Rockfall hazard and risk assessment along a transportation corridor in the Nera Valley, Central Italy

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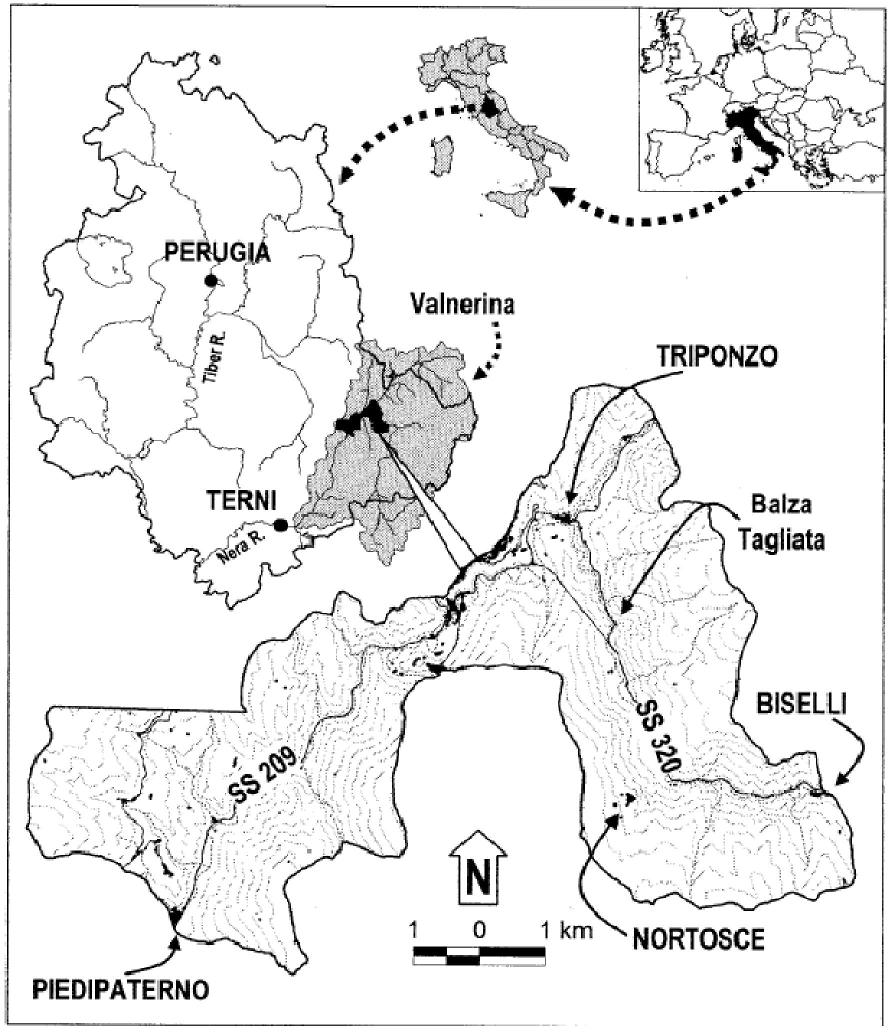
Introduction

- A methodology is presented to:
  - ascertain rockfall hazards
  - determine associated risks along transportation networks

- Based on combined analysis of:
  - recurrence of rockfall events
  - frequency volume statistics of rockfall events
  - results of a physically based and spatially distributed rockfall simulation model

Study Area



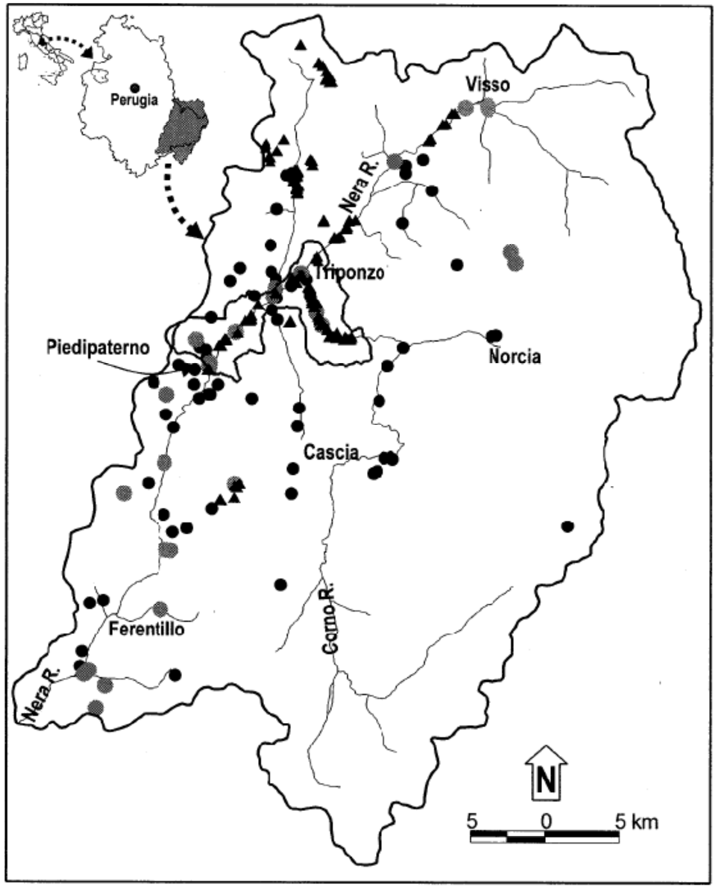
- 48 sq. km. area near Triponzo village in Valnerina region, central Italy

Recurrence Statistics of Rockfalls

- Determined from available historical information on rockfall occurrence
- Two sources:
  - a catalogue of historical earthquakes, with information on ground failures
  - a catalogue of historical landslide events

- Information on seismically induced landslides, including rockfalls, is available for **six earthquakes**, in the **160 years period** from **1838 to 1997**

Recurrence Statistics of Rockfalls



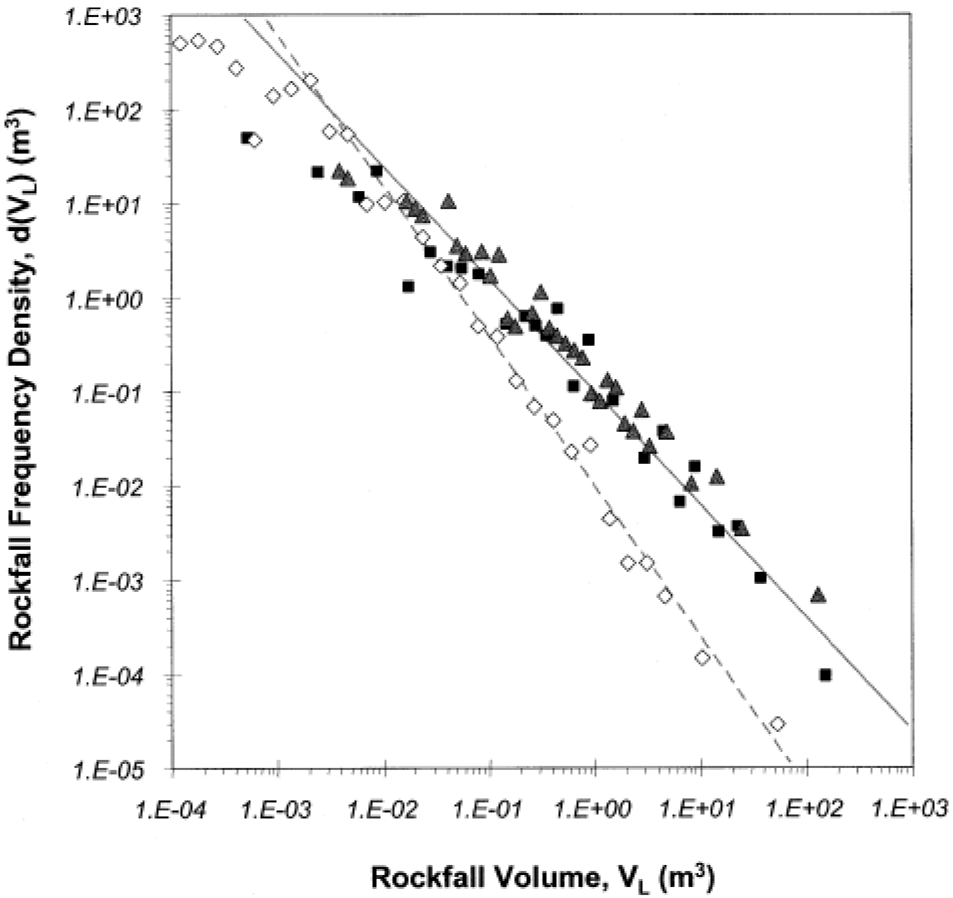
- At least **111 landslide events** at **90 sites** occurred in **Valnerina** during **1918–2002**
- **35 events** were **rockfalls**, **topples** and **minor rock slides** at **27 sites**
- **10 rockfall events** at **9 sites** occurred in **Triponzo study area**

Frequency-Volume Statistics of Rockfalls

- Detailed inventory of rockfalls available for September-October 1997 earthquake in the region
- Three data sets containing information about:

1. **volume of 155 rockfalls** mapped across entire area affected by the earthquake (about 1,100 sq. km.)
2. **volume of 1696 rockfall fragments** measured along a regional road (SS 320) and in a river (Corno) in the region
3. **cumulative volume of 62 rockfalls** obtained by summing volume of each rock fragment based on a common source area

Frequency-Volume Statistics of Rockfalls



- The three data sets obey power laws

  $d(V_L) = 0.1 * V_L^{-1.2}$ (data set 1 & 3)

  $d(V_L) = 0.1 * V_L^{-1.6}$ (data set 2)

- This information is used to ascertain rockfall risk and select volume of boulders for rockfall energy analysis

Spatial Distribution of Rockfall Hazard

- The computer program STONE is used
- Input data required:
    - Location of the detachment areas of rockfalls
    - Number of boulders launched from each detachment area
    - Starting velocity and horizontal angle of rockfall
    - Velocity threshold below which the boulder stops
    - Digital elevation model (DEM) describing topography
    - Coefficients of dynamic rolling friction and of normal and tangential energy restitution, used to simulate the loss of energy when rolling and at impact points.

Spatial Distribution of Rockfall Hazard

- Uncertainty in input data is dealt with by:
    - launching a variable number of blocks from each detachment cell
    - varying randomly the starting horizontal angle, the dynamic rolling friction coefficient, and the normal and tangential energy restitution coefficients

Spatial Distribution of Rockfall Hazard

- Output:
  - two- and three-dimensional rockfall trajectory lines
  - grid (raster) maps portraying:
    - cumulative count of rockfall trajectories that passed through each cell
    - maximum computed velocity
    - largest distance of boulder to ground computed along the rockfall trajectories (flying height)

Spatial Distribution of Rockfall Hazard – Input Parameters

- Data input for STONE obtained from:
  - existing topographic and geological maps
  - interpretation of two sets of large- (1:13,000) and medium-scale (1:20,000) aerial photographs
  - field surveys

- Digital Elevation Model (DEM) describing topography with a ground resolution of 5 x 5 m prepared by interpolating the 10- and 5-m-interval contour lines obtained from 1:10,000 scale topographic maps of the area

Spatial Distribution of Rockfall Hazard – Input Parameters

- Source areas of rockfalls mapped from aerial photographs and verified in the field surveys
- About 3.0 sq. km. of rockfall source areas identified – about 6.25% of the study area.
- For each terrain type, dynamic friction angle and normal and tangential energy restitution coefficients obtained from literature and authors’ experience in the use of STONE
- Land cover information was obtained from a regional land use map through interpretation of medium-scale aerial photographs

Spatial Distribution of Rockfall Hazard – Derivation of Model

- Spatially distributed rockfall model derived through an iterative procedure
- Step 1
  - A preliminary model produced by launching one boulder from each rockfall source cell.
  - The map of rockfall count visually inspected and checked with location of known rockfalls and extent of landslide and debris deposits
  - Model parameters and initial conditions changed until the result was judged satisfactory

Spatial Distribution of Rockfall Hazard – Derivation of Model

- Spatially distributed rockfall model derived through an iterative procedure
- Step 2
  - A second model then produced by launching 30 boulders from each source cell and by allowing model variables to vary randomly within 5% of the predefined values
- Step 3
  - Number of rockfalls launched from each detachment cell varied according to rock type of source area

Spatial Distribution of Rockfall Hazard

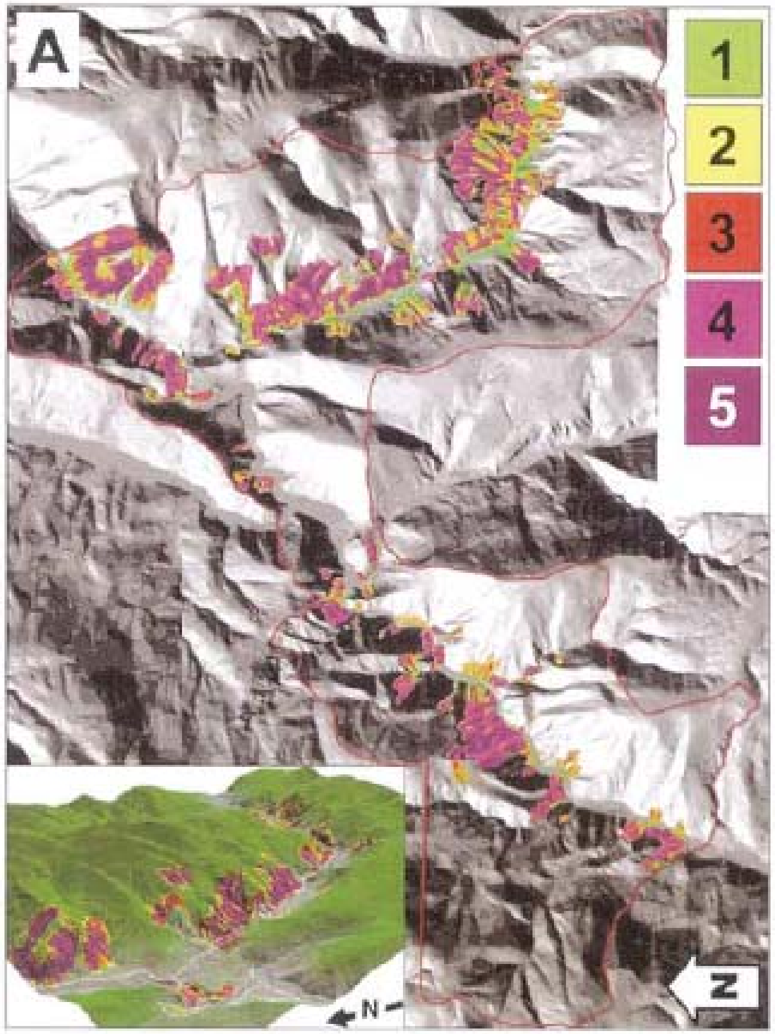
A. Rockfall count	No.	Class	Notes
	1–10	1	Very low frequency
	11–100	2	Low frequency
	101–250	3	Medium frequency
	251–500	4	High frequency
	>500	5	Very high frequency

B. Rockfall flying height	m	Class	Notes
	<1	1	The boulder is rolling
	1–5	2	Height of most of the elastic rockfall fences is 5 m
	5–10	3	Rockfalls are difficult to stop by retaining structures
	10–30	4	
	>30	5	Rockfalls cannot be stopped by retaining structures

C. Rockfall velocity	km/h	Class	Notes
	1.5–25		1.5 m s^{-1} is the lowest limit of rockfall velocity
	25–40	2	Below this threshold a boulder comes to rest
	40–70	3	Blocks of 5 m^3 can be stopped by elastic fences absorbing up to 3000 kJ
	70–115	4	Blocks of 2 m^3 can be stopped by elastic fences absorbing up to 2500 kJ
	>115	5	Rockfalls cannot be stopped by elastic fences

Classification scheme for model output

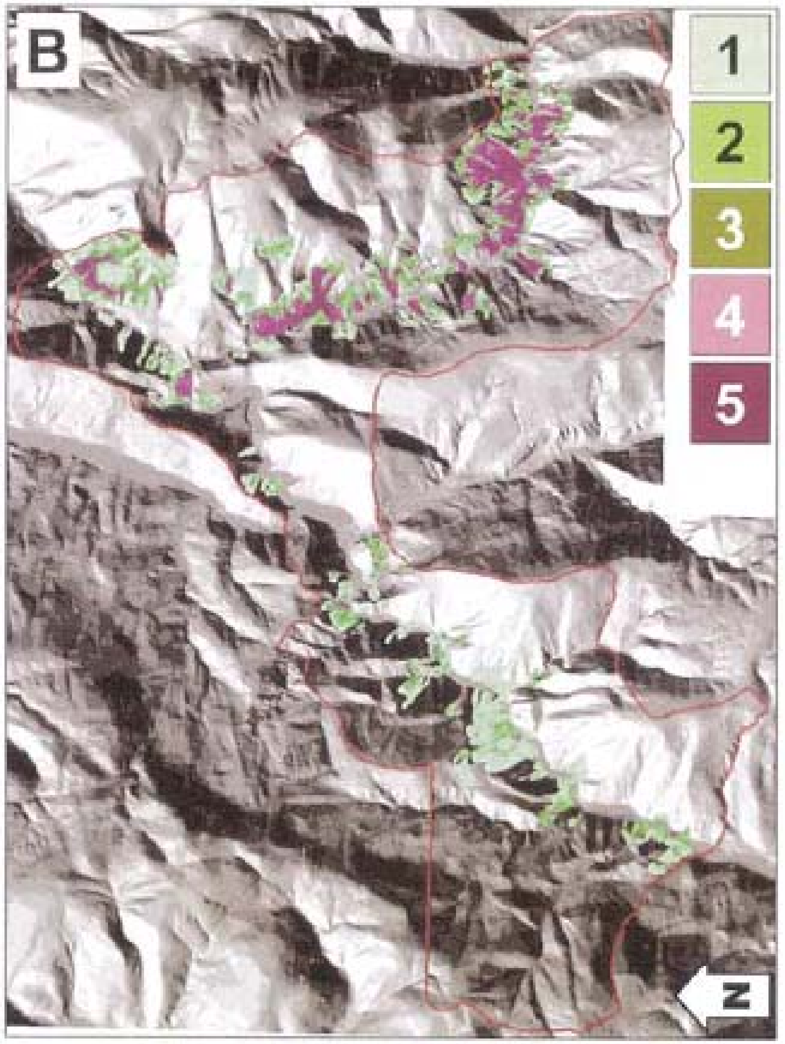
Spatial Distribution of Rockfall Hazard



1 – 10 blocks
11 – 100 blocks
101 – 250 blocks
251 – 500 blocks
> 500 blocks

Cumulative count of expected rockfall trajectories

Spatial Distribution of Rockfall Hazard



< 1 m

1 – 5 m

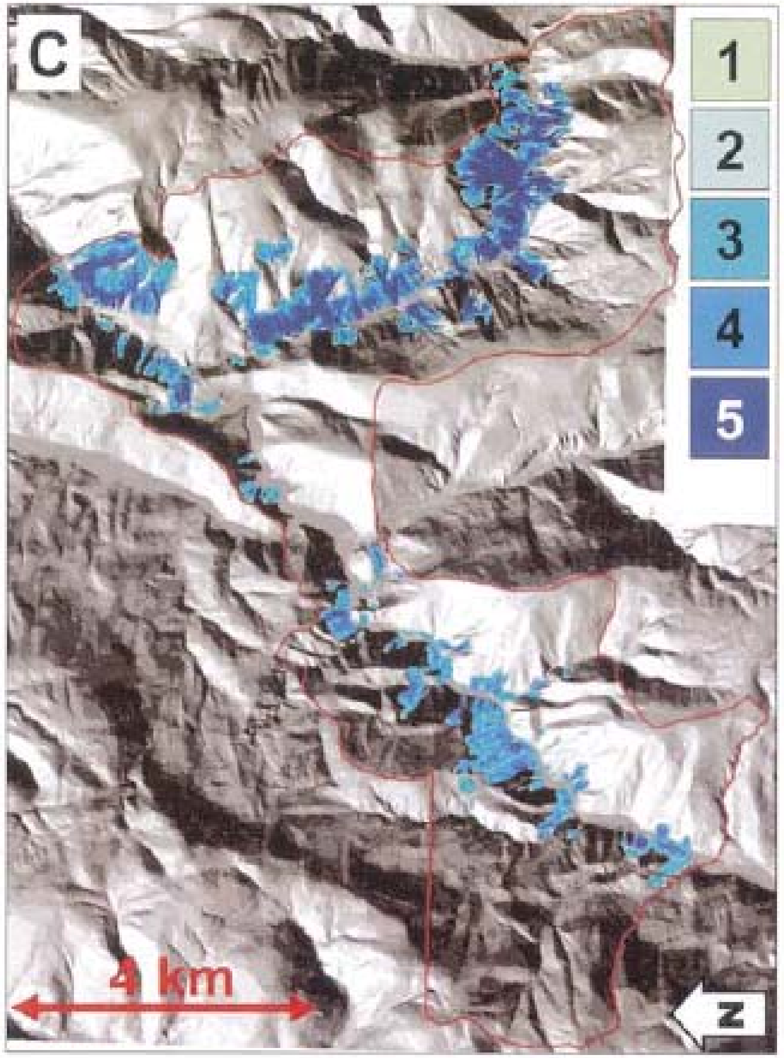
5 – 10 m

10 – 30 m

> 30 m

Maximum rockfall flying height

Spatial Distribution of Rockfall Hazard



1.5 – 25 km/hr

25 – 40 km/hr

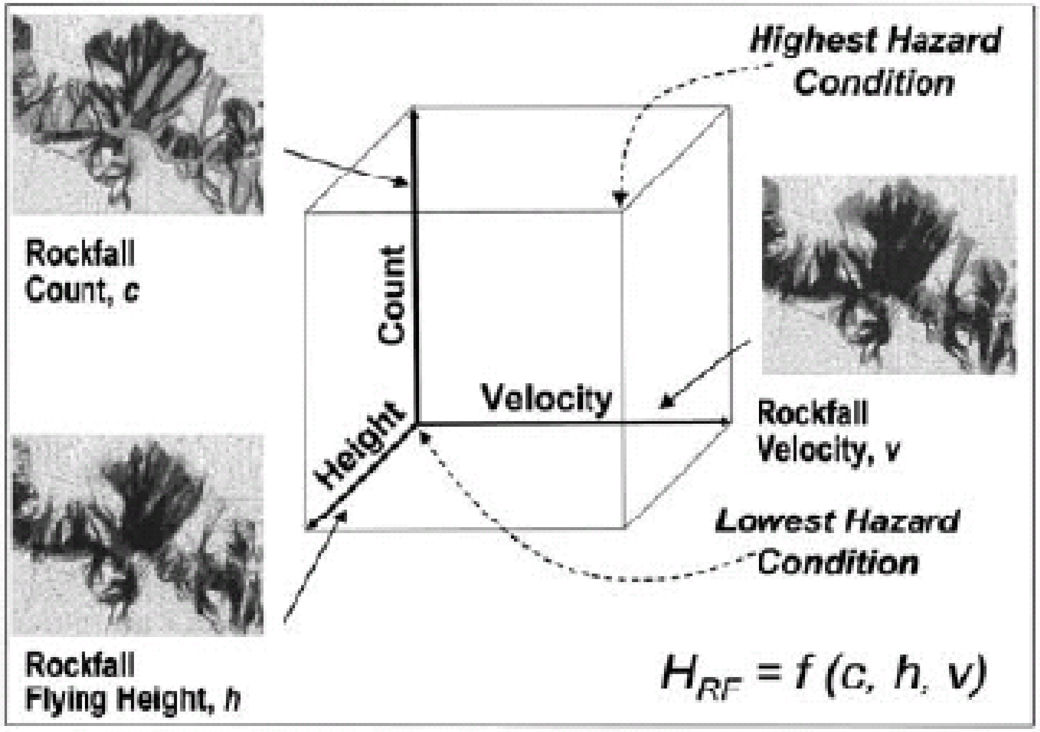
40– 70 km/hr

70 – 115 km/hr

> 115 km/hr

Maximum rockfall velocity

Rockfall Hazard Assessment



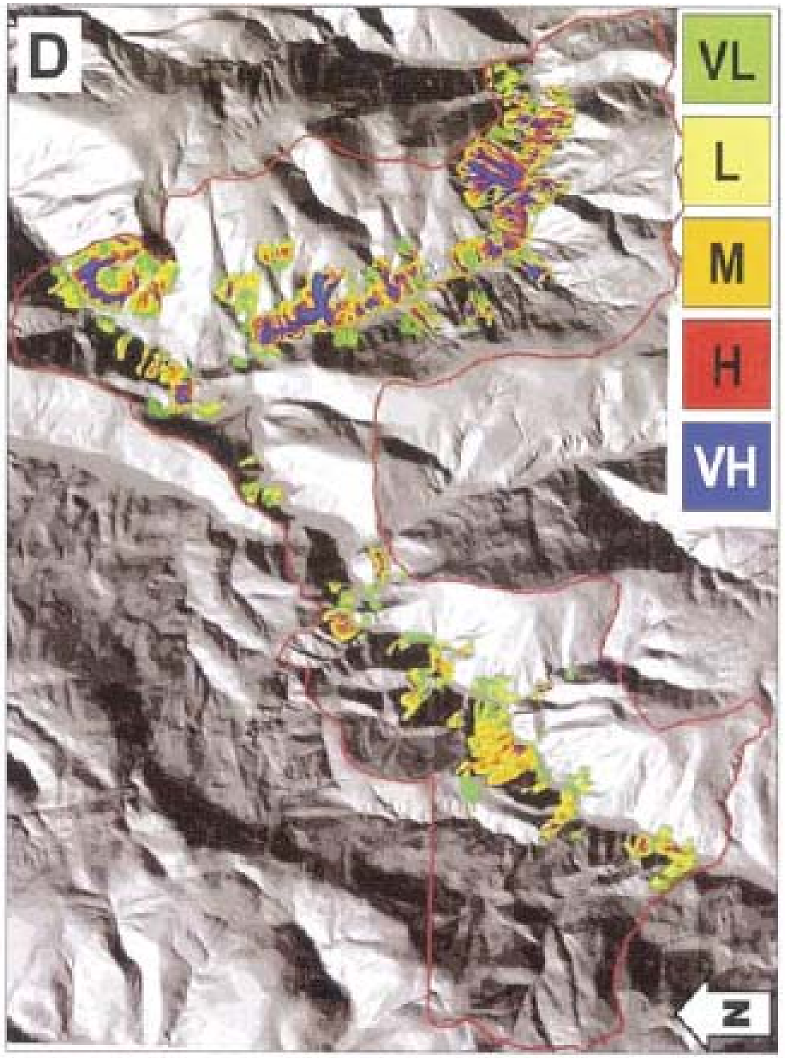
Rockfall Hazard Assessment

H_{RF}			Area			H_{RF}			Area			H_{RF}			Area			H_{RF}			Area			H_{RF}			Area		
c	h	v	m^2	%	Hazard	c	h	v	m^2	%	Hazard	c	h	v	m^2	%	Hazard	c	h	v	m^2	%	Hazard	c	h	v	m^2	%	Hazard
1	1	1	106,750	1.525	VL	2	1	1	166,500	2.378	VL	3	1	1	9,800	0.140	VL	4	1	1	2,100	0.030	VL	5	1	1	1,050	0.015	L
1	1	2	104,600	1.494	VL	2	1	2	300,475	4.292	VL	3	1	2	107,400	1.534	VL	4	1	2	29,500	0.421	L	5	1	2	16,250	0.232	L
1	1	3	140,275	24	VL	2	1	3	570,800	8.153	VL	3	1	3	514,075	7.343	L	4	1	3	427,100	6.101	L	5	1	3	213,875	3.055	M
1	1	4	43,875	0.627	VL	2	1	4	152,125	2.173	L	3	1	4	116,825	1.669	L	4	1	4	171,975	2.456	M	5	1	4	284,650	4.066	M
1	1	5	10,075	0.144	L	2	1	5	9,225	0.132	L	3	1	5	6,400	0.091	M	4	1	5	4,000	0.057	M	5	1	5	12,250	0.175	H
1	2	1	450	06	VL	2	2	1	375	05	VL	3	2	1	25	*00*	*VL*	*4*	2	*1*	*0*	00	*L*	*5*	2	*1*	*0*	*00*	*L*
1	2	2	3,725	0.053	VL	2	2	2	16,425	0.235	VL	3	2	2	3,500	0.050	L	4	2	2	700	0.010	L	5	2	2	275	04	M
1	2	3	36,750	0.525	VL	2	2	3	101,975	1.457	L	3	2	3	112,750	1.610	L	4	2	3	75,750	1.082	M	5	2	3	42,450	0.606	M
1	2	4	62,700	0.896	L	2	2	4	125,500	1.793	L	3	2	4	117,150	1.673	M	4	2	4	168,175	2.402	M	5	2	4	186,575	2.665	H
1	2	5	36,075	0.515	L	2	2	5	40,350	0.576	M	3	2	5	24,750	0.354	M	4	2	5	29,450	0.421	H	5	2	5	54,675	0.781	H
1	3	1	50	01	VL	2	3	1	*0*	*00*	VL	3	3	1	*0*	*00*	*L*	*4*	3	*1*	*0*	00	*L*	*5*	*3*	*1*	*0*	*00*	*L*
1	3	2	625	09	VL	2	3	2	1,300	0.019	L	3	3	2	175	02	L	4	3	2	25	00	M	*5*	*3*	*2*	*0*	*00*	*M*
1	3	3	10,750	0.154	L	2	3	3	13,550	0.194	L	3	3	3	11,925	0.170	M	4	3	3	7,750	0.111	M	5	3	3	4,225	0.060	H
1	3	4	33,075	0.472	L	2	3	4	59,625	0.852	M	3	3	4	52,875	0.755	M	4	3	4	61,600	0.880	H	5	3	4	77,300	1.104	H
1	3	5	37,450	0.535	M	2	3	5	58,525	0.836	M	3	3	5	34,575	0.494	H	4	3	5	43,850	0.626	H	5	3	5	78,000	1.114	VH
1	4	1	*0*	*00*	*VL*	*2*	*4*	1	*0*	*00*	*L*	3	4	1	*0*	*00*	*L*	*4*	3	*1*	*0*	*00*	*M*	*5*	*4*	*1*	*0*	*00*	*M*
1	4	2	250	04	L	2	4	2	125	02	L	3	4	2	25	00	M	*4*	*3*	2	*0*	*00*	*M*	*5*	*4*	*2*	*0*	*00*	*M*
1	4	3	5,700	0.081	L	2	4	3	5,075	0.072	M	3	4	3	3,075	0.044	M	4	4	3	1,625	0.023	H	5	4	3	1,050	0.015	H
1	4	4	33,050	0.472	M	2	4	4	52,925	0.756	M	3	4	4	37,525	0.536	H	4	4	4	39,400	0.563	H	5	4	4	54,075	0.772	VH
1	4	5	74,675	1.067	M	2	4	5	193,775	2.768	H	3	4	5	114,025	1.629	H	4	4	5	124,650	1.780	VH	5	4	5	245,925	3.513	VH
1	5	1	25	00	L	2	5	1	*0*	*00*	*L*	3	5	1	*0*	*00*	*M*	*4*	*3*	*1*	*0*	*00*	*M*	*5*	*5*	*1*	*0*	*00*	*H*
1	5	2	50	01	L	*2*	*5*	*2*	0	*00*	*M*	3	5	2	*0*	*00*	*M*	*4*	*3*	*2*	*0*	*00*	*H*	*5*	*5*	*2*	*0*	*00*	*H*
1	5	3	675	0.010	M	2	5	3	125	02	M	3	5	3	25	00	H	*4*	*3*	*3*	*0*	*00*	*H*	*5*	*5*	*3*	*0*	*00*	*VH*
1	5	4	6,050	0.086	M	2	5	4	8,050	0.115	H	3	5	4	2,300	0.033	H	4	5	4	1,775	0.025	VH	5	5	4	1,075	0.015	VH
1	5	5	28,750	0.411	H	2	5	5	143,250	2.059	H	3	5	5	119,000	1.700	VH	4	5	5	105,650	1.509	VH	5	5	5	247,575	3.536	VH

Heuristic classification of rockfall hazard

- **VL – Very low**
- **L – Low**
- **M – Intermediate**
- **H – High**
- **VH – Very high**

Rockfall Hazard Assessment



Very low
Low
Intermediate
High
Very high

Rockfall Hazard Map

Rockfall Defense Measures in the Region

Passive revetment nets **Elastic rock fences**

Rockfall Defense Measures in the Region

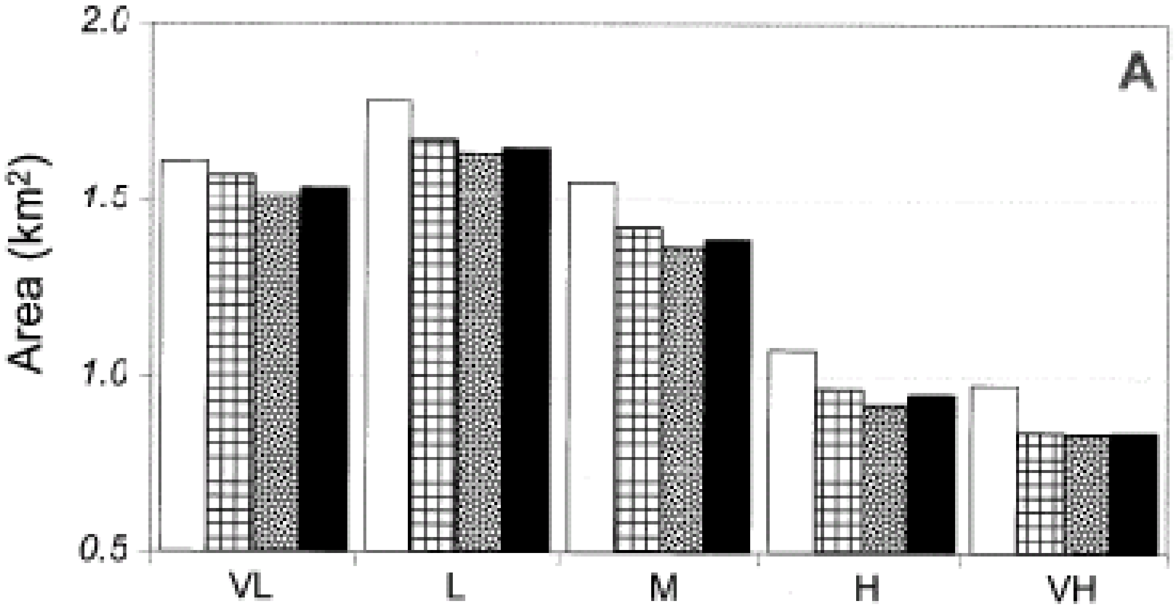
Concrete retaining walls

Artificial tunnels

Rockfall Risk Assessment

- Evaluation of effectiveness of existing defense measures in mitigating rockfall risk carried out in three steps
  1. Presence of only passive revetment nets considered.
  2. Presence of all defense measures considered.
  3. Efficacy of rockfall retaining structures evaluated by considering the possibilities that:
     - maximum height of rockfall trajectories is higher than height of retaining structures
     - a boulder could have enough kinetic energy to break through an elastic rock fence or a concrete wall

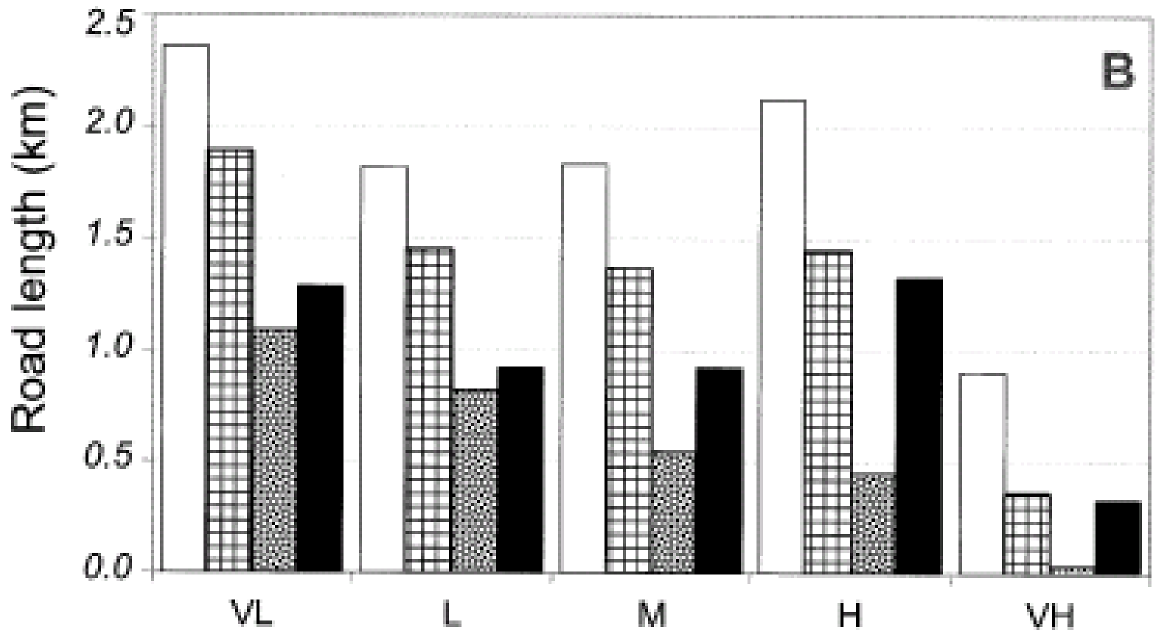
Rockfall Risk Assessment



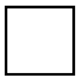
Extent of rockfall prone areas in each hazard class

- All existing rockfall defense structures not considered
- Presence of only passive revetment nets considered
- Presence of all rockfall defense measures considered
- Presence of only “efficient” rockfall defense measures considered

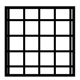
Rockfall Risk Assessment



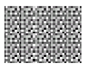
Total length of roads subject to rockfall hazard in each hazard class



All existing rockfall defense structures not considered



Presence of only passive revetment nets considered



Presence of all rockfall defense measures considered

Presence of only “efficient” rockfall defense measures considered

Rockfall Risk Assessment

- Rockfall risk to vehicles estimated by calculating "Average Vehicle Risk" (AVR)
- AVR measures the percentage of time a vehicle will be present in a rockfall hazard zone

AVR = (ADT X SL X VL)/PSL

- ADT is the average daily traffic (in no. of cars per day)
- SL is the length of hazard zone (in km.)
- VL is the percentage of the vehicle that at any time can be within hazard zone
- PSL is the posted speed limit (in km./hr.)

Rockfall Risk Assessment

A. Rockfall hazard class	5 × 5 m cells along roads No.	5 × 5 m cells along roads %	Road length (km)	AVR	Travel time %	Travel time Min	Cars (no.)
Very low (VL)	756	26.10	2.36	10,114	26.05	2.02	4.21
Low (L)	584	20.17	1.83	7,843	20.20	1.57	3.27
Intermediate (M)	588	20.30	1.84	7,886	20.31	1.58	3.29
High (H)	680	23.48	2.13	9,129	23.51	1.83	3.80
Very high (VH)	288	9.94	0.90	3,857	9.93	0.77	1.61
Total	2,896	100	9.06	38,829		7.77	16.18

B. Rockfall hazard class	5 × 5 m cells along roads No.	5 × 5 m cells along roads %	Road length (km)	Reduction (%)	AVR	Travel time %	Travel time Min	Cars (no.)
Very low (VL)	347	37.15	1.08	54.10	4,629	37.11	0.93	1.93
Low (L)	262	28.05	0.82	55.14	3,514	28.18	0.70	1.46
Intermediate (M)	173	18.52	0.54	70.58	2,314	18.56	0.46	0.96
High (H)	141	15.10	0.44	79.26	1,886	15.12	0.38	0.79
Very high (VH)	11	1.18	0.03	96.18	129	1.03	0.03	0.05
Total	934		2.91	67.75	12,471		2.49	5.20

C. Rockfall hazard class	5 × 5 m cells along roads No.	5 × 5 m cells along roads %	Road length (km)	Reduction (%)	AVR	Travel time %	Travel time Min	Cars (no.)
Very low (VL)	403	31.00	1.26	46.69	5,400	30.96	1.08	2.25
Low (L)	284	21.85	0.89	51.37	3,814	21.87	0.76	1.59
Intermediate (M)	255	19.62	0.80	56.63	3,429	19.66	0.69	1.43
High (H)	302	23.23	0.94	55.59	4,029	23.10	0.81	1.68
Very high (VH)	56	4.31	0.18	80.56	771	4.42	0.15	0.32
Total	1,300	100	4.07	55.11	17,443		3.49	7.27

Rockfall risk along roads

Model Uncertainties and Limitations

- Quality of the rockfall hazard model dependent on various factors, including complete and accurate identification of rockfall source cells and the quality of DEM
- Evaluation of efficacy of rockfall defensive structures affected by the completeness and resolution of mapping as well as their degree of efficiency
- Average values of flying height and travel velocity not considered and frequency of extreme values is not known – possible overestimation of risk
- Evaluation of rockfall risk to vehicles does not consider variations in daily traffic volume and vehicle speed

Conclusion

- Rockfall hazard and risk assessment for a 48 sq. km. region in central Italy has been reported
- A rockfall hazard map was obtained through a combined analysis of:
  - recurrence of rockfall events
  - frequency volume statistics of rockfall events
  - results of a physically based and spatially distributed rockfall simulation model
- Efficiency of existing rockfall defense structures was evaluated
- Risks to transportation network and vehicles were assessed