Structural Health Monitoring for Performance Assessment of Bridges under Flooding and Seismic Actions

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Abstract

Bridges can be subjected to damaging environmental actions from flooding and seismic hazards. Flood actions leading to scour are a leading cause of bridge failure. Seismic actions inducing lateral forces may lead to high ductility demand exceeding pier capacity. When combined, seismic actions and scour can lead to effects that depend on the governing scour condition affecting a bridge. Loss of stiffness under scour can reduce ductility capacity of a bridge but can also lead to increases in flexibility that may reduce seismic inertial forces. Conversely, increased flexibility can lead to collapse of a deck due to support loss so there exists some uncertainty about the combined effect of both phenomena. A necessary step toward the performance assessment of bridges under flooding and seismic hazards is to calibrate numerical models able to reproduce structural responses under different actions. A further step is verifying the achievement of performance goals defined by codes. Structural Health Monitoring (SHM) techniques allow computation of performance parameters useful in calibrating numerical models or performing direct checks of performance goal compliance. In this paper, various strategies employed to monitor bridge health against scour and seismic actions are discussed with particular focus on vibration-based damage identification methods.

Keywords: Scour; Seismic; Damage; Hazard; Vibration-based methods

1. Introduction

Bridges are a key component of infrastructure networks and it is paramount that their life expectancy is maximised so as to minimise transport disruption while maintaining high safety standards. Worldwide, bridge assets are aging and in many cases are approaching their original (intended) design lives. For economic reasons, it is often not possible to replace these structures outright. Instead, the field of Infrastructure Maintenance Management (IMM) is concerned with the preservation of the asset stock and prolonging their lives against deleterious actions. Environmental loading, from generally uncorrelated sources such as flooding, earthquakes, wind or temperature fluctuations, is one of the main sources of damage to existing bridges. This paper is concerned with the combined action of flooding and earthquakes, so more attention is given over to discussing these actions herein. Flooding can induce hydrodynamic pushover loads applied to a bridge by increased water stage heights, which can pose problems to lateral stability. More commonly, flooding leads to the generation of foundation scour erosion (1–3), a term used to describe the wash-out of soils from around bridge foundations by hydraulic action. Scour is the leading cause of bridge collapse worldwide for bridges with foundations located in waterways (4–6). It reduces the stiffness and capacity of foundations and can cause sudden failure (7). Earthquakes also pose a significant threat to bridge safety in seismic prone regions and can cause sudden element failure if capacity design principles have not been followed at the design stage. Unfortunately, many existing European bridges are in this condition since the adoption of capacity design principles is quite recent in most seismic-prone European countries.

Bridge design generally takes into account the various damaging actions expected over the bridge lifespan. Scour design involves the calculation of an allowable design scour depth using methodologies such as the Colorado State University (CSU) formula (2) and ensuring the placement of spread footings below this depth (8), or adequate pile lengths to mitigate losses in shaft friction. Furthermore, hydraulic countermeasures such as maintaining wide bridge openings and streamlining pier faces can assist in reducing scour development. For earthquakes, reference design loads are used to ensure adequate capacity. Of growing concern, however, is that the combined action of these uncorrelated events (scour and earthquakes) is generally not well understood or explicitly taken into account in the bridge design process. These uncorrelated events, meaning the origin of the actions are not related or linked, can pose a significantly different effect on a bridge’s response depending on the condition of each. Some recent studies (9–11) have begun to analyse the joint effect of these particular phenomena. For example, scour reducing foundation stiffness leads to higher modal periods which may reduce the effect of seismic inertial forces at a given scoured pier. The loss of foundation capacity due to scour on the other hand, means that an originally benign earthquake load may become critical, especially if scour induces secondary damage effects such as pier tilting, differential settlement or cracking.

In this paper, a survey of the different damage scenarios induced by the actions of scour and/or earthquakes is presented and the relevant monitoring strategies for the individual and combined actions are discussed. Section 2 presents an overview of performance assessment procedures for scour and seismic actions. Sections 3 and 4 present an overview of damage scenarios and monitoring approaches for scour and seismic actions, respectively. Section 5 is devoted to the description of the joint action of the two hazards and to a discussion of the techniques that could be possibly applied to monitor the combined effect of the two types of actions. Section 6 presents a case study of the effect of scour on the seismic response of a multi-span bridge.

2. Performance assessment procedures for bridge structures under seismic or scour hazards

Performance assessment of bridges aims to quantify the safety and performance based on international standards and guidelines. This is discussed herein for seismic and scour actions respectively.

2.1 Seismic Actions

Seismic assessment of bridges in Europe often requires assessing structures that have not been designed for seismic prone areas (due to outdated seismic hazard maps), or have been dimensioned according to outdated design codes. The philosophy underlying the design and assessment of bridges under seismic action varies from the approaches used for more frequent actions that typically do not damage the structures. This philosophy is translated in the following performance goals. The structure must be able to withstand: (i) minor or frequent earthquake shaking without damage, (ii) moderate levels of shaking with only non-structural damage and (iii) severe shaking without collapse and a threat to life safety (12). These performance goals are common to both the traditional prescriptive approach to seismic design and assessment as well as to modern performance-based approaches.

Traditional prescriptive approaches do not address explicitly the hazard level or the costs of the consequences since these are implicitly taken into account in the definition of the actions on the structure (through the response spectrum) and of the capacity (through the behavior factor). In modern (performance-based) approaches the target is the achievement of a certain level of performance, taking into account the related consequences. This requires the explicit evaluation of risk based on hazard, vulnerability and consequences. Current design codes, namely the Eurocodes (13), prescribe a mixed approach, whereby performance goals are defined in terms of Limit States. However, the achievement of these goals is entrusted to the satisfaction of a number of prescriptions in terms of capacity/demand ratio or prescriptions regarding member detailing, for example, the compliance with capacity design principles. Many of these prescriptions come from the capacity design principles, introduced in New Zealand in the 1970s (14), and which are today integrated in most of the design codes (13).

The practical procedure for bridge assessment either with traditional or modern approaches requires modeling of the structural performance for the computation of the capacity (traditional approach) or of the vulnerability (performance-based approach). For existing bridges this poses significant challenges to the assessment procedure due to the large uncertainties related to the limited knowledge of (i) the geometry (dimensions, boundary conditions, etc.), (ii) the material characteristics (strength, elastic modulus, constitutive behavior), and (iii) the damage state of the structure (cracks, corrosion, spalling, carbonation, etc.). Furthermore, computation of the demand (traditional approach) or of the hazard (performance-based) requires information on the actions on the structure. The wider and more precise the information available on external actions and structural performance is, the more complete and reliable the bridge seismic assessment.

2.2 Scour Actions

A critical threat to infrastructure around the world, scour is cited among the five most common causes of bridge failure (15,16). Querying the US National Bridge Inventory (17), the most likely cause of bridge collapses are “hydraulic in nature”, mostly scour, and collapses caused by hydraulic factors are not related to the age of the bridge. In the UK, on the rail network alone, more than 100 bridge collapses since 1843 have been attributed to scour in rivers and estuaries, causing 15 fatalities (18,19). Recent cases include the collapse at Glanrhyd, Wales, in 1987, which led to the deaths of four people when part of a passenger train fell into the River Towy, and the failure of the Lower Ashenbottom viaduct in Lancashire, in June 2002. During the 2009 floods in Cumbria, UK, seven road and foot bridges failed due to a combination of scour and hydrodynamic loading, with the collapse of the Northside road bridge in Workington causing one fatality and significant disruption to communities. More recently 131 bridges were damaged during flooding in the same region, many because of scour (20,21). In the Republic of Ireland, a primary bridge on the main Dublin-Belfast railway line collapsed in August 2009, due to tidal scour (7).

For assessing bridges under scour hazards, deterministic models based on engineering judgement were implemented over years using qualitative assessment methods (22). These methods led to the definition of a scour vulnerability rating as the product between the likelihood and consequence of a failure induced by scour. Such approaches provide a qualitative risk indicator, but not a measure of scour vulnerability. Risk-based asset management concepts are widely applied to help inform these judgements. A risk assessment involves considering the outcomes that could result from a combination of drivers, such as extreme weather events, and the performance of assets when subjected to those events. Kirby et al. (16) and Arneson et al. (2) give comprehensive guidance for scour risk management, including references to numerous industry and government agency scour management protocols, including the UK Design Manual for Roads and Bridges (23), US National

Bridge Inspection Standards (17), and US Forest Service Scour Assessment Processes (15).

Scour risk management guidance typically deals with uncertainty through a combination of quantitative and qualitative analyses within a tiered framework, where relatively inexpensive, rapid "high level" screening is used to prioritize further investment of resources. This is undertaken to achieve more detailed assessments at bridges where scour may be more likely to occur, or where its consequences may be worse. Multiple factors are typically considered at each level within a tiered assessment, including physical characteristics of the bridge structures, the watercourses that they cross, their wider flow and sediment regimes and historical observations or recent changes relating to scour. The scour risk can be expressed in generic terms via the distribution function $F[Y(L,S)]$ of possible outcomes Y when a bridge is subjected to some load representing the source of the scour hazard, where L is a random variable describing the relevant loading condition(s) and S is a state variable that is used to describe the uncertain response of a bridge under a given load (e.g. $S = 1$ if the bridge "fails" due to scour and $S = 0$ otherwise). The distribution function $G(1) = P_R[S = 1 | L < 1]$is the probability of failure conditional on a load event L = l. At this point no precise definition of loading condition or failure is offered. Failure could legitimately be defined as catastrophic collapse of the bridge, or in terms of a failure to continue providing some specified level of service (e.g. safe passage for traffic). The function $G(1)$ can be called a fragility function or vulnerability function, and is central to this type of analysis. In this regard, van Leuwen and Lamb (18) tried to define empirical fragility functions on the basis of the key factors influencing scour risk for bridge structures and the failure probabilities associated with a range of possible loading conditions. Experts were asked to define failure probability values associated with increasing flood return periods, to define in such a way an empirical scour fragility formulation.

A reliable scour index for quality control plan development could be defined as the annual rate of exceedance of a fixed limit state, calculated on the basis of the convolution of a flood hazard curve representing the mean annual rate of exceedance of a flood intensity measure (e.g. the water level), and a flood vulnerability function, expressing the conditional probability of exceeding such limit state given a certain intensity measure level. Such type of scour fragility functions should be calibrated via soil-structure models able to capture the global behavior of the soil-structure system (6,24–26).

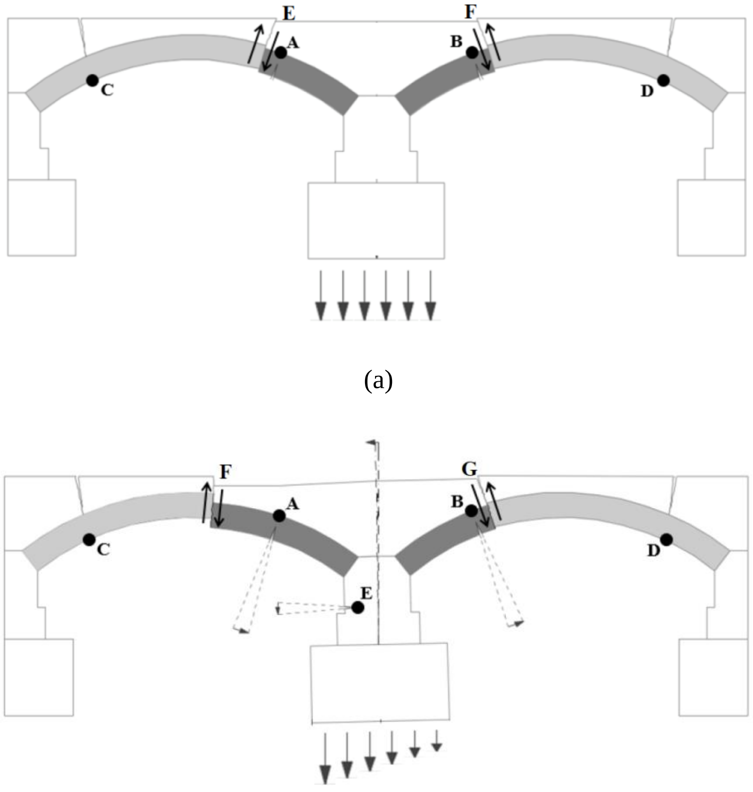
3. Effect of flooding on bridge structures

Flooding is effectively the increase in a river's normal stage height, resulting in faster water flow, which poses increased loading on bridges located in the path of water surges (1). There are several damaging actions that can result from flooding, which can be categorised into primary and secondary damage types. These are discussed in section 3.1.

3.1 Damage scenarios for bridges under flooding

The increased speed of water under flooded conditions results in increased shear stresses acting on streambed sediments (27), which leads to the generation of scour erosion. The critical shear stress is defined as the stress imposed by the water on the sediments at the point movement begins to occur (28), and is the typical parameter used to ascertain if scour will occur under a given flow condition. Other factors at play include the geotechnical conditions of the subgrade such as subgrade type, density and coarseness, among others.

Where local water-flow characteristics suddenly change, such as at the location of a bridge pier, local scour can occur (primary damage). Downward flow is induced at the upstream end of bridge piers, leading to local scour in the direct vicinity of the structure (1). Scour is one of the most important threats to bridges over rivers and estuaries, and has been the cause of numerous bridge failures (4,5,7). Aside from total bridge collapse, scour can cause secondary damage in the superstructure such as cracking, pier titling and differential settlement. For example, Figure 1 shows a schematic of the type of damage that an arch type bridge structure can experience under symmetric and asymmetric scour affecting a central pier.



(a)

(b)

Figure 1 Arch Bridge Damage Scenarios (29), (a) Failure under symmetrical scour, (b) Failure under asymmetrical scour

Zampieri et al. (29) investigated failure mechanisms for scoured masonry bridges (see Figure 1). A case study was used to carry out a failure analysis, simulating the evolution of the structural behavior of a six-span masonry arch bridge using a Finite Element (FE) model, correlated with a local scour profile. Results indicated that when undermining of the foundation occurred, the settlements become significant leading to crack development in the arches. The structure can fail by rigid-block sliding of the elements, as shown in Figure 1. Differential settlement gives rise to cracking in the pier and for both symmetric and asymmetric scour, failure occurs due to loss of equilibrium.

3.2 Monitoring approaches and methods for scour and flood-damage detection

Despite visual inspections remaining popular with asset managers, their subjectivity and discrete undertaking makes them potentially very unreliable, especially due to the added difficulty of observing scour holes in turbid waters. In recent years, many innovative monitoring methods have become available that are capable of remotely monitoring the depth of a scour hole near a foundation of interest, or can be used as part of discrete maintenance checks. Table 1 outlines the nature and operational advantages and drawbacks of a number of these types of systems (30).

Table 1 Scour measuring devices and methods

Type	**System**	**Modus Operandi**	**Advantage**	**Drawback**
Single-Use/Reset (31,32)	Tethered Buried Switch	Mechanical device buried near bridge pier – indicates when scour reaches its depth by floating out and sending signal	Simple mechanical operation	Requires reinstallation after floating out and can only indicate scour has reached its depth with no further information
Radar/Pulse (33–36)	Ground Penetrating Radar (GPR)	Determines water-sediment interface using radar and is manually operated	Gives clear subterranean features from high frequency radar signals	Requires manual operation and thus not suited to remote monitoring
Driven/Buried (31,35,37,38)	Vibration-Based Sensor	Dynamic strain sensor measures changes in natural frequency of a	Can give indication of scour depth by fitting subgrade	Can only detect scour local to sensor and may miss global scour

		driven rod due to scour	modulus to reference numerical model of system	effect
Fibre-Bragg Grating (FBG)(8,30,39,40)	FBG-Water Swellable Polymer	Water swellable polymers swell upon contact with water (scoured soil) and FBG sensors detect the tension	Fitting a number along a rod allows for scour depth to be monitored at discrete points	Requires multiple sensors to be deployed as it can only detect scour local to the sensor
Sound-Waves (30,35,41)	Sonic Fathometer	Fixed-in-place to the bridge element above the waterline – measures water-sediment interface	Continuously measures scour local to element	Can be affected by entrained air in turbulent flow

Scour (and flooding) can induce secondary damage effects in a structure, which can result in element or total failure. The instruments outlined in Table 1, though useful for measuring the depth of a scour hole, are not particularly suited to evaluating the damage that scour can cause. Table 2 outlines some of the secondary damage types that can result from scour and a brief outline of methods of detection and monitoring.

Table 2 Secondary damage monitoring

Damage Type	**Monitoring Method**	**Advantage**	**Drawback**
Pier settlement	Strain Gauge at deck	Easy installation and simple measurement	Requires power and may be susceptible to environmental damage
Pier tilting	Inclinometer	Easy installation	Needs to be very accurate to detect minor rotations
Pile group tilting	Inclinometer	Easy installation	Needs to be very accurate to detect minor rotations

Lateral pile buckling	Accelerometers	Provide inference to stiffness	May be difficult to install onto piles
Deck buckling due to differential settlement	Inclinometer / strain gauge	Easy measurement	May not provide sufficient accuracy prior to failure of element
General settlement	Camera	Can provide image-by-image data of movements	Requires installation away from structure and may be susceptible to environmental damage

4. Effect of seismic actions on bridges

In the subsequent sections, the effect of seismic actions on structures is discussed in the context of damage caused (section 4.1) and methods of monitoring (section 4.2).

4.1 Damage scenarios for bridges due to seismic actions

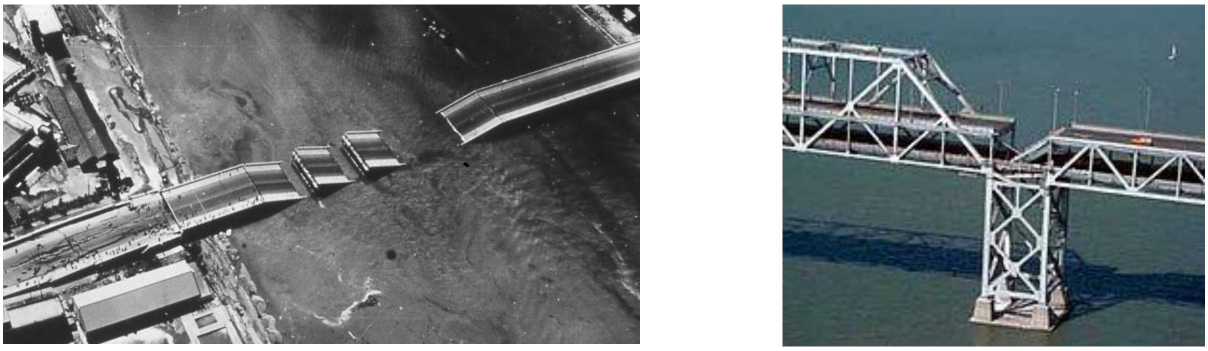
Earthquakes can severely compromise bridge functionality and cause strong damage to their main structural components, which can lead to structural failure. Damage due to earthquakes, an extreme example of which can be observed from the well-known earthquake in Japan (Figure 2) have revealed some obvious lack of design practice and the need for their upgrading. This has resulted in new codes in the United States as well as in Europe with the application of the Eurocodes (13), where the new approaches are characterized with the requirement of strength increase and improved detailing in order to obtain ductile (medium or high) responses of the structure.

Figure 2 Example of poor seismic design (Japan, 1995 Hyogo-Ken Nanbu earthquake) (42)

Regarding damage scenarios induced by earthquake occurrence, past earthquakes have shown that for common girder bridges failure may occur due to: (i) collapse of the piers for bending or even for shear if capacity design prescriptions are not applied, or some combination thereof; (ii) collapse of the pier foundations if a capacity design is not applied, or (iii) collapse of the deck due to unseating induced by high seismic displacement.

Reinforced concrete girder bridges can be affected by pounding phenomena, i.e. the impact between girders at the expansion joints, and the collapse of some of the main girders as a result of large relative movements between adjacent pier columns. Expansion joints can also be affected by such type of deck displacement, causing a compression or tension failure respectively when pushed against each other or pulled apart. Another collapse mechanism is the unseating of a bridge deck (see Figure 3) that could be dually affected by scour (see Section 5). This can usually be attributed to insufficient seat width, and/or inadequate restraining force capacity. This phenomenon is mainly connected to outdated bridge construction methods and simply supported span bridges. The increased flexibility due to scour increases the maximum potential displacement of the deck induced by seismic actions thus increasing the probability of failure due to unseating of the deck. A consequence of deck unseating could also be damage in girders, however, usually they are not subject to significant nonlinear behavior. On the contrary, piers are very exposed to seismic actions, and usually represent one of the weak elements in a bridge. Most damage to the columns can be ascribed to inadequate detailing, limiting the ability of the columns to deform in the non-elastic range (43). Piers have to be designed with a ductile capacity in order to avoid shear failures and be able to withstand large deformations in the event of earthquake occurrence.

In case of significant ground shaking, the abutments can also suffer due to excessive settlements. Shear failures (Figure 4) of concrete bridge columns occur at relatively low structural displacements, when the longitudinal reinforcement may not yet have yielded. Alternatively, since shear strength degrades with inelastic loading cycles, shear failure can occur after flexural yielding (44).



(a) (b)

Figure 3 Failure due to seismic actions – (a) slab unseating, Japan 1964; (b) slab unseating, USA 1989

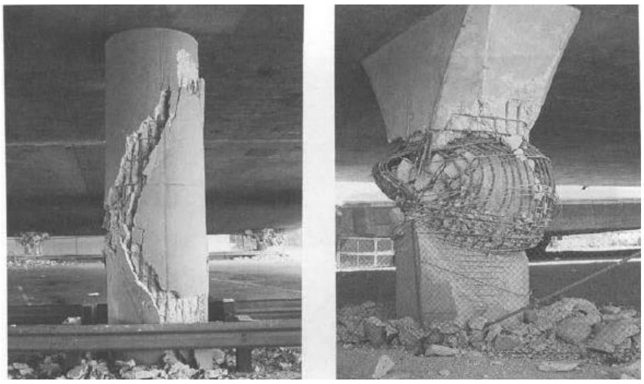


Figure 4 Damage of the column due to shear failure in 1971 San Fernando earthquake (45)

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 the event of earthquake occurrence.

4.2 Monitoring approaches for seismic damage detection

Visual inspections are the easiest method to observe major post-event damage such as deck unseating, or partial and complete structural collapse. However, less obvious damage such as hidden cracks, stiffness reduction due to nonlinear large-strain deformation or loss of joint-capacity are not easily observed using visual approaches. Even the use of methods such as ultrasounds and radar require significant manual input and can be very laborious and time-consuming to undertake. A promising alternative, capable of providing information on the structural health after a (possibly) damaging event consists of analysing the dynamic behaviour of the bridge. Several monitoring programs are currently in operation worldwide providing valuable data that can be used for development and validation of damage identification methods, to assess bridge performance and to provide real-time information for safety assessment in the aftermath of an extreme event (46–49).

After a seismic event or a flood, using the responses retrieved from sensors and applying appropriate damage detection techniques (50), a quick assessment of the damage state of a bridge can be obtained. For seismic SHM, three main categories of acceleration responses are typically sought (49): (i) 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 condition and on the spatial variation of the acting ground motion; (ii) recorded motions in the free-field close to the structure; and (iii) ground failure arrays in the vicinity of the structure. Analysis of the responses in real time using vibration-based damage identification algorithms, can be used to make informed decisions related to the performance of the bridge. In recent years several approaches have been proposed for damage identification based on the analysis of responses to vibrations recorded on structures (51,52). Analysing changes in modal characteristics between the original (undamaged) state and the (possibly damaged) current state of a bridge (or element) is the most common approach to SHM. Methods based on frequency changes can be reliably applied to detect damage (6,24,53), however, they are usually unable to provide adequate information about the location of damage (recent studies related to scour have focussed on damage localisation, see Prendergast et al. (26)). More effective methods for localization of seismic-induced damage include those based on the analysis of changes in modal (52) or operational shapes (54–58) or of their derivatives. In addition to information on the global behaviour of the bridge such as increased elemental flexibility due to damage or the dependency of the modal parameters on the amplitude of the input excitation, for example, distributed sensors can also provide local information about possible failures. Examples of this include malfunction or unintended-function of bearings and of connections, which can critically affect performance (59).

5. Combined actions of flooding and earthquakes

Structural damage rarely occurs in isolation and recently the phenomenon of damage arising in a structure from uncorrelated sources is gaining increasing interest. Damage arising due to one mechanism can completely change the result of a separate mechanism. In this paper, the joint actions of earthquakes and scour are considered in the context of how an originally benign earthquake could pose a significantly exacerbated threat, or otherwise, on a bridge already damaged by scour. Critical damage combinations are discussed in the next section and health monitoring approaches for combined actions are subsequently discussed.

5.1 Critical damage combinations

Changes in the dynamic behavior of bridges associated with the presence of a scour profile lead to increased fundamental periods for deeper scour depths (6,32,54,60,61). The increase in the period may be beneficial in combination with an incident earthquake as it will lower the inertial forces transferring to the superstructure. In reality however, this benefit is often mitigated by the presence of secondary damage effects arising from the scour process such as cracking, differential settlement, pier tilting, compromised pile lateral capacity among others thus reflecting in a higher vulnerability for the bridge. Moreover, the reduced load transfer to a scoured pier is likely mitigated by an increased transfer to adjacent piers or elements. Furthermore, phenomena like deck unseating, previously described, can be exacerbated by the increased flexibility of the structure. As shown by Wang et al. (62), who analyzed the influence of scour on the seismic response of reinforced concrete bridges, the fundamental period of the bridge (increased by the scour depth) determines to what extent the inertial force caused by the earthquakes can transfer to the structure.

In masonry arch structures, compromised support and differential settlement due to scour can be very detrimental under an incident earthquake action, significantly increasing the likelihood of shear cracks occurring at a compromised pier. Restoration of foundation stiffness by maintenance activities can increase the transfer of inertial forces into the superstructure under an earthquake action, which once again can have catastrophic consequences if unseen secondary damage exists.

5.2 Health monitoring for combined actions

Due to the wide range of primary and secondary damage types that can affect a bridge as a result of scour and seismic actions, it is very difficult for maintenance personnel to adequately characterise this damage using traditional approaches. Even the recently developed scour monitoring sensors (30,33–36,63) as described previously are only really capable of measuring the depth of scour affecting a structure but typically give no information on the condition of the structure due to this scour.

In the authors’ opinion the most feasible and widely applicable approach to monitor structural damage due to scour and seismic actions is based on vibration methods (64), typically using accelerometers (or other motion sensors) to measure the structural vibration response. These methods have already gained significant traction in the seismic damage detection field, however they are also quite well developed separately for scour monitoring in recent years (6,26,32,54,61,65–69), thus their applicability to monitoring joint-actions and their effects (cracking, foundation stiffness loss, nonlinear behaviour) is timely.

There exist many methods of damage detection based on measuring structural vibrations, both in the time and frequency domain, either on the structure (70,71) – online monitoring, or on a passing reference vehicle (72–74) – offline monitoring. Methods include frequency-based approaches (6,32,66,68,75), mode-shape based approaches (52,72,76), mode-shape curvature approaches (54), and damping-based approaches (77) among several others. Limitations in the approaches such as the influence of environmental effects on the modal properties (78) are constantly being challenged and overcome. In the particular case of multiple hazard conditions some of the advantages of vibration-based techniques applied using sensors installed on the bridge are:

- the possibility to have a constantly updated signature of the structure so that damage can be identified and the vulnerability of the structure updated accordingly;

- the possibility to build calibrated and continuously updated numerical models of the structure to assess the structural health and to assess the structural behaviour (prognosis) under forecasted values of the actions. The possibility to manage both the in-service and the emergency situations with the same network of sensors thus increases safety at a reduced cost;

- the potential to detect losses in stiffness in a structure due to the primary effects of scour (the foundation damage), secondary effects of scour (crack propagation) and the effects of an earthquake (distribution of structural cracking and inelastic element damage).

A number of questions related to the use of vibration-based monitoring systems for multi-hazard situations are still open and require further consideration. Some of them are:

- the definition of the optimal performance parameters that can be computed using data recorded on the structure to identify the damage scenarios induced by the different hazards. A similar concern relates to the sensitivity of proposed damage identification algorithms to detect the changes induced by the joint action of scour and seismic actions. Issues relate to sensor noise and to limited excitation of the structure induced by ambient vibrations.
- the optimization of the number and location of recording sensors for multi-hazard conditions e.g. both scour and seismic damage to a bridge, but also degradation due to fatigue or other environmental sources. In relation to scour, sensor placement has previously been studied by Bao et al. (79), who investigated various sensor locations (vertical and horizontal) along a laboratory-scale pier and the resulting variation in measured predominant natural frequencies. However, in relation to multi-hazards for a full bridge, this remains a challenge.

- the influence of environmental variability on performance parameters that can produce their variation even on an undamaged structure. Variations in environmental conditions such as temperature fluctuations or wind-induced vibrations can add significant ‘noise’ to the measured signals. In the context of frequency measurements, temperature for example can induce an apparent shift in frequency, which can over-shadow the changes due to damage. One method to mitigate this is to use a temperature sensor and develop interaction diagrams of temperature vs frequency to remove this trend from damage-induced changes. Moreover, structural vibration for measurement purposes is typically excited from passing vehicles (6), which can induce vehicle-related frequencies and other distortions to the vibration spectra (26,80). These frequencies include axle impulse frequencies and frequencies related to the rate of passage of the vehicle across the structure. One way to reduce the influence of these effects is to only measure the vibration after a vehicle departs the structure. Significant challenges still remain in the accurate characterisation of damage effects from vibration data where the relevant spectra is polluted with environmental and vehicle-related noise.
- the application of these techniques in ‘real world’ conditions that is using data recorded on actual structures under multi-hazard scenarios. Most of the algorithms proposed in literature are able to correctly identify damage when working on data simulated using numerical models but fail when applied to real bridges. Further efforts should be made to move to full-scale real-world testing.

6. Case Study – Effect of scour on bridge seismic response

A simple case study is presented in this section whereby scour is implemented in a numerical model around a single pier of a multi-span bridge and the effect of this scour on the seismic response is investigated. The numerical modelling is undertaken using OpenSees (81), an open-source software for simulating the seismic response of structural systems. The bridge model is described in section 6.1 and the analysis and results are presented in section 6.2.

6.1 Multi-span bridge model

A simplified multi-span bridge model with six spans, supported on five I-shaped bridge columns is modelled in this case study. A schematic of the bridge geometry is shown in Figure 5. The bridge deck is modelled as an elastic beam and the abutments are modelled as roller supports, to enable the bridge move in the longitudinal direction. Modelling the bridge deck as an elastic beam is a simplification in this analysis as it will not allow non-linear behaviour to develop at this location. A future study will develop further on this with a more comprehensive model for each element. The bridge column non-linear response is modelled using a lumped plasticity Giberson model (82). Pier 1 and Pier 5 have elastomeric bearings modelled using elastic springs with stiffness proportional to the shear modulus and geometrical characteristics representing typical bearings. Remaining piers 2, 3 and 4 are connected to the superstructure by means of pinned connections. The base of each pier is modelled incorporating a non-linear spring, the characteristics of which are based on the tri-linear idealization of the full moment-curvature analysis of a column cross-section. Takeda hysteretic rules (83) are used to define the non-linear spring behaviour. The material characteristics including discretised steel fibres, unconfined and confined concrete are developed based on the recommendations of Eurocode 8/2 and 8/3 (84,85).

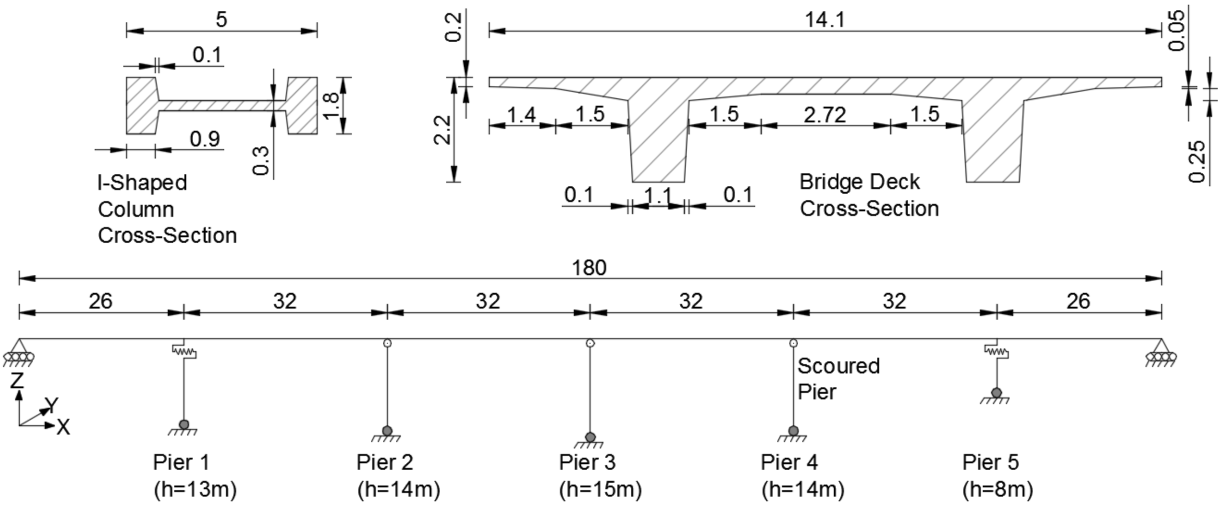


Figure 5 Schematic of nonlinear numerical bridge model (all dimensions are in m)

Scour is modelled as an increase in the effective length of Pier 4, in line with the procedure undertaken by Elsaid and Seracino (54). For the analysis in this paper, scour is implemented around Pier 4 in increments of 2m from 0m to a maximum 10m deep scour hole to ascertain the effect on the seismic response of the bridge under progressive local scour (6). Note, a 10m scour hole may be unlikely to develop, at least in isolation, but is implemented in this analysis to ascertain the seismic response under this extreme case (6).

6.2 Analysis and results

In this section, the results of both an eigenvalue modal study performed in the numerical model and a seismic response analysis of the bridge under scour are presented. The mode shapes of the bridge are extracted from the OpenSees model by obtaining a solution to the Eigenproblem (86). The first two mode shapes of the bridge under zero scour and 10m of Pier 4 are presented in Figure 6.

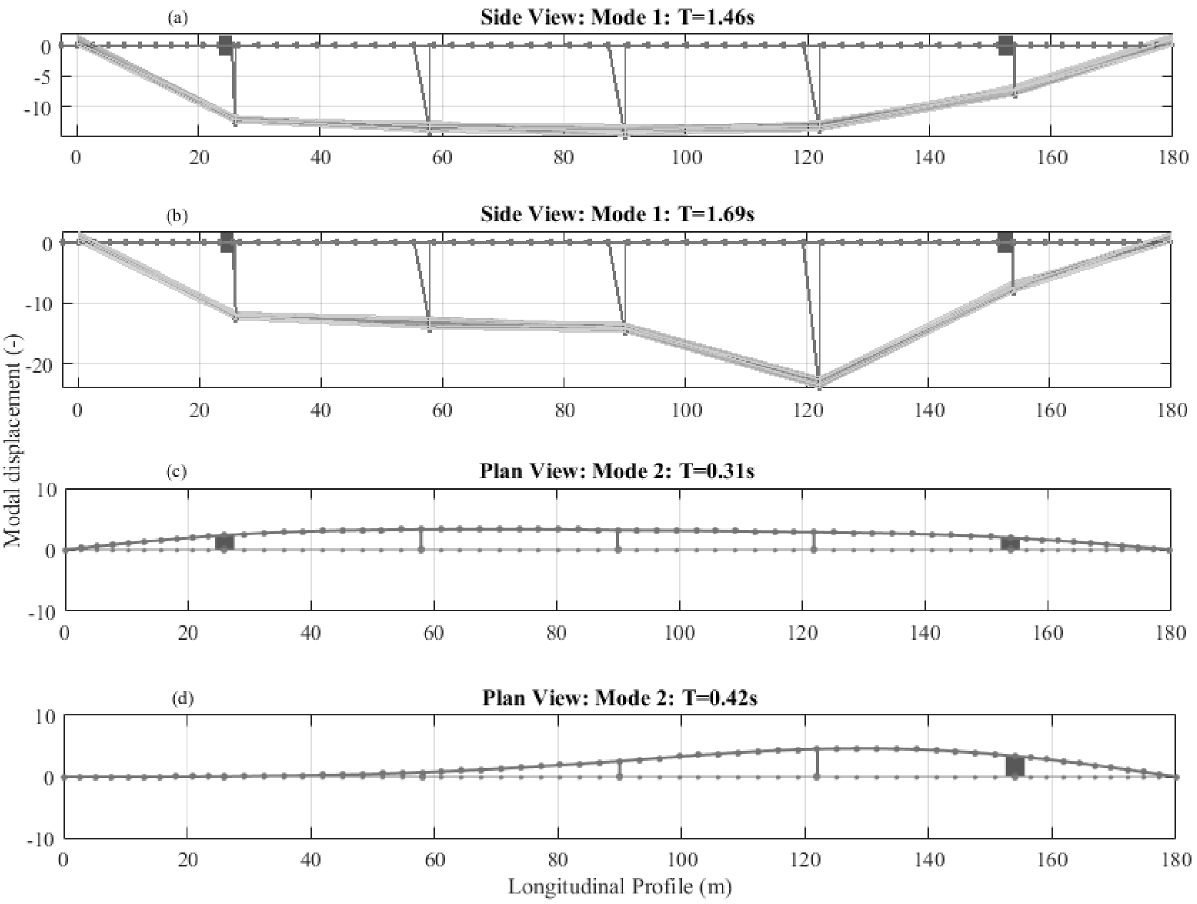


Figure 6 Bridge mode shapes under zero and 10m scour of Pier 4, (a) mode 1 of the bridge – no scour, (b) mode 1 of the bridge – 10m scour, (c) mode 2 of the bridge – no scour, (d) mode 2 of the bridge - 10 m scour.

The first mode of the bridge, Figure 6(a), is a longitudinal mode and the second mode of the bridge, Figure 6(c) is a lateral mode. Figure 6(b) shows the change in the longitudinal mode 1 due to scour of Pier 4 and Figure 6(d) shows the change in lateral mode 2 due to the same scour case. The effect of scour on modal parameters is quite evident and easily detectable using most vibration based damage identification algorithms. Modal periods of the first and second modes increase by 16% and 35% with respect to the initial values and the mode shapes exhibit localized variations at the location of the scoured pier.

Further insights can be obtained investigating the response of the bridge under an applied seismic load for the case of no scour up to a maximum of 10m scour of Pier 4. A 40 second long seismic motion (Athens 1999 earthquake) scaled to a peak ground acceleration (PGA) of approximately 10 m/s^2 is considered in this analysis. The time history and the response spectrum of the earthquake are shown in Figure 7(a) and (b) respectively. For this analysis, the motion is applied to the bridge in the lateral direction, perpendicular to the direction of traffic (y-direction in Figure 5).

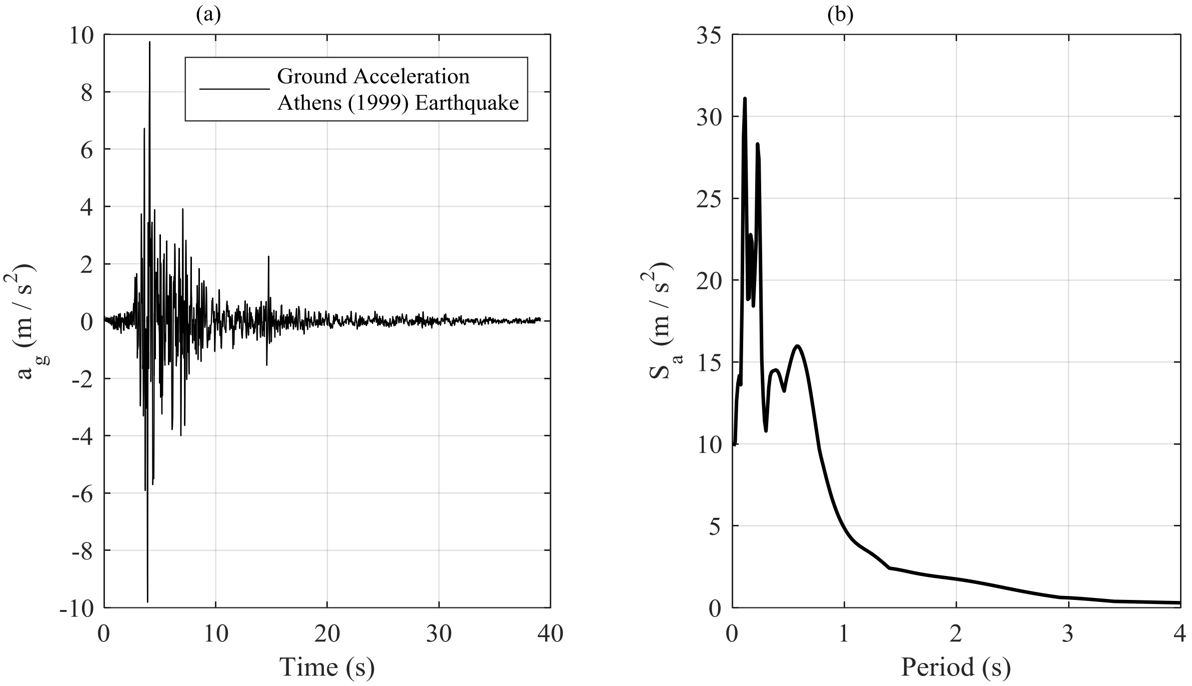


Figure 7 Seismic input ground acceleration (a) Athens 1999 earthquake time history, (b) Spectrum of ground acceleration in part (a)

For the applied seismic time history in Figure 7, the absolute accelerations and displacements extracted from the deck level of Pier 4 for progressive scour is illustrated in Figure 8. Figure 8(a) shows the displacements of the deck at Pier 4 for scour depths ranging from 0m to 10m, in 2m increments. The level of residual displacements (the level of damage) increases in the responses for larger scour depths. The peak displacement of the top of Pier 4 under the incident earthquake increases from 0.1m for 0m scour to 0.12m for 10m scour due to the increased flexibility of the bridge. Figure 8(b) shows the acceleration response of the same point on the structure under the earthquake load for various scour depths. The peak structural acceleration increases from 11.6 m/s^2 under 0m scour to 12.4 m/s^2 under 10m scour. This increase is due to the changed mode shape and shift of the second modal period toward values corresponding to a higher amplification as shown by the response spectrum in Figure 7. Figure 8(c) and (d) show zoomed in portions of the displacement and accelerations responses from parts (a) and (b) respectively, for the cases of zero scour and 10m scour, respectively.

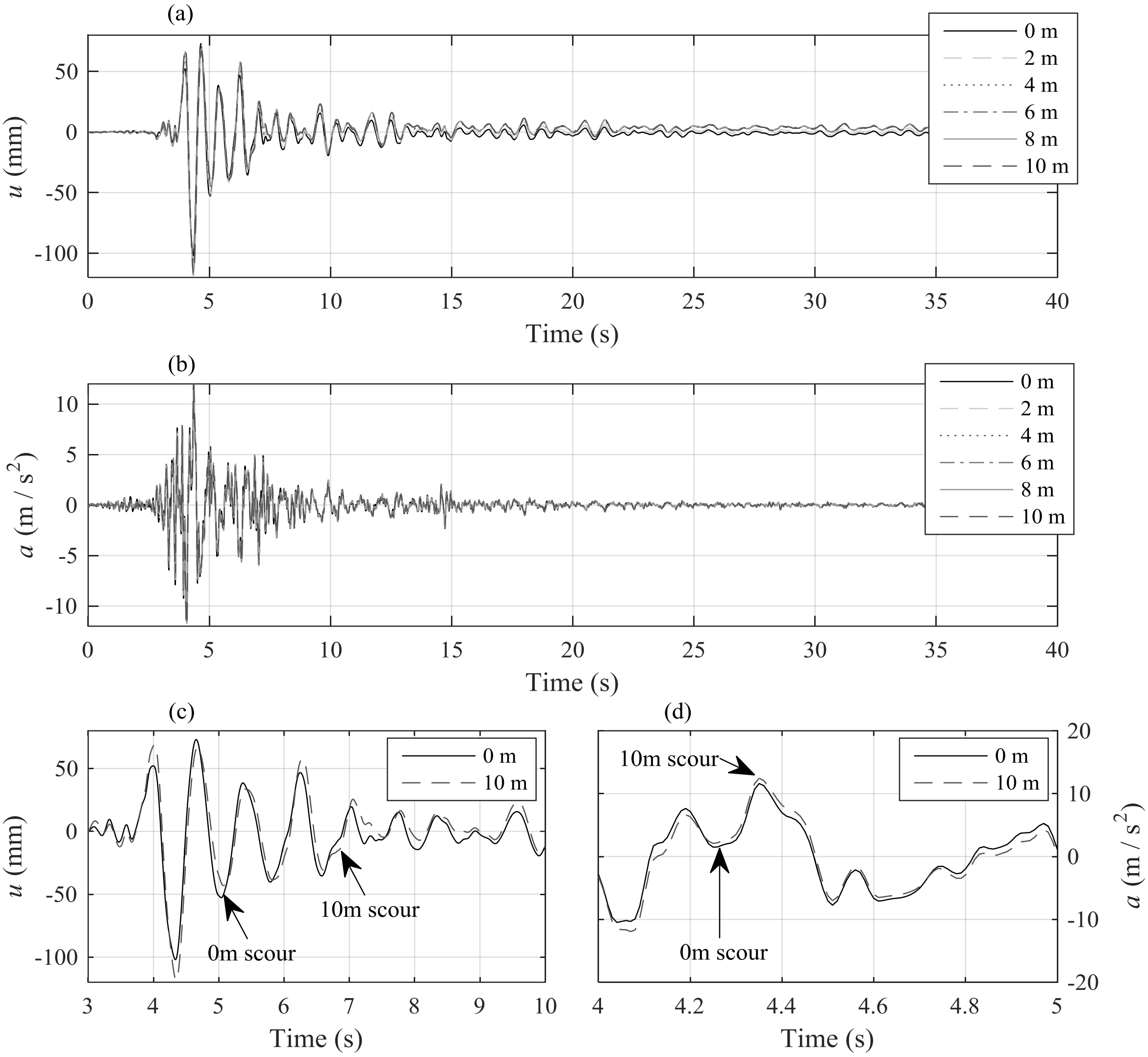


Figure 8 Seismic response of the bridge deck (lateral) at pier 4 under progressive scour conditions, (a) absolute lateral displacements of the deck, (b) absolute lateral accelerations of the deck, (c) zoomed in displacements between *t*=3s and *t*=10s for 0m and 10m scour, (d) zoomed in accelerations between *t*=4s and *t*=5s for 0m and 10m scour

Table 3 presents the maximum shear forces in each of the 5 bridge piers (see Figure 5) for the incident earthquake load under progressive scour of Pier 4 as well as the sum of the shear forces across all piers. As the scour depth at Pier 4 increases from S=2m to S=10m, the shear force (*F*) measured at Pier 4 decreases by almost 50% with respect to the unscoured value. This occurs in combination with increases in the shear force by values between 2% and 5% in the remaining piers (except Pier 1 and 5, which have elastomeric bearings). Scour is therefore beneficial in terms of reducing the shear forces in the scoured pier under an incident earthquake however it results, to some extent, in a redistribution of these forces to the other piers. The increased flexibility of the bridge when one of the piers is scoured leads, in this case, to an overall reduction in total shear F_T, however this benefit is mitigated by the redistribution of the shear forces internally to the other piers (for example in Pier 3 from 5.76 to 5.90 kN for scour depth 0 and 10 m, respectively).

Table 3 Maximum shear forces in each pier under progressive scour of Pier 4

	Scour (m)	**0**	**2**	**4**	**6**	**8**	**10**
***F* (kN)**	Pier 1	1.56	1.56	1.52	1.52	1.52	1.52
	Pier 2	5.63	5.65	5.75	5.81	5.85	5.90
	Pier 3	5.76	5.77	5.89	5.90	5.91	5.90
	Pier 4	5.72	4.94	4.32	3.77	3.30	2.92
	Pier 5	1.01	1.03	1.02	1.03	1.04	1.04
F_T (kN)		19.7	18.9	18.5	18.0	17.6	17.3

7. Conclusion

Bridge performance against damaging actions is an area of growing societal interest due to increased failure rates and associated costs. Generally, bridges are monitored periodically using visual-based inspection methods. Highly subjective and discrete in nature, the primary disadvantage of these approaches is that they may miss the damage due to access issues or low frequencies of inspection.

In the fields of seismic and scour effects on bridges, inspection and monitoring methods have been separately developed to date. Despite these events being uncorrelated, it is very possible that they may co-exist on a bridge, with resulting changes in the bridge’s behaviour. The presence of scour can alter and change the effect of an earthquake, generally increasing its danger. Scour may sometimes be beneficial at a local level, by reducing the inertial forces transferred to the superstructure as a result of the increased flexibility. Generally speaking, however, secondary damage effects that scour can cause tend to weaken a structure thus exacerbating the earthquake damage potential. Moreover, the local reduction in inertial load transfer is likely mitigated by increased load transfer to other elements on the bridge.

Significant effort has been made in recent years to develop instruments capable of monitoring the evolution of the depth of a scour hole near a bridge foundation. Though this is useful, it has the distinct disadvantage that these types of sensors can give no information on the distress experienced by a structure due to the presence of scour. More recently, vibration-based damage detection methods have come to the fore of research, which aligns with similar developments in the seismic damage detection fields. The many advantages related to vibration-based methods for damage identification lead to postulate that their use offers the most practical way to ensure the identification of a wide variety of damage scenarios occurring under scour and seismic actions.

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