

Structural Health Monitoring and Design Code compliance for performance assessment of bridges under scour and seismic hazards

Mariano Angelo Zanini¹, Flora Faleschini¹, Naida Ademovic², Luke J Prendergast^{3,4}, Ken Gavin^{3,4}, Maria Pina Limongelli⁵

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 ¹University of Padova, Dept. of Civil, Environmental and Architectural Engineering, Via Marzolo 9, 35131 Padova, Italy,
 ²Faculty of Civil Engineering, University of Sarajevo Patriotske lige 30, 71000 Sarajevo, Bosnia and Herzegovina ³Gavin and Doherty Geosolutions Unit A2 Nutgrove Office Park, Rathfarnham, Dublin 14, Ireland
 ⁴Faculty of Civil Engineering and Geosciences, Delft University of Technology Stevinweg 1, 2628 CN Delft, Zuid-Holland, Netherlands
 ⁵Politecnico di Milano, Dept of Architecture, Built Environment and Construction Engineering Piazza Leonardo da Vinci 32, 20133 Milano, Italy.

¹marianoangelo.zanini@dicea.unipd.it;²naidadem@yahoo.com;^{3,4}k.g.gavin@tudelft.nl; ^{3,4}l.j.prendergast@tudelft.nl;⁵mariagiuseppina.limongelli@polimi.it

Abstract. When dealing with asset management of infrastructural systems, maintenance planning of bridges and other critical structures has to be thought against natural deterioration due to environmental conditions, but also taking into account potential criticalities induced by the occurrence of seismic and flood hazards. The aim of this work is to focus on potential damage scenarios, assessment methods for common bridge structures potentially subject to earthquake loading and scouring phenomena due to flooding hazards.

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

1 Introduction

In infrastructural networks, bridges can be considered key elements and their functionality must be preserved. Bridge structures have therefore to be adequately maintained, since structural deterioration combined with the occurrence of hazardous events like earthquakes or floods can compromise structural stability, and lead to bridge failure (Deng et al. 2016). In recent years bridge failures induced by natural hazards were drastically increased, due to lack of adequate monitoring and preventive maintenance actions, but also for the higher number of natural disasters that yearly hit different regions worldwide. With reference to bridges and viaducts, floods and earthquakes could be considered among the most critical events causing significant damage. Flooding phenomena usually affect substructures of bridges crossing rivers, causing local scouring phenomena at the base of pier foundations set in the river bed. This can be exacerbated by natural channel evolution and the resulting settlements may affect the whole structural stability. Consequences of such events and potential critical points in road networks can be previously identified based on weather forecasts, thus reducing the probability of human and economic losses. Scouring effects could be particularly dangerous for ancient (e.g. masonry arch) bridges due to the shallow foundations (Zanini et al. 2016). The increase of the hydraulic outflow speed causes turbulences and vortex shedding (HEC18, 2001) close to the bridge piers, generating local scouring at the base of pier foundations. Scour of bridge foundations is one of the most frequent causes of structural collapse in United States, with about 600 bridges failed during the last 30 years (Briaud et al. 2005), but also in Europe, particularly in the United Kingdom (Maddison 2012) and central Europe (Tanasic 2016). In regions prone to seismic hazard, ground motions may induce damages on bridge structural components like piers, abutments and bearing systems. Several regions in Europe have both seismic and scour hazards however the traditional approach to bridge design does not take into account the increased hazard induces by the joint action of the two phenomena. 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 (Song et al., 2015). In recent years researchers have begun investigating the performance of bridges, or of bridge components under multiple scour and seismic hazard (Haney al., 2010, Alipour et al, 2013, Ganesh et al, 2013).

In this contribution a brief overview of potential damage scenarios induced by flooding and seismic actions and by the combined action of the two, is first illustrated. Assessment procedures currently in use against such natural hazards are briefly reviewed and some current research trends reported.

2 Damage scenarios due to scour and seismic actions

Both scour and earthquake events can cause heavy damages to bridges, leading in some cases to the structural failure. Scour has a deleterious effect on the stability and capacity of bridge foundations and can give rise to several major forms of damage, see Figure 1 for an example of two bridge failures due to scour. Depending on the type of bridge and the nature of the foundation this damage can be extremely detrimental to the operational capacity of the structure and may result in serviceability or ultimate failure. For bridges founded on shallow foundations, scour undermining the foundation can give rise to adverse settlements which can lead to cracking at the deck level and at other supports. In masonry arch structures, this damage can be even more severe and may compromise arch stability. Even when scour does not undermine a bridge pad foundation, the reduction in soil level around the foundation can give rise to geotechnical stability problems in the remaining soil and exacerbate flow conditions around the foundation element. For piled foundations, there are a number of critical damage scenarios. The loss of lateral pile support may give rise to the possibility of pile buckling. This could cause a very sudden and severe issue to arise and may result in total bridge collapse. For severe scour around piles, the loss in shaft resistance may result in adverse settlement issues, which has ramifications for the bridge in terms of crack propagation in the superstructure. Differential settlement of different foundations may lead to severe cracking, deck buckling or total failure, whereas global settlement may induce serviceability failure with unacceptable settlement to the deck, for example. For pile groups, the possibility of differential block settlement may arise inducing unacceptable tilting of the supported pier or abutment. This tilt may cause a deck to slide on its supports or buckle, depending on the nature of the structural connection. Moreover, block failure of a pile group due to scour may also lead to sudden catastrophic failure of a bridge component or a particular span.



Figure 1 Failure due to scour – (a) pier settlement, Croatia 2009; (b) pier failure, Dublin 2009

Regarding the damage scenarios induced by earthquake occurrence, past earthquakes have shown that for common girder bridges failure may occurr due to: collapse of the piers for bending or even for shear if capacity design prescriptions are applied; collapse of the pier foundations if a capacity design is not applied or collapse of the deck due to unseating induced by high seismic displacement. Scour may exacerbate the dynamic behavior of bridges under seismic actions since it causes the loss of lateral support and of axial friction from the soil at the level of the bridge foundations. This, beyond producing a change in the capacity of the foundation, may alter the hierarchy of failures required by capacity design thus leading the foundation to collapse before the flexural failure of the columns takes place. On the other hand the increase of modal periods induced by the reduced stiffness of the foundations can even have a beneficial effect in terms of reduction of the foundation. The final effect of scour on the seismic fragility of bridges depends on which effect dominates the response: degradation of the foundation or increased flexibility of the piers (Wang et al. 2014).





Figure 2 Failure due to seismic actions – (a) slab unsitting, Japan 1964; (b) slab unsitting, USA 1989

Beyond the ones related to the bridge columns and to the foundations, seismic actions may activate other collapse mechanisms such as the unseating of bridge deck (see **Figure 2**) that could be affected by scour as well. The increased flexibility due to scour increases the maximum displacement of the deck induced by seismic actions thus increasing the probability of failure due to unseating of the deck. For masonry arch bridges, 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. Failure mechanisms induced by seismic actions can be categorized in this case in in- and out-of-plane mechanisms. The first ones can be local if only arches are subjected to the creation of a kinematic mechanisms or global when also piers are involved in the failure. The latter can be represented by the failure of the spring walls (local) or the global out-of-plane when slender piers are present. 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 Performance assessment through Structural Health Monitoring (SHM)

3.1 SHM for seismic actions

Structural health monitoring is an important tool in seismic areas for both rapid post-event assessment and also for a prompt assessment of damage before the structure reaches a critical state. Traditional methods of damage detection based on walk-through visual inspections or experimental techniques such as radiography or ultrasound require that the vicinity of damage is already known and easily accessible. These techniques may be costly, taking a long time to be performed and impractical to detect damage in long bridges. Furthermore they may fail if damage is not visibly evident. A promising alternative, able to provide information on the structural health consists in the use of responses recorded by digital accelerometers commonly installed on instrumented bridges. Several monitoring programs are running all over the world providing valuable data that are currently used for development and validation of damage identification methods, to assess the bridge performance, to provide real-time information for safety assessment in the aftermath of an extreme event (e.g. Mufti 2002, Smyth et al, 2003, Pezeshk at al 2004, Ko and Ni 2005, Celebi, 2006)

After an earthquake, basing on the responses retrieved from the sensors and applying appropriate damage detection techniques, a quick assessment of the damage state of the bridge can be obtained. In the last twenty years significant technological progress has been made in the area of commercially available innovative sensors (e.g. fiber optic sensors) capable of providing reliable information about loading, environmental effects and structural health. Long term monitoring networks of sensors installed on bridges may include several types of sensors (strain gauges, accelerometers, displacement transducers, GPS, fiber optic, tilt-meters, seismometer, video cameras and temperature sensors) and techniques for data fusion are needed in order to exploit efficiently the large amount of different data retrieved by the sensors network.

For seismic SHM 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

If responses are made available and analyzed in real time by proper damage identification algorithms, the SHM system can be used to make informed decisions related to the performance of the bridge such as inspection or closing for maintenance or reparations. In the last twenty years several approaches have been proposed for damage identification based on the analysis of responses to vibrations recorded on the structures. In references Yan et al., 2007 and Fan et al. 2011 comprehensive state-of-the-art are reported. A very diffuse approach to the problem of damage detection is based on the analysis of changes of modal characteristics between the original (undamaged) state and the (possibly damaged) current state. 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 (Fan et al. 2011) or operational shapes (Limongelli 2014) or of their derivatives.

In addition to information on the global behavior such as increased flexibility due to damage or dependency of the modal parameters on the amplitude of the excitation, monitoring networks can give local information for example about possible malfunction of unintended-function of the bearings and of the connections (Fujino et al, 2008).

3.2 SHM for scour

The assessment of scour around critical bridge infrastructure to date has broadly been undertaken using visual inspections of the foundation condition by trained divers. Visual inspections typically involve rating a structure based on the perceived condition, whereby the rating denotes the necessity for intervention or the time before the next inspection. A variety of non-scour related defects are widely measured in this way such as cracking, water ingress, concrete spalling, etc., see (Irish National Roads Authority 2008a; Irish National Roads Authority 2008b). Visual inspections for scour aim to assess the nature and magnitude of a scour hole around a critical foundation element such as a pier or abutment foundation, and alert bridge managers when a scour hole is deemed to have surpassed some pre-determined threshold condition. Although no specific rating schemes are globally in existence for this, a number of individual rating systems have been implemented (by universities and local authorities) on various networks throughout Europe.

Туре	System	Primary Operation	Advantages	Disadvantages
Single-use device	Float-Out Device	Buried at specific depth and floats out when scour reaches level	Simple operation method, indicates float- out by triggering a switch	Require expensive installation, have only a single use, can only detect scour at installation depth
Pulse/radar device	Time-Domain Reflectometry (TDR)	Uses changes in the dielectric permittivity constants between materials to determine a depth of scour at a particular location	Easy to read results – provides direct view of scour depth	Requires long probes installed in riverbed, measurement accuracy affected by channel temperature variation
Drive/Buried Rod Systems	Magnetic Sliding Collar	Physical probe positioned around a rod augured into the soil moves downward with scour progression closing magnetic switches	Easy to read data, direct measurement of scour	Only detects scour condition at location of sensor, may miss global effect
Sound-wave devices	Sonic Fathometer	Fixed to bridge pier, these emit sonic pulses to continuously establish the water- sediment interface	Continuous scour measurement in vicinity of bridge pier with easy to read data output	Susceptible to measurement error from entrained air in highly turbulent flow

Table 1. Overview of some instruments capable of direct scour measurement

These surveys also look for secondary damage as a result of scour such as cracking of foundations and visible damage to piles with compromised lateral stability among others. While relatively straightforward to undertake, there are a number of critical drawbacks to these types of surveys, most notably the subjective nature of the information gathered and the discrete nature of the assessment process. In addition, unlike typical bridge damage such as crack formation, scour can occur quite rapidly under increased flow conditions (as during a flood) and it is usually not possible to undertake diving inspections during these critical timeframes. To



overcome limitations in this assessment process, significant efforts have been made to design remote systems capable of relaying information about scour reducing the need for manual intervention. These systems can be broadly categorized as follows (Prendergast & Gavin 2014): single-use devices (NCHRP 2009; Briaud et al. 2011), pulse or radar devices (Forde et al. 1999; Yu 2009; Yankielun & Zabilansky 1999), buried or driven rod systems (NCHRP 2009; De Falco & Mele 2002; Zarafshan et al. 2012; Fisher et al. 2013), sound-wave devices (Nassif et al. 2002; Fisher et al. 2013; Anderson et al. 2007), fiber-Bragg grating devices (Lin et al. 2006; May et al. 2002) and electrical conductivity devices (Anderson et al. 2007). Table 1 gives an overview of the function and detection methodology of a number of types of instrument available.

In recent years, direct measurement of the response features of a bridge to varying scour conditions has come to the fore as a potentially more reliable indicator of the performance. The compromised stability of a bridge foundation due to adverse scour hole formation gives rise to a change in the response features of a bridge such as increased pier tilting, pier settlement, changes to dynamic characteristics, increased strain at deck level, crack formation due to differential settlement among other indicators. Primarily, the change in support conditions gives rise to a change in the dynamic characteristics (Doebling et al. 1996; Prendergast et al. 2016b; Prendergast et al. 2016a; Foti & Sabia 2011; Elsaid & Seracino 2014; Briaud et al. 2011; Prendergast et al. 2013), and this may become a primary indicator of performance. Vibration-based scour detection is a significant advance over the instruments discussed in Table 1, in that it focuses on measuring the response of the structure itself to the formation of scour in lieu of inferring the bridge stability from a measured scour depth. This is primarily due to the fact that a scour depth measuring instrument may miss the global (true) effect of scour due to poor positioning and natural channel evolution. By monitoring the change in a dynamic parameter of interest (natural frequency, damping, mode shapes, mode shape curvature and flexibility-based deflection among others) perhaps before and after a major flood event, it may be possible to detect a loss in structural performance arising due to compromised foundation capacity as a result of scour. These methodologies may become increasingly used in national bridge inspection guidelines, and in terms of scour, are much more applicable than visual ratingbased inspections.

3.3 SHM for seismic actions and scour: future developments

For the time being, to the knowledge of the authors, integrated monitoring systems for bridges under seismic actions and scour are still in the research phase. Based on the current applications in the two different fields a common denominator is found which consists in the use of vibration based techniques for the identification of changes in modal parameters. Both scour and seismic actions may induce variation of modal frequencies that can be detected using accelerometers installed on the bridge. The availability of a network of accelerometers installed on the deck of the bridge could probably allow localizing variations of the deformed shapes induced by the increased flexibility of the piers due to scour or to a seismic damage. The more refined inverse methods based on a calibrated model of the bridge, could be the tool to assess the severity of damage e.g. the depth of the scour or the amount of stiffness reduction induced by an earthquake.

4 Performance assessment according to Design Codes

4.1 Methods for seismic assessment

Modern design codes are based on Performance Based Design (PBD) method requiring the structure to achieve an expected level of performance. This method is formalization of the objectives of designing structures to withstand minor or frequent earthquake shaking without damage, moderate levels of shaking with only non-structural damage and severe shaking without collapse and a threat to life safety (ATC, 1978). PBD entered into the practical engineering filed at the beginning of the 20th century, in New Zealand. The new philosophy is to design structures in such a way that a specified performance limit state is obtained under a specific level of seismic intensity (Calvi G.M., et al, 2008). The fundamental component of PBD is nonlinear dynamic analysis where an attempt is made to capture the real behavior of the structure by explicitly modeling and evaluating post-yield ductility and energy dissipation when subjected to actual earthquake ground motions. PBD can be force or displacement based. The main difference between the two approaches is that Force Based Design (FBD) uses displacements to perform a final check of the structural performance while Displacement Based Design (DBD) uses displacements (or strains) as the target performance.

It should be mentioned that DBD procedures are now well-established for buildings (Kappos 2010), however for bridges, besides its numerous advantages, the procedure still has some disadvantages. Their application is mainly limited to bridges that can be modeled by single degree of freedom for calculating seismic demand and its applicability is in the scope of preliminary design. Reasoning behind this lies in the importance of the higher modes in the transverse response of bridges even of some relatively short ones (Paraskeva and

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Kappos, 2010), which complicates the proper assessment of the displaced shape of the bridge and the target displacement. In this case not one target displacement is required but a target displacement profile.

Current design codes are based on a FBD utilizing the behavior factor q, to reduce expected elastic levels of base shear strength to acceptable design levels taking into account the ductile behavior of the structure. In many European countries, up to the 20th century bridges were designed without taking into account any seismic actions and only in the last 20-30 years codes based on seismic FBD were enforced in regions with medium to high seismicity. The Italian Standard Code (NTC 2008) and European Standard, Eurocode 8 (CEN,2004) define general criteria for the seismic assessment of common bridge types, with special focus on simply supported – continuous girder bridges. Scaling factors for uniform hazard spectra are proposed with reference to each bridge type and indications on the most suitable type of structural analysis are provided. Prescriptions for the assessment are provided, evidencing how the engineer has to check the compliance to the capacity design rules, the dimensions of the plastic hinges and additional criteria related to the execution of retrofit intervention, e.g. the insertion of isolators or dissipation devices. At research level, other probabilistically-based indicators can be considered for the assessment of bridge seismic response, like seismic vulnerability (Zanini et al. 2013), through the construction of fragility functions and resilience indexes.

4.2 Methods for scour assessment

The performance of bridges under scoured conditions is dependent on the nature of the situation, such as type of bridge, nature of traffic, foundation type, redundancy, and others. New bridges are specifically designed with scour in mind whereas existing or legacy-era bridges may be subjected to retrofitting to account for scour occurrence. Typically, new bridges are designed with a design scour depth incorporated. A variety of methods exist to calculate a design scour depth based on a given flow condition, see (Kirby et al. 2015; May et al. 2002). These broadly empirical methods, an example of which is the Colorado State University (CSU) method (Arneson et al. 2012), derive a design scour depth based on the geometry of the pier, the depth of flow upstream, the flow velocity, the flow angle to the bridge, and the nature of the bed material among other variables. The bridge geometric parameters are then optimized to reduce the design scour depth below some threshold value, such as 2.3 times the bridge pier diameter for example. In Italy few prescriptions are provided by the Italian Code for Constructions (NTC 2008). When designing new river bridges, it is necessary to provide a hydrological report and an associated hydraulic one mainly focused on the design solutions adopted against scouring phenomena. The Code suggests to avoid, where possible, to design bridges with piers placed in the river bed, indicating when necessary a distance between consecutive piers of at least 40 m. At European level, Eurocode 1 in Section 4.9 suggests how to take into account actions without giving specific formulations for the assessment of scour depths.

4.3 Methods for joint seismic and scour assessment: current research trends

Fragility curves describe the relationship between a certain intensity measure and the probability of failure. Ter Huene (2014) describes the development of fragility curves for bridge scour, the form is shown in **Figure 3**.



Figure 3 Development of fragility curves for the effect of scour on bridges

The approach is particularly useful for considering separate damage (limit states), in this case the impact ranging from minor damage to complete collapse to the probability of failure of a bridge due to scour depths of up to 6m. Whilst the approach is commonly applied to single hazard analysis, and is particularly useful in



considering the effect of hazards such as earthquakes, it has only recently been applied to consider joint multiple hazards occurring simultaneously or with some small time-lag.

The importance of analyzing multiple-hazards, both natural and man-made is widely recognized. An approach that calculated the reliability indices of a bridge to combined effects from earthquakes, wind, scour and vessel collision over some time interval ΔT was developed by Ghosn et al. (2003). Prasad and Banerjee (2013) note that flood induced scour is not in itself a load event, rather it is the result of a flood event and its effect is to amplify the impact of other load events on the bridge performance. Therefore, superposition of individual load events is not a reliable means of assessing impact; instead a hazard-specific analysis is required to consider the bridge performance. The authors performed assessments of the effects of combined scour and earthquakes hazards on the dynamic response of four reinforced concrete bridges with spans. The bridge supports were piled and the spans varied from 2 to 5 and the response of the pile groups used at support locations were modelled using p-y springs acting on a single equivalent pile. Scour was modelled by incrementally removing springs. Five damage states were considered, ranging from no damage to complete collapse, the boundaries between damage states were based on the displacement ductility. Modelling was performed based on the assumption that some flood induced scour precedes an earthquake event. The study found that non-linear changes of the seismic fragility characteristics of the bridge occurred as scour progressed. Changes were rapid during the early stages of scour and for the systems considered became negligible for scour depths greater than 3m. The diameter of the pile foundation was seen to have an effect on the response with larger piles mitigating the effects of scour, whilst the bridge length was also shown to impact the fragility response.

Wang et al. (2014) also modelled the effect of earthquakes following a scour event on the seismic response of three forms of reinforced concrete bridges; single frame box-girder, a three span simply supported girder and a three-span continuous girder bridge. Finite element models were developed for each of the bridges and scour was induced by removal of lateral (p-y) and axial (t-z) soil springs. The analyses showed that the periods of the first few vibration modes increased with scour for all bridge types considered. The degree of change in natural frequency was dependent on the bridge type, with the three-span simply supported structure being more sensitive to change in scour depth. Interestingly when considering component analysis of the bridge columns, in some cases (for the three-span bridges) scour had a beneficial effect on the column response due to the much longer vibration periods that result.

Gehl and D'Ayala (2015) propose a component based approach to multi-hazard fragility analysis of road bridges. Damage dependent fragility curves are derived at a component level and a Bayesian Network approach is used to assemble these component level curves into a system level assessment. As a result multi-variation fragility functions can be derived wherein each input variable represents an intensity measure for a specific hazard. The hazards considered included earthquakes, ground failures and fluvial floods.

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. The combined action of different types of hazard, such as scour and seismic actions, may have significantly higher impact damage on bridges with respect to the separate actions and can even lead to service limit states or partial or total collapse. Scour may exacerbate the effect of the seismic actions causing the loss of lateral support and of axial friction from the soil at the level of the bridge foundations. This may lead to the occurrence of the collapse of the foundation before the bending failure of the columns thus altering the hierarchy of failures required by capacity design.

Structural health monitoring has been identified as an effective tool for performance assessment of bridges under seismic actions and several monitoring and NDT techniques are currently used to investigate scour. 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.

Also, design codes define general criteria for the seismic assessment of common bridge types and some prescriptions are provided regarding protection from scour but design procedure for the joint action of the two actions are not yet available.

Recently several researchers have tackled the problem through numerical analysis focusing on the use of fragility curves to study the seismic behavior of bridges degraded by scour. Results show that there is a strong impact of scour on the seismic behavior of bridges thus, considering the two sources of hazard separately, may underestimate the effect of their combined action. Furthermore the fragility curves for seismic hazard are affected non-linearly by the amount of scour and the combined effect of the two actions may significantly depend on the structural type of the bridge. This points out the urgent need of further investigations in the field of both structural health monitoring techniques and of design procedures effective in taking into account the joint hazard of seismic actions and scour and allowing the computation of performance indicators able to properly describe the performance of a bridge with respect to the combination of the two actions.

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