power-law distribution for all range of volumes or show a distinct roll-over or a flattening of curve for small volumes, and (4) the roll-over for small landslide volumes could be real and not an artifact due to the sampling discrepancies.

The present study considered only those landslides that occurred on cut slopes, and therefore the conclusions are limited to shallow debris slides on cut slopes along transportation corridors with similar terrain conditions and triggering factors.

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References

Brardinoni F, Church M (2004) Representing the landslide magnitude-frequency relation: Capilano river basin, British Columbia. Earth Surf Process Landf 29:115–124

Brardinoni F, Slaymaker O, Hassan M (2003) Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data. Geomorphology 54:179–196

Brunetti MT, Guzzetti F, Rossi M (2009) Probability distributions of landslide volumes. Nonlinear Process Geophys 16:179–188

Catani F, Casagli N, Ermini L, Righini G, Menduni G (2005) Landslide hazard and risk mapping at catchment scale in the Arno River basin. Landslides 2:329–342

Corominas J, Moya J (2008) A review of assessing landslide frequency for hazard zoning purposes. Eng Geol 102:193–213

Dai FC, Lee CF (2001) Frequency-volume relation and prediction of rainfall-induced landslides. Eng Geol 59:253–266

Fell R, Finlay PJ, Mostyn GR (1996) Framework for assessing the probability of sliding of cut slopes. In: Senneset K (ed) 7th International symposium on landslides, vol 1. A.A. Balkema, Trondheim, pp 201–208

Fell R, Corominas J, Bonnard C, Cascini L, Leroi E, Savage WZ (2008) Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Eng Geol 102:85–98

Fujii Y (1969) Frequency distribution of the magnitude of landslides caused by heavy rainfall. J Seismol Soc Jpn 22:244–247

Guthrie RH, Evans SG (2004) Magnitude and frequency of landslides triggered by a storm event, Loughborough inlet, British Columbia. Nat Hazard Earth Syst Sci 4:475–483

Guzzetti F, Carrara A, Cardinali M, Reichenbach P (1999) Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31:181–216

Guzzetti F, Malamud BD, Turcotte DL, Reichenbach P (2002) Power-law correlations of landslide areas in Central Italy. Earth Planet Sci Lett 195:169–183

Hovius N, Stark CP, Allen PA (1997) Sediment flux from a mountain belt derived by landslide mapping. Geology 25:231–234

Hungr O, Evans SG, Hazzard J (1999) Magnitude and frequency of rock falls and rock slides along the main transportation corridors of south-western British Columbia. Can Geotech J 36:224–238

Hungr O, McDougall S, Wise M, Cullen M (2008) Magnitude-frequency relationships of debris flows and debris avalanches in relation to slope relief. Geomorphology 96:355–365

Jaiswal P, van Westen CJ (2009) Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds. Geomorphology 112:96–105

Jaiswal P, van Westen CJ, Jetten V (2011) Quantitative assessment of landslide hazard along transportation lines based on historical records. Landslides. doi:10.1007/s10346-011-0252-1

Malamud BD, Turcotte DL, Guzzetti F, Reichenbach P (2004) Landslide inventories and their statistical properties. Earth Surf Process Landf 29(6):687–711

Picarelli L, Oboni F, Evans SG, Mostyn G, Fell R (2005) Hazard characterization and quantification. In: Hungr O, Fell R, Couture R, Eberhardt E (eds) Landslide risk management. Taylor and Francis, London, pp 27–61

Seshagiri DN, Badrinarayanan S, Upendran R, Lakshmikantham CB, Srinivasan V (1982) The Nilgiri landslides. GSI misc pub no 57

Stark CP, Hovius N (2001) The characterization of landslide size distributions. Geophys Res Lett 28(6):1091–1094