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# REAL-TIME ASSESSMENT OF PERFORMANCE INDICATORS FOR BRIDGES TO SUPPORT ROAD NETWORK MANAGEMENT IN THE AFTERMATHS OF EARTHQUAKE EVENTS

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**Abstract**

*CIPCast DSS, is a complex yet user-friendly and interoperable Decision Support System platform supporting the risk assessment and the real-time 24/7 operational monitoring of interdependent distributed critical infrastructures. CIPCast DSS is the reference platform for EISAC.it, the Italian node of the European Infrastructure Simulation and Analysis Centre.*
*This paper presents the customization of CIPCast DSS to support the management of road networks in the aftermaths of an earthquake event, providing information on the damage and residual functionality of viaducts and bridges and the estimations of the earthquake-induced impacts in the surrounding natural and built environments. CIPCast DSS allows to support the identification of the areas and sections of the road networks that have been exposed to the ground shaking, and to estimate, in a simplified way, earthquake-induced damages for the road network components. Towards that fragility curves, numerical model analysis and data from Structural Health Monitoring (SHM) systems and sensors are used. The paper proposes physical damage indicators for bridges to be included in CIPCast DSS and the possible layout of SHM sensors to support their detection.*

**Keywords:** Highways, Bridges, Decision Support System, Emergency management, Earthquake-induced damage and impact, Structural Health Monitoring System.

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# 1 INTRODUCTION

In Italy the road network is still the main transportation means for both people and goods; every year, about 8 millions vehicle and nearly 2 billion tons of goods (87% of the total Italian traded goods) travel along the Italian highway network [1]. Some sections of the Italian highway network (such as A24 and A25) are crucial for emergency operation in the event of crises and disasters. The business-as-usual maintenance and post-event effective management of highway networks are therefore fundamental to guarantee the well-being of the served communities, to support the logistic and the functionality of the economic systems and to guarantee a rapid and effective reconstruction and recovery after critical events.

Italy has more than 50 thousand kilometres of road and counts more than 2 thousand kilometres of artworks, more than half built before 1980 [1] when seismic prescriptions were almost inexistent. A meticulous assessment of the structural integrity of these structures is therefore imperative together with an evaluation of the resilience of the road network.

Particular attention should be paid to the vulnerability assessment of bridges and viaducts, considering the traffic load demand which they are subjected to (that might be higher than the one they were designed for), and the possible presence of pre-existing damage induced by environmental degradation and/or by critical event, such as earthquakes and floods.

Towards that the "*Linee Guida ponti*" [2] i.e. *"Guidelines for Risk Classification, Risk Management, Safety Evaluation and Monitoring of Existing Bridges"* released by MIT, Italian Ministry for Infrastructure and Transports, have defined a detailed operative framework for the classification and the structural safety assessment of the Italian bridges.

The idea presented in this paper is to embed the aforementioned institutional framework for the risk assessment of bridges in *CIPCast (Critical Infrastructure Protection risk analysis and foreCAST) Decision Support Systems* (*DSS*), referred hereafter as *CIPCast DSS*, where scenario analysis can be performed considering also interdependencies and cascading effects, to support risk assessment and resilience enhancement of the whole road network. After a brief overview on worldwide initiatives to promote the resilience of highways and road networks and a non-exhaustive literature review on related DSS, the Italian platform *CIPCast DSS* is introduced and described as a potential tool for the risk analysis, the real-time monitoring, the business as usual as well as emergency management of Italian highway networks. In particular, the possible use of *CIPCast DSS* to support the post-earthquake management of highway networks is showcased in this paper, to provide to the control rooms and to the highway managers information on the earthquake-induced damage and residual functionality of bridges of the highway network as a whole, and on the possible impacts on the surrounding natural and built environments. In particular, the actual state and residual functionality of bridges is estimated in *CIPCast DSS* through Key Performance Indicators KPIs by combining the results obtained from empirical methods, numerical models, and, when available, performance indicators assessed from the data collected by SHM systems [3, 4].

# 2 OVERVIEW ON INITIATIVES AND TOOLS TO SUPPORT THE RESILIENCE OF HIGHWAY NETWORKS

The resilience and risk management of Critical Infrastructures (CIs), including highway networks, has been the subject of several ventures at national government level worldwide in the last decades.

In 2006, the U.S. Department of Homeland Security published the National Infrastructure Protection Plan (NIPP), subsequently revised in 2009 and in 2013, to outline how private sector parties and government departments should operate and interact to evaluate the security, to ensure the resilience and to manage the risk of CIs. The main purposes of the NIPP are the identification of threats and hazards that might affect CIs, the reduction of CIs vulnerabilities and the development of strategies for mitigating the potential consequences induced by critical events. Industrial Control Systems (ICS), new Operational Technology (OT), as well as Intelligent Transport Systems (ITS) and Road Network Operations (RNO) have been introduced in order to reach these goals.

In 2011, following Fukushima natural and nuclear disaster (March 11$^{th}$, 2011), Japan developed a program to promote the resilience of CIs (including energy, water and transportation infrastructures) to critical events, investing on the program approximately 210 billion dollars [5]. In 2018, Japan approved the F*undamental Plan for National Resilience* defining the principles that governs the resilience of CI aiming to prevent loss of human life, to avoid the dysfunctionality of administrative and economic systems, to reduce physical damages on structures, infrastructures and goods and to ensure a rapid and effective recovery after critical events.

In 2015, the Australian government released the *Critical Infrastructure Resilience Strategy* to ensure the continued operation of CI in the face of different possible hazards; the aim being to support CI owners and operators to be efficient in the management of both foreseeable and unforeseeable risks.

In Europe, in 2018, the white paper "*Resilience Management Guidelines for Critical Infrastructures"*[1] was outlined by combining the outcomes of 5 Horizon 2020 projects[2] the white paper promotes the implementation of an *European Resilience Management Guideline for Infrastructures*.

As far as DSS tools are concerned, among several existing valid prototypes and operational tools, two have been selected for a brief presentation in this section as they have a god fit for purpose as far as the aforementioned CI resilience initiatives and policy frameworks are concerned, namely: REDARS$^{TM}$ and CIPCast DSS.

REDARS$^{TM}$ 2, Risks from Earthquake Damage to Roadway Systems [6] is a public-domain software promoted and financially supported in the U.S.A. by the Federal Highway Administration (FHWA) that, since 1993, has been sponsoring a Seismic Research Program.

REDARS$^{TM}$ 2 can support the assessment of seismic-induced hazards including ground motion, liquefaction, and surface fault rupture and, by considering the vulnerability of the highway assets, can support the estimation of earthquake-induced damages for different components of the highway network, for both simulated and real events.

After the assessment of earthquake-induced physical damage on the road network, REDARS$^{TM}$ 2 can be used for assessing the post-disaster traffic states and to evaluate their influence on traffic flows aiming to estimate the increased travel-time along key life-line routes and the resulting economic losses and impacts on the served community.

Simulated events can be run in REDARS$^{TM}$ 2 for planning purposes to estimate the effectiveness of various seismic retrofitting options and strategies towards the mitigation of the seismic risk for the highway network.

In case of real event REDARS$^{TM}$ 2 can support network managers to conduct an informed and aware decision-making process towards an effective emergency management [6] and to identify the needed remedial actions, their cost and benefits.

[1] https://smr-project.eu/fileadmin/user_upload/Documents/Resources/WP_7/DRS_7_WHITE_PAPER_final_April2018.pdf
[2] H2020 DRS-07-2014 Projects i.e.: DARWIN (https://h2020darwin.eu/), IMPROVER (http://improverproject.eu/), RESILIENS (http://resiliens.eu/), RESOLUTE (http://resolute-eu.org/) and SMR (http://smr-project.eu/home/);

CIPCast DSS is a WEBGIS-based software developed as part of the EU-funded FP7 project Critical Infrastructures Preparedness and Resilience Research Network, CIPRNet [7] for the real-time and operational (24/7) monitoring and risk analysis of built and natural environments, with special focus on the analysis of interdependent critical infrastructures such as electric power, water, telecommunication, road networks and strategic buildings.

CIPCast DSS is the main tool used by EISAC, the European Infrastructure Simulation and Analysis Centre, a European-wide network of national centres aiming to support the protection and resilience enhancement of Critical Infrastructures; the Italian EISAC center, namely[3] EISAC.it, already actively collaborating with providers of essential services, asset managers and operators of Cis, aims to collaborate with the Italian Department of Civil Protection (DPC), to support scenario and risk analysis for the protection and resilience enhancement of CIs.

In the following paragraphs, the functionalities of CIPCast DSS are briefly presented and discussed in relation to its possible use for supporting the emergency management of highway networks in the aftermaths of earthquake events and for risk mitigation purposes.

## 3 CIPCAST DSS FOR THE EFFECTIVE POST-EARTHQUAKE MANAGEMENT OF ROAD NETWORKS

CIPCast DSS could be applied in the management of highway networks, particularly in the decision-making process after an earthquake event [8]. The idea is to provide to operators and managers of the highway networks a tool, connected and interfaced with other tools, and deployed sensors (Figure 1), to be used both for the effective management of road networks in the aftermath of emergencies induced by natural events, including earthquakes. The focus of this paper is on the parameters used by CIPCast DSS to provide information to the asset managers on the safety and residual functionality of viaducts, and bridges in the aftermath of an earthquake event. A brief overview of how CIPcast DSS works, and which relevant databases are included in CIPCast geodatabases is provided here; a more exhaustive overview on the functions included in the platform can be found in [7], [8].

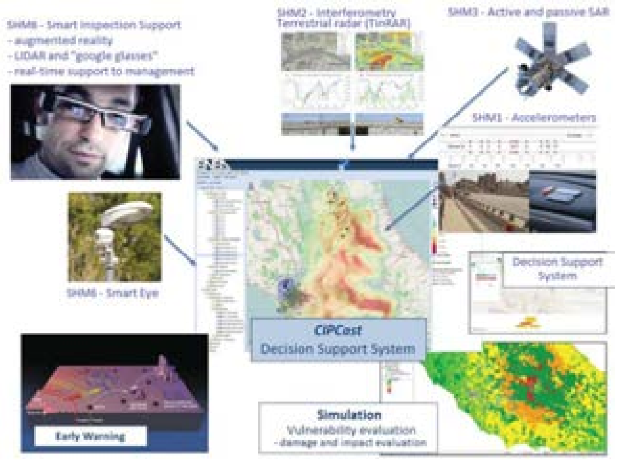
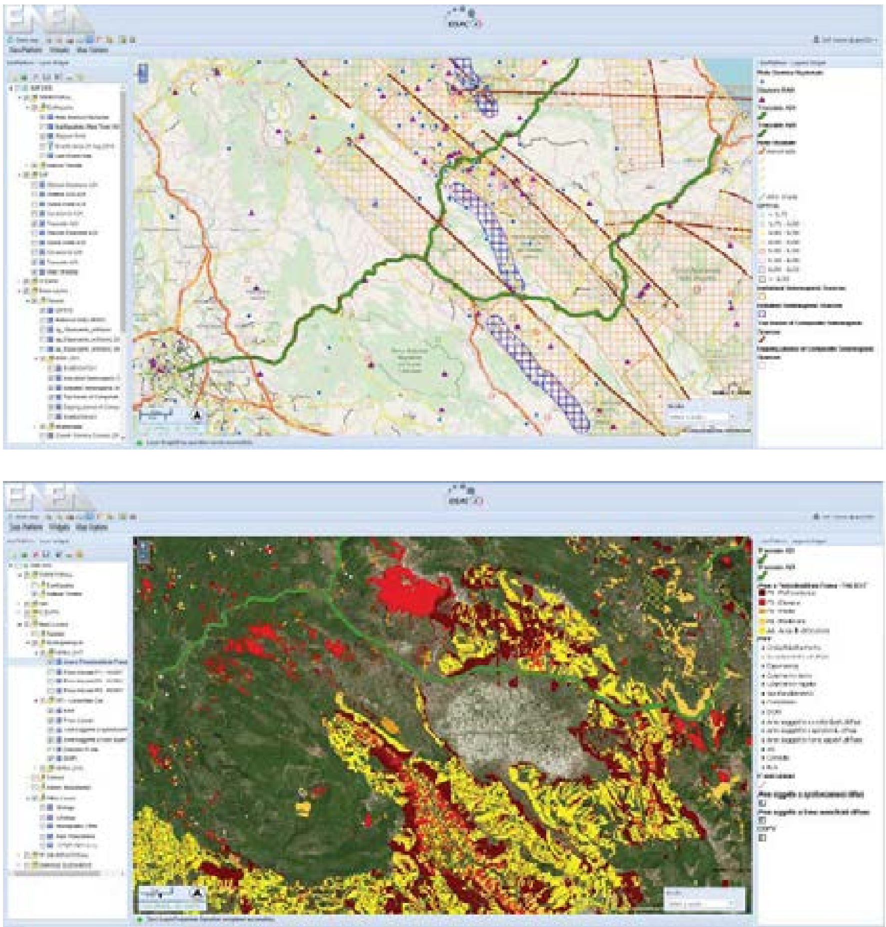



Figure 1: CIPCast DSS and possible connected tools and applications.

[3] EISAC.it (http://www.eisac.it/) was established in 2018 thanks to a collaboration agreement between ENEA, the Italian Agency for New Technologies, Energy and Sustainable Economic Development (https://www.enea.it/en) and INGV, the National Institute of Geophysics and Volcanology (http://www.ingv.it/en/).

CIPCast GeoDatabases, referred hereafter as CIPCast DBs allow the storing and management of large quantities of geospatial data obtained through GIS processing or from external sources including, among others, Open Data, field sensor data, third party or distributed repositories. The data can be stored locally or in different remote servers, accessible through services compliant with the Open Geospatial Consortium (OGC) standards. As far as the seismic assessment and management of the road networks is concerned CIPCast DBs include data for the assessment of both the seismic ground motion and seismic induced-hazard and for the characterisation of the seismic vulnerability of critical components such as bridges, viaducts tunnels and embankments. CIPCast DBs for the seismic hazard characterisation include among others: microzonation, faults location, surface faulting, liquefaction potential, earthquakes historical parametric catalogue; landslide and rock-fall hazard maps from past event and from satellite data SAR (Synthetic Aperture Radar) can be used (Figure 2).



(a)

(b)

Figure 2: Example of geodata included in CIPCast DBs: (a) known faults location from INGV; and (b) landslide risk maps from P.A.I. (Piano Assetto Idreogeologico).

As far as the characterisation of viaducts or other artefacts are concerned, CIPCast can interface with external databases, via webservices, to collect and collate any already existing information thus avoiding duplication of data and waste of time. The idea is actually to promote the creation of a standardised interoperable platform, connected to CIPCast that will collate any relevant databases for viaducts or other road artefacts and that will allow to record new data [9]. As a matter of fact, since several years, ENEA, as part of the PELL (Public Energy Living Lab) project supported by the Italian Ministry of Economic Development,

MISE, has been promoted and boosted the digitization of data[4] and information related to the public administration, with special focus on energy-intensive and strategic infrastructures. The PELL standardised platform is already operative in several Italian municipalities for Public Lighting (PELL-IP, i.e. "Illuminazione Pubblica" in italian) and is under development as far as schools [10, 11] and hospitals (PELL-Edifici, i.e. PELL-buildings) are concerned.
For a possible PELL-viadotti [9] (i.e. Pell-viaducts), the idea would be: to collate, among others, data already included in national catalogues such as the "National Informatic Catalogue of Public Structure", AINOP[5], launched and managed by the Italian Ministry of Infrastructures and Transportation, MIT; to digitalise data that might have been collected in paper form by the PdCM (schede livello 1-2 ponti); to store, in a digital format, the data that need to be newly collected according to the forms expressly set by Linee Guida of the Italian MIT [2].

CIPCast-DSS for road neworks (Figure 3) allows road network operators and emergency managers to gain, via a user-friendly WebGIS interface, real-time information on the position and extent of the ground motion and induced seismic hazard, in the aftermath of an earthquake event, as well as an estimate of the possible damage and impacts suffered by their network, that is continuously updated and made more reliable thanks to the flow of key performance indicators, KPIs, calculated from data collated through sensors deployed on some monitored components of the network.

In the first instance CIPCast DSS allow to visualise the position (coordinates of epicentre and hypocentre depth) and wave magnitude, $M_W$, of any occurring seismic event (overcoming the $M_W$=3 threshold), in real time as soon as the information are made available by INGV (generally few minutes after the event).

Based on that, ground shaking maps are immediately computed by automatically implementing Ground Motion Prediction Equations (GMPEs) that can account also for possible site amplification. At the time, the GMPE provided by Bindi et al. [12] is implemented, but any other GMPE can be considered. The availability of this first estimate of the extent and severity of the seismic ground shaking along the road network allows identifying the segments and critical components, such as viaducts and embankment, that have presumably sustained higher accelerations and displacements and that might be worth inspecting as soon as possible. Possible 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.) are on the same time released by CIPCast. The official INGV shakemaps[6] are substituted to the simulated ones, as soon as they are made available (generally within an hour after the event).

Based on the simulated shake maps first, and on official shake maps then, a first estimate of the possible earthquake-induced physical damage to the main viaducts is performed by CIPCast implementing simplified approaches (Tier 1 and 2 approaches as explained in Section 4), based on the shaking sustained and accounting for any further possible concurrent hazards if necessary. Simultaneously, if a monitoring system is installed on viaducts, CIPCast can tune complement the estimation with the KPIs resulting from the data collected by the sensors (Tier 3 approach) thus allowing to obtain a more reliable assessment of the actual condition of the structure.

[4] According to the standards set by AgID, Agency for Digital Italy (https://www.agid.gov.it/en)
[5] https://ainop.mit.gov.it/portale#/
[6] http://shakemap.rm.ingv.it/shake4/

Thanks to all the aforementioned real-time assessment, the most affected segments of the road are identified (Figure 3), and useful information on the residual functionality of the highway networks and on possible safe paths to evacuate the traffic can be evaluated. Through all the information displayable on the WebGIS interface of CIPCast, the asset managers can perform a more aware and participated decision-making process towards a safer and more effective emergency management.

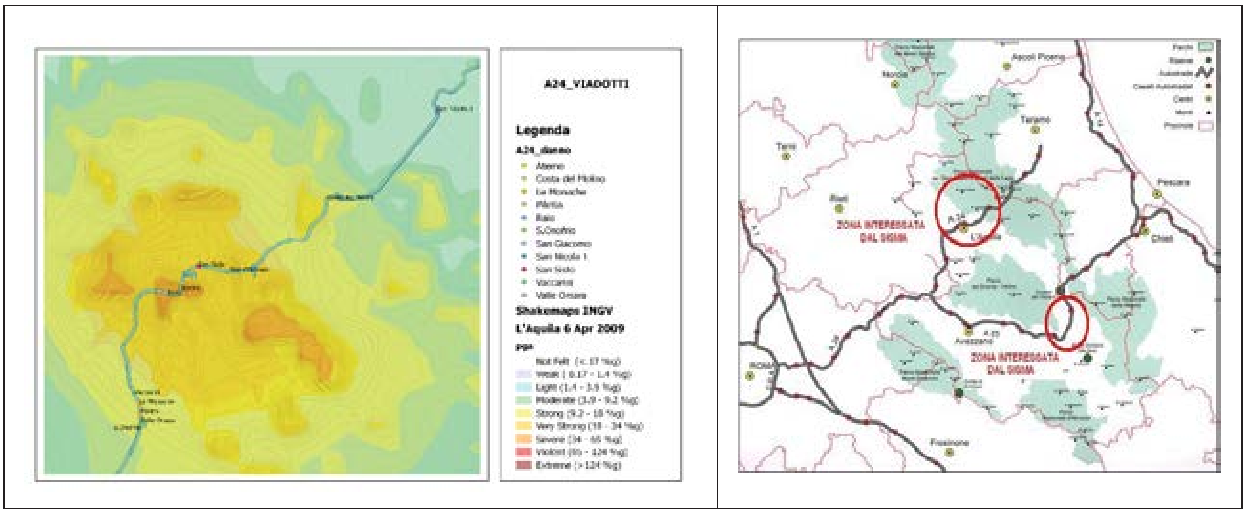



Figure 3: Ground shaking map of the April 6, 2009 L'Aquila Earthquake, overlaid with the highway route; the more severe damage to viaducts were actually identified in the viaducts located in the areas that experienced higher ground shaking.

## 4 RISK INDICATOR AND SHM IN THE ACTIVE MANAGEMENT OF SEISMIC EVENT

During seismic emergency, as said before, CIPCast can evaluate the damage and the safety of viaducts through different methods based on the available information.

In CIPCast, three different tier of damage estimation would be implemented. Each tier corresponds to a different reliability which depends on the number of information required by the method of damage assessment. In Table 1, the three adopted tiers, in order of reliability, and their features are summarized.

For each tier, a Key Performance Indicator for the functionality level $KPI_{SLO}$ and the damage level $KPI_{SLV}$ can be defined to quickly evaluate the state of a bridge (Table 2) and actuate the most appropriate emergency plan.

### 4.1 Tier 1 approach: empirical fragility curves

The first tier assesses the damage using fragility curves, which represent the probability of exceeding a predefined damage state (DS) as function of engineering demand such as peak ground acceleration (PGA), spectral acceleration (Sa) or spectral displacement (Sd).

A fragility curve can be defined through analytic or empirical methods. Analytic methods required a number of information too high to be used as a first level of damage assessment. So, CIPCast DSS implements the empirical method defined in the framework of RISK-UE project, based on empirical data collected after different seismic event.

The method divides viaducts into 15 categories, based on the parameters summarized in Table 2 and Table 3, and defines 4 different Damage State:

- D1: Minor damage,
- D2: Moderate damage,

- D3: Extensive Damage,
- D4: Complete Damage.

| | Required information | Demand Parameter | Approach | Risk or damage KPI |
|---|---|---|---|---|
| Tier 1 | Material, Column Bent Type, Span, Continuity Design (conventional or seismic) and Skew angle | Spectral acceleration $S_a(1s)$ | Fragility curves | $KPI_1$ |
| Tier 2 | Geometry, Material, Construction details and all the information to create a numerical model of the bridge | Time-history acceleration of the seismic event at the base of the structure | Numerical Model | KPI2 |
| Tier 3 | Geometry, material, construction detail | Quantity registered by SHM system | SHM | KPI3 |

Table 1: Tiered Approach.

| Functionality level | $KPI_{SLO}$ | Damage level | $KPI_{SLV}$ |
|---|---|---|---|
| Operative bridge | <1 | Low | <1 |
| Bridge to verify | =1 | Medium | =1 |
| Inoperative bridge | >1 | High | >1 |

Table 2: Value of KPI to evaluate the state of a bridge.

| 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 3: Risk-UE classification of bridges.

For each category, the method allows to define the probability of exceedance of the predefined damage states, knowing:

- The skew angle, i.e. the angle between the principal axis of minimum inertia of the pier and a line normal to roadway centreline
- The spectral acceleration at T=1s ($S_a$(1s)) obtained from the response spectrum of the considered earthquake
- The number of spans.

Fixing the probability of the Damage State for which the viaduct is considered inoperable (SLO), and extremely damage (SLV), the value of the $S_a$(1s) inducing such states is defined respectively as $S_{a\_SLO}$ and $S_{a\_SLV}$. For example, D2 and D3 levels of damage can be considered respectively to assess the spectral acceleration of the functionality level and the damage level. These values can be compared to the $S_a$(1s) of the response spectrum of the considered earthquake. Therefore, two KPIs can be defined by equations (1) and (2), respectively for the functionality level and the damage level.

$$KPI_{1(SLO)} = \frac{S_a}{S_{a(SLO)}} \tag{1}$$

$$KPI_{1(SLV)} = \frac{S_a}{S_{a(SLV)}} \tag{2}$$

### 4.2 Tier 2 approach: numerical models

The second tier assess the damage through a numerical model of the bridge. The required information on the viaduct increases with respect to tier 1. In order to create the numerical model, at least the following information are required:

- Structural type
- Materials and their properties
- Detailed geometry
- Construction details

If more information, such as presence of degradation phenomena, are known, the reliability of the method increases.

After the seismic event, based on the available information on both the earthquake and the structure, a linear or nonlinear analysis of the viaduct can be performed, and the dynamic response of the structure can be assessed. Some relevant parameters can be obtained to define the state of the viaduct. For example, for bridge with simple supported beams, considering an elastic numerical model, the following parameters should be determined:

- The horizontal displacements $\mathbf{\Delta_t}$ and $\mathbf{\Delta_b}$, at the top and at the base of the piers, respectively, in order to calculate the drift of the pier $\boldsymbol{\delta_p}$
- The rotations $\boldsymbol{\theta_t}$ around the horizontal axis, at the top of the piers
- The horizontal relative displacement $\boldsymbol{\delta_t}$ between the deck and the top of the piers, if any
- The rotation $\boldsymbol{\theta_h}$ of beam section at the bearings
- The vertical displacement $\boldsymbol{\delta_0}$ of the beam at the half span

If a non-linear analysis is carried out, also the rotations $\boldsymbol{\theta_b}$ around the horizontal axis, at the base of the piers, should be evaluated. These parameters are simply represented in Figure 4.

In CIPCast DSS, the value of these parameters is compared to different threshold value, determined in order to detect the the functionality level and the damage level. Naming $\mathbf{X_i}$ the i-th parameter assessed from the model and $X_{\mathbf{i(SLO)}}$ and $X_{\mathbf{i(SLV)}}$ the threshold value, respectively for the functionality and the damage level, the key performance parameters are defined by equations (3) and (4), respectively.

$$KPI_{2(SLO)} = \min\left(\frac{X_i}{X_{i(SLO)}}\right) \quad (3)$$

$$KPI_{2(SLV)} = \min\left(\frac{X_i}{X_{i(SLV)}}\right) \quad (4)$$

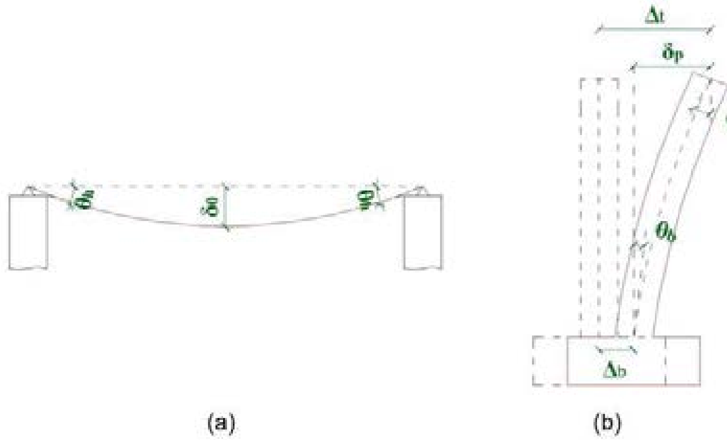



Figure 4: Relevant parameter to assess structural damage (tier 2).

### 4.3 Tier 3 approach: SHM data processing and integration in the assessment

The third tier considers the use of a Structural Health Monitoring SHM system. In the following, the procedure to design a SHM system is reported:

1) Achievement of an accurate knowledge of the structure
2) Definition of the purpose of the monitoring system
3) Design of the monitoring system
4) Definition of the modality of data acquisition
5) Definition of the algorithm to elaborate the data
6) Choose of the interpretative model
7) Definition of the management process

Knowing the structure and the purpose of the monitoring, the SHM system must be design considering a great number of issues [13]. The monitoring time window (temporary or permanent system), the kind of sensors (inclinometers, strain gauges, displacement sensors, accelerometer…), the technologies (MEMS sensors, optical fiber sensors…), and instruments layout are chosen based on the scope of the monitoring [14].

In order to assess the actual health condition of a bridge during an earthquake, a permanent SHM system is required. The sensors work 24/7 but, to reduce the memory dimension of the data storage, the data recording starts only after a fixed number of sensors exceed a threshold value. So, CIPCast DSS receives, almost immediately, only the recordings of meaningful seismic events. For this purpose, different kind of instrument layout can be considered.

To immediately obtain time-histories of the same quantities evaluated by a numerical model and compare them to the threshold fixed value to eventually activate a state of alert or emergency, with reference to a viaduct with simple supported beams, the following instruments layout can be used:

- displacement sensors (LVDT) at the top and base of the piers to measure their horizontal displacements,
- inclinometers at the top and base of the piers to measure their rotation around the horizontal axis,
- relative displacement sensors, for example radar sensor, between the header and the deck beams to monitor their relative horizontal displacement, if any,
- inclinometers on the deck beams to measure their rotation around the transversal axis,
- vertical displacement sensors of the beam at the half span.

This layout represents the minimum number of sensors required to assess the displacement of the structure only through a SHM system. Actually, for very different reasons, a smaller number of sensors could be used. In this way, there are no enough recording data to assess the state of the structure and the information must be updated with some parameters obtained performing a time-history analysis on the numerical model. The time history analysis is always possible if, at the base of the structure, 3 accelerometers are installed in three different perpendicular directions.

Another instruments layout, involving accelerometers, can be implemented. In this case, the following layout can be used:

- at the ground: 3 accelerometers to measure its acceleration along the longitudinal, transversal, and vertical directions,
- at the pile caps: almost one accelerometer along longitudinal, transversal, and vertical directions. If a more accurate evaluation is required, almost three unaligned sensors for each direction must be settled,
- on top of the piers: almost two accelerometers along the longitudinal direction and one along the transversal direction,
- on the beam: more sensors are required to properly assess its behaviour. The essential sensors are three unaligned vertical accelerometers: one (two) sensor at one-third of the span and two (one) sensors at three-third of the span. In addition, two unaligned accelerometers along transversal direction can be settled, one at one-third and the other at two-third of the span. Furthermore, one or two sensors in longitudinal direction can be disposed.

The values of the recorded acceleration provide some indication about the stress of the structure and, integrating the signal, information on velocity and displacement can be obtained.

However, this kind of pattern is commonly used to assess the dynamic properties of the bridge during an earthquake. Through a frequency domain analysis, the firsts modal shapes and their frequencies can be obtained. These values, evaluated for different earthquakes, can be compared, as shown in Figure 5, for the case of Cesi viaduct. The frequencies vary between the different seismic events and they decrease when the Arias Intensity of the Earthquake, calculated at the base of the bridge, increases. The strongest seismic event occurs on October 30, 2016. After this event, the frequencies returned to their initial values. The structure showed an elastic behaviour and, probably, the decrease of the frequencies is caused only by a non-linear behaviour [15].

To achieve a full representation of the health condition of the bridge both the first and second proposed layout can be implemented. Figure 6 shows an example of layout implemented in the monitoring of the jetty of Manfredonia. Figure 6(a) shows the accelerometer layout, which is repeated every six spans. Figure 6(b) shows the displacement sensor layout of a span.

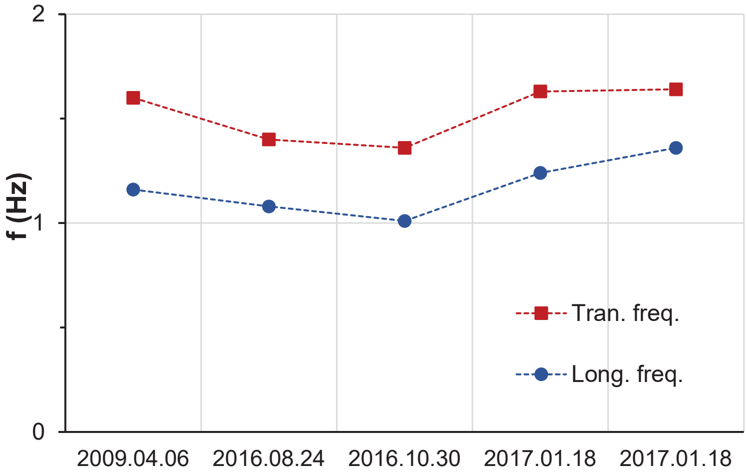
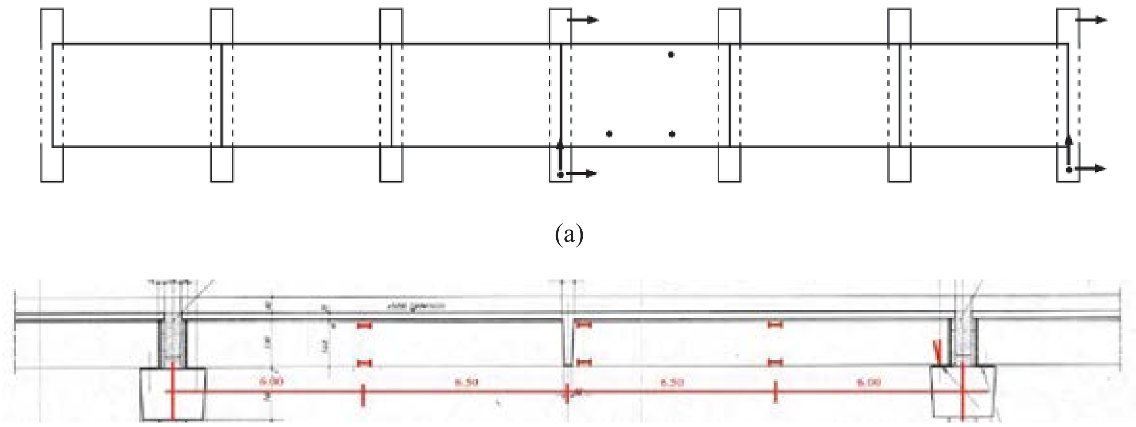



Figure 5: First natural frequency of Cesi viaduct during some consequent earthquakes.



(a)

(b)

Figure 6: Layout of the (a) accelerometer and (b) displacement sensors for the jetty of Manfredonia.

This kind of monitoring system is useful also to assess the behavior of the structure in serviceable condition, considering ambient and traffic-induced vibrations [16]. Decreasing the threshold values which activate the data recording, CIPCast DSS can receive data of potential dangerous situation caused by travelling loads. The SHM efficiency increases if Weight In Motion (WIM) systems are included. These systems allow to obtain the weight and the speed of the vehicle crossing the bridge. Knowing this information, if, for equal weight and speed of vehicles, the deformations increase, the structure can be damaged. Detected the damage, the maintenance works can be scheduled.

In order to obtain complete information on the bridge status, also temperature sensors and weather control units, which measure humidity, air pressure, intensity of rain, and intensity and direction of wind, must be installed.

The analysis of all these sensor data allow to accurately define the actions on the bridge both in seismic and serviceable condition and, so, to better understand the structural response of the viaduct and promptly detect dangerous situations. An example of such integrated and complete SHM systems is represented by the new San Giorgio bridge [17].

Depends on the features of the SHM system implemented on a bridge, the KPIs could be defined differently. The purpose of the authors is to define suitable $KPI_3$ for the most common situations.

## 5 CONCLUSIONS

After a briefly overview on the worldwide initiatives to promote the resilience of Critical Infrastructures and on develop Decision Support System for the management of the road networks, the features, and potentialities of the CIPCast DSS in use at EISAC.it have been described.

CIPCast DSS is a complex, yet user-friendly technological platform including different interoperable tools that enable the monitoring, the analysis, and the risk assessment of Critical Infrastructure. CIPCast DSS gathers and connects different vertical tools and through a powerful WebGIS interface, allows end-users to query databases DBs and to run simulation for supporting what-if analysis and decision-making processes. In the aftermaths of an earthquake, CIPCast DSS can effectively support the assessment of the residual functionality of the highway network. The paper has outlined the approached implemented within CIPcast and has originally introduced Key Performance Indicators, assessed from SHM system data, that CIPCast can use to tune and make a reliable estimation of possible damage. Therefore, CIPCast can assess the impact on the highway network functionality through simplified approaches, allowing an informed and aware decision-making process in the aftermath of seismic emergencies. The integration between CIPCast and SHM systems installed on viaducts, can effectively contribute to create “Smart Highway”, where different tools, analysis method and technologies work together 24/7 to ensure the resilience of the highway system.

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