

A New Approach to Assess the Vulnerability of a *Road Infrastructure System* Affected by Rockfalls

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Abstract. To assess the rockfall risk of a road infrastructure system, it is very important to obtain detailed information about the territory and the road.

This paper aims to create a model for analyzing the vulnerability of a road infrastructure system.

The new proposed approach consists in different phases linked to the different parameters contributing to the assessment of the final risk: the rockfall intensity, the susceptibility assessment (by using an Artificial Neural Network approach), the exposure to the risk and the value of the exposed elements (road and human life).

Definitely, this paper deals with the development of an integrated numerical model allowing to obtain the vulnerability level of a road infrastructure system due to rockfall phenomenon. This approach can be used to obtain more useful information on a territory prone to mass movements allowing planners to manage emergencies in the best possible way.

Keywords: Element at risk · Magnitude · Province of Potenza · Rockfalls · Vulnerability

1 Introduction

The most conspicuous natural processes that occur along the slopes and can involve road communication lines are the landslides and the mass movement.

This last general term indicates all the phenomena of rockfalls, toppling or sliding that may involve rocky masses, surface soils or both, due to the gravity.

This phenomenon represents one of the most frequent geological risks in the national territory, especially in mountain environments, with serious consequences on the viability of the road sections, on infrastructures, and consequent serious inconvenience to inhabited areas.

The detachment of the blocks from one side of a slope is strongly influenced by the structural conditions of the rocky mass (discontinuity families, persistence, spacing), by the geometry (position and orientation of the discontinuities with respect to the slope), by the mechanical characteristics (shear strength of the discontinuities, traction resistance

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of some rock bridges) and possible external stresses (presence of pressurized water in the discontinuities, earthquakes, etc.) (Losasso et al. 2017a).

The risk on the transportation infrastructures and on roads due to such particularly dangerous phenomena, can be assessed in successive phases by estimating the hazard, the exposure and the vulnerability and then overlapping the above information (Losasso et al. 2017b). The first step for the assessing of the risk level on the road infrastructures, therefore, consists in the assessing of the hazard. It regards, in principle, the prediction of the event and its possible effects. The hazard is a measure to assess the level of expectation with respect to the occurrence of a given event and tries to establish its magnitude, as well as its spatial and temporal definition. In other words, a depth study of the hazard should be able to establish where, how and with what consequences a particular event can occur. The second step that needs to be done for the risk assessment, after the hazard analysis, is the exposure assessment. The study of exposure allows to identify areas particularly sensitive to the presence of people, artifacts, goods, etc. The distribution of these elements at risk is clearly not uniform on the territory, it is large where the density of the population is greater, or where there is a higher concentration of products (for example in the industrial areas). As it is clear, population, artefacts and goods do not have the same degree of priority, in fact the safeguarding of human life always has a greatest importance.

The analysis of the population exposure is the main step to assess the final vulnerability level but it is also the most difficult. The population can't be considered only as a static entity, but it has its own dynamism, given the possibility that it has to move in the territory (Budetta and Nappi 2013). For this reason, there will be several areas, especially in the urban ones, particularly exposed to the risk; moreover, this exposure varies in time in a cyclical way, so that the exposure will also have a temporal dimension, as well as a spatial one. In the Table 1 there some of the typologies and definitions of vulnerability proposed by several authors.

The vulnerability study of a transportation infrastructure is an important topic of growing interest in terms of road infrastructure. The concept of vulnerability does not have a univocal and commonly accepted definition, but it has been defined according to the context. There are, therefore, different definitions of the vulnerability in the literature, as there are different ways to evaluate it.

Vulnerability (V), in general, expresses the degree of loss of an element or group of elements exposed to the risk and therefore depends on both the type of element at risk and the intensity of the mass movement phenomenon. Ultimately, it is a particularly relevant parameter in the risk assessment (Leone et al. 1996) which links the intensity of the phenomenon to its possible consequences.

The vulnerability assessment can be based on statistical criteria and on particularly more subjective criteria. As regards the statistical methods, it is possible to adopt them in the case of repeatable and frequent phenomena.

For example, in the case of rockfalls, it is possible to estimate, on a statistical basis, the probability that the detachment of a boulder produces a certain damage on a structural and infrastructural element (Canuti and Casagli 1996).

However, as previously mentioned, in general the estimation of vulnerability is based on particularly subjective criteria; moreover, there are different currents of opinion: some

include in the estimation of vulnerability an evaluation of the unpredictability of the phenomenon, while the other ones include simply considerations on the elements at risk. This is a fundamental step in the analysis of landslide risk along the road transportation corridors. It is expressed in a scale from 0 (no loss) to 1 (total loss) (Fell 1994; Wong 1998) and is therefore a function of the intensity of the phenomenon and the type of involved element at risk. In general, when the element at risk is represented by human life, the vulnerability may express the probability that the occurrence of a mass movement may cause death, injuries and/or homelessness.

For this reason, it can be considered directly proportional to the population density of an area exposed to the risk. On the other hand, if an infrastructure is considered as an element at risk, many authors usually express the vulnerability as a percentage of the economic value (by considering structure or homogeneous areas) that can be impaired following the occurrence of a landslide phenomenon (Canuti and Casagli 1994).

In the following table, different definitions of Vulnerability proposed by several authors are briefly described.

As presented for the general concept of vulnerability, there is not a univocal definition of vulnerability of a road network in the literature. Husdal (2004) identifies the vulnerability as the composition of three types of vulnerability of a road network, the composition of which determines the global vulnerability:

- Structural Vulnerability, referring to the construction characteristics of the road, such as the geometry of the road and the works connected to it;
- Natural Vulnerability, referring to the characteristics of the territory crossed by the road;
- Relative/generated by traffic Vulnerability; referring to the traffic flow affecting the infrastructure and its variations in particular situations (peak times, maintenance operations, special days, etc.).

The difference between vulnerability and reliability of the network is very important: the first one is linked to the malfunction and collapse of an element, while the second one is linked only to its work. Not everyone, however, considers a clear distinction between the two concepts; in fact, according to Berdica (2002), reliability is a concept that allows to assess the vulnerability of the network.

Vulnerability is defined as the susceptibility of a network to accidents, where an accident means a reduction in serviceability, ie the possibility of using a transportation network during a given period. In other words, the vulnerability does not concern the safety of a road network, but the reduction of accessibility due to the event, where accessibility means the possibility for people to take part in the activities that take place in the territory thanks to the transportation systems.

Reliability becomes a measure of vulnerability because it is linked to the probability that an event can occur (Husdal 2004). Other authors (Bleukx et al. 2005), link the concept of vulnerability to the configuration of the network, identifying the most vulnerable scheme in particular traffic conditions or network interruptions.

Table 1. Some of typologies and definitions of Vulnerability

Type of vulnerability	Definition
Sistemic Vulnerability (Sdao et al. 2013)	It measures the relationship between extreme event's magnitude and direct and indirect consequences of this event on the territory system
Direct Vulnerability (Cafiso et al. 2011, D'Andrea and Condorelli 2006)	Propensity of a single element, simple or complex, to be damaged by a natural event
Induced Vulnerability (Cafiso et al. 2011, D'Andrea and Condorelli 2006)	It refers to the effects on the organization of the territory due to the collapse of one or more elements that make it up
Deferred Vulnerability (D'Andrea and Condorelli, 2006)	It refers to all the effects that occur in the phases following the event such as the modification of the habits and behavior of the populations located in those areas
Functional Vulnerability (Cafiso et al. 2011; D'Andrea and Condorelli 2006)	It refers to the lack of functionality of some elements that could cause significant damage after the occurrence of a calamitous event
Socio-economic Vulnerability or Social Vulnerability (Cutter et al. 2003)	It refers to the social, economic, politic conditions that characterize the territory affected by an event
Structural Vulnerability (Cafiso et al. 2011; Husdal 2004)	It refers to the infrastructure and to its constructive characteristics
Natural or Biophysical Vulnerability (Cutter et al. 2003; Husdal 2004)	It refers to the characteristics of the territory and to the natural risk of the territory
Vulnerability of the traffic (Husdal 2004)	It refers to the characteristics that describe the traffic flow and the conditions deriving from the variation of the traffic flow

2 Materials and Methods: A New Approach to Assess the Road Infrastructure System Vulnerability in the Rockfall Prone Areas

In this paper a new approach to assess the vulnerability of Road Infrastructure System in areas prone to landslides and in particular characterized by intensive rockfall events has been presented.

According to the authors, the road infrastructure system is a network system that connects various spatial areas guaranteeing a multitude of essential and indispensable services for the survival of the population, not less important the possibility of providing aid in places affected by natural disasters. Because of the importance of the transportation network, ensuring its functionality is of central interest both for the system users and for the managers. For these latter, it is also essential to have the tools available to effectively manage the limited financial resources available to reduce their vulnerability as far as possible.

In the proposed methodology, the vulnerability is expressed, in general terms, as the susceptibility of an element to be damaged by a natural event of a given intensity. According to the authors, in the proposed approach the vulnerability concept considers three characteristics: the type of risk the network is vulnerable to, the most vulnerable elements and the ways in which the vulnerability occurs.

The final level of vulnerability can be assessed by following several consecutive steps as shown in the following flowchart and description (Fig. 1).

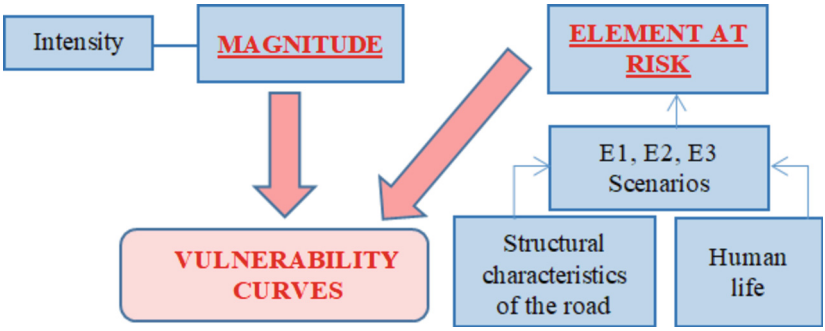

Fig. 1. Different phases to assess the vulnerability

2.1 Intensity Assessment of the Rockfall Phenomenon

Intensity assessment (or severity) of a phenomenon is a topic of the increasing interest for local technicians, administrators and local programmers.

The concepts of intensity and localization in the space generally is linked to the definition of the hazard expressed as the probability that a given phenomenon of a given intensity will occur in a given area (Varnes et al. 1978).

The first step for the assessment of the mass movement risk along the transportation corridors consists, therefore, in analyzing the geometric severity of the phenomenon by considering the parameters enumerated in the Table 2.

The intensity of the phenomenon is expressed in a relative scale describing the parameters related both to the physical characteristics of the phenomenon (volume, energy, etc.) (Canuti and Casagli 1996) and to the speed, as proposed by Hungr (1990), since it is not possible to precisely define a functional relationship between them.

In this case the definition of the intensity is linked to hypotheses on the possible consequences of the phenomenon; moreover, different speed thresholds are provided delimiting seven well-defined classes (Cruden and Varnes 1996).

Rockfalls are phenomena from rapid to extremely rapid (Cruden and Varnes 1996); in particular, the estimation of speeds in general can be obtained from the type of phenomenon and its state of activity.

The zoning of the territory in intensity classes occurs through the critical interpretation of the data collected in the inventory map, integrated with the information derived from the other basic documents.

The mass movement phenomena recorded in the inventory maps must be classified according to the area extension and the presumed speed.

The phenomena characterized by low intensity, in principle, do not compromise the structural integrity of the road infrastructure, nor the integrity of human life.

The medium intensity processes, on the other hand, can cause, depending on the circumstances, serious damages, without compromising, however, the structural stability of the infrastructure.

High intensity processes cause significant structural damages. In fact, the stability of the roads can be severely compromised and this could therefore imply large costs for repairs. Total restoration is often unavoidable (Table 3).

Another problem related to high-intensity rockfall phenomena is certainly linked to the deposit of collapsed material in the riverbed, that can compromise the normal flow of water, forming natural barriers (Landslide dams) (Dal Sasso et al. 2014) causing landslide lakes, debris flows, poor stability, overflowing of rivers and soil erosion.

The intensity mass movement scale proposed with the present assessment method, therefore, takes into account the speed of the movement and is associated with a scale of damages similar to the Mercalli scale of earthquakes (Canuti and Casagli 2004), divided into 10 classes.

The parameters to be analyzed in order to obtain the corresponding intensity class are listed in the table and described below.

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The parameters to be analyzed in order to obtain the corresponding intensity class are listed in the Table 2.

Table 2. Rockfall intensity assessment matrix.

ROCKFALL INTENSITY ASSESSMENT				
PARAMETERS	**RATING CRITERIA BY SCORE**			
Volume of rockfall per event (m³) - y = 3^x	$Y = 3^{V/2.3}$			
Block size (cm)	$Y = 3^{Db/30}$			
Speed (m/s)- (Hungr, 1981; Cruden & Varnes, 1994)		**5*10^-4 - 5*10^-2 RAPID (for neoformed and reactivated rock slides)**	**5-10^-2 - 5 VERY RAPID (for rockfalls and neoformed rockslides)**	**>= 5 - EXTREMELY RAPID (for Rockfalls and avalanches)**
SCORE		9	27	81
Run out (Km)	**< 10^-3**	**10^-3 - 10^-2**	**10^-2 - 10^-1**	**10^-1 - 10^-0**
SCORE	3	9	27	81
Affected area (Km²)	**< 0,01**	**0,01 - 0,5**	**0,5 - 0,75**	**> 0,75**
SCORE	3	9	27	81

2.2 Block Diameter and Rockfall Volume Per Event

The rockfall intensity assessment involves, first of all, the evaluation of the dimensions of the collapsing rock. In the RHRS method (Pierson et al. 1990) and in many subsequent modifications it is not specified if the block diameter is considered before or after the detachment; this aspect is very important to proceed to the intensity assessment of the phenomenon since, during the fall, substantial changes may occur with regard to the shape, size, conditions of motion, the variation of instantaneous kinetic energy that the boulder can undergo during the course and before the impact on the carriageway (Budetta 2004). Therefore, the roads that can be traveled in this direction can be mainly 2 to obtain the level of intensity or geometric severity with which a rockfall phenomenon can occur along a road:

1) Potential intensity assessment by considering mainly outcrops that, due to their size, homogeneity in the distribution of families of discontinuity, lack of vegetation and persistence of situations of potential risk, allow to better define the characteristics of the rock mass and, subsequently, the level of the potential risk of the underlying road;
2) Evaluation of the Rockfall Intensity Assessment (RIA) that has already occurred in the past by parameterizing all the predisposing factors and by determining the phenomenon through a back-analysis identifying the reach angle (see Losasso et al. 2016) and consequently the hazard levels of the slope, the vulnerability and the value of elements at risk.

In the first case the size of the phenomenon can be assessed considering the volume of the block (V_b) possessed at the time of the estimated rockfall, evaluating the spacing data for each system of joints and the angles that they form. Once this value has been obtained, the diameter can be assessed indirectly as:

$$D_b = \sqrt[3]{V_b}$$

In the second case, to obtain the size of the phenomenon, it is possible to consider the total volume of the "swarm" of already collapsed blocks in order to parameterize the original volume of the cluster by means of a back analysis.

Table 3. Magnitude class and Intensity level for the Rockfall phenomenon.

TOTAL SCORE	15	16-58	59-101	102-144	145-187	188-230	231-273	274-316	317-359	360-405
MAGNITUDE	I	II	III	IV	V	VI	VII	VIII	IX	X
INTENSITY	VERY LOW								VERY HIGH	VERY LOW

2.3 The Hazard Assessment

The parameter linked to the intensity, in addition to the vulnerability, is the hazard (Losasso and Sdao 2018). The maps of spatial hazard can be realized by using different modeling approaches with different complexity degrees. In particular, it is possible to use qualitative or quantitative methods. Quantitative approaches can be traced back to statistical models (Ayalew and Yamagishi 2005), probabilistic (Chung and Fabbri 1999) and may also refer to Soft Computing methods such as Artificial Neuronal Networks (ANNs). The ANNs are the reference evaluation models for many approaches and are used in the implementation of the hazard map for the study area, considering as input parameters the rockfall potential source areas, the detachment niches of already collapsed rock masses, the values of kinetic energy of propagation, lithology, slope and land use (Losasso and Sdao 2018).

2.4 The Element at Risk: Two Exposure Scenarios

Table 4. Typology of element at risk: two scenarios

TIPOLOGY OF ELEMENT AT RISK: TWO SCENARIOS				
RATING CRITERIA BY SCORE				
STRUCTURAL CARACTERISTICS OF THE ROAD	**POINTS 3**	**POINTS 9**	**POINTS 27**	**POINTS 81**
Ditch Effectiveness	Good catchment: properly designed according to updates of Ritchie's ditch+passive defense works	Moderate catchment: properly designed according to updates of Ritchie's ditch design chart without passive defense works	Limited catchment: wrongly designed	No catchment
Roadway width **(Pierson, 1990)**	Y = 3 ^(21.5-Lc)/6			
	21.5	15.5	9.5	3.5
Number of lines per each direction	3	2	2	1
HUMAN LIFE	**POINTS 3**	**POINTS 9**	**POINTS 27**	**POINTS 81**
% of decision sight distance	Y = 3^(120-%Da)/20			
	100%	80%	60%	40%
Average Veihcle Risk	Y = 3 ^AVR/25			
	25%	50%	75%	100%

To assess the final risk level, it is necessary, after the hazard assessment, to evaluate the element at risk, represented by population, goods, economic activities, public service and environmental goods present in a given area exposed at risk, that is to say more prone to the danger after a calamitous event. In the presented approach, an index that takes into account two categories for the assessment of the exposure degree of a road traveled by a vehicle has been considered. The element exposed at risk is, first of all, the road; for this reason, the expected damage is strictly connected to the design characteristics of the road. That's why 2 categories have been considered: in the category 1, represented by the road, the design characteristics of the road (such as the presence of rockfalls valley, the road width, the number of lines in each direction, …) has been assessed by using a scoring method. To assess the direct exposure of a road infrastructure and, consequently, of the vehicles passing through it (Category 2), it is possible to assess the Average Vehicle

Risk, a parameter directly proportional to the Average Daily Traffic, that is a parameter capable of representing the ordinary conditions of circulation (Table 4).

The sum of the scores relating to category 1 and category 2 provides three exposure classes (Table 5) that is to say 3 scenarios to be used later in the assessment of Vulnerability.

Table 5. Exposure classes

E1	**LOW EXPOSURE**	**15-101**
E2	**MEDIUM EXPOSURE**	**102-273**
E3	**HIGH EXPOSURE**	**274-405**

2.5 The Vulnerability Assessment of the Road Infrastructure System

The curves representing the vulnerability values according to the intensity of the phenomenon have been realized by considering different approaches proposed in the literature: for example the probability of human consequences for the different types of intensity (DRM 1990), or the vulnerability evaluation (possibility of death or injury) considering the intensity of the phenomenon based on the speed of movement (for speed $>$ 1 m/s human life can be directly vulnerable as proposed by Hungr 1981; for Cruden and Varnes (1994), on the other hand, this limit is reduced to 0.05 m/s or about 3 m/min).

In general, vulnerability curves are represented by an expression such as:

$$\mathbf{1} + \mathbf{e}^{\alpha \mathbf{t}} \tag{1}$$

represented by a Gaussian curve known as the Gauss function corresponding to an exponential mathematical function.

There are numerous studies in the literature about the curves of the elements vulnerable to disasters, such as mass movement and floods (Pascale et al. 2009) considering as elements exposed at the risk constructions and communication lines (ie elements with different physical, social and economic characteristics).

For this reason, the elements at risk, to assess their vulnerability, are categorized in general into three groups with different physical, social and economic characteristics: A, B and C (Fig. 2), each of which has a different response to the stress to which it is.

The vulnerability of the elements exposed to the risk ranging from 0 to 1 (Fig. 2), therefore, it is described by the following Eq. (2010; Sdao et al. 2013, Pascale et al. 2010; Papathoma et al. 2015):

$$y = 1 - \frac{ae^{-\alpha\xi^{2.2}}}{\left(1 + e^{-\alpha\xi^{2.2}}\right)} \tag{2}$$

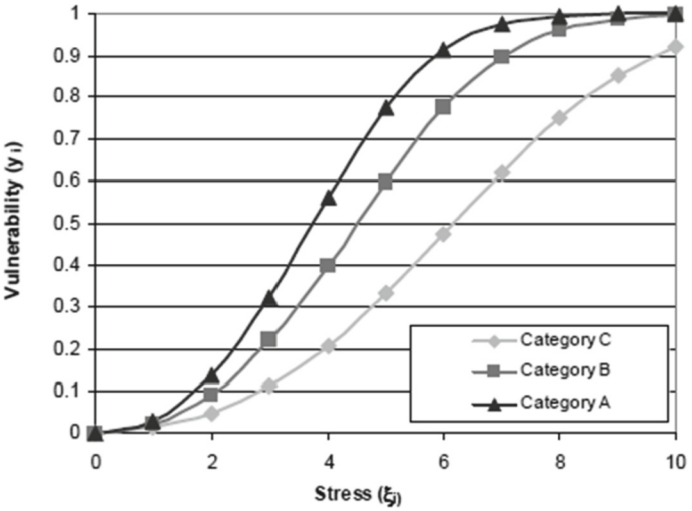

Fig. 2. Vulnerability curves for different types of risk elements

where: **y** represents the vulnerability on the occasion of the specific considered natural disaster;

ξ stands for a deterministic variable calculated from a scenario analysis (speed, dimension, energy,… of the analyzed process) that identifies the intensity of the phenomenon expressed as a scalar quantity;

a is a constant obtained by setting boundary conditions while **α** represents a variable introduced to model the curves.

The above-described approaches have therefore been further modified to be adapted to the assessment of the vulnerability of the road infrastructure system (Eq. 3) in order to obtain three curves for each scenario (for a total of 9 curves) that allow to assess the degree of vulnerability based on the importance of the artery in terms of practicability.

$$y = 1 - a\frac{e^{-\alpha\xi^{\gamma}}}{\left(1 + e^{-\alpha\xi^{\gamma}}\right)} \tag{3}$$

In Eq. 3, ξ indicates the magnitude (intensity) and is expressed by a scalar quantity (previously evaluated and divided into 10 classes according to the obtained score), the constant has been calculated by setting specific boundary conditions, that is to say by imposing y = 0 representing zero vulnerability (no loss) for ξ = o.

The parameter α is also assessed by imposing boundary conditions: for example, for the curve belonging to the E3 category when the phenomenon falls in the 6, 7, 8, 9 and 10 intensity classes, the vulnerability varies from 0.9 to 1, for intensity equal to 3, 4, 5, and 6, the vulnerability falls in the middle class in a vulnerability range of 0.3–0.9, finally low vulnerability for disastrous phenomena characterized by a stress or intensity level of 1, 2 and 3, obtaining three different values for the three different curves (Sdao et al. 2013).

In the considered approach, vulnerability is expressed as a function of the elements at risk, represented by the road (structural characteristics) and by the vehicles that can cause damage to human life.

Since the elements at risk are closely correlated (and for this reason expressed through three scenarios), the vulnerability has been considered with reference to three curves showing the three different exposure scenarios (Scenario E1, Scenario E2 and Scenario E3).

Therefore, the scenarios E1, E2, and E3 (Fig. 3) represent the elements exposed to the risk in the infrastructure system (ie vehicles and roads).

The relevance of these scenarios increases passing from class E1 (lower exposure) to class E3 (high exposure).

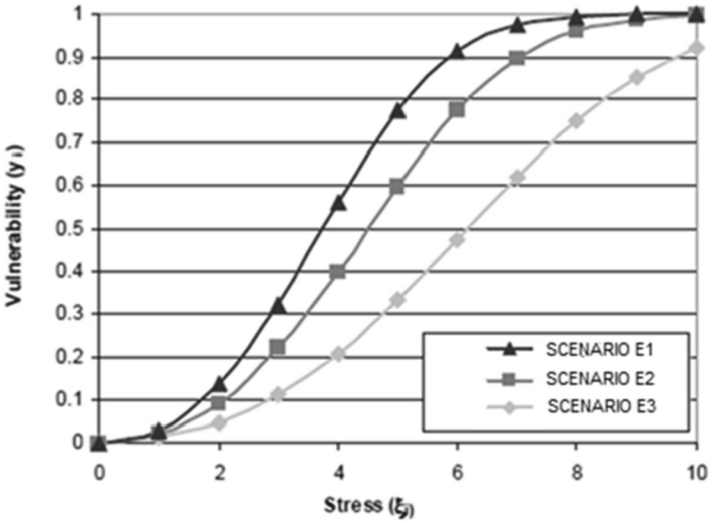

Fig. 3. Vulnerability curves for the different risk exposure scenarios

In this specific case, the values necessary for the implementation of the vulnerability curves relating to the road infrastructure system are summarized in the following table (Table 6):

In the light of the above, it is possible to represent the final graph (Fig. 4) which shows the 9 vulnerability curves with the different risk exposure scenarios representing the values of magnitudes in abscissa and the levels of relative vulnerabilities in the ordinate. The different exposure scenarios are reported with three different colors: the green curves represent the elements most exposed to landslide risk i.e. corresponding to E3 scenario, the red curves represent the E2 scenario and finally the blue curves the E1 scenario. Each curve in turn contains three different curves: a, b and c which correspond to a different degree of vulnerability and take into account the "exposure density" of the elements at risk, i.e. they represent the number of accesses to the road;

Table 6. Assessment of the parameters related to the vulnerability curves

PARAMETERS	VALUES	ASSESSMENT
γ	2.2	travel alternative>2
γ	2.4	travel alternative =2
γ	2.6	travel alternative =1
α	0.02	E1 scenario
α	0.04	E2 scenario
α	0.06	E3 scenario

- the curve "a" represents the streets with a single access point, this means greater traffic flow, therefore a greater possibility that a vehicle can transit along the road during the occurrence of a calamitous event;
- the curve "b" indicates a number of accesses equal to 2: this means that the traffic can be "reduced", therefore if a rockfall phenomenon involves the closure of the road, this problem does not imply any isolation of the inhabited centers as easily accessible from other accesses.
- Finally, the curve c, which corresponds to a lower degree of vulnerability with the same intensity, indicates the possibility to access to a given inhabited area through different accesses.

In this way, based on the intensity degree of a given rockfall phenomenon, it is possible to assess the corresponding degree of vulnerability (Table 7).

2.6 Conclusion

In this study, some existing methods for vulnerability assessment related to landslides has been reviewed. From the analysis of the different approaches, a lot of difficulties in their implementation has been detected (for example data availability).

The new proposed approach allows to assess the rockfall vulnerability of each element at risk by considering a process of a given magnitude as a function of rockfall hazard.

The proposed curves for the evaluation of the road infrastructure system vulnerability are objective and the reproduction is possible and applicable for other studies and regions. In particular, the effects of changing the vulnerability of elements at risk can be analyzed, so scenarios of potential future developments can be calculated.

The most important advantage of the new proposed methodology is its versatility and the its user friendliness.

Table 7. Values relative to the vulnerability curves of the road infrastructure system

E1	>2 γ=2.6	0.03066	0.12522	0.30874	0.545844	0.784871	0.918601	0.976585	0.994804	0.999104	0.999851
	2 γ=2.4	0.03072	0.14244	0.37625	0.667189	0.898155	0.978688	0.99717	0.999762	0.999987	0.999999
	1 γ=2.2	0.03078	0.16195	0.45467	0.7856	0.965552	0.996987	0.999877	0.999997	0.999999	0.999999
E2	>2 γ=2.6	0.02044	0.08372	0.20961	0.387024	0.607713	0.783098	0.901203	0.962842	0.988357	0.996476
	2 γ=2.4	0.02048	0.09532	0.25783	0.490794	0.750921	0.906995	0.975085	0.995176	0.999324	0.999913
	1 γ=2.2	0.02052	0.10849	0.31586	0.608512	0.873588	0..974036	0.996895	0.999787	0.9999991	0.999999
E3	>2 γ=2.6	0.01022	0.04193	0.10598	0.201358	0.338718	0.482828	0.628719	0.758105	0.8557837	0.919362
	2 γ=2.4	0.01024	0.04776	0.013113	0.262278	0.452255	0.638216	0.798053	0.906267	0.963906	0.986926
	1 γ=2.2	0.01026	0.05441	0.016208	0.339279	0.587615	0.794229	0.924129	0.979602	0.996007	0.999303
		I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**

LOW VULNERABILITY
MEDIUM VULNERABILITY
HIGH VULNERABILITY
VERY HIGH VULNERABILITY

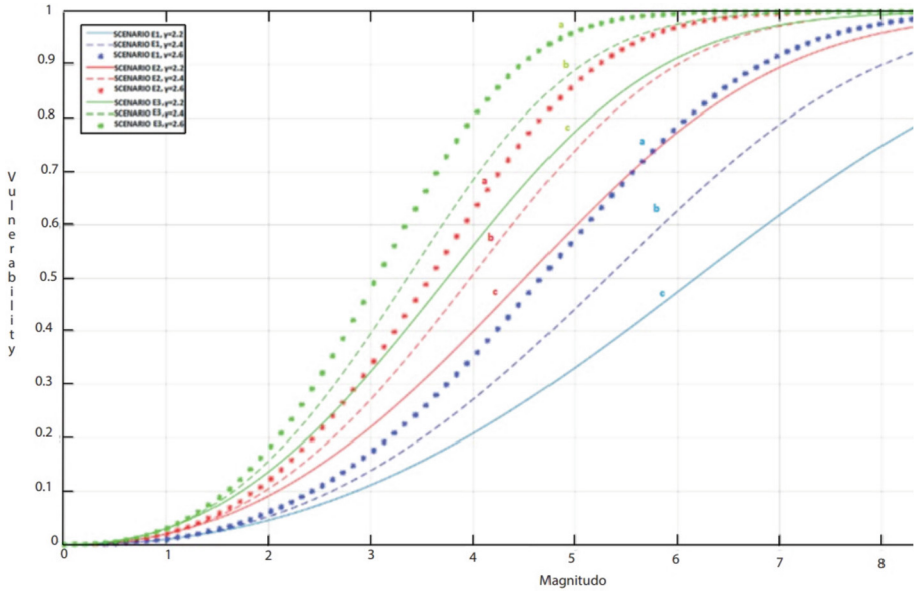

Fig. 4. Vulnerability curves of the road infrastructure system

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