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A fuzzy methodology to evaluate the landslide risk in road lifelines

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Abstract

The purpose of this study is identifying, through the fuzzy logic methodology, the stretches of the road SS106 Reggio Calabria – Bova Marina, considered like a "lifeline" in the metropolitan area of Reggio Calabria, subjected to landslide risk. The mentioned infrastructure has a very low qualification level due to the old design and construction, other than to the land morphology. Its importance comes from its use since it is the only highway which could be considered important strategically for a probable emergency management. Thanks to the elaboration of thematic maps by PAI (*Piano di Assetto Idrogeologico*, 2001), made available by the *Autorità di Bacino* of Calabria Region, the landslide risk is evaluated by the combination of the software Quantum – GIS and by a hierarchical system at one level with two inputs and one output through Fuzzy Logic Toolbox in MATLAB environment, where the input number corresponds to the linguistic variables ("Indicators") and the output represents the "Level of Attention" evaluated for the considered infrastructure. Fundamental step of the process is analysing the importance of the road and considering it like a "lifeline" in case of catastrophic events (e.g. earthquakes, landslides, floods, etc). Through the presented model, it would be possible to identify the road portions subjected to landslide risk, classify them and understand how their damage and their reduced functionality would be a problem for the emergency management other than for the costs.

Keywords: landslide risk, fuzzy logic, road lifelines.

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1. Introduction

A natural hazard can be defined as a potentially harmful physical event that can cause loss of human life or injured, material damages, environmental degradations, social and economic damages. Growing population and expansion of settlements in hazardous areas have largely increased the impact of natural disasters both in industrialized and developing countries. However, the effects of natural disasters on the society would be considerably reduced thanks to the application of new forecasting models and protection measures. Several models were created to assess the vulnerability (that is the susceptibility of the considered system to cope under a given hazard) of urban society, and to evaluate the risk. Risk can be defined as the possibility of adverse effects like loss and injury caused by exposure to hazards (Ganoulis, J., 1994). The most important accepted risk analysis approaches are the quantitative, the holistic and the qualitative ones. Engineering risk analysis is mainly based on the quantification of various uncertainties which may occur in the evolution of physical processes. Furthermore, taking to account how processes might develop under uncertainty in the future, probabilistic approaches are more appropriate for this purpose than deterministic methods. Probabilities and the fuzzy set theory (or fuzzy logic) are suitable tools for quantifying uncertainties, which may induce a risk. Fuzzy logic invented by Zadeh L. A. in the 1960's combines the concept of classical logic and the Lukasiewicz sets there by defined graded membership. According to Zadeh L. A. (1965), fuzzy logic can work with uncertainty and imprecision and it can solve problems where there are no sharp boundaries and precise values. The concept of a fuzzy set provides mathematical formulations that can characterize the uncertain parameters involved in a risk analysis method.

Landslides are the most common consequence of the soil instability due to the seismic activity and the hydrogeological problems. In regions where urban residential areas coincide with mountainous terrains, like Calabria, the risk is higher for people and the economic costs include relocating communities and repairing physical structures. Moreover, considering the analysed route as a lifeline, it is essential understanding which sections could be at risk and compromise the transport circulation during a catastrophic natural event.

The analysis in the present work provides an assessment of the risk level for the stretch Reggio Calabria – Bova Marina of the road SS106 due to potential landslides and it demonstrates how these results can be used to identify "hot spots" along the route where risk reduction measures could be prioritised. The assessment was based on the analysis of thematic maps, provided by the *Autorità di Bacino* of Calabria Region in Quantum - GIS, and on a fuzzy logic model in MATLAB environment.

Nomenclature

H_{max}	maximum height of the considered area
H_{min}	minimum height of the considered area
ΔH	height difference
% i	average slope

2. Transport lifelines

Lifelines are defined as "network systems that provide an essential services for the daily life of communities such as transport, electricity, gas and liquid fuels, aqueducts and sewers, telecommunications - on which health, comfort and, more generally, socio-economic wellbeing - allowing, at the same time , an effective emergency response" (Paton D., Johnston D. M., 2006). Definitively, lifelines can be defined as the set of structures, infrastructures and services (such as water distribution network, gas network, power system, telecommunication network, main roads network) considered as indispensable for the maintaining and the protection of the life of a system. This latter must have a proper planning of lifelines that would be very useful also to prevent many of the harmful effects induced by the various natural calamities. Recent experiences highlighted the extreme importance of the lifelines functioning in the emergency conditions which follow a catastrophic event (Casari M. et al., 2005; Chang S.E. et al., 2001). Some lifelines have to guarantee effectiveness and efficiency in the immediate aftermath of the disaster (Bakir S. A., et al., 1994), in some cases also during the event, to allow a rapid and efficient access, assistance and rescue, guaranteeing evacuation, and more in general maintaining access for all emergency services (Miller H.J., 2000), like in the case of transport lifelines (Cirianni et al. 2008). Therefore, it is fundamental that the whole system of the lifelines, if damaged during the event, could be repaired in the shortest time, and consequently rehabilitating accessibility and primary services, necessary for the sustenance of the population and the rescue process.

The main characteristic which differentiates transport infrastructures from other types of lifelines is the human access for individual use and, in general, for all needs of mobility. Therefore, the exposition to a risk of the transport infrastructures implies an exposition of the users, and for this reason the transport network vulnerability assumes a primary interest in the risk assessment (Cirianni et al., 2012). Moreover, during an event of emergency, transport lifelines play an important role in all four phases of emergency management: mitigation, preparation, response and recovery. Summarizing, the transport infrastructure to be considered a lifeline must:

- guarantee accessibility to the affected areas;
- guarantee the arrival of emergency assistance from outside;
- guarantee access to civil protection structures, health facilities, power stations and power lines and to all the other strategic elements of the system;
- guarantee the continuation, after emergency, of the productive activities of a given region.

3. Case study

The Metropolitan Area of Reggio Calabria (Italy) is the zone with the highest population density in Calabria for its extension of 3.183 km^2 and its ninety-seven towns and villages with a total of 550.000 residents. The analysed stretch of the road SS106 is 46 km long (showed in figure 1-a) and it connects Reggio Calabria to Bova Marina. The logistical importance of this road in the Metropolitan Area is because of its connection with several mountain, hilly and coast villages. Among the infrastructures with a particular relevance, the SS106 certainly represents the route that requires greater attention, considering it as a lifeline seeing as how it is the only one that allows the connection between outlying villages and the emergency centres and the hospitals of Reggio Calabria.

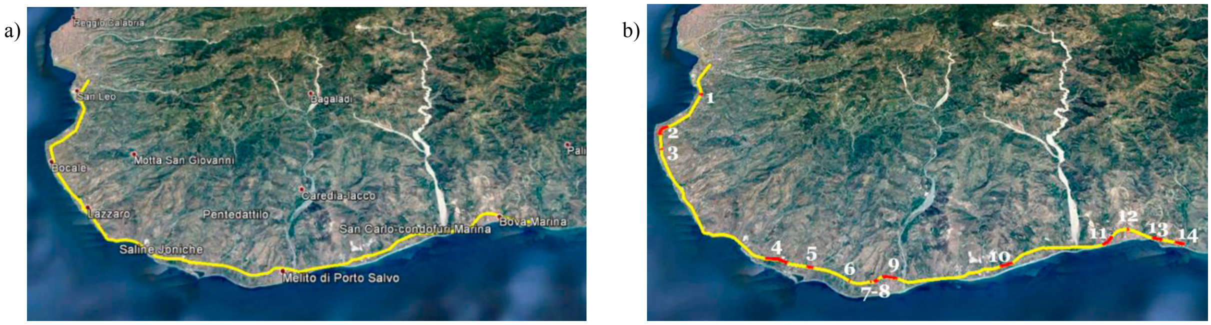

Fig. 1. (a) The analysed stretch of the road SS106; (b) Sections exposed to the landslide risk.

Around the 60% of the Region territory is above the quote of 300 m m.l.s. and the analysed area has strong height differences. The regional geological arrangement is one of landslide causes, but also the presence of small rivers with a high longitudinal pendency and, so an elevated capacity of erosion and solid material transport, has a powerful influence.

The *Autorità di Bacino* of Calabria Region, considering the various mentioned problems, has made available several thematic maps for a complete hydrogeological balance (PAI - *Piano di Assetto Idrogeologico*, 2001). These maps are accessible through Quantum – GIS and they describe the landslide hazard and risk areas in the whole Region, but they do not give any information about the landslide risk assessment in the strategical infrastructures. For this reason, in the present paper a simple model for the landslide risk assessment is proposed combining the information obtained by the maps of Quantum – GIS with the Fuzzy Logic in MATLAB environment. The risk assessment was estimated by a simple fuzzy system with two inputs and one output, where the input number corresponded to the linguistic variables and the output represented the risk level for the considered infrastructure. In particular, landslide risk was assessed in each road section where the infrastructure appeared to be adjacent or crosses landslide hazard and risk areas identified by the PAI. For the analysed route of the SS106, fourteen road sections were identified as exposed to the landslide risk (represented by red segments in Fig. 1-b).

4. Fuzzy logic application

The implemented risk assessment scheme was based on the evaluation of the potential impact of a landslide event on the considered transport lifeline. This potential impact is considered dependent on: (i) average slope and (ii) height difference.

In order to define the landslide risk level in the identified road sections, a simple fuzzy inference model was implemented with two inputs and one output in MATLAB environment (Fig. 2) (Zlateva P. et al., 2011; Nithya S. E. et al., 2012; Leonardi G. et al., 2016).

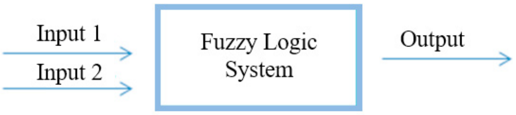

Fig. 2. Fuzzy inference model.

The number of inputs for the system was represented by the two linguistic variables such as the "height difference" (ΔH) and the "average slope" (i) of the landslide hazard and risk areas identified by PAI, that were adjacent to the road (as an example, fig. 3-a and 3-b show two of these areas). Using GIS, the indicators values were calculated for each considered area (fig. 4 and table 1).

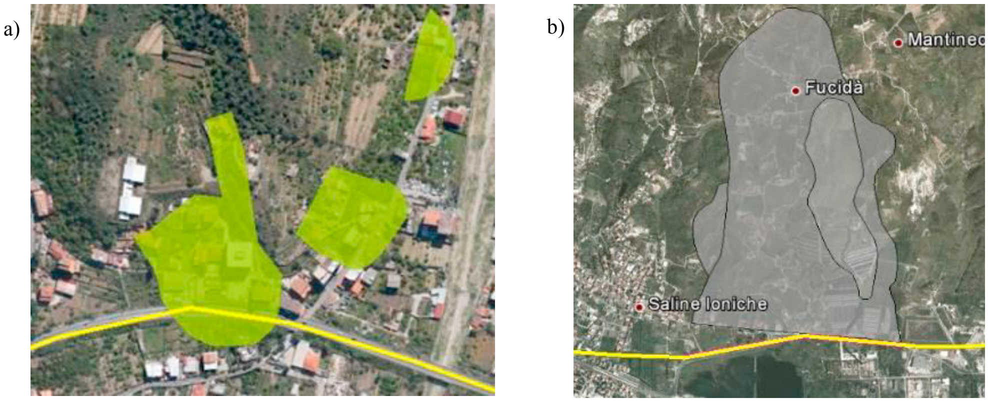

Fig. 3. (a) Landslide hazard areas identified by PAI; (b) Landslide risk areas identified by PAI.

In the fuzzy logic system, the two input linguistic variables (height difference and average slope) were represented by five fuzzy membership functions: "Very Low", "Low", "Medium", "High" and "Very High". The input variable “height difference” was evaluated in the range [0, 220] with trapezoidal membership functions (Fig. 5-a), while the second one "average slope" in the interval [0, 40] again with a trapezoidal membership function (Fig. 5-b).

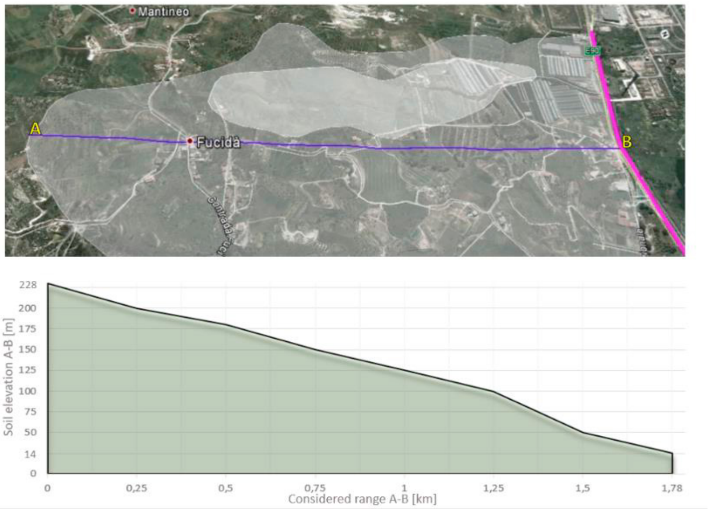

Fig. 4. “Height difference" (ΔH) and "average slope" (i) evaluations for section n. 1

The output of the fuzzy logic system "landslide risk level" was also described by five fuzzy membership functions: "Very Low", "Low", "Medium", "High" and "Very High" in the interval [0, 100] using triangular membership functions (Fig. 6). After the definition of the ranges and the functions, the inference rules were constructed through the linguistic rule "IF - THEN".

Table 1. “Indicators” values.

Sections	Adjacent landslide risk area	Adjacent landslide hazard area	H_{max} (*m*)	H_{min} (*m*)	ΔH (*m*)	% i
1		X	228	14	214	12,3
2		X	158	25	133	13,5
3		X	48	15	33	9,8
4		X	72	25	47	37,9
5	X		92	32	60	17,8
6	X		113	32	81	29,3
7		X	116	29	87	30,5
8		X	87	19	68	27,7
9		X	95	17	78	30,9
10	X		130	28	102	17,4
11		X	56	9	47	15,6
12	X		75	42	33	11,9
13		X	115	70	45	32,9
14	X		104	85	19	11

Overall, twenty-five inference rules were defined, based on the analysis of scientific publications and similar studies proposed in the literature (Cirianni et al., 2012; Leonardi et al. 2016; Barrile et al, 2016); some of them are shown below as an example:

IF “height difference” is "Very Low" and “average slope” is "Very Low" then "the level of landslide risk " is "Very Low";

IF “height difference” is "Low" and “average slope” is "Medium" then "the level of landslide risk " is "Medium";
IF “height difference” is "High" and “average slope” is "Low" then "the level of landslide risk" is "Medium";
IF “height difference” is "High" and “average slope” is "Medium" then "the level of landslide risk " is "High".

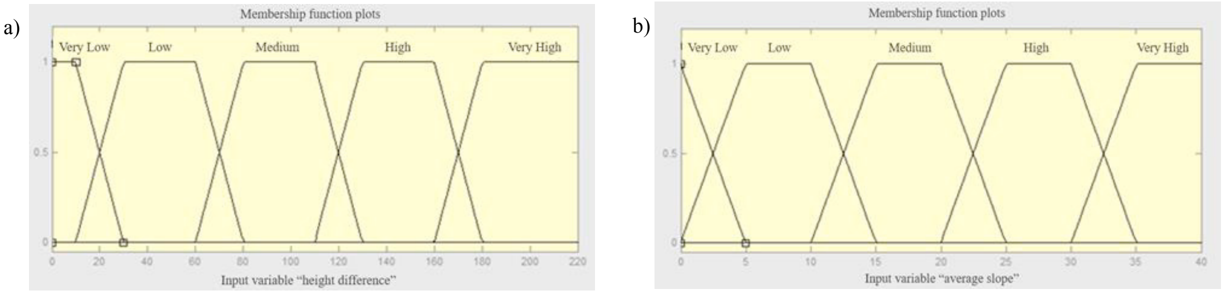

Fig. 5. (a) Membership function plot for the input variable: “height difference”; (b) Membership function plot for the input variable: "average slope".

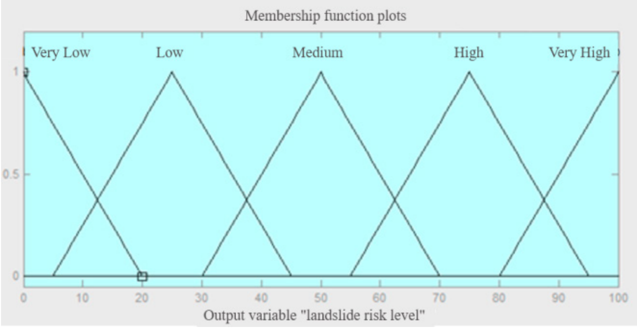

Fig. 6. Membership function plot for the output: "landslide risk level"

The fuzzy logic system was built with the type of fuzzy Mamdani inference system (Jang, J. S. R., 1997). The relationship between the two inputs and the output was shown graphically in figure 7 through the 3D inference surface. The obtained values (showed in table 2) allowed to identify the level of landslide risk in percentage for the identified infrastructure sections; furthermore, these results were intended to be an integration to the assessments and information already provided by the PAI of the Calabria Region.

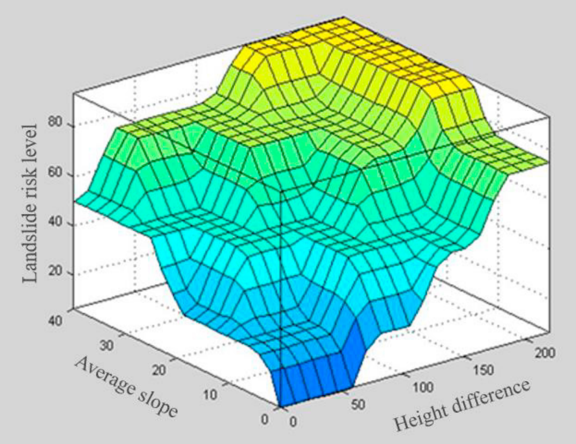

Fig. 7. 3D inference surface for landslide risk.

Table 2. Input and output values for each section.

	INPUT		OUTPUT
Sections	ΔH (*m*)	%i	Landslide risk level
1	214	12,3	79,5
2	47	37,9	75
3	81	29,3	75
4	87	30,5	75
5	78	30,9	71,4
6	133	13,5	66,4
7	45	32,9	64
8	68	27,7	60,6
9	60	17,8	50
10	102	17,4	50
11	47	15,6	50
12	33	11,9	35,2
13	19,0	11,0	32,3
14	33	9,8	25

It should be noted that the assessed risk levels for each section did not consider the impact of mitigation measures. In several cases, the risk could be significantly reduced through implementation of such measures.

5. Conclusions

In this paper a fuzzy methodology was used to evaluate the landslide risk in a 46 km long section of the road SS106. The risk assessment for the strategic infrastructures considered lifelines, as SS106, has a particular relevance, as explained above, and the results of this study underlined a real problem for analysed stretch. Indeed, eleven out of fourteen analysed sections had a landslide risk level greater than or equal to 50%, evaluated through a 3D inference surface in which the input data were the height difference and the average slope of the areas close to the road.

The presented method could represent a fundamental starting point in order to reduce the damage of the infrastructure and the related risks and the economic losses. The results of this preliminary susceptibility analysis could give indispensable information on the relative criticality of the different road sectors, thereby allowing attention and economic budgets to be shifted towards the most critical assets, where structural and non-structural mitigation measures could be implemented.

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