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 due to flooding and seismic hazards. Flood actions that result in scour are a leading cause of bridge failure, while seismic actions that induce lateral forces may lead to high ductility demand that exceeds 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 the ductility capacity of a bridge but can also lead to an increase in flexibility that may reduce seismic inertial forces. Conversely, increased flexibility can lead to deck collapse due to support loss, so there exists some uncertainty about the combined effect of both phenomena. A necessary step towards the performance assessment of bridges under flooding and seismic actions is to calibrate numerical models that can 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 the computation of performance parameters that are useful for calibrating numerical models and 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 a particular focus on vibration-based damage identification methods.

Keywords: scour; seismic; damage; hazard; vibration-based methods

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 ageing and in many cases are approaching their original (intended) design lives. For economic reasons it is often not possible to replace these structures outright. Thus, the field of infrastructure maintenance management (IMM) is concerned with the preservation of asset stock through prolonging the service lives of structures by protecting them against deleterious actions. Environmental loading from generally uncorrelated sources such as flooding, earthquakes and wind and 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 to discussing these actions herein. Flooding can induce hydrodynamic pushover loads that are applied to bridges 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 washing away of the soil 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] as 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's 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 using 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 that the origin of the actions are not related or linked, can have a significantly different effect on a bridge's response depending on the condition of each action. Some recent studies have begun to analyse the joint effect of these particular phenomena.[9–11] For example, a reduction in foundation stiffness due to scouring 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. The next section presents an overview of performance assessment procedures for scour and seismic actions. After this, an overview of damage scenarios and monitoring approaches is presented for scour and then for seismic actions. This is followed by a description of the joint action of the two hazards and a discussion of the techniques that can potentially be applied to monitor the combined effect of the two types of action. A case study of the effect of scour on the seismic response of a multi-span bridge is then presented, and finally conclusions based on the findings of this study are drawn.

Performance Assessment Procedures for Bridge Structures under Scour and Seismic Actions

Seismic Action

The performance assessment of bridges aims to quantify safety and performance based on international standards and guidelines. In Europe, the assessment of bridge performance under seismic action often requires assessing structures that have not been designed for seismic-prone areas (due to outdated seismic hazard maps) or that have been dimensioned according to outdated design codes. The philosophy underlying the design and assessment of bridges under seismic action varies from the approaches relating to more frequent seismic actions that typically do not damage structures. This philosophy is translated in the following performance goals. The structure must be able to withstand: (a) minor or frequent earthquake shaking without damage, (b) moderate levels of shaking with only non-structural damage, and (c) severe shaking without collapse or threat to life.[12] These performance goals are common to both traditional prescriptive approaches and modern performance-based approaches to seismic design and assessment. Traditional prescriptive approaches do not explicitly address 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 the definition of the capacity (through the behaviour 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. The 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 standards related to the capacity–demand ratio and to member detailing, such as compliance with capacity design principles. Many of these standards come from the capacity design principles introduced in New Zealand in the 1970s,[14] which are now integrated into most of today's design codes.[13]

The practical procedure for bridge assessment in both traditional and modern approaches requires the modelling of structural performance in order to compute the capacity (traditional approach) or 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: (a) the geometry (dimensions, boundary conditions, etc.), (b) the material characteristics (strength, elastic modulus, constitutive behaviour), and (c) the damage state of the structure (cracks, corrosion, spalling, carbonation, etc.). Furthermore, computation of the demand (traditional approach) or hazard (performance-based approach) 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.

Scour Action

A critical threat to infrastructure around the world, scour is cited among the five most common causes of bridge failure.[15,16] Querying the United States (US) National Bridge Inventory,[17] the most likely cause of bridge collapses are "hydraulic in nature", mostly caused by scour or other hydraulic factors that are not related to the age of the bridge. In the United Kingdom (UK) on the rail network alone, more than 100 bridge collapses since 1843 have been attributed to scour in rivers and estuaries, causing fifteen 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, 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 judgements have been implemented over the 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. 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. Refs. [2, 16] give comprehensive guidance for scour risk management, including references to numerous industry and government agency scour management protocols such as the UK *Design Manual for Roads and Bridges*,[23] the US National Bridge Inspection Standards,[17] and the 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, wherein relatively inexpensive and rapid "high-level" screening is used to prioritise 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 the 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 the 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 $L = 1$. At this point, no precise definition of loading condition or failure is offered. Failure could legitimately be defined as catastrophic bridge collapse, 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, Ref. [18] attempts 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 the failure probability values associated with increasing flood return periods in order to define an empirical scour fragility formulation.

A reliable scour index for a quality control plan 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 the exceedance of a flood intensity measure (e.g. the water level) and a flood vulnerability function expressing the conditional probability of exceeding such a limit state given a certain intensity measure level. Such scour fragility functions should be calibrated via soil-structure models in order to capture the global behaviour of the soil-structure system.[6,24–26]

The Effect of Flooding on Bridge Structures

Flooding is effectively the increase in a river's normal stage height, resulting in a faster water flow that poses increased loading on bridges located in the path of water surges.[1] Several damaging actions can result from flooding, which can be categorised into primary and secondary damage types, as discussed below.

Damage Scenarios for Bridges under Flooding

The increased water speed during flooding results in increased shear stresses acting on the streambed sediment,[27] which leads to the generation of scour erosion. The critical shear stress is defined as the stress imposed by the water on the sediment at the point at which movement begins to occur,[28] and is the typical parameter used to ascertain whether or not scour will occur under a given flow condition. Other factors at play include the geotechnical conditions of the subgrade, such as the subgrade type, density and coarseness, among others.

When local water-flow characteristics suddenly change, such as at the location of bridge piers, 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 greatest threats to bridges spanning 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 to the superstructure such as cracking, pier titling and differential settlement. For example, *Fig. 1* shows a schematic of the type of damage that an arch-type bridge structure can sustain due to symmetric and asymmetric scour affecting a central pier.

In Ref. [29], the failure mechanisms for scoured masonry bridges are investigated (*Fig. 1*). A case study was used

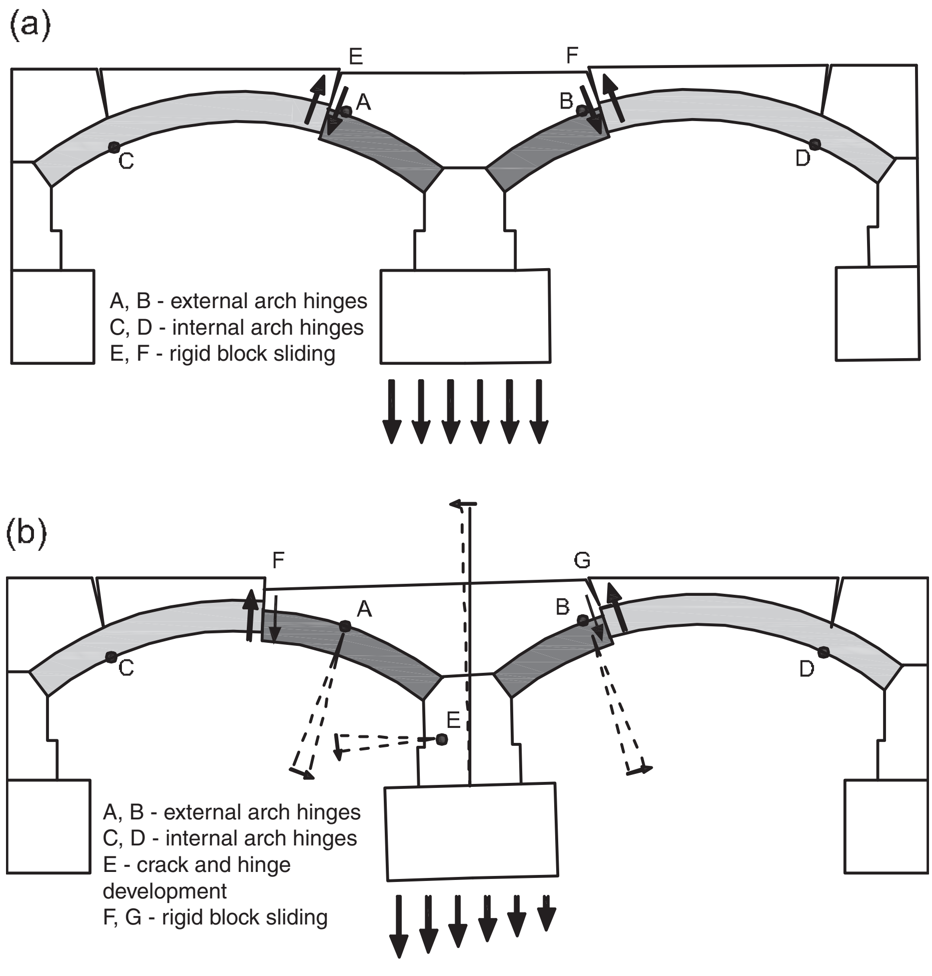


Fig. 1: Arch-bridge damage scenarios: (a) failure under symmetrical scour; (b) failure under asymmetrical scour[29]

to carry out a failure analysis by simulating the evolution of the structural behaviour of a six-span masonry arch bridge using a finite-element method (FEM) model correlated with a local scour profile. The results indicate that when undermining of the foundation occurs, the settlements become significant, which leads to crack development in the arches. The structure can fail due to the rigid-block sliding of the elements (*Fig. 1*). Differential settlement gives rise to cracking in the piers, and failure occurs due to loss of equilibrium under both symmetric and asymmetric scour.

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 been developed that are capable of remotely monitoring the depth of a scour hole near a foundation of interest, and can be used as part of discrete maintenance checks. *Table 1* outlines the nature, operational advantages and drawbacks of a number of these types of systems.[38] Scour (and flooding) can induce secondary damage effects in structures, which can result in element or total failure. The instruments outlined in *Table 1*, although 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, along with a brief outline of methods for detection and monitoring of secondary damage.

The Effect of Seismic Action on Bridges

In this section, the effect of seismic action on structures is discussed in the context of the damage that can be sustained and the methods available for monitoring this damage.

Damage Scenarios for Bridges due to Seismic Action

Earthquakes can severely compromise bridge functionality and cause significant 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 effects of a well-known earthquake in Japan (*Fig. 2*), have revealed some obvious deficiencies in design practice and the need for their resolution. This has resulted in the application of the new Eurocodes[13] in the US and Europe, whose new approach is characterised by requirements for strength increases and improved detailing in structures in order to obtain (medium or high) ductile responses.

Regarding damage scenarios induced by seismic action, past earthquakes have shown that failure may occur in common girder bridges due to: (a) the collapse of the piers due to bending or even shear if capacity design prescriptions have not been applied, or some combination thereof, (b) collapse of the pier foundations if a capacity design has not been applied, or (c) collapse of the deck due to unseating induced by high seismic displacement.

Reinforced concrete girder bridges can be affected by pounding phenomena—namely, the impact between girders at the expansion joints—as well as by the collapse of some of the main girders due to large relative movements between adjacent pier columns. Expansion joints can also be affected by deck displacement, causing compression or tension failure when pushed against each other or pulled apart, respectively. Another collapse mechanism is caused by the unseating of the bridge deck (*Fig. 3*), which can be dually affected by scour (as detailed later in this study). This can usually be

Device Type	System	Modus operandi	Advantages	Drawbacks
Single-use/reset[30,31]	Tethered buried switches	Mechanical device buried near bridge pier; indicates when scour reaches its depth by floating up and sending signal	Simple mechanical operation	Requires reinstallation after floating up and can only indicate scour has reached a certain depth, providing no further information
Radar/pulse[32–35]	Ground penetrating radar (GPR)	Determines water–sediment interface using radar; manually operated	Gives clear subterranean features from high-frequency radar signals	Requires manual operation and thus is not well suited to remote monitoring
Driven/ buried[30,34,36,37]	Vibration-based sensors	Dynamic strain sensors measure changes in natural frequencies of driven rods due to scour	Gives indication of scour depth by fitting subgrade modulus to reference numerical model of system	Only detects scour local to sensors and may miss global scour effects
Fibre Bragg grating (FBG)[8,38–40]	FBG water swellable polymers	Water swellable polymers swell upon contact with water (scoured soil) and FBG sensors detect resulting tension	Fitting a number along a rod allows the scour depth to be monitored at discrete points	Requires multiple sensors to be deployed as it can only detect scour local to each sensor
Soundwaves[34,38,41]	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

Table 1: Scour measuring devices and methods

Damage type	Method	Advantages	Drawbacks
Pier settlement	Strain gauges at the deck	Easy installation and simple measurement	Requires power and may be susceptible to environmental damage
Pier tilting	Inclinometers	Easy installation	Needs to be very accurate to detect minor rotations
Pile group tilting	Inclinometers	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	Inclinometers/ strain gauges	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

Table 2: Secondary damage monitoring devices and methods

Fig. 2: An example of poor seismic design: the Hyogo-Ken Nanbu earthquake in Japan, 1995[42] *(© Copyright 2018, Lecturas Digitales SA de CV)*

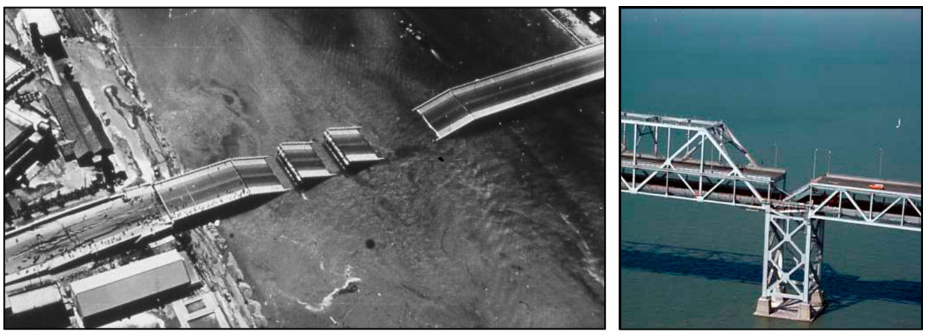
attributed to insufficient seat width and/or inadequate restraining force capacity—the phenomenon is mainly connected to outdated bridge construction methods and simply-supported span bridges. Increased flexibility due to scour increases the maximum potential displacement of the deck due to seismic action, thus increasing the probability of failure due to the unseating of the deck, which can in turn cause damage to girders—although they are usually not subject to significant non-linear behaviour. In contrast, piers are highly exposed to seismic action and usually represent one of the weakest elements of bridges. 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 failure and withstand large deformations in the event of an earthquake.

In the case of significant ground shaking, the abutments can also suffer due to excessive settlement. The shear failure of concrete bridge columns occurs at relatively low structural displacements, when the longitudinal reinforcement may not yet have yielded.[44] Alternatively, since shear strength degrades with inelastic loading cycles, shear failure can occur after flexural yielding.[45]

For masonry bridges, failure mainly affects spandrel walls in the out-of-plane direction, whereas criticalities at the 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, and pier longitudinal and transversal slenderness). For multi-span masonry arch bridges, transversal seismic action can induce shear cracks in squat piers, whereas for slender piers the structural response has to be globally analysed in order to assess potential bending failure. 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. In the case of masonry bridges situated in riverbeds, for which a residual scour depth can be observed after transient flooding phenomena, if any maintenance action is undertaken then a worsened seismic response can be observed in the event of an earthquake.

Monitoring Approaches for Seismic-Damage Detection

Visual inspections are the easiest method for observing major post-event damage such as deck unseating or partial or complete structural



(a) (b)

Fig. 3: Failure due to seismic action: (a) slab unseating in Japan, 1964 (© The Japanese Geotechnical Society); (b) slab unseating in the US, 1989 (Credit: U.S. Geological Survey/photo by C.E. Meyer)

collapse. However, less obvious damage such as hidden cracks, stiffness reduction due to non-linear large-strain deformation and loss of joint capacity are not easily observed using visual approaches. Even the use of methods such as ultrasound and radar require significant manual input and can be very laborious and time consuming to undertake. A promising alternative that is capable of providing information on structural health after a potentially damaging event has occurred consists of analysing the dynamic behaviour of the structure. Several monitoring programmes are currently in operation worldwide which provide valuable data that can be used for the development and validation of damage identification methods, in order to assess bridge performance and provide real-time information on safety in the aftermath of an extreme event.[46–49]

After a seismic event or a flood, by applying appropriate damage detection techniques to the responses retrieved from sensors,[50] a quick assessment of the structural condition of bridges can be obtained. For seismic structural health monitoring (SHM), three main categories of acceleration response are typically sought: (a) the response of the superstructure (deck, piers, towers), which retrieves the fundamental modal parameters, and the response of the foundation (bases of the piers, abutments), which provides information on the soil-structure interaction condition and the spatial variation of the acting ground motion, (b) the recorded motions in the free field close to the structure, and (c) the ground failure arrays in the vicinity of the structure.[49] Analysis of responses in real time using vibration-based damage-identification algorithms can be used to make informed decisions related to the bridge performance. In recent years, several approaches to damage identification have been proposed based on the analysis of structures' responses to vibrations.[51,52] Analysing changes in modal characteristics between the original (undamaged) state and the current (potentially damaged) state of a bridge (or element) is the most common approach used in SHM. Methods based on frequency changes can be reliably applied to detect damage,[6,24,53] although they are usually unable to provide adequate information about the location of the damage (however, for a recent study related to scour damage localisation, see Ref. [26]). More effective methods for detecting the location of seismic-induced damage include those based on the analysis of changes in modal[52] or operational[54–58] shapes or their derivatives. In addition to information on the global behaviour of bridges 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 localised information on potential sites of failure. Examples of this include malfunction or unintended functioning of bearings and connections, which can critically affect performance.[59]

The Combined Action of Flooding and Earthquakes

Structural damage rarely occurs in isolation, and recently the phenomenon of structures sustaining damage from uncorrelated sources is gaining increasing interest. The damage caused by one mechanism can completely change the result of that caused by another mechanism. In this paper, the joint action of earthquakes and scour are considered in the context of how an originally benign earthquake could pose a significantly exacerbated threat, or otherwise, to a bridge that has already been damaged by scour. Critical damage combinations are discussed in this section, and SHM approaches to damage caused by combined actions are subsequently discussed.

Critical Damage Combinations

Changes in the dynamic behaviour of bridges associated with the presence of a scour profile lead to increased fundamental periods for deeper scour depths.[6,31,54,60,61] This increase in the period may be beneficial in combination with earthquakes as it lowers the inertial forces transferred to the superstructure. In reality, however, this benefit is often negated by the presence of secondary damage effects arising from the scour process such as cracking, differential settlement, pier tilting and compromised pile lateral capacity, among others, thus resulting in increased vulnerability to seismic action. Moreover, the reduction in load transfer to a scoured pier is likely negated by an increased transfer to adjacent piers or elements. Furthermore, previously described phenomena like deck unseating can be exacerbated by structures having increased flexibility. As shown in Ref. [62], which presents an analysis of 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 earthquakes can transfer to the structure.

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

SHM 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 action, it is very difficult for maintenance personnel to adequately characterise such damage using traditional approaches. Even the recently developed scour monitoring sensors described previously are only really capable of measuring the depth of the scour affecting a structure, as they typically give no information on the condition of the structure due to the impact of this scour.[32–35,38,63]

The most feasible and widely applicable approach to monitoring structural damage due to scour and seismic action is based on vibration methods, typically using accelerometers (or other motion sensors) to measure the structural vibration response.[64] These methods have already gained significant traction in the seismic damage detection field, and independently they have also advanced significantly in terms of scour monitoring in recent years, thus they are becoming increasingly well suited to monitoring the effects of joint action (cracking, foundation stiffness loss, non-linear behaviour, etc.).[6,26,31,54,61,65–69]

There exist many methods of damage detection based on measuring structural vibrations, both in the time and frequency domains, through either online monitoring instruments located on and in the structure itself,[70,71] or offline monitoring using a passing reference vehicle.[72–74] Methods include frequency-based approaches,[6,31,66,68,75] mode-shape-based approaches,[52,72,76] mode-shape curvature approaches,[54] and damping-based approaches,[77] among others. Limitations in these approaches such as the influence of environmental effects on modal properties are constantly being challenged and overcome.[78] In the particular case of multiple hazard conditions, some of the advantages of vibration-based techniques applied using sensors installed on bridges are as follows:

- The presence of a constantly updated structural signature, which allows damage to be quickly identified and structural vulnerability to be updated accordingly.
- The creation of calibrated, continuously updated numerical models to assess structural health as well as structural behaviour (prognosis) under forecast action.
- The capability to manage both in-service and emergency situations with the same network of sensors, which increases safety while reducing costs.
- The capability to detect losses in stiffness in structures due to the primary effects of scour (foundation damage), the secondary effects of scour (crack propagation) and the effects of seismic action (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. They include:

- Defining the optimal performance parameters that can be computed from recorded structural data with the aim of identifying the damage scenarios induced by 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 action. Issues relate to sensor noise and the limited excitation of the structure induced by ambient vibrations.
- Optimising the number and locations of recording sensors for multi-hazard conditions, for example to detect not only scour and seismic damage but also degradation due to fatigue and other environmental sources. In relation to scour, one study tested various sensor locations (vertical and horizontal) along a laboratory-scale pier and examined the resulting variation in the measured predominant natural frequencies.[79] However, in relation to multi-hazards for an entire bridge, this issue remains a challenge.
- Understanding the influence of environmental variability on performance parameters that can produce variations even in undamaged structures. Variations in environmental conditions such as temperature fluctuations and wind-induced vibrations can add significant “noise” to measured signals. In the context of frequency measurements, temperature for example can induce an apparent shift in frequency which can overshadow 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 by 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 vehicles across structures. One way to reduce the influence of these effects is to only measure the vibration after a vehicle has passed across the structure and departed. Nevertheless, significant challenges still remain in the accurate characterisation of damage effects from vibration data where the relevant spectra are polluted with environmental and vehicle-related noise.
- Applying these techniques to “real-world” conditions—that is, using data recorded on actual structures under multi-hazard scenarios. Most of the algorithms proposed in the literature can correctly identify damage when working on data from numerical models but then fail when applied to real-world bridges. Further efforts should thus be made to move to full-scale real-world testing.

Case Study: Effect of Scour on a Bridge’s Seismic Response

A simple case study is presented in this section whereby scour is implemented in a numerical model around one 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] open-source software for simulating the seismic response of structural systems.

Multi-Span Bridge Model

A simplified multi-span bridge with six spans supported on five I-shaped bridge columns is modelled for this case study. A schematic of the bridge geometry is shown in *Fig. 4*. The bridge deck is modelled as an elastic beam and the abutments are modelled as roller supports in order to enable the bridge to move in the longitudinal direction. Modelling the bridge deck as an elastic beam is a simplification as it does not allow non-linear behaviour to occur at this location. A future study is planned which will involve developing a more comprehensive model for each element. The bridge column non-linear response is modelled using a lumped plasticity Giberson model.[82] Piers 1 and 5 have elastomeric bearings that are modelled using elastic springs with stiffnesses proportional to the shear modulus and geometric characteristics that are representative of typical bearings. Piers 2, 3 and 4 are affixed to the superstructure by means of pinned connections. The base of each pier is modelled by incorporating a non-linear spring, the characteristics of which are founded on the tri-linear idealisation 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 and unconfined and confined concrete—are developed based on the

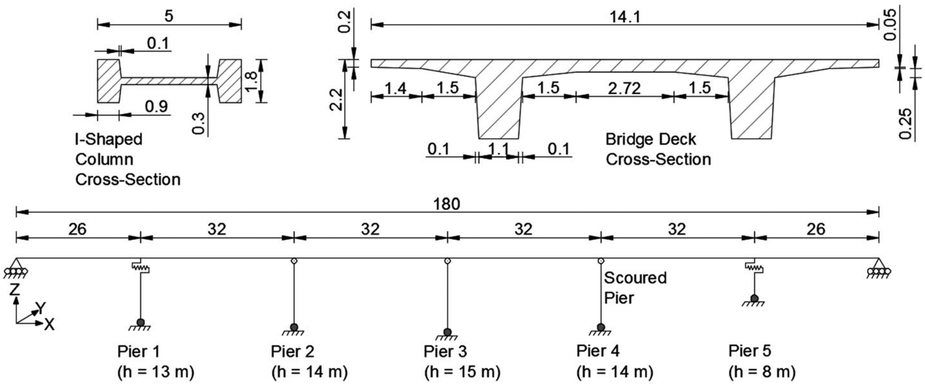


Fig. 4: Schematic of the non-linear numerical bridge model used in the case study (Units: m)

recommendations of Eurocode 8/2 and 8/3.[84,85]

The scour is modelled as an increase in the effective length of Pier 4, in line with the procedure undertaken in Ref. [54]. For the analysis in this paper, the scour is implemented around a scour hole in Pier 4 in 2-m increments from 0 m to a maximum depth of 10 m in order to ascertain the effect on the seismic response of the bridge under progressive local scour.[6] It should be noted that a 10-m scour hole is unlikely to develop in the real world, at least in isolation, but is implemented in this analysis to ascertain the seismic response in this extreme case.[6]

Analysis and Results

In this section, the results of both an eigenvalue modal study of the numerical model and a seismic response analysis of the bridge under scour are presented. The mode shapes of the bridge were extracted from the OpenSees model by obtaining a solution to the Eigenproblem.[86] The first two mode shapes of the bridge with Pier 4 under no scour and 10 m scour are presented in *Fig. 5*.

The first mode of the bridge is longitudinal (*Fig. 5a*) and the second mode of the bridge is lateral (*Fig. 5c*). *Figure 5b* shows the change in the longitudinal mode due to scour and *Fig. 5d* shows the change in the lateral mode. The effect of the scour on the modal parameters is quite evident and easily detectable using most vibration-based damage identification algorithms. The periods of the first and second modes increase from their initial values by 16% and 35%, respectively and the mode shapes exhibit localised variations around the scoured pier.

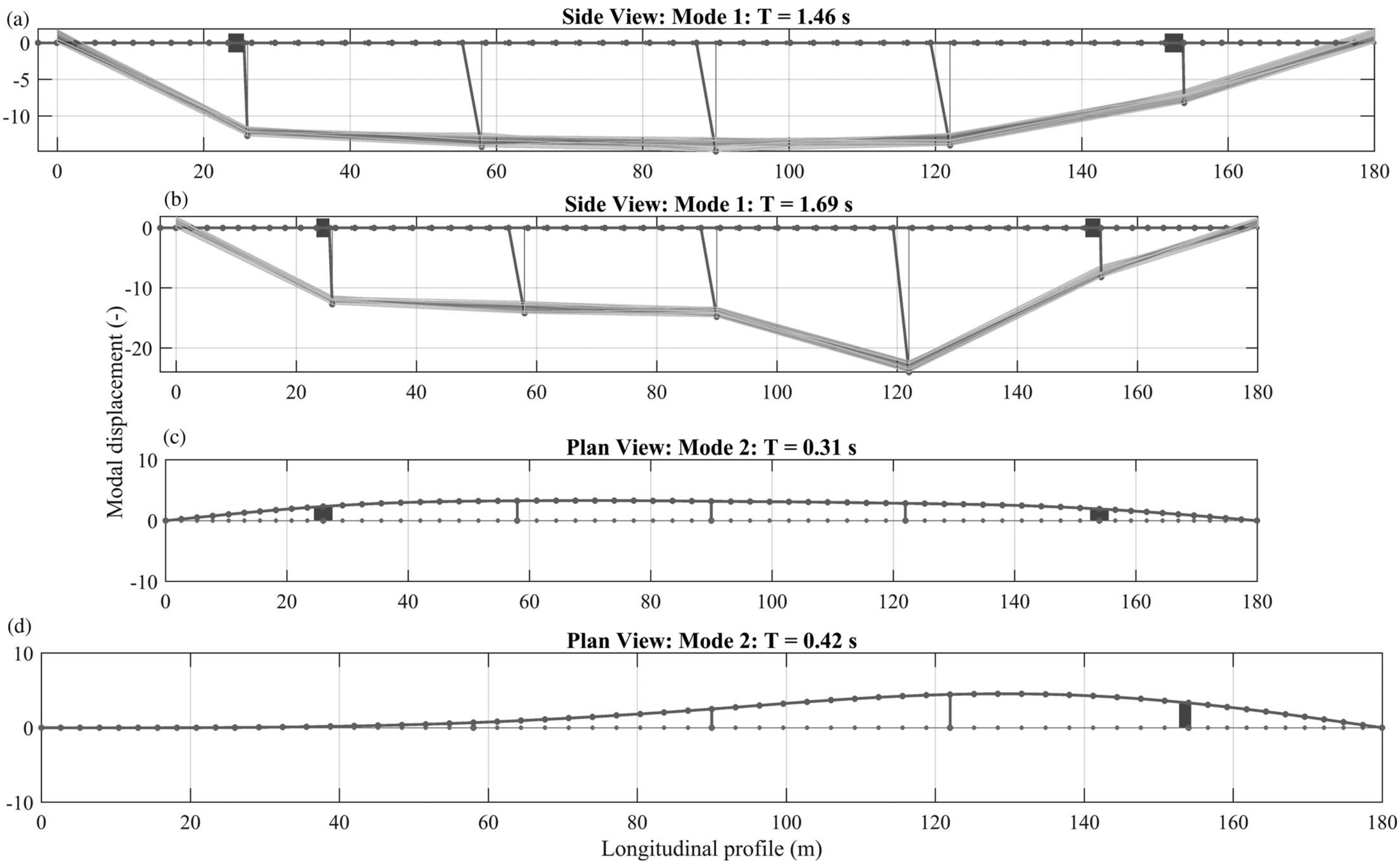


Fig. 5: Bridge mode shapes under zero and 10 m scour of Pier 4: (a) mode 1 of the bridge – no scour, (b) mode 1 of the bridge – 10 m scour, (c) mode 2 of the bridge – no scour, (d) mode 2 of the bridge –10 m scour

Further insight can be gained from investigating the response of the bridge under an applied seismic load for the case where Pier 4 is subjected to 0 m scour up to a maximum of 10 m scour. A 40-s seismic motion (simulating the 1999 Athens earthquake) scaled to a peak ground acceleration (PGA) of approximately 10 m/s^2 is considered in this analysis. The time history and response spectrum of the earthquake are shown in *Figs. 6a* and *6b*, respectively. For this analysis, the motion is applied to the bridge in the lateral direction, perpendicular to the direction of traffic (the *y*-direction in *Fig. 4*).

For the applied seismic time history in *Fig. 6*, the absolute accelerations and displacements extracted from the deck level of Pier 4 for progressive scour are illustrated in *Fig. 7*. *Figure 7a* shows the deck displacement at Pier 4 for scour depths ranging from 0 to 10 m in 2-m increments. The level of residual displacement (the level of damage) increases as the scour depth increases. The peak displacement of the top of Pier 4 under seismic action increases from 0.1 m with 0 m scour to 0.12 m with 10 m scour due to the increased flexibility of the bridge. *Figure 7b* 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 0 m scour to 12.4 m/s^2 under 10 m scour. This increase is due to the changed mode shape and shift of the second modal period towards values corresponding to a higher amplification, as shown by the response spectrum in *Fig. 6*. *Figures 7c* and *7d* show magnified portions of the displacement and acceleration responses from *Figs. 7a* and *7b*, respectively for the cases of 0 and 10 m scour, respectively.

Table 3 presents the maximum shear forces in each of the five bridge piers (see *Fig. 4*) for the incident earthquake load with Pier 4 under progressive scour, as well as the sum of the shear forces across all piers. As the scour depth at Pier 4 increases from 2 to 10 m, 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 of between 2 and 5% in the remaining piers (except Piers 1 and 5, which have elastomeric bearings). Scour is therefore beneficial in terms of reducing the shear forces in the scoured pier under seismic action; 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, but this benefit is negated 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 a scour depth of 0 and 10 m, respectively).

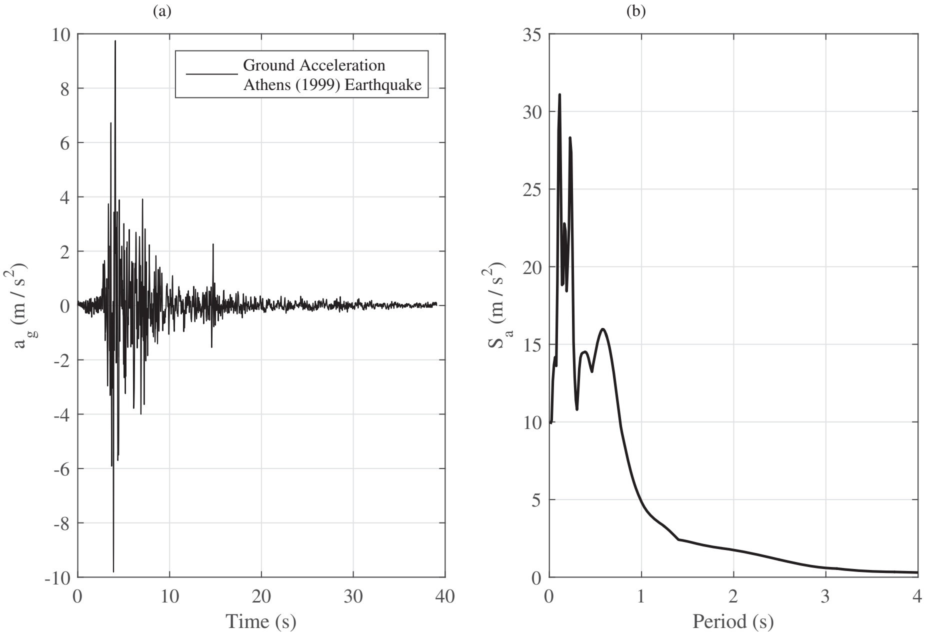


Fig. 6: Seismic input ground acceleration for the 1999 Athens earthquake: (a) time history; (b) spectrum of ground acceleration

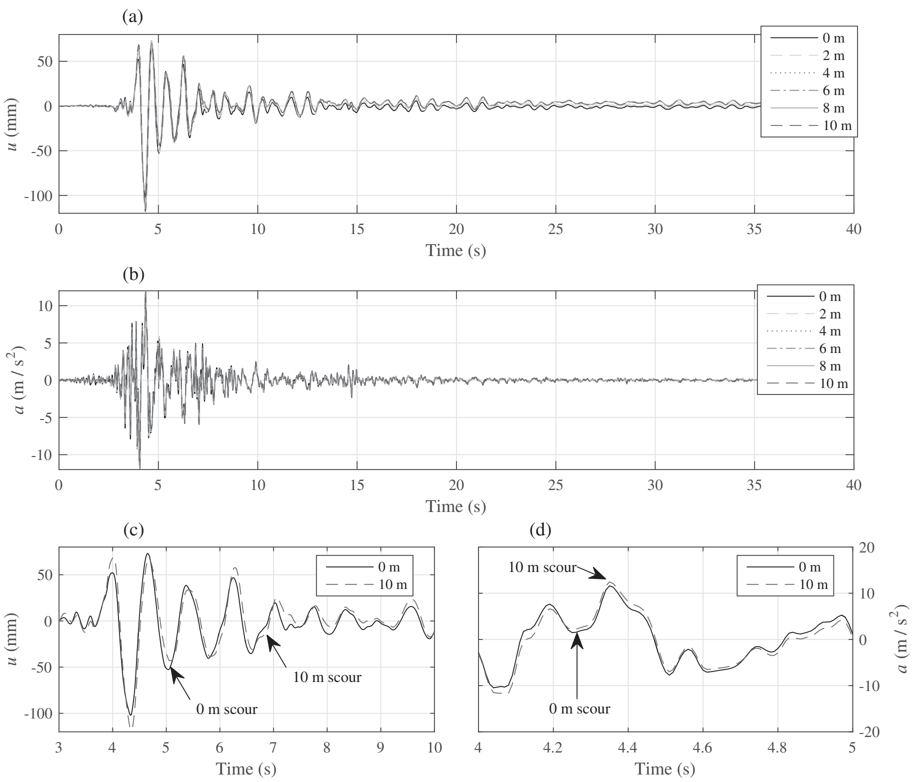


Fig. 7: Seismic response of the bridge deck (lateral) at Pier 4 under progressive scour conditions: (a) absolute lateral displacements of the deck; (b) absolute lateral accelerations of the deck; (c) magnified displacements between t = 3 s and t = 10 s for 0 and 10 m scour; (d) magnified accelerations between t = 4 s and t = 5 s for 0 and 10 m scour

	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	5.9
	Pier 3	5.76	5.77	5.89	5.9	5.91	5.9
	Pier 4	5.72	4.94	4.32	3.77	3.3	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	17.6	17.3

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

Conclusion

Bridge performance under damaging action is an area of growing societal interest due to increasing failure rates and their 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 there may be damage present that is missed due to access issues or infrequent inspection. In the separate fields examining the effects of seismic action on bridges and the effects of scour on bridges, inspection and monitoring methods have been developed in parallel. Despite flooding and earthquake events being uncorrelated, it is very possible that they may both impact the same bridge, causing changes in the bridge's behaviour. The presence of scour can alter and change the impact of earthquakes, generally increasing their danger. Scour can sometimes result in localised benefits due to causing increased flexibility that in turn reduces the inertial forces transferred to the superstructure. Generally speaking, however, the secondary damage effects that scour can cause tend to weaken structures, thus exacerbating the earthquake damage potential. Moreover, the local reduction in inertial load transfer will likely be negated by increased load transfer to other elements of the bridge.

Significant efforts have been made in recent years to develop instruments capable of monitoring the evolution of the depth of scour holes that form near bridge foundations. Although this is useful, it has the distinct disadvantage that these types of sensor can give no information on the distress experienced by structures due to the presence of scour. More recently, vibration-based damage detection methods have come to the fore, aligning with similar developments in the seismic-damage detection field. The many advantages related to vibration-based methods for damage identification lead to postulation that their use offers the most practical way to ensure the identification of a wide variety of damage scenarios occurring under scour and/or seismic action.

Nomenclature

a	acceleration
a_G	ground acceleration
F	shear force
F_T	total shear force
G	distribution function
h	height of pier
L	random variable describing a load condition
P_R	probability of failure
S	state variable describing uncertain response of a bridge under a given load
S_a	Spectral amplitude
T	modal period
u	displacement
Y	Possible outcomes when a bridge is subjected to some load representing a source of a scour hazard

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