VII Simposio Nacional sobre Taludes y Laderas Inestables
Barcelona, 27 – 30 de Octubre de 2009
E.Alonso, J. Corominas y M. Hürlimann (Eds.)
CIMNE, Barcelona, 2009

LANDSLIDE HAZARD AND RISK ASSESSMENT ALONG A TRANSPORTATION CORRIDOR IN INDIA.

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ABSTRACT

Landslide hazard and risk assessment is a complicated process which requires a large amount of data. One of the most essential data types consists of historical landslide information. This paper presents a quantitative approach for landslide risk assessment for a road and a railway alignment in parts of Nilgiri hills in southern India. The method allows estimating direct risk affecting the alignments, vehicles and people. The method uses three basic parameters to quantify direct risk: hazard, vulnerability and value of exposed elements. Hazard in a given return period is expressed as the number of landslides of a given magnitude per kilometer per annum obtained using Gumbel distribution and magnitude-frequency statistics. A total of 1040 landslides were collected from historical records, of which 95.5% occurred in cut slopes along the railway and road alignment. All landslides were grouped in different magnitude classes. In total 18 hazard scenarios were generated using three magnitude classes (class I to III) and six return periods (1, 3, 5, 15, 25 and 50 years). The assessment of vulnerability of the alignment was based on the damage records, combined with expert opinion. Direct specific losses for the alignment (railway line and road), vehicle (bus, lorry, car and motorbike) and train were expressed in monetary values, and direct specific loss of life of commuters was expressed in annual probability. The detailed estimation of direct risk will facilitate to develop landslide risk mitigation and management strategies for transportation lines in the study area.

1. INTRODUCTION

Landslides are generally isolated natural processes, which individually may not be of very large size but can occur with a high frequency. Landslide inventories can be prepared through various methods (Wieczorek, 1984; van Westen et al., 2008) such as historical archive studies, interviews, detailed geomorphologic fieldwork, and mapping from remote sensing data and topographic maps. Each of the methods indicated above has its drawbacks. Often, due to the lack of sufficient historical information on landslides, stereoscopic interpretation of aerial photographs or satellite images from the past is used as the main source for obtaining a multi-temporal landslide inventory. Event-based inventories are prepared just after a prominent triggering event which depicts all slope failures caused due to that particular triggering event (Guzzetti et al., 2005). This paper demonstrates the possibilities for quantitative hazard and risk assessment for a situation where there is a (nearly) complete landslide record available.

Landslides are an increasing concern in India due to the ongoing expansion of the population into hilly terrain. Landslides affect vast areas within India, in particular in the entire Himalayan chain in the North and Eastern part of the country and the Western Ghats in the Southwest.

The Geological Survey of India (GSI) has been designated as the nodal agency for landslides by the Indian government. In the border zones of the country, including the entire Himalayan range the use of topographical maps and airphotos has been restricted for security purposes. Thus the generation of landslide inventory maps has always been a major problem. Due to the unavailability of airphotos in large parts of India, satellite remote sensing data has become the standard data input for landslide inventory mapping. The National Remote Sensing Center (NRSC) under the Indian Space Research Organisation (ISRO) has been very active in the use of satellite data for landslide inventory mapping and susceptibility assessment. Especially the use of high resolution stereo imagery from Cartosat has proven to be very useful for landslide studies. Due to the difficulty in obtaining base maps and multi-temporal landslide inventory maps, the development of new approaches for landslide hazard and risk assessment, including the use of spatially distributed deterministic models and statistical models, run-out modelling and probabilistic approaches have had still a rather limited application in India. However, although official landslide inventory maps are often not available, there are other sources of information that can be used, such as the road and railway maintenance records that have been collected over a fairly large period of time. In this paper we would like to present some results of using such data for landslide inventory, hazard and risk assessment that are applied to a transportation corridor in the Nigiri area in the Western Ghats of India.

2. THE STUDY AREA

Figure 1 shows the location of the study area in the Western Ghats. The study area is located in Nilgiri (Tamilnadu) and includes a 19 km long small track historic railway, which is

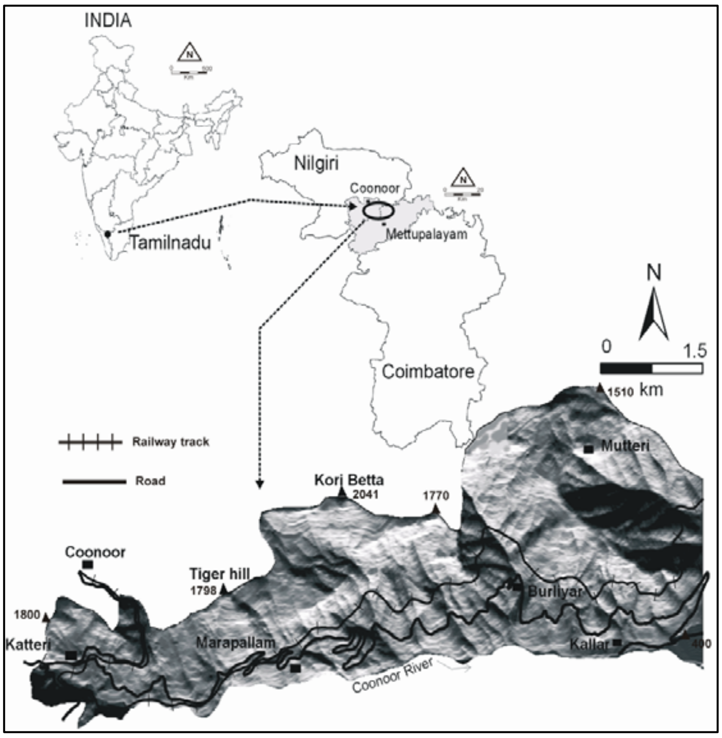
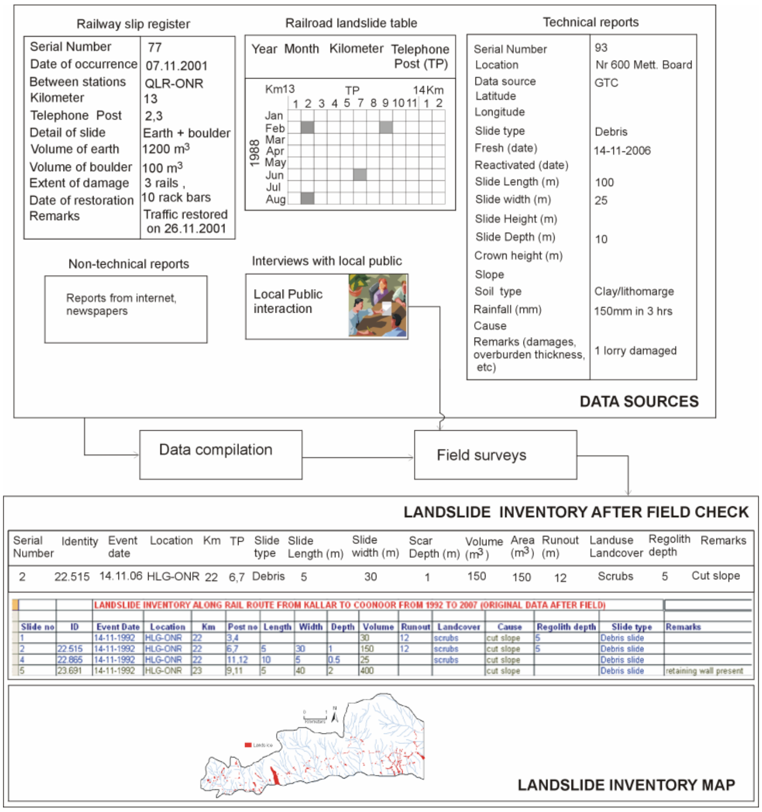


Figure 1: Study area in the Western Ghats**.**

declared as a world heritage site by UNESCO and a 24 km long national highway connecting Mettupalayam and Coonoor in the state of Tamilnadu in southern India. The railroad was constructed in the late 19th century and became operational in 1899. Both transportation lines run parallel to each other on the southern slopes of the Nilgiri plateau. The lines are cut through soil and laterite, underlain by charnockite and garnetiferrous quartzo-felspathic gneisses belonging to the Charnockite Group of Archaean age (Seshagiri and Badrinarayanan, 1982). The regional strike of the foliation is ranging from ENE-WSW to E-W direction with moderate to steep dips. The sub-tropical climate and intense physical and chemical weathering have resulted in a thick yellowish to reddish brown soil. The regolith thickness varies from less than one meter to 20 meters, as observed in the cut slopes along the road and railway. The study area forms a part of the Nilgiri plateau with steep slopes to the south and gentle slopes to the north and near ridge tops. The area has an elevation difference of 1641 m with lowest areas near Kallar farm (400 m) and highest at Kori Betta ridge (2041 m). Most part of the transportation corridor is either under reserved forest or tea plantation and settlements are sparse. Landslides are abundant in the area and occur mostly in cut slopes of the transportation routes. These are mostly shallow translational debris slides and flows and are invariably triggered by rainfall.

3. GENERATION OF A LANDSLIDE DATABASE

In the study area it was possible to generate a very detailed landslide inventory based on historical data. The main data sources were railroad maintenance records and technical reports. The data were present in an analog (paper) form recorded in a register or table and maintained by the Southern Railway office and the road office in Coonoor. The slips register are updated soon after the occurrence of a landslide triggering event and used for tendering contracts for railroad clearance. It contains data on the spatial distribution of landslide debris on the railroad for the period since 1992. The other form of historical records was a summary table of landslides along the railroad, which provided the spatial distribution of debris on the railroad in different months and sectors from 1987 to 1991. Landslides prior to 1987 were also recorded in the form of a landslide table but for the study area older records were not available. The data format and an example of the type of data available in the records are shown in Figure 2. The records also provide additional information on damages and the date of restoration of the railroad for traffic.



Railway slip register

Serial Number	77
Date of occurrence	07.11.2001
Between stations	QLR-ONR
Kilometer	13
Telephone Post	2,3
Detail of slide	Earth + boulder
Volume of earth	1200 m^3
Volume of boulder	100 m^3
Extent of damage	3 rails , 10 rack bars
Date of restoration	
Remarks	Traffic restored on 26.11.2001

Technical reports

Serial Number	93
Location	Nr 600 Mett. Board
Data source	GTC
Latitude	
Longitude	
Slide type	Debris
Fresh (date)	14-11-2006
Reactivated (date)	
Slide Length (m)	100
Slide width (m)	25
Slide Height (m)	
Slide Depth (m)	10
Crown height (m)	
Slope	
Soil type	Clay/lithomarge
Rainfall (mm)	150mm in 3 hrs
Cause	
Remarks (damages, overburden thickness, etc)	1 lorry damaged

LANDSLIDE INVENTORY AFTER FIELD CHECK

Serial Number	Identity	Event date	Location	Km	TP	Slide type	Slide Length (m)	Slide width (m)	Scar Depth (m)	Volume (m^3)	Area (m^3)	Runout (m)	Landuse Landcover	Regolith depth	Remarks
2	22.515	14.11.06	HLG-ONR	22	6,7	Debris	5	30	1	150	150	12	Scrubs	5	Cut slope

LANDSLIDE INVENTORY ALONG RAIL ROUTE FROM KALLAR TO COONOOR FROM 1992 TO 2007 (ORIGINAL DATA AFTER FIELD)

Slide no	ID	Event Date	Location	Km	Post no	Length	Width	Depth	Volume	Runout	Landcover	Cause	Regolith depth	Slide type	Remarks
1		14-11-1992	HLG-ONR	22	3,4				30	12	scrubs	cut slope	5	Debris slide	
2	22.515	14-11-1992	HLG-ONR	22	6,7	5	30	1	150	12	scrubs	cut slope	5	Debris slide	
4	22.865	14-11-1992	HLG-ONR	22	11,12	10	5	0.5	25		scrubs	cut slope		Debris slide	
5	23.691	14-11-1992	HLG-ONR	23	9,11	5	40	2	400			cut slope		Debris slide	retaining wall present

Figure 2: Different types of data sources and methodology used to prepare landslide inventory.

The landslides were compiled in standardized forms, and rearranged based on the location description. This data formed the basis for field mapping where all the landslide dates related to one specific location were listed in a tabular form. All landslide sites reported in the historic archives were visited and an attempt was made to identify the landslide scars. Some of the landslide scars and run-out areas were not clearly discernable due to the removal of debris and remedial works. After identifying the exact location of a landslide it was then mapped on a 1:10,000 scale topographic map and its initiation (source) and run-out area were separately marked. The morphological parameters were plotted after carefully measuring them in the field. The mapped landslides were digitized as polygons or points and entered in a geo-database of ArcGIS. Separate layers were prepared for the landslides associated with cut slopes and natural slopes. A unique identification number (ID) was assigned to each landslide (polygon or point), which provided a link between the spatial and non-spatial attributes.

In total 1040 landslides were compiled from the historical records and field work within a 22 km^2 area covering 21 years period from 1 January 1987 to 31 December 2007. The inventory was nearly complete for the period, particularly along the railroad. Landslides were triggered on 116 different dates. From the total of 1040 landslides, 643 landslides (62%) were obtained from the railway slips register, 259 (24%) from the landslide summary table along the railroad, 132 from technical reports and six from the other sources. Through field mapping it was possible to identify 67% of the compiled landslides. Some of the smaller landslides were not identifiable in the field due to possible reactivations which have obliterated the earlier morphology. The volume of these small landslides was therefore taken directly from the

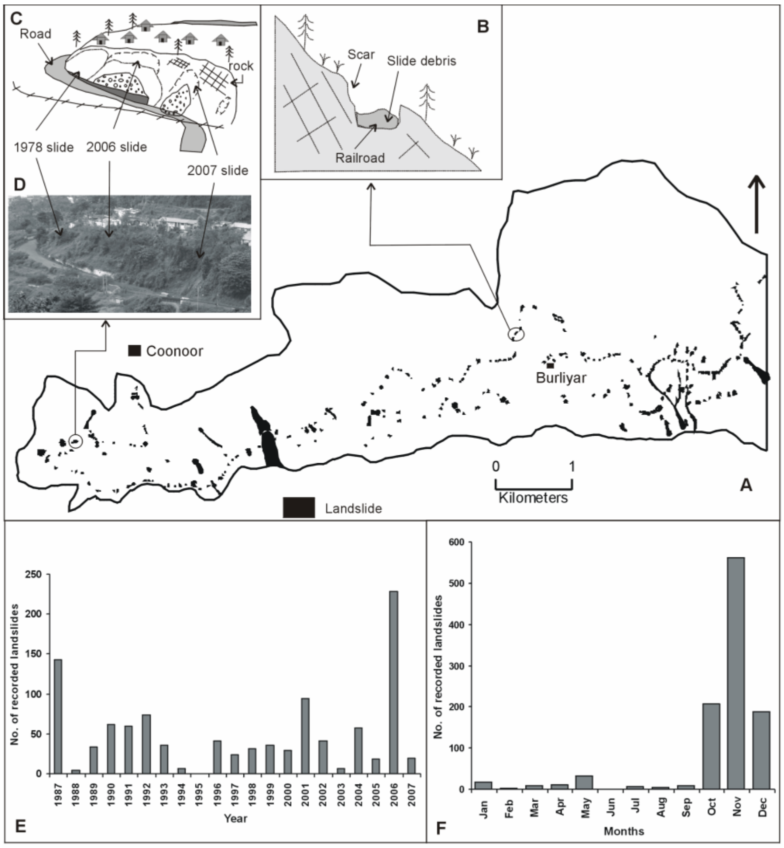


Figure 3: A: Landslide inventory map; B: Sketch of the railroad having cuts lopes on both sides; C: Sketch showing landslides in different years in one slope; D: Field photograph of landslides in cut slope at Katteri; E: Distribution of landslides over the past 21 years; F: Annual distribution of landslides.

original source data. Since they were small and located along the road or the railroad, it was presumed that most of the released material from these landslides was accumulated on the road and the railroad. Therefore, the measured volume from the maintenance records was considered a good representation of the size of these landslides. Landslides were classified as debris slide and debris flows. About 97% of the landslides are debris slides. Most of these are shallow translational with a depth of the slip plane less than 5 meters. The landslides are further regrouped into cut slope and natural slope failures based on the location of their source area. Smaller landslides in the cut slopes are found to have a short run-out as the road and the railroad provided a horizontal base for accumulation of the debris. In terms of the volume of material displaced, most these landslides (91%) lie within the range of 2 to 500 m^3. The landslide distribution map is shown in Figure 3. The annual distribution of recorded landslides in the past 21 years is shown in Figure 3E. Landslides occur annually in the area (except in 1995) with an average rate of 20 landslides per year. At some locations the same slope is affected by landslides in different periods (e.g., Figure. 3C and 3D). Completeness of an inventory can be tested by studying the magnitude-frequency relation of landslides. In most cases, the structure of the magnitude-frequency relationships were found to have a power law distribution with a flattening of the curve at lower magnitudes, termed as ‘rollover’ (Malamud et al., 2004). For the study area volume-frequency analysis was also performed and the structure showed a power law distribution with power law scaling exponent β equals -1.62 for all landslides with volume ranging from 2 to more than 10^4 m^3. For the same dataset, the probability distribution for landslide area also showed power law structure with β equals -1.67. According to Malamud et al., (2004) if the rollover is due to the incompleteness of the inventory as a result of the under-sampling of small landslides, then the power law distribution obtained in this study does indicate that the present inventory is complete.

4. HAZARD ASSESSMENT

The landslide hazard assessment along the transportation lines (road or railroad) requires the evaluation of two essential parameters:

(1) The probability that landslides are of a given magnitude, and
(2) The total number of landslides per kilometer per annum in a given return period.

In literature no established classification for landslide magnitude is available. Some researchers have used landslide area or volume as a proxy for magnitude, for certain landslide types such as slides or flows (Guzzetti et al., 2005). In this study, a different landslide magnitude class is proposed. All landslides in the inventory are grouped into different classes based on landslide type, volume and other characteristics such as location of the source, scar depth, run-out distance, etc. The landslides in cut slopes are grouped into three magnitude classes. The classification is semi-quantitative and derived on the basis of the historical information obtained during the inventory mapping. The probability that a landslide belong to a given magnitude class was estimated using magnitude-frequency relationships. The probability was obtained from the probability density, for which a scatter plot was generated with landslide volume (in m^3) on the x-axis and probability density on the y-axis. The probability density function of landslide volume was found to have a good correlation with a power law distribution of type:

$$p(V_L) = k(V_L)^{-\beta} \qquad (1)$$

where k and β are constant and β is the power-law scaling exponent.

The number of landslides per annum was estimated using the Gumbel distribution (Gumbel, 1958) with input being the total number of landslides per section of the road/railroad per year. The method provides an estimate of the number of landslides expected to occur per annum and their return period (annual probability). In literature other methods such as Poisson and Binomial distribution models are commonly used for estimating the annual exceedance probability (*AEP*) of landslides i.e. the probability of experiencing one or more landslides during any given time (e.g., Coe et al., 2000; Guzzetti et al., 2005). The Poisson and Binomial models provide estimate of probability of experiencing one or more landslides and not the specific number of landslides, which is essential for estimating direct risk along a transportation line. The number of landslides is essential to estimate the probability of a landslide hitting a vehicle.

Along the railroad, Gumbel analysis was carried out for each kilometer length thereby producing 19 Gumbel plots for the total 19 km railway line. Along the road, the Gumbel analysis was performed on two sections: a section with 10 km length (SI from km-390 to km-400), and a section of 14 km length (SII from km-400 to km-414). The total number of landslides in a year per section was selected from the inventory covering 21 years period from 1987 to 2007. During the period, the entire railroad was affected by 898 landslides of which the lowest was recorded along km-26 (14 landslides) and the highest along km-12 (101 landslides). The maximum number of landslides in a year was recorded in 2006 (25 landslides along km-11). During the period from 1987 to 2007 the road was affected by 124 landslides with an average of 4.76 landslides per kilometer. At each section of the road and the railroad the expected number of landslides with 1, 3, 5, 15, 25 and 50 years return period were then estimated. A five kilometer stretch along the railroad (from km-9 to km-13) is relatively more prone to be hit by landslides, as is the 10 km section (from km-390 to km-399) along the road. An example showing the results of the railroad are shown in Figure 4.

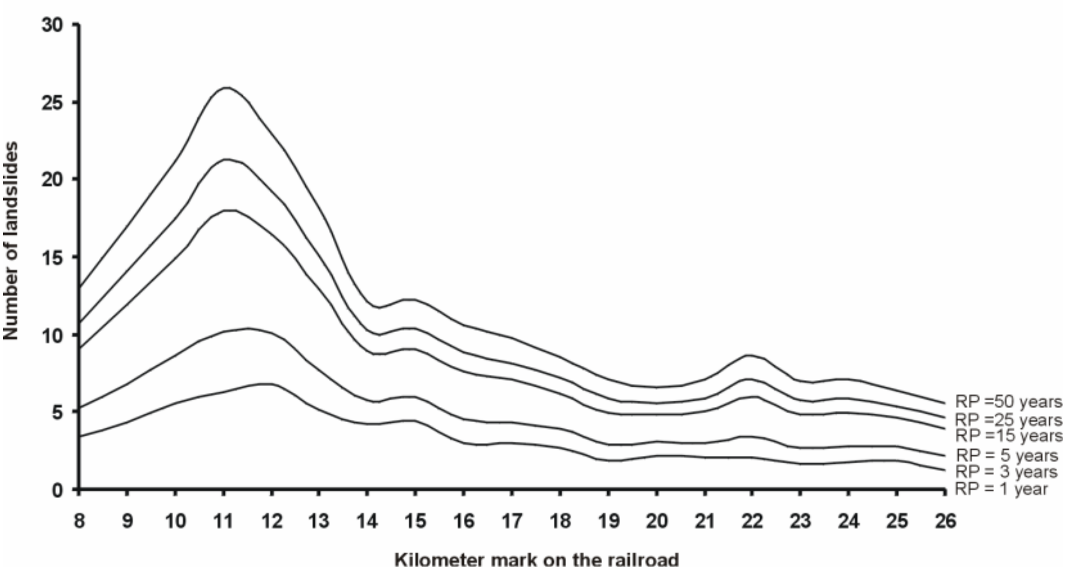


Figure 4: Number of landslides in a year in different return periods along the railroad.

Finally, landslide hazard was calculated by multiplying the total number of landslides per kilometer per annum obtained using Gumbel distribution with the landslide occurrence probability for different magnitude classes obtained from volume-frequency distribution. Thus, based on the guidelines given by the Joint Technical Committee on landslides and Engineered Slopes, JTC-1 (Fell et al., 2008) the landslide hazard in cut slopes is expressed as the number of landslides of a given magnitude per kilometer per annum. The hazard estimation can be performed for a number of scenarios using different combination of landslide magnitude class and return period. For this study 18 hazard scenarios were generated using three magnitude classes (class I to III) and six return periods (1, 3, 5, 15, 25 and 50 years).

5. RISK ASSESSMENT

Specific risk to the infrastructure (railroad Rs_{rl} and the road Rs_{rd}) due to landsliding for a given return period was estimated using the following equation (adapted from Fell et al., 2005):

$$Rs_{prop} = H_i \times P_{T:L} \times P_{S:T} \times V_{prop:i} \times A \tag{2}$$

where, Rs_{prop} is the expected loss to the infrastructure property (US$), H_i is the hazard due to landslide with a magnitude class 'i' (Number/ km/ annum), $P_{T:L}$ is the probability of a landslide with magnitude 'i' reaching the infrastructure (0-1), $P_{S:T}$ is the temporal spatial probability of the infrastructure (0-1), $V_{prop:i}$ is the vulnerability of the infrastructure property (monetary loss) for a landslide of magnitude 'i' (0-1), and A is the present value of the property (US$).

The value of $P_{S:T}$ was taken as 1.0 as both the elements are stationary object and always remain on or in the path of the landslide. The value of $P_{T:L}$ was also taken as 1.0 because the infrastructures are located below the cut slopes and all landslides from cut slopes invariably reach the properties. The assessment of vulnerability was based on the detailed analysis of the past damage records obtained from the Southern railway and highway office located at Coonoor. For the railroad, vulnerability (V_{rl}) was calculated as the ratio of the total restoration cost (US$/m) of the damaged railroad due to a landslide of a given magnitude to the actual value of the railroad (US$/m). The total restoration cost includes the cost of removing landslide debris from the railroad and cost of replacing the damaged structure (i.e. rail, rake bar and sleeper). The vulnerability of the road (V_{rd}) was calculated as the ratio of the total restoration cost (US$/m) of the damage road due to a landslide of a given magnitude to the actual value of the road (US$/m).

Specific risk to a moving vehicle, i.e. vehicle being hit by a landslide, mainly depends on the temporal spatial probability ($P_{S:T}$) of the vehicle at the time of occurrence of the landslide. This value of probability ($P_{S:T}$) can be used to calculate specific risk to a moving vehicle for a given return period using the following three expressions (adapted from AGS, 2000):

$$Rs_v = P(V_i) \times V_{veh:i} \times A \tag{3}$$

$$P(V_i) = 1 - (1 - P_{S:T})^{NR} \tag{4}$$

$$P_{S:T} = (ADT \times L) / (24 \times 1000 \times V_v) \tag{5}$$

where, Rs_v is the expected loss of a vehicle (US$), $P(V_i)$ is the probability of the vehicle being hit by a landslide with a magnitude 'i' (0-1), $V_{veh:i}$ is the vulnerability of the vehicle for a landslide of magnitude 'i' (0-1), A is the cost of the vehicle (US$), $P_{S:T}$ is the temporal spatial probability of the vehicle (0-1), NR is the number of landslides of magnitude 'i', ADT is the average daily traffic (vehicles per day), L is the average length of the vehicle (m), and V_v is the velocity of the vehicle (km/hr).

The assessment of vulnerability of different types of moving vehicles (bus, lorry, car and motorbike) and train was carried out based on the historical record and experience of the local people. Other variables were obtained from historical records and field calculations. The average speed for the vehicles and train was measured as 26 and 11 km/hr, respectively. The ADT for bus, lorry, car and motorbike is obtained as 137, 309, 554 and 90 vehicles per day, respectively and for train it is two per day. The average length (L) of a bus, lorry, car, motorbike and train was measured as 12, 8, 5, 2 and 55 m, respectively. By using Eq. (3-5), specific risk to a bus (Rs_b), lorry (Rs_l), car (Rs_c), motorbike (Rs_{mb}) and train (Rs_t) was calculated for each hazard scenario. If more than one vehicle of a given type (e.g. bus) was present in a landslide zone at any given time then the loss was multiplied by the total number of vehicles present. The total number of vehicles N_V can be obtained using the expression: N_V = ADT × SL / 24 × V_v where *SL* is the length of the landslide affected zone (km). The length of landslide affected zone along the road and the railroad was calculated from landslide density, which is the ratio of the total landslide scar width to the total length of the transportation line. The total *SL* along the road and the railroad is 2.10 and 3.84 km, respectively.

The risk of life or the annual probability of a person losing his/her life while travelling in a vehicle depends on the probability of the vehicle being hit by a landslide and the probability of death of the person (vulnerability) given the landslide impact on the vehicle. The vulnerability of commuters to a landslide depends on the type, speed and size of the landslide, the speed and type of the vehicle, and whether the person is in the open or enclosed in a vehicle (Wilson et al., 2005). It also depends on whether the debris has directly hit the vehicle from the top or moved horizontally and hit the side of the vehicle. Even with the availability of some known incidents and damaged records the assessment of vulnerability of death still remains fuzzy. Due to such large variability of factors the assessment of vulnerability was somewhat subjective and knowledge driven. The specific risk to commuters in terms of annual probability of the person most at risk losing his/her life by travelling in a bus (Rs_{Db}), lorry (Rs_{Dl}), car (Rs_{Dc}), motorbike (Rs_{Dmb}) and train (Rs_{Dt}) for a given return period was estimated using the following expression (adapted from AGS, 2000):

$$R_c = P(V_i) \times V_{D:i} \tag{6}$$

where, R_c is the annual probability of death (0-1), $V_{D:i}$ is the vulnerability of the individual (probability of death) given the landslide impact on the vehicle (0-1). The parameter $P(V_i)$ is estimated using Eq. (3-5).

The total landslide risk is the summation of all the specific risks related to landslides in an area. It is obtained when the hazard for all landslide type and magnitude is multiplied with the expected losses for all different types of elements at risk (van Westen et al., 2006). In this study, total landslide risk of property loss was calculated by adding all the specific direct risks of a given return period as given below:

$$RT(P) = \sum_{i=I}^{III} \left[(Rs_{rl} + Rs_{rd} + Rs_b + Rs_l + Rs_c + Rs_{mb} + Rs_t) \right] \tag{7}$$

where, *RT(P)* is total risk for monetary loss (US$). The total landslide risk for the loss of life, *RT(D)* expressed as number of people per annum was calculated by adding all specific loss of lives, as given below:

$$RT(D)=\sum_{i=I}^{III}\left[Rs_{Db}+Rs_{Dl}+Rs_{Dc}+Rs_{Dmb}+Rs_{Dt}\right] \tag{8}$$

The output of the result of the total monetary loss was displayed as a risk curve, containing the relation between hazard with different annual probabilities and the corresponding total losses.

6. RESULTS

The total direct loss obtained for the railroad, road, moving vehicles and trains in 3, 5, 15, 25 and 50 years return period is around US$ 92,026; US$ 141,759; US$ 241,462; US$ 283,122 and US$ 341,038, respectively.

The annual probability of the person most at risk losing his/her life by driving along the road using different modes of travel such as bus, lorry, car or motorbike in a hazard of 3, 5, 15, 25 and 50 years return period is estimated as 2.9×10^{-5} , 5.7×10^{-5} , 1.1×10^{-4} , 1.4×10^{-4} and 1.7×10^{-4} /annum, respectively. For rail users these values are 3.6×10^{-5}, 5.5×10^{-5}, 9.2×10^{-5}, 1.1×10^{-4}, 1.3×10^{-4} /annum, respectively. The total annual risk for the road users travelling by bus and car was also estimated. It was assumed that each bus and car carries an average of 50 and 6 persons, respectively. In a 3 years return period the annual risk (loss of lives) for both bus and car travelers is estimated as 0.03 persons/annum. The total annual risk of death, in case of road vehicles and trains in which commuters are travelling are hit by landslides, is found to vary from 0.08 persons/annum (in 3 years return period) to 0.5 persons/annum (in 50 years return period).

The result of the total direct risk (monetary loss) is displayed as a risk curve, showing the relation between hazards with different annual probabilities and the corresponding total specific losses (Figure 5). The result indicates that the loss increases with the decrease in the annual probability of landslide event.

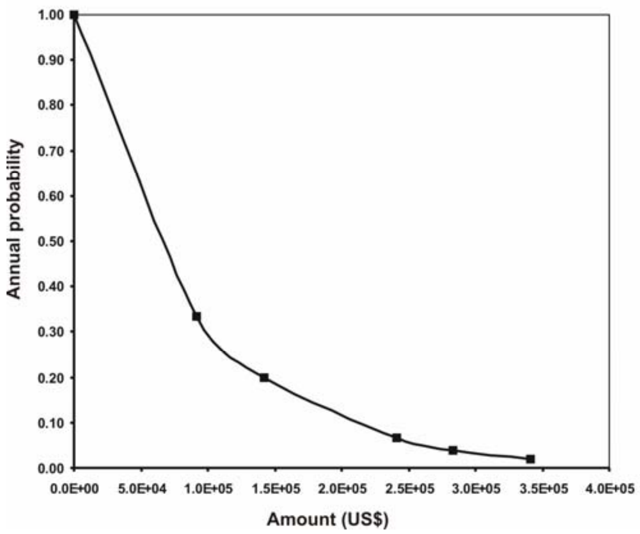


Figure 5: curve for direct losses expressed in monetary value (US$).

7. CONCLUSIONS

The study showed that a direct landslide hazard and risk assessment can be carried out if a complete landslide inventory is available. Hazard estimation in terms of number of landslides per kilometer and per annum is possible only if the rate of occurrence of landslides is known and for such analysis continuous records of landslide incidences over a period of time is required. Any gap in the record may result in the over or underestimation of the probability. The Gumbel distribution used in this study is very appropriate in modeling extreme events such as incidences of large number of landslides. It helps in establishing a relation between the return period and number of landslides. The inclusion of the proposed magnitude class in the hazard assessment will help in analyzing the phenomena both in terms of risk to life and property. Ideally it should be quantified based on absolute values of landslide velocity, its intensity, its peak discharge, etc. But such parameters are very site specific and vary with local condition such as channel geometry, terrain roughness, and land use, etc. and thus difficult to obtain and integrate in the hazard map. Due to this limitation and the complexity of landslide phenomena, the proposed classification is considered the best solution for this study. For the risk analysis, hazard assessment based on the number of landslides per kilometer in a given return period is a workable solution.

In order to derive at landslide risk, many assumptions have to be made. Landslide risk is the last part of a chain and incorporates all uncertainties of the previous parts. Whereas landslide risk assessment is starting to become a formal practice in some developed countries, in particular along transportation lines, this might still be a step too far.

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