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MONITORING-BASED PERFORMANCE PARAMETERS FOR ASSESSMENT OF BRIDGES UNDER SCOUR AND SEISMIC HAZARDS

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ABSTRACT

In infrastructural networks, bridges can be considered key elements and their functionality must be preserved. Floods (leading to scour erosion) and earthquakes could be considered among the most critical natural events that may become more frequent with climate change, causing significant damage to bridges. Several regions in Europe have both seismic and scour hazards. The two types of hazards are actually independent as to the generation process but the loss of surrounding soil due to scour may significantly reduce the lateral strength of pile foundations thus increasing the earthquake damage potential. Bridge assessment has thus to take into account the possible increased risk induced by the joint action of the two phenomena. Monitoring systems can be an effective support in bridge assessment procedures providing updated information about the structural state and performance thus allowing both the prompt detection of a possible damage state after an event and also support for long term assessment of the structural conditions. Several performance parameters can be used to perform bridge assessment with respect to several hazards at different levels: element, structure, and network. The aim of this paper is to give an overview of monitoring-based performance parameters that can be used for separate seismic and flood related hazard in order to identify possible selection of parameters effective in describing the joint hazard due to both phenomena.

Keywords: bridge performance assessment; scour; seismic actions; structural health monitoring; natural multi-hazards

1. INTRODUCTION

Natural hazards can significantly affect network functionality and thus involving significant impact to traffic users and communities. Damage to network components can in fact disrupt connectivity ensured in ordinary conditions, and therefore strengthening measures have to be implemented by owners with the aim to minimize such consequences. In this contribution, first an overview of potential damage scenarios to bridge structures is described, accounting for earthquakes and floods as

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main causative natural hazards that can impact roadway networks. In the second part of the work a description of the methodologies currently adopted for monitoring damage and related performance measures is explained, considering both system-level and network-level issues. Lastly, procedures for seismic and scour assessment are illustrated, with some remarks also to the particular case of the joint presence of both scour and seismic damage.

2. DAMAGE SCENARIOS

2.1 Damage scenarios due to floods

During flood events scour processes can develop around foundations for piers and abutments situated in watercourses. Scour is the general term used to describe the removal of soil from around the foundation system or river bed. There are three main forms of scour (See CIRIA C742) namely; local scour, contraction scour and general scour. Whilst local scour results from the impact of flow in the vicinity of the individual structural element (e.g. a bridge pier, See Figure 1), contraction scour affects the entire channel bed and general scour is used to describe any other processes (e.g. long-term degradation). All three processes can occur simultaneously and the combined effects can lead to significant impacts on the serviceability and safety of bridges. For example as soil is removed from beneath a shallow foundation, the applied stress levels increase for the portion of the foundation still supported. As a result the stiffness of the entre foundation system reduces inducing settlement, possible tilting and ultimately collapse if the bearing capacity of the underlying soil is exceeded. Whether a bridge will be susceptible to a scour hazard is determined by the (i) hydrological conditions - e.g. the channel shape and flow characteristics, (ii) geotechnical conditions including the stratigraphy and strength of the river soils and rocks forming the river bed, and (iii) type of foundations – e.g. shallow foundations are much more at risk than piled foundations.

Figure 1. Scour around a rail bridge over the River Sava, Zagreb (picture courtesy of Croatian Railways 2009)

Scour erosion of bridge foundation soil is the number one cause of bridge failure in bridges located over waterways (Melville & Coleman 2000; Shirole & Holt 1991; Forde et al. 1999). One study found that 53% of 500 bridge failures occurring between 1989 and 2000 in the United States occurred as a result of flooding and/or scour problems (Wardhana & Hadipriono 2003). This issue presents a significant cost burden on bridge owners/managers worldwide between inspections, scour protection installation and repairing damage caused by scour (Prendergast and Gavin 2014). In the United States, the average cost for flood damage repair of highways is estimated at $50 million per year (Lagasse et al. 1995). Scour failures typically occur quite suddenly and generally without prior warning, which can potentially lead to loss of life.

2.2 Damage scenarios due to seismic actions

For **reinforced concrete** bridges damage due to earthquakes is often the result of poor seismic design leading to the lack of a ductile response of the structure (see Figure 2). Old seismic codes did not consider at all seismic design or did not apply capacity design principles. Past earthquakes have shown that for common girder bridges, if capacity design principles are not applied, failure may occur due to collapse of the pier foundations or of the piers for bending or shear or collapse of the deck due to unseating or pounding.


Figure 2. Unseating of bridge deck (left). Shear failure due to insufficient detailing (Courtesy of NOAA/NGDC)

The collapse of **foundations** can be induced by settlement, overturning and excessive drift of foundations. Liquefaction in non-cohesive soils also plays a significant role if not properly taken into account. **Piers** are very exposed to seismic actions, and usually represent one of the weak elements due to inadequate detailing that limit their capacity to deform in the non-elastic range without sensible reductions of strength (ductility). Flexure-shear failure may occur, for example due to insufficient development of the longitudinal reinforcing bars. The excessive spacing of the stirrups in critical regions (where the plastic hinges form) is a frequent cause of brittle shear failure of piers that are common if capacity design principles are not enforced as was the case for old technical codes. Shear failures (Figure 2) of concrete bridge columns occur at relatively low structural displacements, when the longitudinal reinforcement may not yet have yielded leading to brittle failures.

The deck girders may collapse due to large relative displacements between pier columns that can originate compression or tension failures of girder beams at expansion joints when pushed against each other or pulled apart. The unseating of a bridge deck is another frequent collapse mechanism in simple supported span bridges due to insufficient seat width (see Figure 2), and/or inadequate restraining force capacity. In simply supported span bridges the unseating of the bridge deck could be dually affected by scour due to the increased flexibility that increases the maximum potential displacement of the deck induced by seismic actions.

In **steel bridges** buckling and rupture of braces (see Figure 3) are the main damage mechanism that can be fostered by corrosion of both the structural members and at the connecting joints.


Figure 3. Disconnection and buckling of braces. Tennoh Bridge. Japan (Kawashima K (2012))

For **masonry** bridges, failures can affect mainly spandrel walls in the out-of-plane direction, whereas criticalities at arch and pier level can be observed for the in-plane direction. Susceptibility to damage is clearly influenced by geometrical parameters (e.g. geometrical ratios between arch rise, length and thickness, pier longitudinal and transversal slenderness). For multi-span masonry arch bridges transversal seismic actions can induce shear cracks in squat piers, whereas for slender piers the structural response has to be globally analyzed to assess potential bending failures. Essentially, the main issues are related to the loss of equilibrium, rather than to the failure of the material for stresses higher than the ultimate resistance. For masonry bridges situated in river beds, where a residual scour depth can be observed after the transient flooding phenomena, if any maintenance action is made, a worsening of the seismic response can be observed in case of earthquake occurrence.

3. MONITORING-BASED PERFORMANCE INDICATORS

3.1 Monitoring-based performance indicators for seismic assessment at the structure/element level

Structural monitoring is an important tool for the prompt detection of damage before the structure reaches a critical state. The advantage of structural monitoring lies essentially in the fact that measurement of the structural response is collected continuously over a long period of time or for short periods at defined time intervals. Traditional methods of damage detection based on walk-through visual inspections or non-destructive testing based on radiography or ultrasound require that the vicinity of damage is already known and easily accessible. These techniques may be costly and may fail if damage is not visibly evident. An alternative able to provide information on the structural health consists of the use of techniques for the estimation of performance parameters and of their changes related to damage, based on responses to vibrations, see Table 1.

Table 1 Methods for structural monitoring

Traditional methods	**Techniques for estimating performance parameters**
Visual inspection	Vibration-based damage detection techniques
Non-destructive testing	Changes of modal characteristics (frequency, mode shapes, derivatives of mode shapes, modal damping)

For seismic assessment in general three main categories of responses in terms of accelerations are sought (Celebi, 2006):

1. Response of the superstructure (deck, piers, towers) to retrieve the fundamental modal parameters and of the foundation (base of piers, abutments) to provide information on the soil-structure interaction and on the spatial variation of the ground motion,
2. Strong motion recorded in the free-field close to the structure,
3. Ground failure arrays in the vicinity of the structure.

One of the most important aspects of these ‘vibration-based damage detection techniques’ is the definition of a performance parameter able to reliably assess the structural state that is easily recoverable from the structural responses. Several approaches have been proposed in literature for damage identification based on the analysis of responses to vibrations recorded on the structure. Several methods are based on the updating of a numerical model of the structure or on the use of neural networks (Friswell 2007, Nakamura et al. 1998). These methods usually require an accurate three-dimensional (3D) numerical model that, for the great part of structures, have a large computational demand and usually require some time for their calibration and updating thus slowing down the process of damage detection. A different approach is based on the analysis of changes of modal characteristics between the original (undamaged) state and the (possibly damaged) current state. A state-of-the-art is given in Yan et al. (2007) and Fan et al. (2011). Methods based on frequency changes can be reliably applied to detect damage, but they are hardly able to give information about the location of damage. To this aim are more effective methods based on the analysis of changes of modal or operational shapes or of their derivatives (Pandey et al. 1991, Kim et al. 2002, Ho et al 2000, Chen and Swamidas 1994, Dong et al. 1994, Limongelli 2010, Limongelli 2011, Domaneschi et al 2012). Modal damping has been proposed by some authors as a possible parameter able to describe the seismic behavior of bridges (Yamaguchi 2005). Obtaining a reliable estimation of this parameter is still challenging for operating structures using the available identification tools. To this respect a strategic point is the location of accelerometers that may include a) piers, b) along the height of columns, c) footings, d) along the depth of the piles, e) at different depths in the soil. In addition to information on the global behavior monitoring networks can give information about local components revealing malfunction or unintended-function of the bearing (Fujino et al, 2008).

3.2 Monitoring-based performance indicators for scour at the structure/element level

At an element level, scour affects the foundations of bridges in a generally uncorrelated manner, meaning that a multiple foundation bridge may experience scour at one or several of the piers/abutments. The nature of this means that scour monitoring methods must focus on the detection of scour on an element-wise basis. There has been a significant increase in works reporting novel performance indicators for scour damage in recent years. These indicators fall into one of two general categories, (i) indicators based on direct scour measurements and, (ii) indicators based on indirect measurement using the structure/element response features. The former focusses on instruments and methods designed to be placed into or near the riverbed that use some form of technology to detect the scour depth affecting a foundation. While useful at measuring scour depth changes over time, these methods generally fail to detect the distress experienced by a structure/element due to the presence of the scour damage. For this reason, more focus is being given to type (ii) methodologies. The most straightforward way to infer damage or distress on an element level is to use the response of a structure and analyze changes in response features. In this context, response refers to dynamic movements of the element. The dynamics of a structural element will be sensitive to changes in the stiffness, mass or boundary conditions, as was put forward by (Doebling et al., 1996). Scour affects the boundary condition of an element, in effect by removing soil stiffness leading to the elongation of the element. Methods have been developed that use natural frequencies (Bao et al., 2017; Briaud et al., 2011; Chen et al., 2014; Klinga and Alipour, 2015; Prendergast et al., 2017, 2016, 2013), mode-shape curvature (Elsaid and Seracino, 2014), flexibility-based deflection (Elsaid and Seracino, 2014; Xiong et al., 2017), root-mean-square (RMS) of acceleration signals (Briaud et al., 2011), covariance of acceleration array along foundations (Foti and Sabia, 2011) among other methods, summarized in Table 2. Regardless of the methodology, all of the aforementioned works share the common theme of using the dynamic response features of an element or structure to infer scour. The nature of performance indicators is that they can be used to infer the condition of a system based on some response feature. For the aforementioned works, natural frequency (for example) is measured and changes in this parameter are used to infer a problem. Linking the natural frequency changes to scour occurrence, and separation from other effects, such as other damage or environmental influences (Sohn et al., 2004), is where the challenge lies. This also relates to the conversion of a measurement into an indicator of performance. This is further discussed in section 3.3.

Table 2 Methods to infer scour presence on an element level

Performance indicators for scour at the structure- element level	
Scour monitoring methods focus on element-wise basis:	a) Direct scour measurement b) Indirect scour measurement
Developed methods:	a) Natural frequencies b) Modal-shape curvature c) Flexibility-based deflection d) Root-mean-square of acceleration signals e) Covariance of acceleration array along foundations

3.3 Monitoring-based performance indicators for seismic and scour at the network level

The consequences of natural hazards like earthquakes and flooding at the network level have to be accounted for considering the vulnerability of bridges due to limitations in the previous design approaches and to the exposure to environmental aging, that can worsen bridge capacity thus increasing bridge vulnerability. The approach to risk assessment at the network level is to minimize the consequences induced by the occurrence of possible future natural hazards. Several performance indicators have to be computed to design specific retrofit network plans aimed at reducing the overall network vulnerability: at the network level, the goal is to minimize the global consequences of a potential hazardous event or a set of probable scenarios. This requires a comparative analysis of different alternative plans of seismic risk mitigation at a network level (e.g. a set of seismic retrofit interventions implemented on a subset of bridges belonging to the network) aimed to identify the one leading to the most beneficial effects in terms of reduction of potential impacts. The performance goals for a roadway infrastructural network with respect to the occurrence of a hazardous event can be differentiated in relation to the target time dimension of interest: in the immediate aftermath of a strong seismic event, the network has to guarantee rescue and evacuation procedures in the affected areas, whereas during the medium-to-long term recovery period it has to guarantee a suitable flow capacity in relation to the traffic demand. Both criteria can be included in the "Availability" KPI, in accordance with RAMSHEEP classification.

Regarding the short-time dimension, the performance indicator at a network level is the accessibility, that can be quantified in a probabilistic way with a value ranging between 0 (not-accessible) and 1 (fully-accessible). Accessibility is a property of the site, but is strictly influenced by seismic fragility of the components of a network. The aim of the accessibility analysis is to evaluate if, in case of a hazard in a roadway network (represented as a system of nodes and links), the connection between different pairs of nodes is still ensured. Different types of modeling strategies can be performed when dealing with disaster accessibility. For example, Ertugay et al. (2015) present a practical example considering a system of health and shelter services in the Municipality of Thessaloniki, Greece. Accessibility can be assessed by modeling an area with zone-based; isochronal-based or raster-based techniques. Focus in such cases is on evaluating if each link can fail in case of a hazardous event due to the failure of one or more structural systems belonging to it (e.g. bridges) or interacting with it (e.g. jutting buildings in historical centers, see as example Argyroudis et al. 2015, Zanini et al. 2016). In such a way, assuming only bridges as vulnerable components within each network link, the vulnerability of the link (i.e. the probability of failure of a connection) can be directly linked with seismic fragilities of the bridges belonging to it (see Augusti et al. 1994; Augusti et al. 1998; Zanini et al. 2013).

Regarding the medium-to-long term consequences, damage to bridges at network level reflects in reductions of flow capacity for some links of the infrastructure. This implies a redistribution of the traffic flows that is a function of the origin-destination matrix, strictly related to the type of traffic assignment model identified. Such type of traffic redistribution can have serious impacts on the overall network functionality, causing not-negligible travel delays. Different performance indicators can be used for quantifying this type of consequence: among others, network resilience can represent the overall functionality reduction during the restoration process (Alipour and Shafei 2016). The network resilience is defined as the level of functionality of the network over time and can take values ranging between 0 (disrupted) and 1 (full functionality). However, for an economic quantification of consequences at the network level associated with the occurrence of a hazardous event, it is usually preferred to compute the total travel delay (Alipour and Shafei 2016) as the difference between the total travel time on the network in the pre-event conditions and the total travel time in the damaged configuration. The increased travel time in the damage scenario to bridges, with respect to the normal conditions, represents the total travel delay. A modified version of this parameter can be computed by considering the environmental impacts associated with the increase of travel time, as an equivalent (fictitious) increase of the travel time. Table 3 summarizes the short-term and medium to long-term dimensions.

Table 3 Time effects on performance

Performance indicators for seismic and scour at the structure- network level	
Short-term dimension	**Medium-to-long term dimension**
Accessibility: a) Modelling an area with zone-base techniques b) Modelling an area with isochronal-based techniques c) Modelling an area with a raster-based techniques	a) Reduction of flow capacity b) Overall network functionality - network resilience

In order to reliably estimate the seismic fragilities of the bridges belonging to the network their nonlinear behavior under strong seismic events has to be modelled. To this aim the availability of responses recorded by a monitoring system during strong motions can be of paramount importance particularly for the case of scoured bridges under seismic actions. Some investigations are reported in literature but are limited to particular types of bridges (Wang et al. 2014) and are based on theoretical expressions for the modelling of the structural performance. The availability of the structural responses from a monitoring system installed on the structure can greatly increase the accuracy of results thanks to the added value of the information from measurements.

4. SEISMIC AND SCOUR CONDITION ASSESSMENT BASED ON PERFORMANCE INDICATORS

To date, even if a number of bridges are monitored with permanent network of sensors, and several among them may be under the combined hazard of scour and seismic actions, a limited number of studies have been devoted to this topic. In reference Anzlin et al. (2018) an investigation on the effect of seismic actions on a scoured bridge base on the use of modal frequencies, displacements and accelerations at the top of the piers as vibration-based performance parameters is presented. The joint effect of the two actions, namely scour and seismic behavior, is discussed.

In general, in order to carry out a seismic and/or a scour assessment or to remotely monitor damage using vibration-based performance indicators, some transformation procedure is necessary to convert changes in dynamic parameters (in this case) into meaningful quantitative information. For example, if natural frequency of an element is being monitored over time, in order to link the changes in frequency to the condition of the structure, some reference scheme or system is required. There are two main approaches which can be undertaken, (i) a reference numerical (finite-element, FE) model of the given asset is developed and tuned to the real conditions or (ii) a data-driven model is developed and updated based on the real conditions. The former is the generally applied current state of practice. However, developing a reference FE model has numerous distinct disadvantages including (1) model updating may be required thus requiring information from multiple points on the actual system, (2) the real system may be too complex for ease of modeling, (3) a lot of information is required if damage assessments are being undertaken network-wide and, (4) there will be significant time and labor requirements as well as data storage problems for asset management systems. Data-driven approaches are becoming more prevalent. Using distributed sensors across the structure can be used to develop a modal model of the bridge, whereby the actual in-situ conditions at the time of sensor installation are used as the benchmark (datum) for normal operating behavior. Several data driven vibration-based algorithms of damage localization have been proposed in literature and can be used for the case of bridges under seismic excitation (Doebling et al. 1996, Limongelli 2010, 2011, 2014, Kim et al. 2002, Pandey et al. 1991, Ratcliffe 2000, Zhang et al 1998, among many others). Damage due to seismic actions, in case of structures designed according to capacity design principles, leads to the formation of plastic hinges at critical locations. In this case damage is rather distributed thus affecting the global modes of the structure. On the contrary in structures designed according to old technical codes, or not designed at all for seismic actions, may occur local damage scenarios affecting local modes that involve the damaged elements. Similarly, damage due to scour will lead to changes in local modes of a bridge, i.e. the mode local to the element affected by scour will experience a change in its own frequency (Chen et al., 2014; Prendergast et al., 2017). This can be benchmarked against static modal data, such as a vertical deck frequency, which is not expected to change much under scour (Elsaid and Seracino, 2014). This may also assist in the separation of environmental influences from the data. Modal methods of this type, while useful to avoid the necessity for large numerical model development, still suffer from difficulty in quantitative damage detection. Essentially, linking the change in frequency to a scour depth may still require manual intervention or measurements. However, broadly speaking if local modes are experiencing a change in their dynamic properties, for example modal frequencies, this can be used to flag an issue in an asset management system and trigger a manual inspection. For the localization of damage, parameters related to deformed shapes (modal or operational) need to be considered. Several attempts are reported in literature to use modal frequencies for damage localization but successful results have been obtained only for very simple structures tested in laboratory (Fan et al. 2011). For the identification of damage severity and type, both for the case of scour and of damage due to seismic actions, the availability of a physical model is necessary.

If a reliable model of the structural performance is available together with a model of the future actions, the fourth step of damage identification according to Rytter classification (Rytter 1993) that is the prognosis, can be carried out. At the time being, for the case of damage related to natural hazards such as earthquakes or floods, this is still a challenging topic due to both the insufficient knowledge about the structural behavior under extreme events that hampers reliable structural modeling and also to the impossibility - particularly for the seismic actions - to forecast the actions on the structure.

The availability of a physical model is also necessary to perform the structural assessment under extreme hazard, either acting independently or jointly, based on vibration-based performance indicators. The assessment requires the verification of the performance parameters against pre-defined performance goals and these are usually not defined in terms of vibration-based performance parameters. For seismic action, for example, performance goals are defined in terms of ductility or reliability but not in terms of modal parameters that cannot be used for a direct assessment. They are instead very useful to calibrate a numerical model of the structure that can be used to perform a safety or a serviceability assessment.

5. DISCUSSION AND CONCLUSIONS

In recent years failures of bridges have increased due to natural disasters on one hand and to the lack of adequate monitoring and preventive maintenance actions on the other. Combination of scour and earthquake action may have significantly higher impact damage on bridges with respect to the separate actions and can even lead to serviceability limit state failure or even partial or total collapse. Monitoring has been identified as a useful tool for confirmation of both the reliability and the availability of the structural elements and the whole system. As there is an interconnection between scour and earthquake actions on the dynamic characteristics of the bridge, vibration-based monitoring has been identified as a tool for performance assessment of bridges under these actions. Vibration-based monitoring systems appear promising for the joint monitoring of seismic and scour effects but at the time being a very limited number of applications exist. This points out the urgent need of further investigations in this field enabling the computation of performance indicators that are able to describe the performance of a bridge with respect to the combination of the two actions in an adequate way.

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