Rainfall-based temporal probability for landslide initiation along transportation routes in Southern India

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ABSTRACT: We present a temporal probability model for the initiation of shallow translational debris slides along cut slopes of a railroad sector in southern India, for which an extensive landslide database was available, covering a time span of 15 years. The model is based on rainfall thresholds and gives the likelihood of occurrence of rainfall that can trigger landslides with a certain density. Rainfall thresholds were established based on the relationship of daily and antecedent rainfall. The temporal probability was calculated as the joint probability of annual exceedance probability of the rainfall threshold, determined using a Poisson probability model and the probability of landslide occurrence once the threshold had been exceeded. The model was tested for a 19 kilometer long railroad alignment in the Nilgiri hills of southern India. The annual probability varies from 0.27 to 0.49. The result of the model was extended to the nearby roadroute, which had similar geo-environmental condition. More than 60% of the recorded landslides along the road occurred where temporal probability was high (> 0.40). The temporal probability derived from the model forms the basis for future landslide hazard analysis along the transportation routes.

1 INTRODUCTION

Varnes (1984) defined landslide hazard as "the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon". Thus, landslide hazard has two independent components: the spatial and the temporal components. Some workers have also included landslide magnitude or intensity as a component to evaluate damages related to a landslide (Guzzetti et al. 1999 and 2005). Numerous publications are available on the determination of the spatial susceptibility, but much less work was done to estimate the temporal probability of landslides. Some models used landslide occurrence in an area to calculate the temporal probability, by assuming that the rate of occurrence of landslide events will remain the same in future under the given geo-environmental conditions (Coe et al. 2000, Guzzetti et al. 2005). These models require that a sufficiently complete landslide inventory is available, and the results obtained are generally only applicable to the modeled area.

The temporal probability of rainfall induced landslides can be analyzed by evaluating the temporal probability of the rainfall events themselves, combined with an analysis of the rainfall threshold. A rainfall threshold is the minimum intensity or duration of rainfall required to trigger a landslide, and can be calculated using empirical methods. Rainfall thresholds are established investigating the rainfall conditions that have resulted in landslides and this includes intensity, duration and cumulative precipitation during an event (Wieczorek 1987, Crozier 1999, Chleborad 2000, Aleotti 2004, Jakob et al. 2006). In this paper, we propose a method to determine the temporal probability for landslide initiation using the probability of exceedance of a rainfall threshold and the probability of occurrence of landslides related to the rainfall threshold. The method is applied along a railway route in southern India, for which we obtained historical landslide and rainfall information.

2 SITE CHARACTERISTICS

The study area includes a 19 km long small-track historic railway and a 26 km long national highway connecting Mettupalayam and Coonoor (Fig. 1). Both the transportation routes run parallel on the southern face of the Nilgiri plateau, and are built on soil and laterite underlain by charnockite and garnetiferrous quartzo-felspathic gneisses belonging to the Charnockite Group of Archaean age (Seshagiri & Badrinarayanan 1982). In the area, landslides are mostly shallow translational debris slides and debris flows, and occur primarily in the period from October to December due to rainfall (Fig. 2). Of the 790 landslides identified from historical records in the 21-year period 1987-2007, including railway slip registers (from 1992 to 2006) and technical reports (from 1987 to 2007), 94% occurred along cut slopes and 6% in natural slopes. The majority of the failures (97.2%) were shallow translational debris slides, and only 2.4% were debris flows. The volume of the failed material reported by the historical records ranges from 2 to 1.5×10^5 m^3 (average = 404 m^3). The historical records also provide information on the date of occurrence of the landslides.

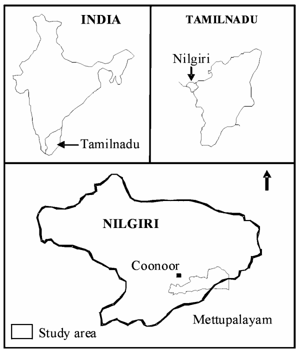

Figure 1. Map showing location of the study area.

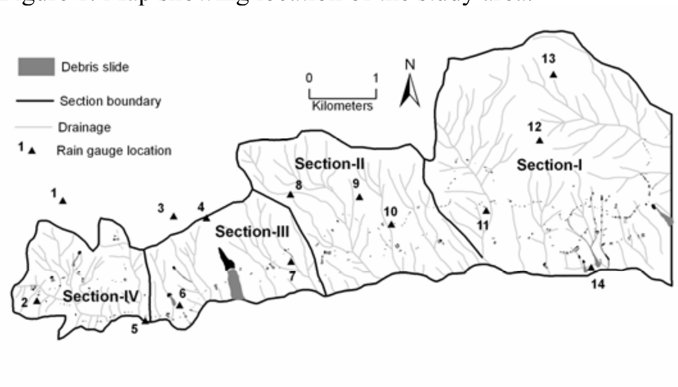

Figure 2. Landslide and rainfall information. Black and grey polygons represent location of landslides. Triangles show the location of 14 rain gauges: 1- Coonoor, 2- Glandale, 3- Upassi, 4- Tiger hill, 5- Runneymede, 6- Katteri farm, 7- Marapallam, 8- Singara_UD, 9- Singara_LD, 10- Benhope, 11- Burliyar, 12- Mutteri, 13- Adderley and 14- Kallar. Sections I, II, III and IV are the areas used for determining rainfall thresholds.

Here, we use the term 'landslide triggering event' for those days for which one or more landslides were triggered. During the investigated period, from 01-01-1987 to 31-10-2007, 94 individual landslide triggering events were differentiated, of which 71 occurred in the months from October to December. Analysis of the daily rainfall records for nine rain gauges revealed that the area experiences rainfall in two periods: from April to August (normal monsoon), and from October to December (retreating monsoon), of which November is the wettest month. The minimum and maximum annual rainfall varies from 750 mm to more than 3000 mm. The number of rain days varies, depending on the season and the area. The maximum rainfall recorded in a single day between October and December is twice the amount between April and August.

3 PROBABILITY MODEL

In the study area, landslides are found to be invariably associated with certain intensity of rainfall e.g. on 14-11-2006 all landslides occurred only around Burliyar area where the recorded rainfall was more than 150 mm. Thus, for our analysis, we assume that the probability of occurrence of a landslide is related to the probability of occurrence of the triggering rainfall. To determine the threshold, the input information consists of the record of the daily rainfall $R_d(t)$, in mm day^{-1}. For a landslide {L} to occur, the daily rainfall must exceed a threshold, which is a function R(t) of the total rainfall in a period, and of the amount of the antecedent rainfall $R_{ad}(t)$,

$$R(t) = f[R_d(t), R_{ad}(t)] \quad (1)$$

where, R(t) is the rainfall in a given period (e.g. daily), in mm, and $R_{ad}(t)$ is the antecedent rainfall, also in mm. The function of R defines the probability of occurrence of the landslide L: P{L}. If R_T is the threshold value of R then,

$$P[L \mid R > R_T] = 1$$
$$P[L \mid R \leq R_T] = 0 \quad (2)$$

Thus, in this simplified model, landslides always occurs when R exceeds R_T, and landslide never occur when R is less than or equal to R_T. In the former case, the probability of occurrence of a landslide P{L} consists of the exceedance probability of $P[R > R_T]$.

In reality, the threshold may be exceeded without resulting in a landslide. This may be due to other factors which influence the initiation of a landslide locally and are not fully understood (Aleotti & Chowdhury 1999). The difference can be reduced when the probability is viewed as the conditional probability of a given threshold exceedance $[P\{R > R_T\}]$ and the probability of occurrence of a landslide [P{L}], given the exceedance (Floris & Bozzano 2008). Thus, the probability of landslide occurrence is the intersection of two probabilities:

$$P\{(R>R_T)\cap L\}=P\{R>R_T\}P\{L \mid R>R_T\} \quad (3)$$

The probability of $\{R > R_T\}$ can be obtained by determining the exceedance probability of the rainfall threshold. The probability of $\{L \mid R > R_T\}$ relies on the frequency of occurrence of a landslide when the threshold is exceeded.

4 ESTABLISHING THE RAINFALL THRESHOLD

To determine the rainfall threshold, we selected the shallow translational debris slides and debris flows occurred in the cut slopes along the railway in the months from October to December. This subset represents 82% (648) of the total number of recorded landslides. For the study, we selected a threshold model based on antecedent rainfall, because only daily rainfall data were available. The 5-

day antecedent rainfall, determined adopting the method suggested by Zezere et al. (2005), was considered suitable for the analysis.

To determine the rainfall threshold (R_T), a scatter plot was prepared showing daily rainfall against the corresponding 5-day antecedent rainfall, for each day with one or more triggered shallow landslides. For the purpose, the 19 km long transportation corridor was divided into four sections (Fig. 2), based on topography, land use types, and terrain gradient. Rainfall conditions at each section were determined from the nearest rain gauge. The sections east of Burliyar, around Hillgrove, around Marapallam, and east of Runneymede up to Coonoor, are represented by the threshold equation: $R_T = 66 - 0.93\ R_{5ad}$, $R_T = 165 - 1.32\ R_{5ad}$, $R_T = 230 - 1.32\ R_{5ad}$, and $R_T = 250 - 1.5\ R_{5ad}$, respectively (Fig. 3).

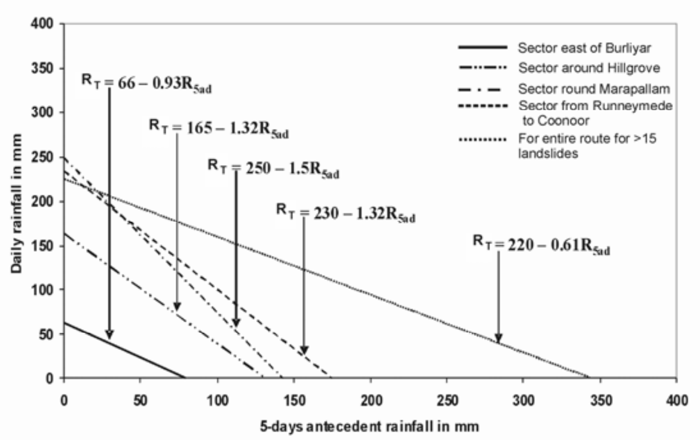

Figure 3. Thresholds for shallow translational debris slides and debris flows, for different sections along the railway. R_T is rainfall threshold and R_{5ad} is 5-day antecedent rainfall.

In the above mentioned threshold equations, R_T is the amount of rainfall above which a landslide occurs, given the 5-day antecedent rainfall amount (R_{5ad}).

Besides the rainfall threshold for the four individual sections, a general threshold was established for major landslide events. During the period 1992-2006, the railway route has experienced 14 landslide-triggering rainfall events that have resulted in several landslides per day (from 15 to 118 failures). Such events have affected different parts of the route in different years. The determination of a threshold for the individual sections was not possible, due to the paucity of data. A threshold for the entire railway route was determined for the events that have individually resulted in 15 or more landslides. This threshold is given by the equation $R_T = 220 - 0.61\ R_{5ad}$ (Fig. 3).

For all the listed thresholds, the lower boundary of the threshold line was set to zero daily rainfall. In a few cases, landslides were reported when no rainfall was measured on any specific day. We attribute the failures to pore pressure rising due to water percolating from upslope areas. In our model, some of the daily rainfall related to no-landslide events have occurred above the threshold line. These are events which rainfall was relatively high, but did not result in landslides.

5 TEMPORAL PROBABILITY OF LANDSLIDE INITIATION

The annual exceedance probability (AEP) is the estimated probability that an event of a specific magnitude will be exceeded in any given year (Fell et al. 2005). For a given rain gauge, the AEP of a threshold [$P\{R > R_T\}$] was determined using a Poisson probability model. This model has been used to determining the exceedance probability of landslides in time by, e.g., Coe et al. (2000) and Guzzetti et al. (2005). According to the Poisson model, the exceedance probability or the probability of experiencing one or more landslides during time 't' is given by

$$P[N(t) \geq 1] = 1 - \exp(-t / \mu) \quad (4)$$

where μ is the mean recurrence interval between successive landslides, which can be obtained from the multi-temporal landslide inventory data.

To determine the AEP of the rainfall threshold for a particular area, the rainfall threshold (R_T) is calculated from the corresponding threshold equation, and the result is subtracted from the daily rainfall (R). Each phase of continuous positive values ($R > R_T$) is considered as the period of maximum likelihood for possible landslide initiation. In this study, the AEP calculation was based on the 15-year daily rainfall data from 1992 to 2006 in the months from October to December for landslide initiation along the railway route.

In section east of Burliyar (Fig. 2), the threshold was exceeded 53 times in 15 years, in the considered months. From equation 4, the annual exceedance probability [$P\{R > R_T\}$] during these months is 0.97. For the other sections, adopting the threshold equations given in Figure 3, the rainfall threshold was exceeded 29, 27, 30, and 15 times, for section around Hillgrove, around Marapallam, east of Runneymede up to Coonoor and for entire route, respectively. Using equation 4, the corresponding exceedance probability [$P\{ R>R_T \}$] were determined as 0.85, 0.83 0.86, and 0.63, respectively (Table 1).

After defining the AEP for the rainfall threshold [$P\{R > R_T\}$], the next step consisted in the assessment of the probability of occurrence of a landslide when the threshold is exceeded. The frequency can be established from the rainfall and the landslide records, for different sections of the railway line (Fig. 2). From this frequency, the probability of {L} conditioned on {$R > R_T$}, i.e. $P\{L|R>R_T\}$, can be estimated. To achieve this, the transportation route was further subdivided into smaller topographic units based on the variation in the land use type and height of cut slope. This was done to account for variation in the distribution of landslides in different units resulting from the unequal response of the terrain towards the threshold due to changes in local relief. In field it was observed, particularly in east of Burliyar that same rainfall intensity over the section had resulted in different number of landslides and this is because of differences in the height of cut slope and availability of larger upslope area for landslide to retrograde.

The railway and also the road routes were partitioned into eight topographic units. To the east of Burliyar, the rainfall threshold $\{R_T\}$ was exceeded 53 times in the 15-year period 1992-2006 (Table 1). In 17 cases, landslides were reported in unit I, corresponding to an estimated probability $P\{L| R > R_T\}$ of 17/53, or 0.32. Results for the other topographic units are listed in Table 1.As indicated earlier, the temporal probability of landslide initiation was calculated by multiplying: (i) the annual exceedance probability $P\{R > R_T\}$, i.e. a probability of threshold being exceeded in a year, by (ii) the probability of landslide initiation given that the threshold is exceeded $P\{L| R > R_T\}$.The annual temporal probabilities and their corresponding return periods for different topographic units are given in Table 1. The probability of having one or more rainfall events that can trigger landslides in any given year varies from 0.27 to 0.49. All these events are capable of triggering one or more landslides, in the months from October to December.

Table 1. Temporal probability of landslide initiation along different units of the railway route.

Area	Unit	TEq	NEL	$P[R>R_T]$	$P[L \mid R>R_T]$	TP
East of Burliyar	I	$R_d = 66 - 0.93\ R_{5ad}$	> 1	0.97	0.32	0.31
	II			0.97	0.51	0.49
	III			0.97	0.43	0.41
Around Hillgrove	IV	$R_d = 165 - 1.32\ R_{5ad}$	> 1	0.85	0.41	0.34
	V			0.85	0.48	0.40
Around Marapallam	VI	$R_d = 230 - 1.32\ R_{5ad}$	> 1	0.83	0.33	0.27
West of Runneymede	VII	$R_d = 250 - 1.5\ R_{5ad}$	> 1	0.86	0.36	0.31
	VIII			0.86	0.40	0.34
For Entire route	---	$R_d = 220 - 0.61\ R_{5ad}$	>15	0.63	0.73	0.46

TEq is Threshold equation; NEL is Number of expected landslides; and TP is Temporal Probability.

The rainfall-based temporal probability values that have been obtained for the railway line were used to test their applicability in a nearby road corridor having similar geo-environmental conditions. The frequency distribution of the recorded landslides during the 21-year period 1987-2007 indicates that more than 60% of the recorded landslides occurred within the road sectors with high temporal probability of occurrence (> 0.40) and seven percent in the zones with the lowest probability value (0.27). This validates the predicting performance of the model for shallow translational debris slides associated with cut slopes outside the modeled area.

The distribution of the annual temporal probability in different units of the transportation routes is shown in Figure 4. Highest probability values are assigned to the units II, II and V. These areas also have the higher incidences of reported landslides.

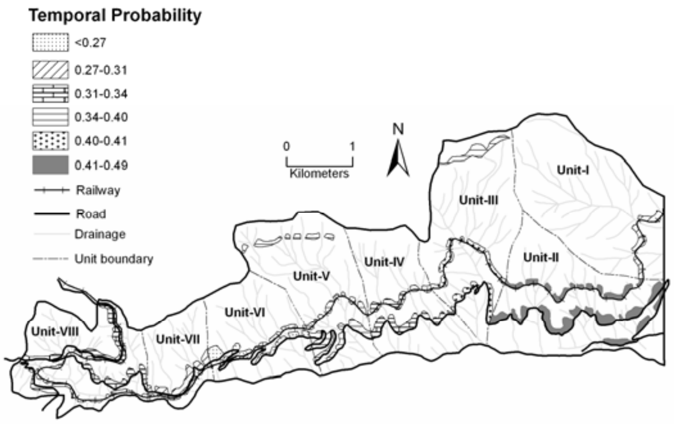

Figure 4. Annual temporal probability of landslide initiation along the cut slopes of the railway and the highway.

6 DISCUSSION

The proposed method allows to determine quantitative temporal probability of landslide initiation along transportation routes in a hilly area. The transportation routes were selected because they have the high incidences of landslides, and they pose a high risk to the traffic. While there is a possibility that landslides initiating on the natural slopes may affect the railway route, such incidences have been rarely reported.

The landslide inventory prepared from historical records is relatively more complete along the railway than along the highway. About 82% of the recorded landslides are associated with the railway cut slopes. The lack of data along the road might be due to the fact that smaller landslides are not reported as they do not cause damage to the road itself. Due to the incompleteness of the inventory along the road it was difficult to determine the temporal probability based on the rate of occurrence of landslides in this part. The proposed model based on the rainfall thresholds allows to extend the result to other areas of similar geo-environment conditions such as road in this case.

The 19 km railway line is represented by four thresholds which on exceedance can result in one or more landslides. For the same landslide event day different areas are represented by different threshold lines. Even a small alignment of 19 km shows a large variation in the threshold rainfall. This variation is largely due to the change in the local terrain conditions. Thus, a proper examination of the terrain is needed before selecting an appropriate threshold. Any attempt to use regionally-derived thresholds could lead to incorrect predictions.

In principle, each time the rainfall exceeds an established threshold, one or more landslides should occur. In reality, this only happens with a probability ranging from 0.32 to 0.73 (Table 1). This means that other factors, including soil shear strength, topography, saturation condition of the ground prior to the rise in the threshold curve, and successive periods of wet and dry days, also control the occurrence of landslides.The Poisson model is used to estimate the probability that a given threshold will be exceed in any give year and area. The model has been successfully tested for determining exceedance probability in spite of certain limitations as discussed by Guzzetti et al. (2005). The thresholds show high exceedance probability, varying from 0.63, for the event that can cause more than 15 landslides, to 0.97, for events resulting in one or more landslides. In spite of this high annual exceedance, landslides were only triggered in 32% to 73% of the cases when the threshold was exceeded. Thus, the temporal probability of occurrence of a rainfall that can result in landslides in any give year from October to December varies from 0.27 to 0.49. This high annual exceedance of the thresholds is well in accordance with the incidences of landslides in the area. Inspection of the historical record reveals that at least one landslide occurs every year but, depending on local terrain conditions, the highest relative temporal probability of experiencing one or more landslide events is estimated to be 0.49.

In this study, we assumed that within a geographic unit the rainfall event does not vary significantly. As a consequence, the temporal probability is expected to be the same within the considered unit. Before using the results of this model, other assumptions must be carefully considered, including (i) that the intensity of rainfall will occur in the future under the same meteorological conditions that have caused them in the past, and (ii) that the mean recurrence of rainfall exceeding the threshold value will remain same in the future, as it was observed in the past.

7 CONCLUSIONS

We have proposed an approach to incorporate a threshold model for determining quantitative temporal probability of landslide initiation over an area. Our results form the basis for an improved assessment of landslide hazard. The proposed model may not be applicable if the exact date of the landslide occurrence is not known, or if the multi-temporal landslide inventory is prepared from remote sensing data where the age of the landslides is relative to the date of the acquisition of the imagery. The study also showed the possibility of extending the results in the areas having similar geo-environmental condition and where data is incomplete, such as roads in this case. It may be noted that the proposed model is applicable only to shallow translational debris slides and debris flows that occur on slopes, and may not hold true for other landslide types, such as rock slides, or to slope failures in the natural slopes.

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