A Decision Support System for the Emergency Management of Highways in the Event of Earthquakes

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ABSTRACT

This paper presents the work under development to customize a Web-GIS Decision Support System, CIPCast DSS, conceived and created by ENEA in the framework of different international research projects, to support the management of highway networks in the event of earthquakes. CIPCast DSS can acquire in real time the coordinates and the magnitude of the seismic event, as soon as the information is made available by INGV, and later on the event shake-maps, as soon as processed by INGV. Referring to the simulated shake-maps, first, and to the shakemaps determined from the instrumentally recorded data (by the seismic stations of the Italian National Seismic Network), CIPCast DSS allows to support the identification of the areas and sections of the highways that have been exposed to the seismic shaking, and to estimate in a simplified way potential damages induced by the earthquake to the main network components, such as viaducts, overpasses and embankments. Based on that and accounting for the possible impacts induced to the natural and build environment in the surrounding areas, CIPCast DSS supports the identification of possible routes for vehicles evacuation. Thanks to a dedicated WebGIS interface that can be made available 24/7 to the operating rooms of the highway concessionaires, CIPCast DSS can support operators to make decisions as "informed" as possible, exploiting data acquired ex-ante and ex-post, and supporting the sharing of those information and of the decision made between other critical infrastructures operators, with the Civil Protection and other first responders.

1 INTRODUCTION

Resilience should be an integral component of any design and emergency management/recovery strategy for highway systems, aiming to guarantee their functionality "at the fullest possible extent" in the event of a natural disaster or crisis situations.

Towards this aim, there is an urgent need to move from theory to practice by providing government departments and highway managers with both legislative and operational frameworks as well as tools and methods to support decision making processes for the mitigation of impacts and the speed-up of an efficient recovery in the event of (natural or man-made) disasters, including earthquakes.

As far as legislative and policy frameworks are concerned, several initiatives have been developed worldwide in the last decades. The U.S. Department of Homeland Security developed the *National Infrastructure Protection Plan (NIPP)* to manage risk, resilience and security of critical infrastructures across a number of sectors (REF). The plan, published in 2006 and revised in 2009 and 2013, outlines how government departments and private sector parties can integrate and collaborate to manage risk. In Australia, *the Critical Infrastructure Resilience Strategy has been created*, aiming at ensuring the continued operation of critical infrastructure in the aftermath of natural hazard events (Australian Government 2015).

In Japan, the "*Japan's National Resilience initiative*" has been set up in response to the Fukushima Daiichi natural and nuclear disasters (2011), including a "*Fundamental Plan for National Resilience*" aimed at building resilience in critical energy, water, transport and other lifeline infrastructures (National Resilience Promotion Office 2015; DeWit 2016). In Europe a White Paper on “Resilience Management Guidelines for Critical Infrastructures” (European Commission 2018) has been prepared joining the outcomes of 5 different H2020 projects, namely: DARWIN[1]; IMPROVER[2]; RESILENS[3]; RESOLUTE[4]; SMR[5]).

As far as an operational support to operators, managers and public authorities, is concerned, a relevant initiative in Europe is the *European Infrastructure Simulation and Analysis Centre (EISAC)* aiming at establishing a collaborative, European-wide network of national centres, empowered by advanced technologies and simulation capabilities to enhance the resilience of critical infrastructures, including highways. The Italian node of EISAC, *EISAC.it*, is the result of a collaboration agreement established in 2018 between *ENEA*, the *Italian National Agency for New Technologies, Energy and Sustainable Economic Development*[6], and INGV National Institute of Geophysics and Volcanology[7]. EISAC.it is empowered by the *CIPCast* Decision Support System platform, *CIPCast DSS*, along with a suit of innovative technological developments feeding data and information to it. *EISAC.it* aims to collaborate with the operators of critical infrastructures and with the providers of essential services to: support risk assessment, impact and “*what if*” analysis for supporting the setting of mitigation and resilience enhancement strategies; and to provide tools to control-rooms and emergency response teams that can inform and support an aware and efficient reaction and response to disasters.

In particular, this paper presents the proposal for an ad-hoc customisation of *CIPCast DSS* to support the management of the Italian highway networks in the event of earthquakes. After a brief and non-exhaustive literature review on similar initiatives at international level, the idea of the ad-hoc *CIPCast DSS* for Italian Highways is summarised. Lastly, an example on how and to what extent the availability and use of *CIPCast DSS* could support the emergency management of highway infrastructures, in the event of an earthquake, is exemplified with reference to the L’Aquila 2009, Mw 6.3 earthquake.

2 DSS FOR ASSESSING AND MANAGING THE SEISMIC RISK IN CRITICAL INFRASTRUCTURES

Earthquakes and earthquake-induced events, such as soil liquefaction, landslides, tsunamis, flooding, and fires, pose risks to highway infrastructure. In U.S. since 1993, the Federal Highway Administration (FHWA), an agency within the U.S. Department of Transportation that supports State and local governments in the design, construction, and maintenance of the Nation's highway system, has been researching methodologies for seismic risk analysis (SRA) as part of its seismic research program. The result of this effort has been the development of an earthquake loss estimation software tool called REDARS™ 2, *Risks from Earthquake Damage to Roadway System*, that is now being operationally used in pilot projects by several State Departments of Transportation (Werner et al. 2003, Werner et al 2006).

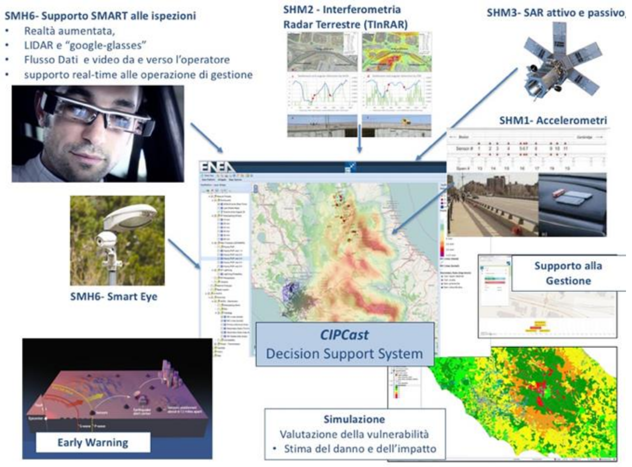

Figure 1. CIPCast DSS and possible connected tools for a real-time and dynamic update of damage and impact scenarios.

In Europe, as previously mentioned, EISAC is promoting the development of *CIPCast DSS* (Di Pietro et al. 2016) to become a risk and loss/impact assessment tool, as well as an operational tool for supporting emergency management and response for different critical infrastructures, where interdependencies and cascading effects are considered and where the estimated damage and impact scenarios can be updated thanks to a real time flow of data and

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[1] https://h2020darwin.eu/,
[2] http://improverproject.eu/
[3] http://resilens.eu/
[4] http://www.resolute-eu.org/
[5] http://smr-project.eu/home/
[6] http://www.enea.it/en
[7] http://www.ingv.it/en/

information through connected innovative sensors and devices (Figure 1). A brief overview of *REDARS™* and *CIPCast DSS* tools is provided in the following.

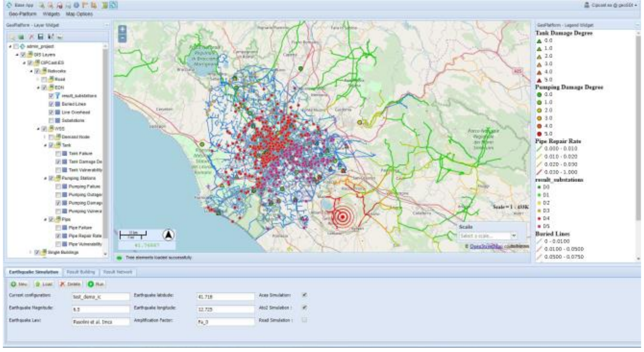
2.1 *REDARS^{TM}, Risks from Earthquake Damage to Roadway System*

REDARS™ has been specifically developed for assessing the performance of highway systems taking into account the inter-connectedness of the network and vulnerability of bridges to seismic loads (Werner et al. 2003). REDARS™ can serve as a pre- or post-earthquake decision-guidance tool. As a pre-earthquake planning tool, it can be used to: (a) estimate the effectiveness of various seismic-upgrade options in reducing earthquake losses; (b) compare costs and benefits (e.g., reduction in traffic-related losses/risks) for each option; and (c) enable decision-makers to use these results in order to make a more informed selection of a preferred option to implement (Werner et al. 2006). As a post-earthquake emergency-response tool in real time, REDARS™ can incorporate actual damage data from the field, and can then develop results to enable officials to assess the relative abilities of various repair options and traffic-management options to facilitate traffic flows. As a further initiative, FHWA is collaborating with the *USGS, United States Geological Survey*, that in the United States operates a nationwide network of seismographic stations and a notification system to disseminate information regarding the location, magnitude, and epicentre of earthquakes, to make available data from both the network and the notification system, soon after an earthquake, to those responsible for bridges and highways to prioritize inspections and response efforts.

2.2 *CIPCast DSS*

CIPCast DSS, is a user-friendly and interoperable Web-GIS platform (Figure 2) and database conceived as a combination of free/open source software environments for the real time and operational (24/7) monitoring and risk analysis of interdependent critical infrastructures. CIPCast DSS provides simulation capabilities for both real or user-defined critical events allowing to periodically assess disaster risks, vulnerability, capacity, exposure of CIs, hazard characteristics and their possible sequential effects at the relevant social and spatial scale.

- *CIPCast DSS*, can provide a 24/7 operational forecast and risk analysis for different critical infrastructures, (CI) in a specific area. CIPCast includes a map of CI elements which could be hit and disrupted by different natural events including flash floods, snow, landslides, flooding and earthquakes. CIPCast allows the estimation of:
- the physical damage to components of CI;
- the impact on service(s) functionality associated with the predicted physical damage, considering possible interdependencies with other networks and cascading effects;
- the consequences of the predicted outages, according to several metrics accounting for economic losses and reduction of citizens well-being.



Current configuration: test_demo_K
Earthquake Magnitude: 6.5
Earthquake Law: Pasolini et al. Imca
Earthquake latitude: 41.718
Earthquake longitude: 12.725
Amplification Factor: Fa_0
Acce Simulation: ☑
Atc2 Simulation : ☑
Road Simulation : ☐

Figure 2. CIPCast-DSS: example of graphical interactive interface for earthquake simulation.

For information on the structure and functionality of CIPCast-DSS and examples of its implementation for assessing the seismic risks and seismic risk scenarios for buildings and for electric power distribution systems can be found in Giovinazzi et al. (2017a, 2017b) and Matassoni et al. (2017).

3 CIPCAST-DSS FOR THE EMERGENCY MANAGEMENT OF HIGHWAYS

CIPCast-DSS for Highways (Figure 1) will provide (and allow an user-friendly visualisation, thanks to a WebGIS interface) to the highway operators and emergency managers the following information:

1. *Position and Magnitude of any occurring seismic event* (overcoming a magnitude threshold of M=3), acquired from INGV, and represented in real time within *CIPCast WebGIS* interface as soon as the information are made available by INGV (generally few minutes after the event);

2. *A first estimate of the extent and severity of the seismic ground shaking in terms of along the route of the highways*, this to allow identifying the segments of the highways and the critical components, such as viaducts and embankment that have sustained higher accelerations and displacements;
3. *Warning about any reached threshold for the possible occurrence of earthquake-induced hazards* (e.g rockfall, landslides, permanent land deformation, liquefaction, fires following earthquake, etc.) or of any concurrent hazardous situation (e.g. severe/extreme weather, forest fires, flooding, etc.);
4. *The identification of "lower risk" areas and evacuation pathway*, in close collaboration with the highways operators and patrols, to support the management and evacuation of vehicles in transit, or accessing the highway, at the occurrence of an earthquake;
5. *INGV shake-maps* [8], to allow for a more reliable estimate of the extent and severity of impacted areas and highway segments and components (as for point 2 above); as soon as they are made available by INGV (generally within an hour after the event);
6. *A first estimate of the possible earthquake-induced physical damage* to the main viaducts, based on the shaking sustained (as for point 5 above) and further possible concurrent hazards (as for point 3 above).

The idea is therefore that the Control Rooms of Italian Highways, in the event of an earthquake, can receive and display in real-time information via *CIPCast-DSS* on the seismic shaking and on the potential earthquake-induced impacts, as well as the conditions of areas and pathways previously identified as "*at lower risk* " to be used for evacuation and emergency management. Such information, can support the decision making process towards the adoption of aware and effective precautionary measures and traffic management; these will be assisted by traffic lights and Variable Message Panels for stopping the vehicles or for guiding them to reach "*lower risk areas*", following "*lower risk pathways*". The definition of the ad-hoc *CIPCast-DSS* for Highways aims at building on and advancing researches and initiatives that have been promoted in Europe to assess and mitigate the seismic risk for highways in Europe (e.g. project RETIS-Risk 2014-2015, "Real-time Seismic Risk of Intercity Highway Networks" SeXtos at al. 2016).

Further information on a couple of the above-mentioned points is provided below.

3.1 Multi-Hazard Risk Ex-ante Assessment

Towards the identification of "*lower risk areas and pathways*", the collection, collation and representation within *CIPCast-DSS webGIS DataBase*, of any existing information characterizing the risk of the territory from a multi-hazard point of view is proposed. The idea is to create an ex-ante multi-hazard risk assessment that could be also summarized in terms of a multi-hazard risk index along the highway routes, and in correspondence with the main artworks (e.g. viaducts, tunnels, embarkments). The collection and homogenization of information layers is, in particular, proposed to include:

- Seismic microzonation;
- Known faults location (Figure 3);
- Surface faulting;
- Seismic-induced landslide potential (Figure 4);
- Seismic-induced rock-fall potential;
- Liquefaction potential;
- Potential for permanent soil deformation;
- Geomorphological hazard;
- Hydraulic/hydrogeological hazard;
- Fire hazard potential;
- Nowcasting of extreme weather events and lightning strikes.

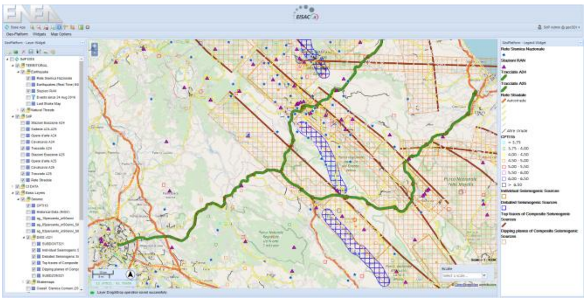


Figure 3. Known faults location maps from INGV displayable into CIPCast-DSS with other hazards and critical infrastructures layers.

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[8] http://shakemap.rm.ingv.it/shake/index.html, Shakemaps are automatically determined from the instrumentally recorded data by the seismic stations of the Italian National Seismic Network

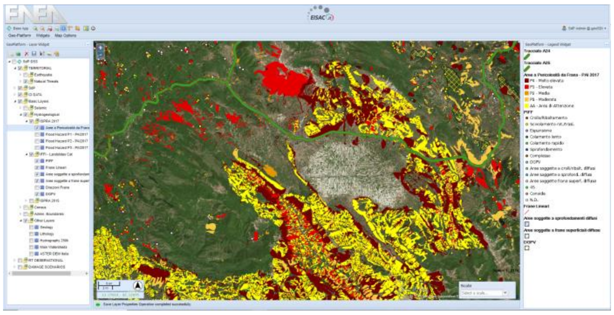

Figure 4. Landslide risk maps from Italian P.A.I. “Piano Assetto Idrogeologico” displayable into CIPCast-DSS with other hazards and critical infrastructures layers.

For the characterization of the geomorphological hazard use will be made of satellite data SAR, Synthetic Aperture Radar; where historical SAR data are available (from 2008 for some areas of the Italian territory), the temporal progressions of vertical land movements, will be verified though differential analysis (i.e. interferometric analysis techniques based on SAR image processing). Thanks to the continuous monitoring of specific points called Persistent Scatterer (PS) information on the speed of soil deformation [mm/year], induced by slow movements or subsidence, can be acquired along the highway layout areas[9].

3.2 Estimation of Extent and Severity of the ground-shaking and possible induced physical damage on viaducts

While waiting for the release of the official INGV shake-maps (point 5 in Section 3), a first estimate of the extent and severity of the ground-shaking will be provided, after any seismic event exceeding a moment magnitude M>3 (step 2 in Section 3). Ground Motion Prediction Equation, GMPE will be used for this purposes. In particular *CIPCast-DSS* implements at the time being the GMPE provided by Bindi et al (2011) to assess PGA and Spectral acceleration shake-maps. Alternative GMPE, that might be particularly appropriate for the territory under analysis can be included into *CIPCast-DSS*. Any effort will be taken to extrapolate information on soil and morphological conditions that might have been collected as part of microzonation studies, with the aim to consider and include in the estimation, although in a simplified way, possible soil and morphological amplification phenomena.

For a first estimate of the possible earthquake-induced-damage to viaducts, *CIPCast-DSS* will use fragility curves developed through empirical methods (i.e mainly based on observed damage data from past earthquakes) such as those used in the United Stated within the HAZUS-MH multi-hazard risk assessment platform (FEMA 1999) and those defined in the framework of RISK-UE project (2004). This to allow for an estimate at territorial scale level, with limited data availability. Clearly, should further or more detailed data on the viaducts and/or advanced numerical analyses become available, reference will be made to them, in lieu of the aforementioned fragility curves.

As far as the Risk-UE (2004) method is concerned, viaducts are classified into 15 categories considering: construction type, material, column and bent type, span continuity and seismic design (Table 1). For each category a fragility curve is assigned (Table 2). Fragility curves represents the probability of exceeding a predefined Damage States (DS) as a function of an engineering demand parameter, e.g a ground motion intensity measure (typically peak ground acceleration, PGA, spectral acceleration. Sa. or spectral displacement. Sd. at a given frequency of vibration). Fragility curves are usually plotted assuming a lognormal distribution function.

Table 1. Viaducts classification according to RISK-UE (2004).

Material	Column Bent Type	Span Continuity	Design	Category
All	Single Span	-	Conventional	1
			Seismic	2
Concrete	Single	Simple Support	Conventional	3
			Seismic	4
		Continuous	Conventional	5
			Seismic	6
	Multiple	Simple Support	Conventional	7
			Seismic	8
		Continuous	Conventional	9
			Seismic	10
Steel	Multiple	Simple Support	Conventional	11
			Seismic	12
	All	Continuous	Conventional	13
			Seismic	14
	Other	-	-	15

Table 2 provides medians Sa values at T=1s to define RISK-UE lognormal fragility curves with dispersions $\beta=0.6$ for each one of the 15 categories in Table 1 and for the 4 different Damage States, D1, D2, D3, D4, namely:

D1, Minor Damage - Minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the pier (damage requires no

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[9] A similar activity is already underway as part of the SCIRES project “Supporting Critical Infrastructure REsilience from Space”. ESA (European Space Agency) Invitation to Tender (ITT) for Space-based Services to support resilient and sustainable Critical Infrastructure.

more than cosmetic repair) or minor cracking to the deck

D2, Moderate Damage - Any pier experiencing moderate (shear cracks) cracking and spalling (column structurally still sound), moderate movement of the abutment (<5cm), extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, anti-seismic restraints failure without unseating, or moderate settlement of the approach

D3, Extensive Damage - Any pier degrading without collapse – shear failure - (column structurally unsafe), significant residual movement at connections, or major settlement approach, vertical offset of the abutment, differential settlement at connections, shear key failure at abutments

D4, Complete Damage: Any pier collapsing and connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure

The calculation of the median Sa(T=1.0s) values to draw RISK-UE lognormal fragility curves requires the assessment of the K_{skew} parameter (Equation 1) for the assessment of definition of RISK-UE fragility curves requires as

$$K_{skew} = \sqrt{\sin(90 - \alpha)} \tag{1}$$

where α is the skew angle, i.e. the angle between the centreline of pier and a line normal to roadway centreline.

Table 2. Median Sa(T=1.0s) values defining RISK-UE fragility curves (2004) for different viaduct categories.

Typology	Damage state			
	Minor	Moderate	Extensive	Complete
Category	Median SA at 1.0S(G) with β=0.6			
1-2	$0.8\times\min(1;2.5\times(\frac{SA(1.0)}{SA(0.3)}))$	$1.0\times k_{skew}\times EQ1$	$1.2\times k_{skew}\times EQ1$	$1.7\times k_{skew}\times EQ1$
3	0.25	$0.35\times k_{skew}\times EQ1$	$0.45\times k_{skew}\times EQ1$	$0.70\times k_{skew}\times EQ1$
4	0.50	$0.80\times k_{skew}\times EQ1$	$1.10\times k_{skew}\times EQ1$	$1.7\times k_{skew}\times EQ1$
5	0.35	$0.45\times k_{skew}\times EQ2$	$0.55\times k_{skew}\times EQ2$	$0.80\times k_{skew}\times EQ2$
6	0.60	$0.90\times k_{skew}\times EQ3$	$1.30\times k_{skew}\times EQ3$	$1.60\times k_{skew}\times EQ3$
7	0.25	$0.35\times k_{skew}\times EQ1$	$0.45\times k_{skew}\times EQ1$	$0.70\times k_{skew}\times EQ1$
8	0.50	$0.80\times k_{skew}\times EQ1$	$1.10\times k_{skew}\times EQ1$	$1.70\times k_{skew}\times EQ1$
9	$0.60\times\min(1;2.5\times(\frac{SA(1.0)}{SA(0.3)}))$	$0.90\times k_{skew}\times EQ2$	$1.10\times k_{skew}\times EQ2$	$1.50\times k_{skew}\times EQ2$
10	$0.90\times\min(1;2.5\times(\frac{SA(1.0)}{SA(0.3)}))$	$0.90\times k_{skew}\times EQ3$	$1.10\times k_{skew}\times EQ3$	$0.70\times k_{skew}\times EQ3$
11	0.25	$0.35\times k_{skew}\times EQ4$	$0.45\times k_{skew}\times EQ4$	$1.70\times k_{skew}\times EQ4$
12	0.50	$0.80\times k_{skew}\times EQ1$	$1.10\times k_{skew}\times EQ1$	$1.7\times k_{skew}\times EQ1$
13	$0.75\times\min(1;2.5\times(\frac{SA(1.0)}{SA(0.3)}))$	$0.75\times k_{skew}\times EQ5$	$0.75\times k_{skew}\times EQ5$	$1.10\times k_{skew}\times EQ5$
14	$0.90\times\min(1;2.5\times(\frac{SA(1.0)}{SA(0.3)}))$	$0.90\times k_{skew}\times EQ3$	$1.10\times k_{skew}\times EQ3$	$1.50\times k_{skew}\times EQ3$
15	0.80	1.00	1.20	1.70

The calculation of so-called EQs parameters is also required, as a function of the number of spans N (Table 3).

Table 3. Definition of the parameters EQi for RISK-UE fragility curves as a function of the number of spans N.

3-dimensional arch action in the deck (K_{3D})						
EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7
$1+\frac{0.25}{N-1}$	$1+\frac{0.33}{N}$	$1+\frac{0.33}{N-1}$	$1+\frac{0.33}{N-1}$	$1+\frac{0.05}{N}$	$1+\frac{0.20}{N-1}$	$1+\frac{0.10}{N}$

Modified Risk-UE fragility curves have been proposed by Zanini et al. (2013) with the aim of taking into account the influence of bridges' degradation on their seismic vulnerability. The authors will consider to implement such modified Risk-UE fragility curves into *CIPCast-DSS* to allow to consider the temporal evolution of the seismic vulnerability and therefore to quantify the benefits of timely retrofitting interventions.

4 POTENTIAL SUPPORT OF A DSS WITH REFERENCE TO L'AQUILA 2009 EARTHQUAKE

4.1 A24 and A25 Highways

The A24 and A25 highways, located in an area between Abruzzo and Lazio Regions, characterised by high seismic hazard, have been affected, in recent years, by several seismic events and sequences, including L'Aquila 2009 earthquake and the Central Italy 2016-2017 earthquake sequence (SDP 2019a).

They have been designed in the late 1950s and built between the 1960s and 1970s, when the anti-seismic criteria and know-how were completely different from and behind the current ones. A24 and A25 infrastructures have been declared infrastructures of strategic importance by the Italian Civil Protection (Law 228 of 24/12/2012), being a fundamental connection route between the high seismic-risk areas located in the Central Italy and the rest of the country. Also, A24 and A25 Highways have been classified by the Italian Ministry of Infrastructure and Transport, MIT, as "mountainous", as they cross the Apennine mountain line, and as such are characterized by a high number of viaduct (174) and galleries (29), construction the majority of which are double carriageways (SDP 2019a).

4.2 *Damages induced by L'Aquila (Italy) 2009, Mw 6.3 earthquake on A24 and A25*

On April 6, 2009, 03:32:40 UTC, a Mw 6.3 earthquake struck the Abruzzo region, in central Italy. The earthquake occurred at about 10 km depth along a normal fault, namely the Paganica fault, located below the city of L'Aquila. Considerable damage to structures and infrastructures was detected over a broad area of approximately 600 km2, including the downtown of L'Aquila and several villages in the Aterno river valley. After the mainshock, three aftershocks with moment magnitude Mw>5 were recorded within a few days.

13 viaducts of A24 and A25 Highways suffered serious damages (for 6.6 km length in total and about 250 bays). Further 3 km of viaducts suffered minor damages. After on-ground inspections the viaducts of the A24 and A25 Highways that suffered earthquake-induced damages were localised in two main areas (Figure 5)

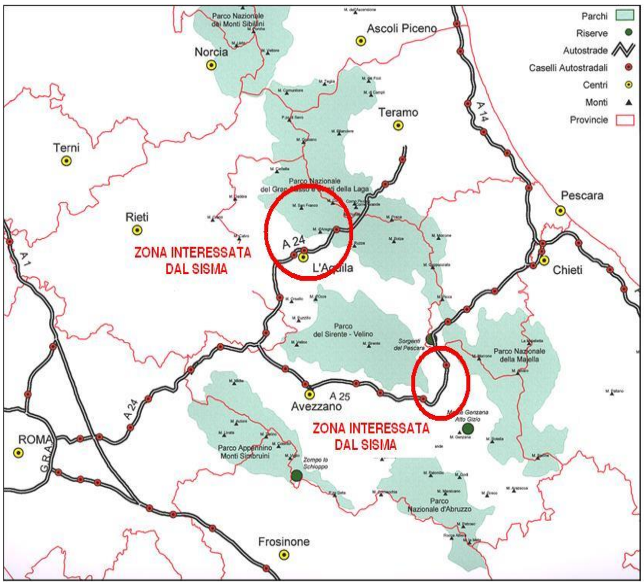

Figure 5. Localisation of the most-affected segments of the A24 and A25 Highways affected by April 6, 2009 L'Aquila earthquake after inspection (SDP 2019b).

In girder-deck viaducts (such as Raio e Aterno viaducts, Figure 6), the earthquake-induced damage included: settlement of the embankment at the abutments and damage to the bearing devices at the abutments. In box-girder viaducts (such as S. Sisto viaduct, Figure 7) connections, bearing devices and anti-seismic restraints were compromised at different level of damage.

Figure 6. Damage to abutments bearing devices in Raio e Aterno viaducts after April 6, 2009 L'Aquila earthquake SDP 2019b).

Figure 7. Damage to girder-deck viaducts after April 6, 2009 L'Aquila earthquake SDP 2019b).

4.3 *Possible use of a DSS for Post-Earthquake Emergency Management of Highways*

Figure 8, extracted from SDP (2019b), shows the INGV shakemap[8] in PGA[%g] April 6, 2009, 03:32:40 UTC, a Mw 6.3, overlaid with the A24 highway route. The image allows to identity the extent of the highways segments affected by the most severe level of shaking.

As explained in Section 3, *CIPCast-DSS*, not available at the time of the L'Aquila earthquake, could provide such a picture, with a GMPE estimated ground-shaking map few minutes after the earthquake and with INGV Shakemaps, as soon as they are made available (Figure 9). The availability of such information could support the identification of the areas potentially more affected, where the prioritization of emergency measures, both in term of inspections to viaducts and evacuation measures for the transiting vehicles might be needed.

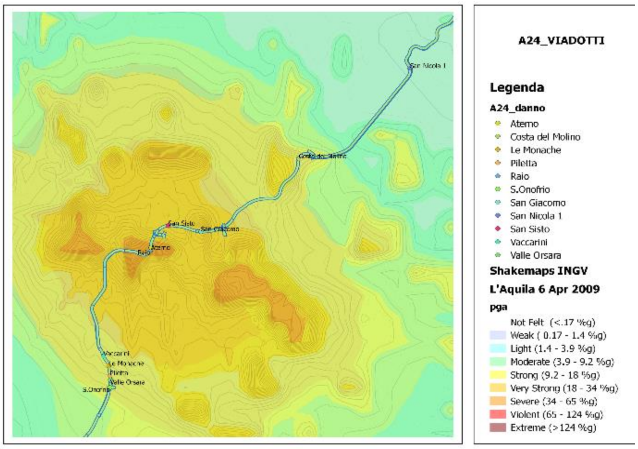

Figure 9. INGV shakemap[8] after April 6, 2009 L'Aquila earthquake overlaid with A24 Highway route.

Further than this, *CIPCast-DSS* might allow a first qualitative estimate of the severity level of the earthquake-induced physical damage for each single viaducts, provided an ex-ante assessment of its seismic vulnerability, and considering the level of sustained ground-shaking.

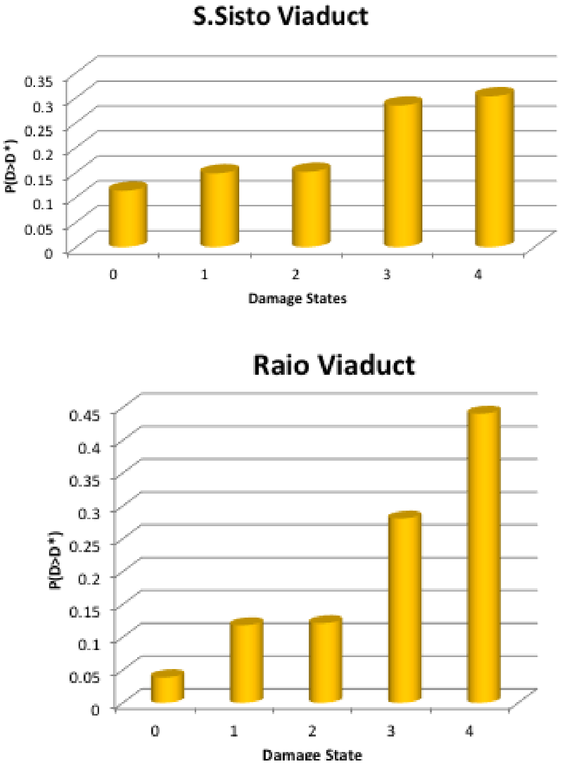

Figure 10. Damage distribution estimated for Raio and S. Sisto viaducts, using RISK-UE fragility functions, with reference to the ground shaking sustained during April 6, 2009 Mw 6.3 L'Aquila (Italy) earthquake.

As briefly explained in Section 3, a first estimate of the damage can be obtained using simplified (empirical or mechanical) fragility curves, or via more specific and advanced models, if available. Moreover, in the future, cross-calibration and complementary direct information on the seismic response of the viaducts could be obtained from accelerometers and/or other real-time monitoring devices, if directly installed on the same viaducts.

As an example Figure 10 shows histograms of the expected damage probability for two A24 viaducts, i.e. Raio and S. Sisto, for the specific ground shaking sustained during April 6, 2009 Mw 6.3 L'Aquila (Italy) earthquake, estimated using RISK-UE fragility functions. Basic data, (made available to the authors by "*Strada dei Parchi*" that operating A24 and A25 highways) have been used for the assessment, including: the viaduct typology, year of construction, number of spans, skew angle and pier natural frequency of vibration. The obtained estimation of the expected damage (in Figure 10) seems to be compatible with the observed damage states (Figure 6 and 7).

5 CONCLUSIONI

The paper provides a brief overview of a Decision Support System currently under development, for supporting the emergency management of highways in the event of earthquakes. It is desirable that such a tool, or similar ones, could be specifically developed and made available to the operators of the highways in Italy and Europe, similarly to what done in other countries. The European Infrastructure Simulation and Analysis Centre, EISAC, is working towards this aim, with the vision that DSS for enhancing the resilience of highways to natural disasters, could be an integral and integrated part of "Smart Highway" where analysis and advanced tools, processing data acquired in real time with smart technologies, can be integrated and benefit from the significant experience of the highways' operators.

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