METHODOLOGY TO ASSESS VULNERABILITY OF ROADS UNDER HYDROGEOLOGICAL EVENTS

Melis D.
PhD Student – University of Cagliari. – dmelis@unica.it
Maltinti F.
Resercher – University of Cagliari – maltinti@unica.it

ABSTRACT

For a long time the reliability of a road net under calamitous events has been ignored into the management process. Nevertheless road nets have a very important and critical role into the different steps of emergency management.

Indeed, to assess the vulnerability of a road net before that a calamitous evet occurs it is necessary, not only to realize emergency and recovery plans, but also to plan apposite adjustment interventions on the net.

Nowadays literature shows different methodologies to assess the seismic vulnerability of a road section. We do not have the same informations to evaluate the hydrogeological vulnerability cause of interactive elements complexity.

This paper shows the initial phase of a wider research aimed to the definition of a criterion for the valuation of the qualitative and quantitative vulnerability of a road section to hydrogeological events.

The first step is the creation of tecnical check-lists that allow to define a qualitative level (low or high) of the vulnerability of a road section and so consequently to assess the reliability and to plan apposite adjustment interventions of the net.

The work has been lead and validated through the study of a case record of hydrogeological nature events that interested some roads in the past.
Keywords: emergency management, vulnerability assessment, reliability assessment

1. INTRODUCTION

One of the possible targets we can attribute to a program of functional requalification of an existing road net, is to identify the optimal and reliable routes to be used during an emergency event.

Road nets have a very important and delicate role into the emergency management process. Indeed, many experiences revealed that road system inefficiency, in emergency conditions, can raise damages on anthropic systems with a magnitude comparable with those caused by calamitous events, overall due to delays in assistance operations.

The analysis of past hydrogeological natural events, that affected territorial network systems, have revealed their vulnerability. Thus, to plan apposite maintenance interventions on the road net, is important to know both the kind and the level of risk before that a disaster happens, and the vulnerability level of the transportation system.

This work shows a methodology to quickly assess hydrogeological vulnerability of road infrastructures. For vulnerability we mean an intrinsic factor of the road related to its “weakness or fragility”; thus it is indipendent from the level of hazard (probability of occurrence of a potentially damaging phenomenon within a specific period of time and within a given area). The product of vulnerability (V) and natural hazard (H), gives the expected degree of loss due to a particular natural phenomenon.

The methodology has been created for the analysis of existing roads. The application of the methodology allows to identify a qualitative reliability level of the arcs of a road network. In this way it is possible to plan apposite maintenance interventions and if it is necessary, to make other studies and elaborations.

2. RELIABILITY AND VULNERABILITY OF A ROAD NETWORK.

Lifeline systems are network systems that connect and serv a country, assuring different services, which are essential for the economy and the development (water supply, energy supply, comunications, sewage disposal etc). The transportation system is the most important lifeline system: the restoration of other lifeline systems and people rescue and recover operations are strictly related to its efficiency. Lifeline systems are very vulnerable to natural disasters (earthquake, landslides, floods, snow avalances, etc) due to their territorial diffusion. Therefore, it is important to reduce the damages caused by a natural phenomenon to assuring a good functionality of these systems, and to know, before an emergency occurs, the level of hazard, vulnerability and the element at risk for a given area, which means to know the transportation network reliability. It leads to the need of identifing those roads which, thanks to their features, are able to function as lifelines.

In particular, the transportation lifeline systems have to:

- assure the accessibility to the areas damaged by a natural phenomenon;
- assure the emergency operations;
- assure the access to the strategic points of a country (hospitals, railway stations, airports, fire stations etc.);
- assure the restoration activities when the emergency ends;

The identification of roads with lifeline features can be made using different maps at different scales. For example:

- a scale of 1:25,000 is rapresentative for the analysis of the road net and the identification of possible alternative routes;
- a scale of 1:10,000 is rapresentative for the analysis of functionality of a single road;
- a scale of 1: 1,000 or 1:500 is rapresentative for the analysis of vulnerability .

The conclusion of this work is the design of a specific map that indicates the roads that can function as lifelines in a given area or a country. So, the identification of lifeline systems can be seen as an iterative process. The first step is an initial cartographic identification; the second step is the study of the vulnerability of indicated roads, in detail; the last step is the confirmation of these roads, or the research of safer alternative roads.

The road vulnerability is related to the concept of reliability: the greater the net reliability is the minor the vulnerability will be, and vice versa. The concept of vulnerability is related to roads features and it is indipendent from external factors.

Depending on map scale and factor analized, the vulnerability concept can be distinguished in:

- induced vulnerability;
- functional vulnerability;
- structural vulnerability.

The induced vulnerability is caused by the system crisis: it refers to the effects of the crisis of the organisation after that one or more elemets have collapsed.

The functional vulnerability can be evaluated into a wide area or into a road net: it assess the lack or the reduction of the system functionality after the event.

The structural vulnerability refers to single road feature and to the tendency that every single element have to be damaged or to collaps as a consequence of a natural phenomenon. Elements can be simple or complex, and the passage from one single element to a group of elements can be difficult.

The vulnerability assessment process can be made by a qualitative or quantitative point of view. By the quantitative point of view vulnerability indicators are used to identify road reliability and its tendency to collapse during or after the event (i.e. those are used to assess seismic or hydraulic structural vulnerability of road bridges). For a qualitative assessment, check lists can be used (i.e. those are used to assess the seismic vulnerability of roads). Literature does not show any methodology to assess the hydrogeological vulnerability of a road section. Thus the aim of this work is the definition of tecnical check-lists that allow to define a qualitative level (low or high) of this kind of vulnerability. The work has been lead and validated through the study of a case record of hydrogeological natural events that interested some Sardinain roads in the past.

In this connection it is important to say that today we do not have a lot of documentation, and there is not any specific database for these events. In particular it was possible to have only a photographic documentation (thanks to the Sardinian ANAS department).

The output of the study of the case record is shown in figure 1. For all the analized cases, possible road deficiencies (due to poor design and construction), that have lead to road damage or collapse, were identified.

The greater percentage of road instabilities (30%) is due to the lack of hydraulic works defending the road network (drainage diches, culverts, gutters, underdrains, slope protection works, etc.). This was a predictable result: in fact, it is well known the importance of hydraulic components in a road. The subsurface and the surface waters can cause great damages to a road: they can change the mechanical ground properties, erode the exposed soils and finally bring to possible falls or slides.

The 17% of analized instabilities are related to the type and the proprierties of the foundation soil, and to the maintenance of the works of art. Design practices always recommend to avoid areas with existing or potential instabilities. Often it does not happen: for example, the figure 2 below shows an initial failure of the fill slope of one road. This road, in particular, was built in an area which critical landform and geology caused different rock falls, debris flows and slope failures.

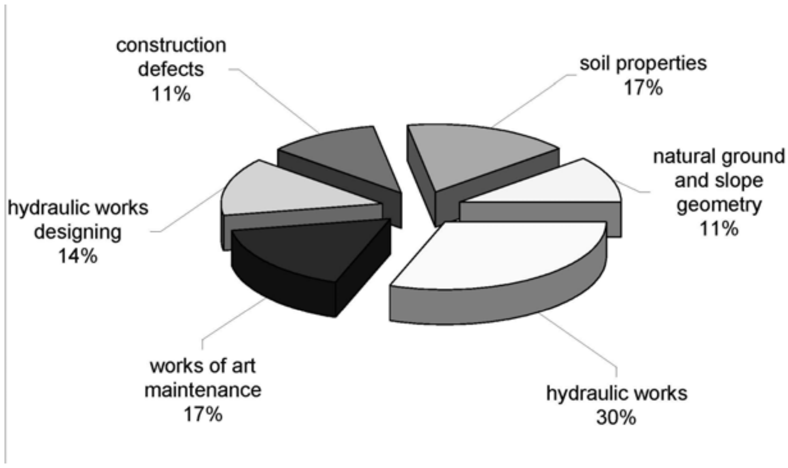

Figure 1 –Causes of road damages after an hydrogeological events

Figure 2 Initial failure of the fill slope in the State Road 198

The 14% of instabilities were related to a poor design of hydraulic works. Figure 3 below shows a failure on the State Road (S.S. n°) 389, which has happened in

December 2004 after a copious precipitations. The existing culvert was not able to drain the surface water because of its inadequate dimensions, the culvert failure caused the total collapse of the road embankment and the road closure for several months.

Figure 3 – Embankment collapse caused by the culvert failure.

Finally the 11% of analized instabilities were caused by construction defects of the road, or by the geometry of the slopes and the natural ground (height, grade etc.). For example, often, construction defects are visible in retain structures, and some of them have failed due to metereological events of low magnitude.

About slope geometry, it is necessary to study the critical slope according to the geotechnical features of the natural soil; otherwise, during intense metereological events, some debris falls, flows or slope failures can happen. This is the case shown in figure 4.

Figure 4 – Slope failure after a metereological event

At the end of the analysis of this case history it was possible to deduce some conclusions:

- considering the percentage of road instabilities due to the lack of hydraulic works (30%), the percentage related to a poor design of the hydraulic works (14%), and the percentage connected to the maintenance of the hydraulic works (17%) it can be said that more than the 60% of road instabilities were caused by the water-road interaction. This conclusion underlines the opportunity to make correct hydraulic and hydrologic survey during the design stage of a road;

- the instabilities of a road section after an hydrogeological event are connected and caused by different interacting factors. Internal factors, like road geometry, ground properties, road facilities etc., and external factors, like landform, geology, precipitations etc.

3. THE PROPOSAL OF A CHEK LIST FOR THE QUICK ASSESSMENT OF HYDROGEOLOGICAL VULNERABILITY

To plan apposite maintenance interventions for a road (i.e., reconstruction and improvement works) and to identify reliable roads to be used during an emergency operation it is necessary to determine which roads or road sections are more vulnerable than the others.

However, considering the road net extension that can be interested by emergency operations, it is necessary to develope a methodology that can be used in a very short time. This methodology must be able to give a first evaluation of road reliability and to identify which part of the net, due to its critical situation, needs deeper studies.

The methodology suggested in this work uses evaluation check lists that allow a fast examination of the road, according to some road features easy to detect. Sometimes this check can be made through a simple visual examination.

The check lists were made for road embankments and through-cut roads. Any evaluation check list was made for bridges and tunnels, since these are problems pertaining structural and geotecnical engineering. The analysis of hydraulic works were made into the two check lists, and concerned their maintenance condition and their presence. In fact, for the complete control of hydraulic works, it would be necessary to make a survey of their geometrical features.

The different steps that were made for the accomplishment of the check lists are:

- identify, for road embankments and through-cut road, which elements can have an effect on road reliability and stability. It was made through the study of different instability cases that had interested some Sardinian roads in the past, and through the literature;
- identify, for each element taken into account, a synthetic parameter which variation can increase the vulnerability of the element and consequently increase the overall vulnerabily of the road.

For some parameters (e.g. height of the embankment, slope grade, shoulder width), it is necessary to make some geometrical survey; for other parameters (e.g. presence or absence oh hydraulic works, maintenance conditions)it is necessary only a visual examination to consequently decide the correspondent vulnerability class.

Table 1 and table 2 below show respectively the check list for embankments vulnerability assessment, and the check list for the through-cut roads vulnerability assessment.

Table 1 Check list for quick vulnerability assessment of embankments

CHECK LIST FOR QUICK VULNERABILITY ASSESSMENT OF EMBANKMENTS				
COMPONENTS		**CORRESPONDING VULNERABILITY CLASS**		
		LOW	**MEAN**	**HIGH**
Embankment height (h, meters)		h< 3 m	3 m <h< 4m	h> 4 m without bench
Grade of the natural ground (i, %)		i<15%	15%< i <20%	i>20% without bench
foundation soils (HRB classification)		A_{1a}, A_{1b}, A_3 A_2 soils, soils without any potential or existing instability form	A_4, A_5, A_6 e A_7 without consolidation processes, soils with potential or existing instability form	
Embankment soils		A_1, A_3 A_{2-4}, A_{2-5} soils	A_{2-6}, A_{2-7} soils	A_4, A_5, A_6, A_7 soils without stabilization processess
Subgrade soils		A_1, A_3 soils	A_{2-4}, A_{2-5} soils	A_{2-6}, A_{2-7} A_4, A_5, A_6, A_7 soils
Embankment slope ratio		< 2:3	= 2:3	> 2:3
Shoulder width (w, meters)		w >1 m	0,5 m <w<1m	w<0,5 m
Embankment protection works		Soils protected from erosion (grass, or other protections), surface drainages in good level of maintenance	Soils protected from erosion (grass, or other protections), surface drainages in poor level of maintenance	Exposed soils without surface drainage
Hydraulic works	**Subsurface water**	Longitudinal underdrains, cross drains	Lack of longitudinal and cross underdrains	
	Surface water	Drainage diches, gutters and others surface drainages	Lack of drainage diches, gutters and others surface drainages	
Hydraulic works maintenance		Good level of maintenance	Poor level of maintenance	
Pavement maintenance		Good level of maintenance	Poor level of maintenance	

Table 2 Check list for quick vulnerability assessment of through-cut roads

<table>
<tr><th colspan="5">CHECK LIST FOR QUICK VULNERABILITY ASSESSMENT OF THROUGH-CUT ROADS</th></tr>
<tr><th colspan="2" rowspan="2">COMPONENTS</th><th colspan="3">CORRESPONDING VULNERABILITY CLASS</th></tr>
<tr><th>LOW</th><th>MEAN</th><th>HIGH</th></tr>
<tr><td colspan="2">Grade of the natural ground (i, %)</td><td>i<15%</td><td>15%<i<30%</td><td>i>30%</td></tr>
<tr><td colspan="2">foundation soils (HRB classification)</td><td>A_{1a}, A_{1b}, A_3 A_2 soils, soils without any potential or existing instability form</td><td colspan="2">A_4, A_5, A_6 e A_7 without consolidation processes, soils with potential or existing instability form</td></tr>
<tr><td colspan="2">Subgrade soils</td><td>A_1, A_3 soils</td><td>A_{2-4}, A_{2-5} soils</td><td>A_{2-6}, A_{2-7} A_4, A_5, A_6, A_7 soils</td></tr>
<tr><td rowspan="2">Slope geometry and geology</td><td>Rocks</td><td>Stabel cut slopes that didn’t present any type of landslide</td><td colspan="2">Unstable cut slopes that presented some type of landslides (rock falls, topples).</td></tr>
<tr><td>Engineering soils (Factor of safety FoS)</td><td>FoS>2</td><td>1,3< FoS <2</td><td>FoS <1,3</td></tr>
<tr><td colspan="2">Height of the back slope (h, meters)</td><td>h < 5 m</td><td>5 m < h < 10 m</td><td>h > 10 m</td></tr>
<tr><td colspan="2">Retainign structures and slope protection works</td><td>Unstable cut slope with retaining structures in good level of maintenance</td><td>Unstable cut slope with retaining structures in poor level of maintenance</td><td>Unstable cut slope without any retaining structures</td></tr>
<tr><td rowspan="2">Hydraulic works</td><td>Subsurface water</td><td>Longitudinal underdrains, cross drains</td><td colspan="2">Lack of longitudinal and cross underdrains</td></tr>
<tr><td>Surface water</td><td>Drainage diches, gutters, others surface drainages and slope erosion protection works</td><td colspan="2">Lack of drainage diches, gutters, others surface drainages and slope erosion protection works</td></tr>
<tr><td colspan="2">Hydraulic works maintenance</td><td>Good level of maintenance</td><td colspan="2">Poor level of maintenance</td></tr>
<tr><td colspan="2">Pavement maintenance</td><td>Good level of maintenance</td><td colspan="2">Poor level of maintenance</td></tr>
</table>

3.1 An applicative example: the Provincial Road 11.

The Provincial Road 11 is located in the Ogliastra district (Sardinia), it connects the village of Jerzu to the State Road 125.

The methodology was applied to a road that is the main connection for the village of Jerzu: it consents the comunications with the regional centre of Cagliari and the district center of Tortoli (along the State Road 125). Thus the Provincial Road 11 is a stategic path that must be always praticable: during an emergency stituation, like a precipitation of high magnitude, it represents the only helpful road for the rescue operations.

In 2002 a restoration intervention was made along the Provincial Road 11 concerning the adjustment of the horizontal radius. Figure 5 shows the old and the new road alignment. The new alignment was placed above the old alignment, in particular, high back slopes and embankments were created to increase some horizontal radius.

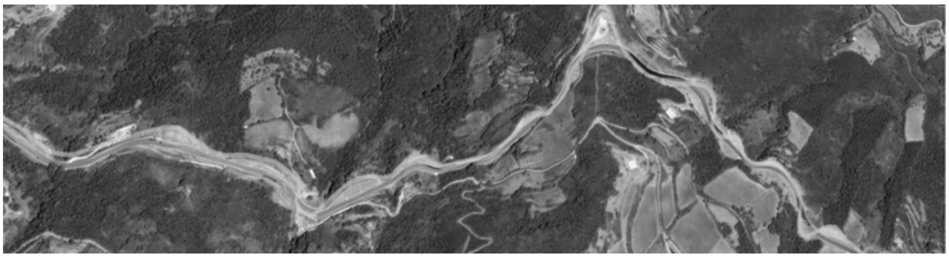

Figure 5 – Old and new aligment of the Provincial Road 11

Since the conclusion of the restoration works the road has shown some instability phenomena. On december 2006, after severe precipitations, the situation get worse and some road embankments showed different important signs of slope failure (figure 6). Moreover some rock falls, from the back slope of the road, reached the roadway: the result was the partial closure of the road with resulting serious economic effects on the resident population.

Figure 6 – Signs of the slope failure along the Provincial Road 11

The check lists proposed above were used for a first assessment of the vulnerability for the Provincial Road 11. In this particular case the analysis was made after the event occured. We think that if the methodology had been aplied during the design stage of the road, or immediately after its realization, it would have been possible to ascertain its high vulnerability, and so consequently to plan apposite adjustement works to decrease the vulnerability level.

For the vulnerability assessment of the road both the check lists were used. The results are summarized in the following points:

- high vulnerability due to the grade of the natural ground: in fact the road was built in a very steep slope;
- high vulnerability due to foundation soils: the landform and the geology of the area interested by the new alignment make it susceptible to different types of landslide. In fact landslides interested in the past the old road alignment, these events are documented into the AVI national catalog: they were mainly rock slides and rock falls. Thus the natural ground vulnerabilty was evident and particularly high.
- high vulnerability due to the cut slope height;
- high vulnerability due to the cut slope geometry;
- high vulnerability due to the lack of retaining and protection structures for the back slopes;
- high vulnerability due to the lack or the poor design of the hydraulic works: this is particurlarly evident along the cut slopes. It is possible to notice the absence of drainage diches above the slope to intercept, collect an drain the surface runoff water, the absence of protection works to limit the scour coused by the superficial water and moreover, the poor design of other hydraulic works that are not able to efficiently drain the roadway.

Figure 1 – Cut slopes along the S.P. n° 11.

Finally the simple application of the two check lists to the Provincial Road11 shows how this road, because of its intrinsic features, was vulnerable and subject to instabilities. The most vulnerable element was the natural groud where the road was built, which features advised against the road execution. There were different vulnerable elements connected one with the other, but the main cause of the road clousure was the landslide caused by the road earthworks execution.

CONCLUSIONS

The road nets vulnerability assessment, under different hydrogeological events, is an useful and necessary elaboration to identify network reliability and consequently to assure rescue operations. The vulnerability is connected to road intrinsic features and it is indipendent from external factors, this can be studied from a qualitative or a quantitative point of view and at different detail scale.

A qualitative analysis of the vulnerability level can be the point of departure to make further more exhaustive surveys. The paper shows a quick methodology to assess road vulnerability to hydrogeological events (floods, lanslides). This methodology is based on the application of two check lists realised using literature informations and studing various case histories of hydrogeological events that in the past interested some roads in Sardinia.

The check lists allow to identify a global vulnerability level of the road. This had been possible considering, for each element constituting road embankments and through-cut roads, a single features considered as an indicator.

The paper also shows a pratical application of the methodology along the Provincial Road 11. This application have proved that it had been possible, before that the instabilities happened, to identify a qualitative vulnerability level of the road and consequently define the maintenance interventions to avoid the road closure.

REFERENCES

ANNUNZIATA, F. BIANCHINI, B. CAPORASO, F. CARAFFA, T. MELIS, D., (2006) – "Parametri ed indicatori relativi alla viabilità di interesse per la protezione civile" – *Proceeding of the XXV Nazional Road Congress*, Napoli, Italy.

ANNUNZIATA, F. CONI, M. MALTINTI, F. PINNA, F. PORTAS, S. (2004) – *Progettazione Stradale Integrata* – Zanichelli, Bologna,.

BENEDETTO, A. COSENTINO, C. (2001) – "Il preannuncio meteorologico per la gestione delle reti viarie in condizioni di emergenza", – *Proceeding of the XI National Conference "Progettazione ed adeguamento funzionale delle infrastrutture viarie. Occasioni di recupero dell'ambiente e di contributo per la protezione civile."*, Verona, Italy.

CAFISO, F. COLOMBRITTA, R. D'ANDREA, A. MUSSUMECI, G. COLOMBRITTA, E. CONDORELLI A. (2001) – "Un modello GIS per la valutazione del rischio sulle infrastrutture stradali nelle emergenze della protezione civile" – *Proceeding of the XI National Conference "Progettazione ed adeguamento funzionale delle infrastrutture viarie. Occasioni di recupero dell'ambiente e di contributo per la protezione civile."*, Verona, Italy.

DM LL PP 11/03/08 – *"Norme tecniche riguardanti le indagini sui terreni e sulle rocce, la stabilità dei pendii naturali e delle scarpate, i criteri generali e le prescrizioni per la progettazione, l'esecuzione e il collaudo delle opere di sostegno delle terre e delle opere di fondazione. Istruzioni per l'applicazione"* – .

FERRARI, P. GIANNINI, F.(1987) – *Ingegneria stradale, corpo stradale e pavimentazioni vol II* – ISEDI, Torino.

KELLER, G.(2002) – "Rural Road Vulnerability Reduction Assessment, Mitigation Measures, and Training" – *Natural Hazard Review*.

MALTINTI, F. RUGGIERI, F. ANNUNZIATA F. (2001) – "Criteri e tecniche di progettazione delle infrastrutture viarie per la prevenzione dei dissesti e la tutela del territorio" – *Proceeding of the XI National Conference "Progettazione ed adeguamento funzionale delle infrastrutture viarie. Occasioni di recupero dell'ambiente e di contributo per la protezione civile."*, Verona, Italy.

(1999) "Natural Disaster Reduction For Roads", *Rapport of the commitee to the XX World Road Congress,* Montreal.

TESORIERE, G. (1984) – *Strade ferrovie e Aeroporti, opere in terra e soprastrutture, vol II* – UTET, Torino.

ACKNOWLEDGMENTS

We would like to thank the ANAS Department of Cagliari and in particular eng. F. Ruggeri.