# Evaluating the benefit of structural health monitoring for improving bridge resilience against scour

# Deliverable D1 – Report on critical review of alternative techniques for bridge scour monitoring

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| **Authors** | Dr. Enrico Tubaldi, Dr. Andrea Maroni and Dr. Neil Ferguson - University of Strathclyde (UK)<br>Prof. Daniele Zonta – University of Trento (IT) | |
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**Project Coordinator:** Dr. Enrico Tubaldi
University of Strathclyde
enrico.tubaldi@strath.ac.uk

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# 1 Introduction

This document is part of the Deliverables Report Collection produced to disseminate the products, models, and software developed within the project "Evaluating the benefit of structural health monitoring for improving bridge resilience against scour". This project has been funded by the National Centre for Resilience (NCR) under the Grant agreement NCRR2021-003.

The aim of the project is to (i) quantify the benefits of structural health monitoring for scour early warning and scour risk management of bridges in transport networks such as those operated by Transport Scotland and Network Rail in Scotland, and (ii) identify optimal scour sensing strategies based on rational criteria. The research questions to be answered by the project is: "What is the expected impact of SHM on bridge scour early warning and risk assessment?"

In particular, this report presents the critical review of the various monitoring techniques available in the literature or deployed in bridges across UK and in particular in Scotland. The considered techniques include visual inspections carried out by divers, techniques providing a direct measurement of the scour at a location (such as smart probes), and techniques measuring the effects of scour (e.g. satellites monitoring bridge settlements due to scour or dynamic identification techniques looking at changes of bridge dynamic properties). The report also shows a comparison among the techniques based on their different features, such as cost and ease of installation, capability to provide continuous measurements, accuracy, distribution of information they provide, and contribution to the four dimensions of critical infrastructure resilience (robustness, redundancy, resourcefulness, rapidity).

## 1.1 Project summary

Flood-induced scour, the erosion of material around bridge foundations due to flowing water, is by far the leading cause of bridge failures worldwide. Current practice for scour estimation at bridges is mainly based on visual inspections, which are expensive, time-consuming and, above all, provide unreliable estimates of scour and of its effects.

An accurate evaluation of bridge scour is essential for any bridge risk management system and for meeting the challenge of developing resilient infrastructure and communities. Structural health monitoring (SHM) can significantly help to achieve this goal, by allowing measuring more precisely the extent of scour at bridge foundations. Although a wide range of techniques have been developed in the last decades for monitoring bridge scour, practical applications of scour monitoring systems are limited either because of their cost or their inherent imprecision. The University of Strathclyde has recently developed a smart probe with integrated electromagnetic sensors, which overcomes the limitations of existing sensors, and particularly the cost issue. The pilot scour sensing system is installed on the A76 bridge on the River Nith (New Cumnock).

This low-cost sensor technology has been deployed in the development of a probabilistic framework and a Decision Support System (DSS) for road bridge scour management. The probabilistic framework, based on a Bayesian network (BN), exploits information from a limited number of scour monitoring systems to achieve a more confined estimate of the scour risk for a bridge network. The DSS is an SHM and event-based decision model used to inform the decisions to be taken concerning bridge closure or traffic management measures.

The approach followed in practice for designing scour monitoring systems is often heuristic, with performance evaluation based on common sense or experience, rather than on quantitative analysis. Thus, there is a need of rational procedures for the design of scour monitoring systems, and of metrics for evaluating their performance. More research is needed to quantify the benefits deriving from the use of sensors such as the smart scour probes in scour early warning and risk management. Moreover, studies demonstrating the potential benefits of the application of SHM sensors for enhancing the resilience of bridges against scour are highly needed. This research contributes to increase the application of scour monitoring techniques in real practice, thus improving the resilience of Scotland's critical infrastructure against the most severe of the threatening natural hazards.

The key activities of the project are listed as follow:

WP1. Review of scour monitoring techniques. A critical review of the various monitoring techniques available in the literature or deployed in bridges across UK and in particular in Scotland is carried out. The different techniques are compared based on their different features, such as cost and ease of installation, capability to provide continuous measurements, accuracy, distribution of information they provide.

WP2. Framework for sensor data fusion. A framework is developed for integrating data from different sensors in the scour risk assessment of bridges. This requires an extension of the BN already developed in previous research to include data observable from sensors different from gauging stations and smart scour probes. The objective is to exploit information from multiple sources for updating the knowledge of scour or even detecting aberrations from the normal state of a structure that indicate an imminent structural health problem.

WP3. Monitoring techniques effectiveness. A rational methodology is proposed to quantify the effectiveness of the alternative monitoring techniques identified in WP1. Two different indicators are used for measuring the monitoring effectiveness, one based on the concept of “pre-posterior variance”, and the other on the concept of “relative entropy reduction”. These concepts are related to the reduction of uncertainty in the estimate of the bridge state due to scour monitoring, which can be quantified once the information from the sensors are entered into the BN developed in WP2. The application of the proposed methodology is illustrated considering the case study of A76 bridge on the River Nith (New Cumnock).

### 1.2 Outline of the report

The report is organised as follow:

- Chapter 2 briefly introduces the background of the scour problem, describing the mechanism the scour process and how the risk of bridge scour is currently assessed and managed by transport operators in the UK;
- Chapter 3 illustrates the state-of-the-art in scour monitoring techniques by illustrating both direct and indirect scour measurement devices. The chapter lists several examples of the commercial version of each device and also describes the few practical scour monitoring system installations in the UK;
- Finally, the report ends with a list of the key findings from the review.

# 2 Scour risk assessment

Scour is a phenomenon responsible for the damage and collapse of many bridges worldwide (see e.g. Figure 1a). It can be defined as the excavation and removal of material from the bed of streams around bridge foundations as a result of the erosive action of flowing water during heavy floods, as illustrated in Figure 1b.


(a) (b)

*Figure 1. (a) Copley bridge (Halifax, UK) failure due to scour (courtesy of Calderdale Metropolitan Borough Council), and (b) detail of scour hole around a bridge pier [1]*

Bridges, culverts and every hydraulic structure founded on riverbed are prone to scour around their foundations [2]. When the depth of scour becomes significant, the load-bearing capacity of pier foundations may be severely compromised, resulting in loss of structural stability and eventually catastrophic failures.

This Chapter provides a review of the scour risk for road and railway bridges: Section 2.2 outlines the mechanism of the scour process and illustrates notable scour bridge failures that have occurred in the past decades. Section 2.3 contains a brief literature review of current scour risk assessment frameworks followed by transport operators in the UK.

## 2.1 Bridge scour

According to Kirby et al. [3], the scour process can be defined as:

> *“the removal of material from the bed and banks of a channel and from around structure foundations by the action of water.”*

Scour occurs naturally, and it may be caused by variations of flow in the riverbed, as part of river morphological evolution, or because of human activity, e.g., the construction of structures in the watercourse [4].

Kirby et al. [3] classify the scour process in compliance with the structures and circumstances that have caused it, and they define the following types of scour (Figure 2):

(i) *Constriction scour*: this type of scour occurs when there is sudden increase in flow velocity, which causes an increase in shear stress, as a result of a reduction of channel cross-sectional area at the bridge location [5]. The erosion of sediments starts when the shear stresses exceed the threshold value of the bed material.

(ii) *Local scour*: it is due to the flow, acting at the upstream end of bridge piers that results in the creation of vortices, which lead to further development of scour holes [6]. Local scour can be exacerbated by the presence of debris in the vicinity of the bridge pier [7]. Debris blockage increases the effective pier width and, therefore, reduces the channel width. The debris-induced constriction of the flow leads to an increase of water velocities in the surrounding of the pier, which in turn worsen scour [8], [9].

(iii) *Degradation scour*: the erosion due to the change of riverbed elevation that causes a lateral instability in the water flow. In a river, this is due to river flow changes, whereas, in the sea, it is because of the action of tidal currents [2]. Degradation scour includes aggradation of material at bends in the river, which can induce channel migration.

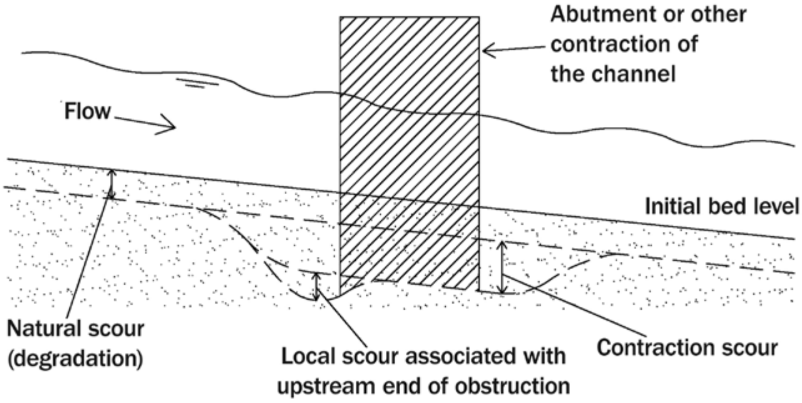


*Figure 2. Schematic illustration of total scour [3].*

The different types of scour events can be classified depending on their nature, but, although triggers are different, they can occur at the same location and in the same time frame. The first two types of scour, i.e., local scour and constriction scour, are related to the existence of a bridge or hydraulic structures, whereas degradation scour is attributable to natural variations in the flow, irrespectively of the presence of a river crossing. These are the main mechanism, but other types of scour exist, such as debris flow scour or boat scour, but they occur in more specific cases and situations [3].

Scour initiates when the shear stresses at the water-bed interface is higher than the critical ones corresponding to the initiation of motion of the soil particles. The type of bed material also plays an essential role in the scour process as the critical shear stress is peculiar to it. For example, the critical shear stress is lower for sand than for limestone [10], [11].

## 2.2 Scour failure of bridges

Flood-induced scour is recognised as one of the most common causes of bridge failures worldwide. In the UK, there are more than 60,000 road and railway bridges crossing waterways [12] and around 95,000 bridge spans and culverts are susceptible to scour. Abutment and pier scour were identified as the most common cause of 138 rail bridge failures recorded in the UK during the period 1846–2013, which in terms of failure rate means 1 bridge every 2.44 years [13]. A total of 15 fatalities resulted from bridge failures occurring due to flooding events between 1846 and 1987 in the UK and Ireland [14]. Significant collapses due to scour in the UK include the Glanrhyd railway bridge disaster in 1987 in Wales [15], where a pier collapsed due to scour resulting in four deaths (Figure 3a).

Following record daily rainfall for the UK in November 2009, 20 road bridges in Cumbria were damaged or destroyed, including the Northside bridge (Figure 3b), which led to one death [16]. In December 2015, Cumbria was again battered by an extreme flood event as a consequence of Storm Desmond, which affected more than 130 bridges. The Pooley Bridge was washed away, and one person died [17]. The winter storms of 2015 resulted in serious damage/destruction to bridges across Scotland as well. This included the Lamington viaduct, which resulted in the closure of the West Coast mainline between Glasgow and London for nearly two months due to a scour failure at one of its piers [18].

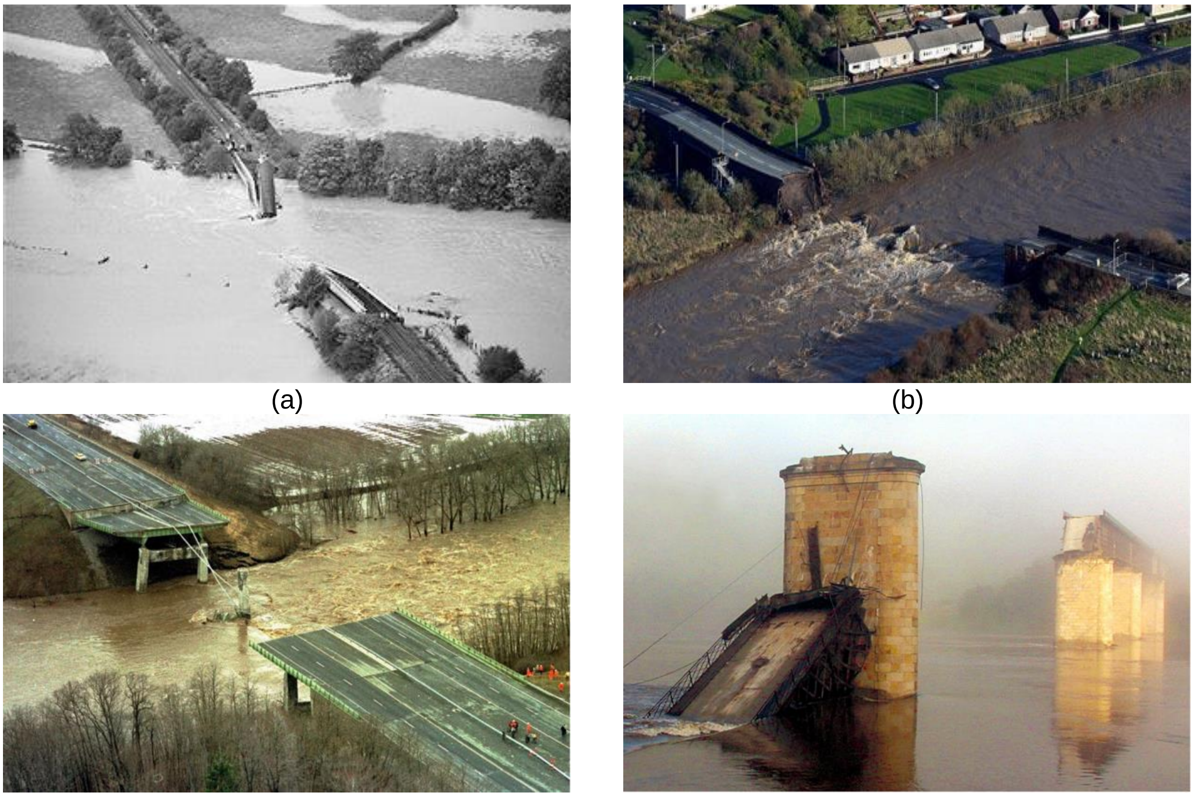

(a) (b)
(c) (d)

*Figure 3. (a) Glanrhyd railway bridge disaster in 1987 in Wales [19], (b) an aerial view of the destroyed Northside bridge in Workington (Cumbria) in 2009 [20], (c) Schoharie Creek Bridge collapse in 1987 in New York [21] and (d) Hintze Ribeiro disaster in 2001 in Portugal [22].*

Two of the worst collapses occurred in the world due to scour are the Schoharie Creek Bridge collapse in 1987 in the state of New York, where 10 people died (Figure 3c), and the Hintze Ribeiro disaster in 2001 in Portugal (59 people died) (Figure 3d). In the United States, it has been estimated that 22 bridges collapse or are closed due to scour every year on average [23]. Moreover, a review of bridge collapses in the US in the 1990s carried out by Wardhana and Hadipriono [24] shows that the 266 combined cases of flood and scour-related collapses constitutes the most dominant bridge failure cause (53% of the total cases of failures). Imam and Chryssanthopoulos [25] carried out a statistical analysis focused on failure/collapse cases of metallic bridges worldwide from the beginning of the 19th century up to 2010. The authors retrieved a total of 164 cases of failure of metallic bridges from the literature. Their review shows that the most frequently encountered modes of failures for metallic bridges is scour of piers/foundations. Although the study was focused only on metallic bridges, flood-induced scour is the principal cause of failures. A similar review of worldwide steel bridge failures has shown an analogous trend in Biezma and Schanack [26], where the authors pointed out scour as the principal cause for failure of the most collapsed steel bridges spanning rivers.

Imhof [27] has established a large database of bridge failures worldwide. He found and collected from the literature 347 bridge collapses during the period between 1813 and 2004. The database includes road as well as railway and pedestrian bridges. The analysis of the database shows that natural hazards along with ship and vehicle impacts are the most common causes to collapses. The analysis involved failures for in-service bridges, omitting collapses at the construction stage in the analysis. Natural hazard is the most important failure cause if all recorded failures are considered. By considering the natural hazard as the cause of collapse, the most frequent cause of collapse is flooding, which induces scour, followed by earthquake. These outcomes also demonstrate that any type of bridge could be subjected to failure because of pier or abutment scour.

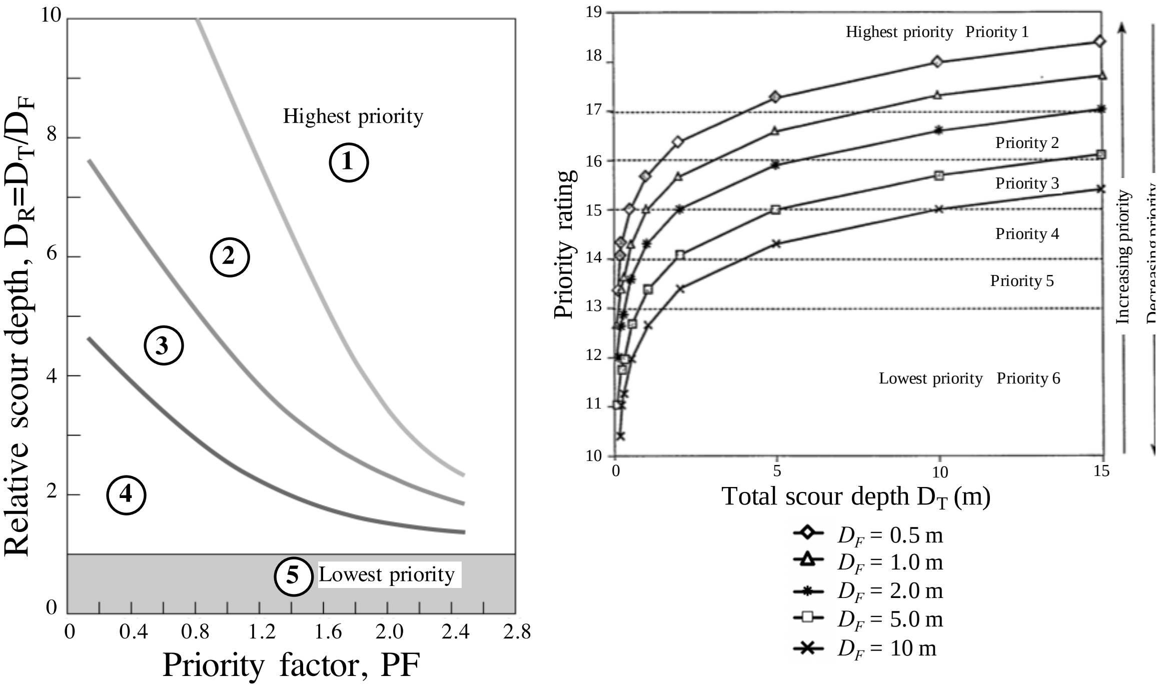
### 2.3 Transport Agencies' scour risk management

In the UK, Network Rail (NR) owns and operates around 19,000 underline bridges nationally: 8,700 of these structures are held within a National Scour Database. For the Scotland Route only, 1,750 structures are routinely inspected for scour, and 58 are considered to be at high risk. Transport Scotland (TS) is responsible for the Scottish trunk road network including 2,029 bridges or culverts over water. Of these, around 8% (or 168 bridges) are currently classified at risk of scour and needing detailed consideration, including possible monitoring and scour protection measures.

National transport agencies in the UK, such as TS or NR, carry out the assessment of the scour risk at highway and railway structures in accordance with the Procedure BD 97/12 [28] and the EX2502 Procedure [29], respectively.

The two procedures [28], [29] classify the scour risk of a bridge through a scour vulnerability index (SVI). The input parameter in TS's classification (Figure 4a) is the relative scour depth $D_R$, that is, the ratio between the total scour depth $D_T$ and the foundation depth $D_F$. The total scour depth $D_T$ is defined as the sum of constriction, $D_C$, and local scour depth, $D_L$, of which the BD97/12 provides the estimation formulas starting from a hypothetical assessment flow (i.e., the flow corresponding to a return period of 200 years). Furthermore, a priority factor $PF$ enters the risk rating to account for several factors, such as the history of scour problems, the type of foundation and the importance of the bridge (i.e., vehicle traffic volume). For instance, if $PF = 2$, the scour risk classes are defined by the value of $D_R$ as follows: Class 5 for $D_R \leq 1$, Class4 for $1 < D_R \leq 1.8$, Class 3 for $1.8 < D_R \leq 2.3$, Class 2 for $2.3 < D_R \leq 3.5$, and Class 1 for $D_R > 3.5$.

The scour risk classification carried out by NR is performed according to the graph depicted in Figure 4b. It shows different curves according to the foundation depth $D_F$, consequently, even if the graph's axis related to scour depth is flipped with respect to TS chart, the two classification methods are equivalent because both transport agencies use $D_R$ to categorise the bridge risk of scour. TS classification consists of five classes while NR method has six classes, and bridges with the highest priority fall into class 1 in both procedures. When a bridge is categorised into category 1 or 2, it is considered at high scour risk for both agencies.



(a) (b)

*Figure 4. Scour risk classification performed by (a) TS [28], and (b) NR [29].*

It is noteworthy that these scour risk assessments generally rely on scour depth formula that are based on laboratory experiments and the assumption that the designed flood acts over an infinite duration [10], while real flood events are characterised by different hydrograph duration and magnitude. Thus, high-flow events (i.e., corresponding to a high-water level) may not necessarily result in the development of a significant scour hole, if e.g. they have a short duration. Moreover, bridges are exposed to sequences of events, each potentially contributing to scouring. Therefore, their safety could be jeopardized by the progressive accumulation of the excavations under multiple events with low return period (i.e., water levels below the FLM) occurring in sequence, as was the case of the Lamington viaduct [18].

Flint et al. [30] outlined that the risk of failure due to scour cannot be directly related to only one design flood scenario and its corresponding return period $T_R$. Their review of 35 historical bridge collapses in the US (16 failure due to scour) shows highly dispersed flow return periods for scour-induced collapses, ranging between one to more than 1,000 years. Interestingly, the majority of analysed bridge collapsed under events with $T_R$ lower than 200 years, i.e., the return period usually adopted for scour bridge design, thus highlighting the problem of accumulation of scour over a number of floods [30].

The Transport Agency also define a plan describing the actions to be taken during or after the occurrence of an extreme flood event and furnishing a systematic and structured approach to how to respond to the threat of adverse weather. For Scotland, the two plans are the “Scour Management Strategy and Flood Emergency Plan” [31] and the “Scotland Adverse and Extreme Weather Plan” [32].

Both the plans identify triggers that determine what actions needs to take place, with a “visual” decision scheme based on water level markers placed on the bridge upstream surface.

When the water exceeds the levels shown on these markers, specific actions must be taken. For example, one action could be the closure of the bridge to traffic. Following the closure, an inspection of the structure, including also underwater parts and the riverbed, is undertaken as soon as it is safe to do so, and the bridge can be re-opened to traffic once water levels have reduced sufficiently and only if there are no visible signs of deformation or structural distress. It is noteworthy that no direct or indirect measure of the actual scour depth enters the decision process until water levels have receded so that inspectors can safely carry out underwater checks.

TS's structures vulnerable to scour are equipped with two different marker plates, the Flood Level Marker (FLM) plate that corresponds to the 1 in 200-year flood level according to the BD97/12. NR decision process is based on water level markers too. The red marker is established on a case-by-case basis based on scour assessments and engineering judgement. However, the red marker is usually fixed in correspondence of the water level leading to a bridge classification in Priority class 2 (i.e., when the Priority rating is higher than 16 meaning Priority class 2).

It can be observed that both transport agencies rely on visual inspections to identify the bridges that may be at risk of scour, to supplement the scour risk assessment provided by their procedures and to manage their bridge asset through their "visual" decision schemes. The inspections are carried out at regular intervals or after major flood events, by involving the use of scuba divers for underwater inspections of bridge foundations.

Although they are the predominant non-destructive evaluation technique used in bridge management to check the bridge condition [33], visual inspections have clear disadvantages. Several elements might affect their reliability such as subject factors (e.g., visual acuity), environmental factors (e.g., lighting and background noise), or organizational factors (e.g., number of inspectors and provided equipment) [34]. In fact, they often involve basic instrumentation to identify structural irregularities and their outcomes are often subjective, depending on the inspector's experience [33]. And above all visual inspections are in general expensive and time-consuming. Furthermore, focusing on the scour evaluation, it is too dangerous to carry out underwater inspections during peak flood events with high velocity and the scour hole may have partially been refilled at the end of the event. It is noteworthy that the redeposited material could be easily scoured at the next flood.

Using only the water level to trigger decisions ensures that the bridge is not inundated or possibly struck with floating debris whilst open to traffic, but it does not allow the directly control of scour risk under floods with return periods different than the one considered for defining the fixed flood level marker. The water level can be considered only a very rough indicator of the scour risk, also considering that no measurement of scour enters the action plan until the river flow and level are considerably reduced, thus allowing the diver teams to safety check the bridge foundations.

Therefore, there is a need to introduce systems capable of monitoring the evolution of scour at bridge foundations during and after extreme weather events, providing clear and direct information about scour and the bridge state in order to support transport agencies in taking the optimal decision about keeping bridges in service.

# 3 Scour monitoring techniques

Structural Health Monitoring (SHM) systems offer a way to overcome the limitations of visual inspections and improve current scour risk management approaches. In general, SHM systems can be defined as methods using sensors to achieve, in near-real time, reliable diagnosis of the “state” (i.e., condition) of structural components or the whole structure [35]. The main benefit of SHM systems over visual inspections is that they are capable of providing objective and quantitative information about the monitored structure, and to furnish continuous data about the structural state, even during an extreme event, (e.g., earthquakes or flood) [36].

The last three decades have seen a growing trend in the development of sensor technologies, data transmission and processing for the assessment of the performance of civil infrastructure under environmental conditions. These developments have resulted in more and more structures equipped with SHM systems [37], and bridges are the structures that have experienced the greatest growth in the application of SHM [38]–[42]. On-site campaigns aiming to continuously monitor real-time scour are still scarce due to accessibility issues under flood events, likelihood of damage, their cost, and their inherent imprecision. Still, a wide range of techniques have been developed in the last decades for monitoring bridge scour [43] and there are a few examples of scour monitoring system installations, especially in bridges experiencing significant scour in the past.

*Table 1. Most widespread scour monitoring techniques and their working principle for direct and indirect measurement devices.*

| **Direct scour measurement devices** | |
|---|---|
| **Scour Monitoring Techniques** | **Working principle to detect scour** |
| (1)Pulse devices | Measure the soil properties through electromagnetic pulse |
| (2)Radar devices | Measure the soil properties through radar signal |
| (3)Single-use or float-out devices | Devices float out when scour depth is reached |
| (4)Fiber–Bragg grating systems | Strain measure of a cantilever rod buried into the riverbed |
| (5)Sounding or driven rod systems | Gravity-based probe moves downward as scour develops |
| (6)Sound wave devices | Measure of travel time of sound waves |
| (7)Electrical conductivity devices | Measure of electrical properties of the medium |
| (8)Dielectric probes | Measure of dielectric permittivity of the medium |
| **Indirect scour measurement devices** | |
| **Scour Monitoring Techniques** | **Working principle to detect scour** |
| (9)Tilt sensors | Monitoring of bridge/pier movement until a threshold angle |
| (10)Accelerometers | Changing in dynamic response of bridge/pier |
| (11)GPS and (12)satellite | Monitoring of bridge deformation from satellite images |

Many of these monitoring techniques provide a direct measurement of the scour depth at a bridge pier, whereas other techniques provide information on the effects of scour on the bridge. These effects can be related to the scour depth at the bridge foundations. Table 1 shows the most widespread scour monitoring techniques, based on both direct and indirect measurement of scour, and Figure 11 illustrates a bridge pier equipped with some of these techniques. After a brief description of each device, the section also introduces the advantages and disadvantages of each scour monitoring system and highlights the importance of monitoring scour.

### 3.1 Direct scour measurement devices

Direct scour measurement devices provide a direct scour depth measurement at bridge piers or abutments. They are illustrated in Table 1 and described separately in the following sub-sections.

*Pulse devices* such as time-domain reflectometry (TDR) devices use electromagnetic pulses to detect interfaces between two mediums, such as sediment and water. A TDR monitoring system generally consists of a pulse generator and sampling oscilloscope, a connection cable, and a probe, which is the waveguide carrying the electromagnetic signal propagating through layers having different dielectric permittivity (Figure 5). The device works by generating a fast-rising step pulse in the form of an electromagnetic wave which propagates down the probe until it is reflected at the sediment-water interface and probe end [44]–[46]. The dielectric permittivity $\varepsilon$ can be inferred by measuring the apparent length $L_a$, which is proportional to the pulse travel time.

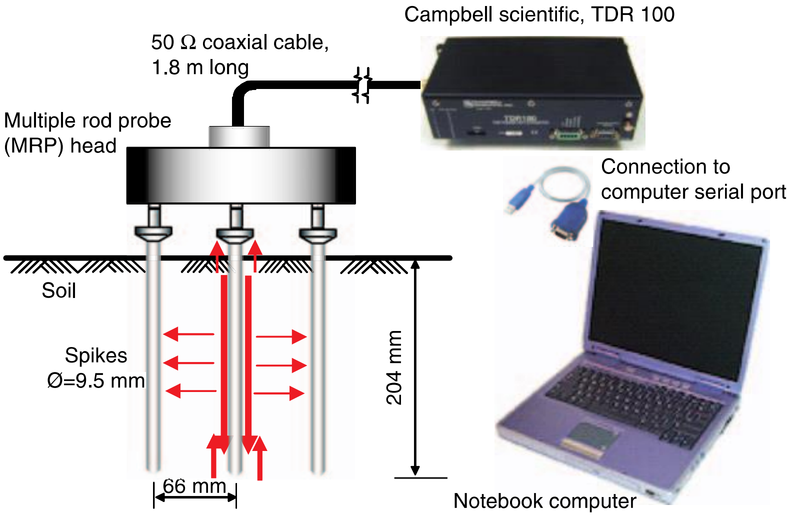


*Figure 5. A typical TDR monitoring system [46].*

Figure 6 shows the typical signal recorded by the TDR in different types of soil, water or air. The apparent length estimated by the travel time of the pulse allows computing the permittivity, thus discriminating the medium around the rod probes.

The principal advantages of TDRs are their capacity to monitor in real-time and to detect the scour depth development in time [47]. Their key limitation is the fact that they provide very localised scour depth estimates [46], where the probe is installed. Moreover, the length of the probes and the cables could result in excessive costs associated with installation. The accuracy of the measurement may be affected by changes in temperature in the channel, though these may be compensated. Relative errors of the order of 5% have been reported in Fisher et al. [44].

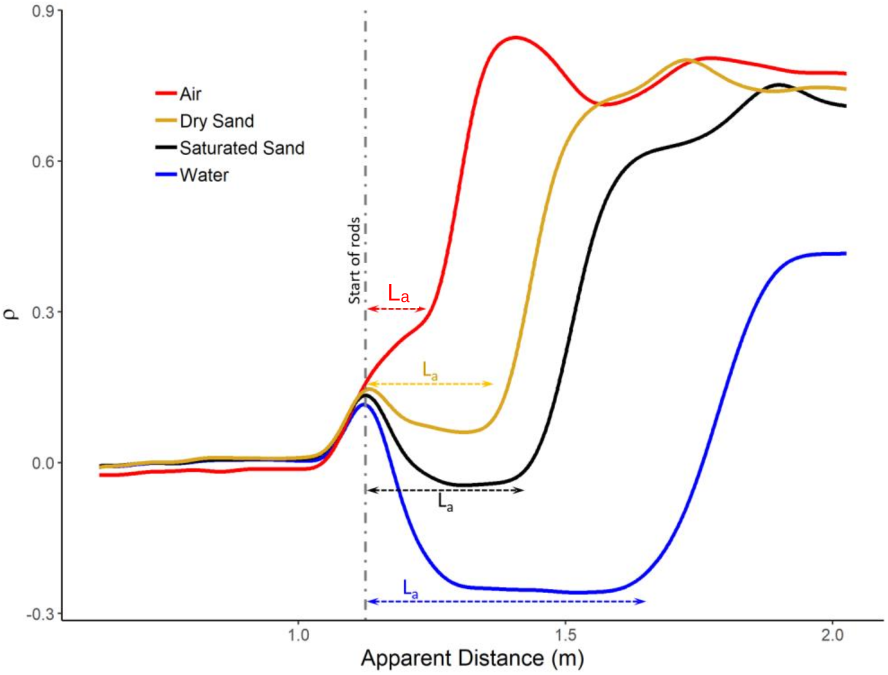


*Figure 6. A typical TDR output signal [48].*

*Radar devices* such as ground penetrating radar (GPR) devices work using similar principles to the TDR. Radar pulses are generated and propagated through water until they reach the streambed and information on the geophysical profile of the riverbed can be obtained based on the energy that is reflected and returns to the receiver (i.e., the magnitude and the arrival time of the reflected signal are recorded by the receiver). The geophysical map is then used to detect the areas where the soil has been eroded and estimate the scour depth [49]–[51]. The method can provide detailed information about the surface condition of the ground but, being a portable device, it cannot be deployed as a continuous monitoring system, especially during heavy-flood events where the risk of scour occurring is higher [49].

*Single-use devices* are float-out transmitters, which are buried in the riverbed at known depths in locations prone to scour. Once the riverbed is scoured from above the device, the sensor will float to the water surface (Figure 7). Its transmitter is activated by its change in the orientation from vertical to horizontal and starts emitting its unique signal, indicating that the scour has reached the depth where they are located [45], [52]. These devices are easy to install, reliable due to their easiness of use, and they can indicate the presence of a scour hole based on their point of installation. However, the maintenance costs are high because they need to be re-buried every time scour occurs [43], [45]. Smart rocks follow a similar principle; they are placed on the riverbed, and, when the scour occurs, they continually fall into the bottom of a gradually growing scour pit during a flood event. The position of the smart rocks is localised thanks to algorithms based on the theory of magnetic field, thus registering the scour depth. The devices were tested both in laboratory [53] and in the field [54], showing that the algorithms are able to localised the smart rocks with errors close to the engineering requirements, but that they still have significant dependence on the position of the stations and the measurement points and on the ambient magnetic field instability due to environmental factor (e.g., traffic on the bridge).

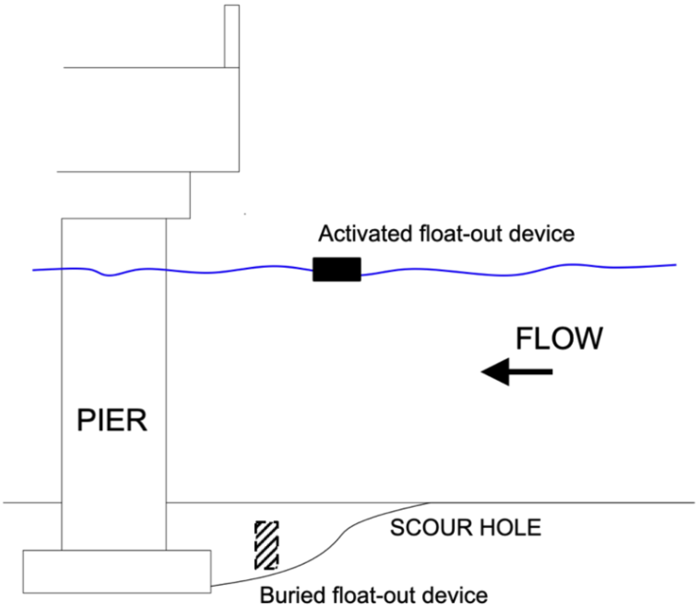


*Figure 7. An activated float-out device.*

*Fiber–Bragg Grating (FBG) sensors* are devices that can operate for real-time and continuous scour monitoring. These sensors are installed in a cantilever rod embedded in the riverbed [43], and they provide scour measurement according to two different approaches. The first one consists of the strain measurement along the fixed rod that bends under the hydrodynamic forces of the water flow when it is partially exposed due to scour. The higher the number of sensors, the higher the resolution of the scour measurement. In the second method, a single FBG sensor is placed on the embedded rod to determine its vibration frequency. Depth of scour can be detected using the inverse relationship between the length of the vibrating embedded rod and its fundamental frequency, given that the latter decreases when a length of the rod is exposed due to scour [55]. FBG devices are a simple technique for monitoring scour; however, the system is highly susceptible to vibrations of the support structure caused by, e.g., traffic, thus affecting the accuracy of the measurement [52].

*Sounding or driven rod systems* are gravity-based physical probes positioned in the riverbed and moved downward due to the scour hole development. An example of these devices is the magnetic sliding collar device. The magnetic sliding collar (MSC) monitoring device consists of a rigid rod fixed to the bridge pier and embedded into the riverbed (Figure 8). The MSC is installed by sliding it down the rod and placed on the streambed surface. The rod is equipped with a number of magnetically activated switches spaced at known intervals of the rod; when the riverbed erodes, the collar slides down the rod and closes the magnetic switches, thus detecting the depth of scour at that particular location [45], [52]. Although they are inexpensive and easy to operate, the MSC devices have several disadvantages. Scour depth detection is very localised, because it can only be measured in the vicinity of the device. The record of the global effect of scour on a bridge pier requires a number of devices. Moreover, the device uses a gravity sensor, and when the collar reaches the lowest switch on the rod, the device must be reset, which can be time-consuming and expensive. Furthermore, the MSC devices cannot provide any information about the process of scour holes refilling [43], [47].

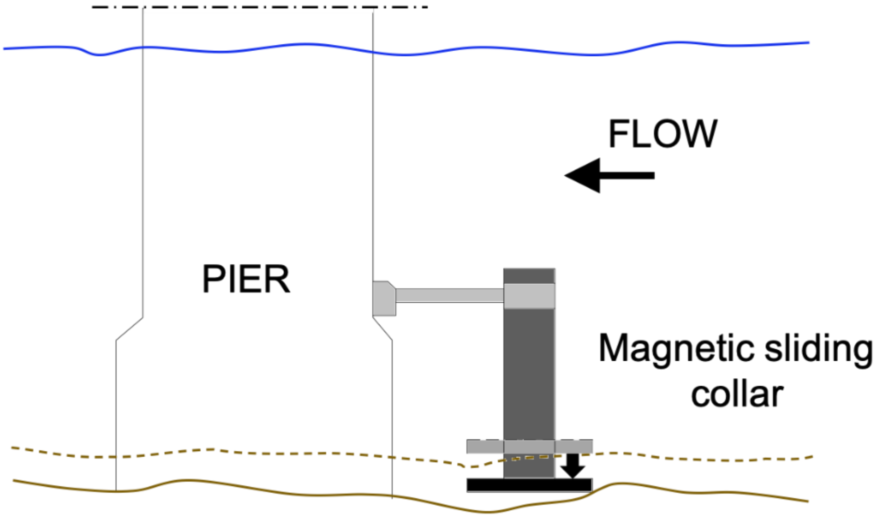


*Figure 8. A magnetic sliding collar installed at a bridge pier.*

*Sound wave devices* operate on the same principles as GPRs but utilising acoustic waves [43] instead of electromagnetic waves. Examples of these devices are the sonic fathometers, which are fixed to the bridge, or portable probes such as reflection seismic profilers and echo sounders [12]. The former is installed on piers or abutments with the transmitter facing the waterline. The transmitter emits an acoustic wave that, when it encounters an object on its path, is reflected and recorded by the receiver. The distance between the transmitter and the riverbed is then established using the travel time of the wave in water, thus providing a continuous streambed profile, tracking scour and sediment deposition processes over time [47], [56]. Unfortunately, this device can only be employed at specific depths (i.e., it has a limited depth tolerance), and the results can be affected by errors due to water salinity and temperature variations, presence of debris or water turbulence during high flows [44].

*Electrical conductivity devices* use the difference of electrical conductivity in various surrounding media such as soil, water or air, to identify them [57]. In particular, these systems measure the electric current between two electrodes, and they are able to detect changes in conductivity values due to increasing concentration of ions in the solution, based on the principle that current flows by ion transport. When there is a change in the material around the electrodes, the conductivity changes, therefore, these devices can detect any erosion in the riverbed by exploiting the difference of conductivity of the riverbed and the flowing water [57]. In contrast to TDR monitoring systems, electrical conductivity devices are a multi-point measurement technology, i.e., several sensors can be mounted on a probe in order to provide measurements of electrical conductivity at different depths along the rod's height.

*Dielectric probes* consist of a series of capacitive sensors installed on a rod, which represent one of the techniques available for measuring electromagnetic properties of the soil [58]. The term "capacitive" refers to the working principle of the electric device, which can be exemplified by considering an LC circuit (L= Inductor, C= Capacitor) [58]. Each sensor is formed by an electrode pair (i.e., the two capacitor ring conductors) which transmits an electromagnetic fringing field that penetrates the external surrounding medium (see Figure 9). Since the two electrode rings have diameter greater than their spacing, the capacitance is not only affected by the medium directly between the conductors (as is the case of the infinite conductors) but also by the medium surrounding the electrodes laterally. Since the configuration and geometry of the probe is the same throughout the probe length, change in capacitance only depends on the dielectric property of the surrounding soil. The capacitor made of the two ring conductors is inserted into an LC-type circuit. The capacitance and, hence, the dielectric permittivity of the surrounding soil, is measured by the resonant frequency of the circuit via an oscillator inserted into the LC circuit as discussed by Tarantino et al. [59].

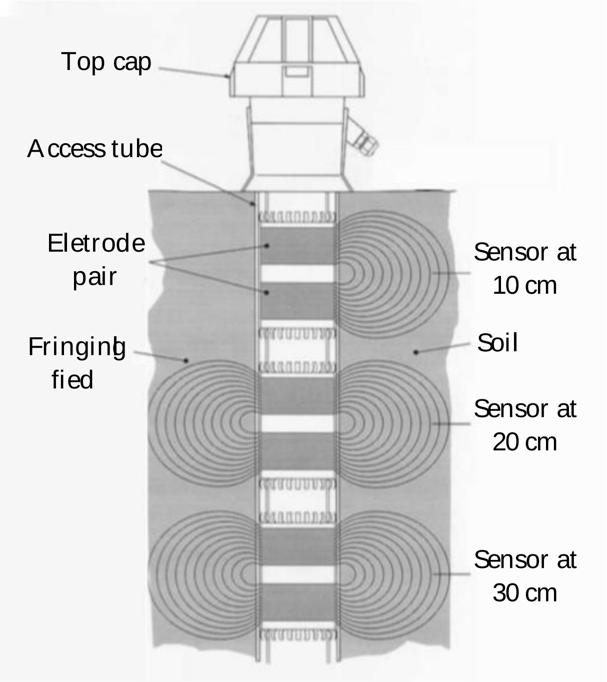


*Figure 9. Schematic of the dielectric probe equipped with electromagnetic sensors.*

The dielectric permittivity can therefore be measured if a calibration function is established to convert the resonant frequency read by the sensors into a permittivity value, which differs between the soil in the riverbed and the water [60]. The system is calibrated to detect erosion and deposition of riverbed sediment in different soil types and under temperature that would commonly occur in a real case-study scenario [60]. The principal advantages of dielectric probes are their capacity to continuously monitor the scour depth, including the capability to track the refill (deposition) process, but the scour detection is localised where the scour probe is installed. (i.e., the sphere of influence is about 14 cm from the external surface of the probe). However, scour probes are one of the few devices allowing for recording during an extreme flood event. The technology is frequently deployed in agriculture to measure the soil water content, thus assisting with irrigation scheduling [61]. Although very appealing, these sensors have been applied only recently in a real-world setting [62].

### 3.2 Indirect scour measurement devices

Indirect scour measurement sensors provide information on the effects of scour on the bridge and its components. Since these devices only detect changes in the structural behaviour (e.g., modifications in bridge’s dynamic properties or inclination of piers due to a certain level of scour), they may recognise the presence of a scour hole when it is already too critical and it may not possible any more to avoid bridge damage and even collapse. The most common ones are listed in the second part of Table 1 and described hereinafter.

*Tilt sensors* (or tiltmeters) measure the inclination of a bridge pier, abutment or deck along two directions in a field of measurement of ±90˚, i.e., parallel and perpendicular to the direction of traffic. The monitoring system based on these sensors are able to detect abnormal rotations of the piers induced by foundation settlements [63] and can send an alert message when these rotations exceed a given threshold (Figure 10). The main drawback of this monitoring system is that it is difficult to establish critical thresholds and pier deflections can be caused not only by scour but also by many other (and often concurrent) actions, such as traffic, wind or temperature [43], [45], [47].

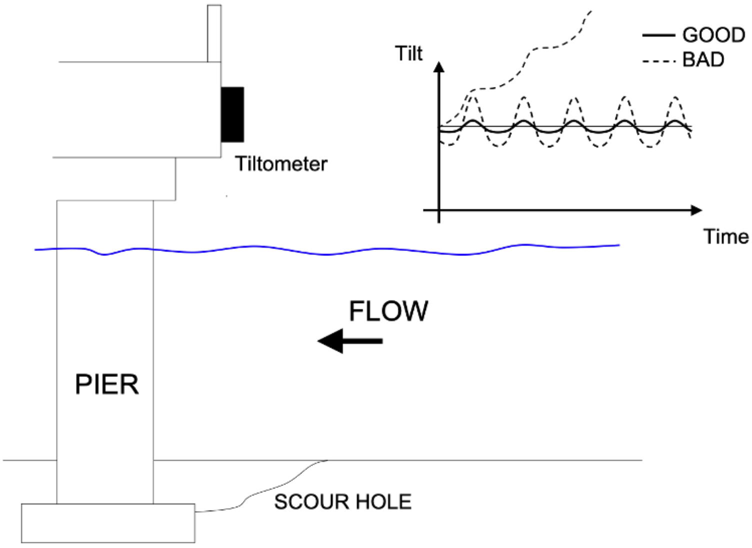


*Figure 10. Schematic of a tilt sensor device.*

*Accelerometers* provide measurements of accelerations that can be used to detect changes in the dynamic properties of the bridge, and particularly changes of vibration modes and vibration frequencies, in response to a modification in boundary conditions due to e.g. scour. Several authors have explored the suitability of using dynamic measurements to observe the existence of a scour hole beneath bridge foundations [56], [64]. Numerical models of the bridge [65], [66] may also be developed to establish a relationship between foundation scour and bridge dynamic properties. The problem is however very complicated because bridge dynamic properties are also influenced by many other actions. Moreover, scour may occur at multiple locations, and thus different scour configurations may lead to the same change of frequency, thus resulting in an indeterminate scour identification problem.

*GPS/Satellites.* Two modern geodetic techniques, namely the *Global Positioning System* (GPS) [67] and *Interferometric Synthetic Aperture Radar* (InSAR) [68], have revolutionized the way land and hydrographic surveys are performed, and they started to play an essential role for monitoring dams, buildings, bridges and many civil engineering infrastructures. The working principle of the two techniques is similar since they both use electromagnetic waves to measure the distance between satellites and ground targets and evaluate structural displacements. Considering bridge monitoring specifically, GPSs have been used for dynamic displacement measurements for long-span bridges [69] whereas the InSAR has been used to monitor bridge movements to ascertain structural behaviours and deformations (e.g., thermal expansion) [70][71] and bridge pier settlements [72]. Thanks to their capacity to measure displacements and deformations, the technologies might be promising applications in the context of early warning systems for scour failure [73]. However, satellites do not provide continuous measurements of deflections, and their spatial resolution is quite low. Moreover, the accuracy of GPS and satellites (of the order of millimetres) may not be sufficient to provide sufficient warning of scour occurrence at the bridge foundations. In fact, as shown in Tubaldi et al. [63] and Scozzese et al. [66] for the case of masonry bridges with shallow foundations, pier displacements and rotations due to scour are very low until a very critical condition is attained, after which they increase very rapidly.

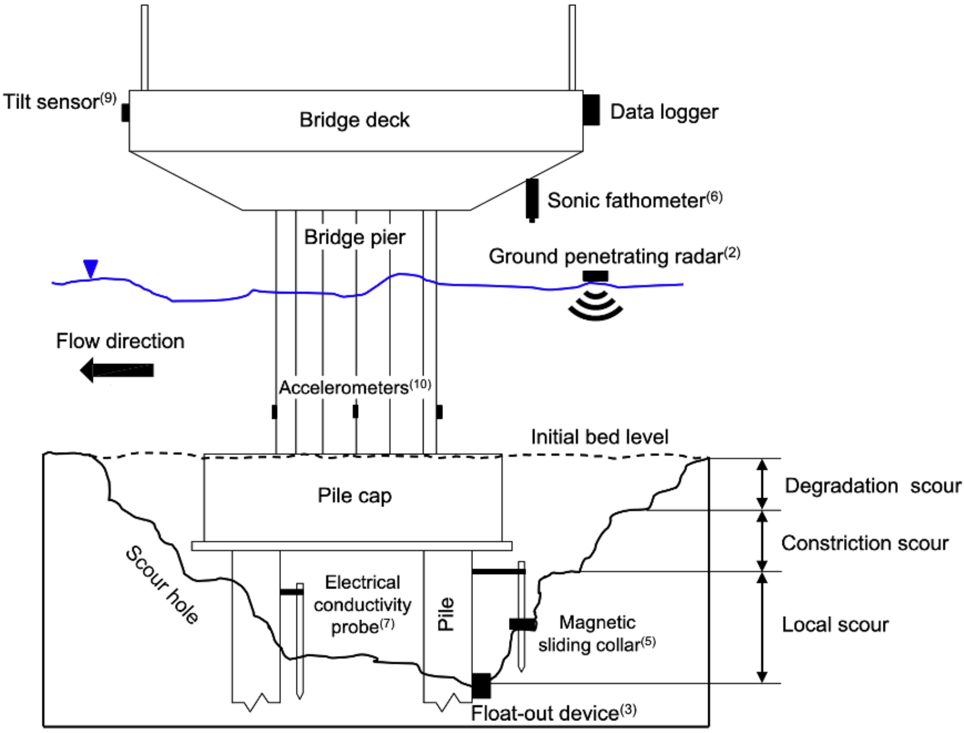


*Figure 11. Direct and indirect monitoring techniques for bridge scour measurements.*

## 3.3 Scour devices available on the market

This section provides information on some of the devices available on the market and/or already applied for scour detection. It is noteworthy that several of the techniques described in the previous sections were developed only for academic research purpose, have not been commercialised, are no more available on the market or the authors of the report could not find information about them. Among these, we can list:

- Single-use devices such as the float-out device.
- Fiber-Bragg grating system. It is a simple device because it consists of a rod equipped with one or more fiber optic sensors; however, no one has never developed a commercialised version.
- Sounding or driven rod systems such as the Scubamouse, an early sliding collar device originally developed in New Zealand, or the BRISCO$^{TM}$ Monitor, a sounding-rod instrument developed by Cayuga Industries (New York). Only few information about

the devices is available in the literature but no commercial version has been found surfing the web.

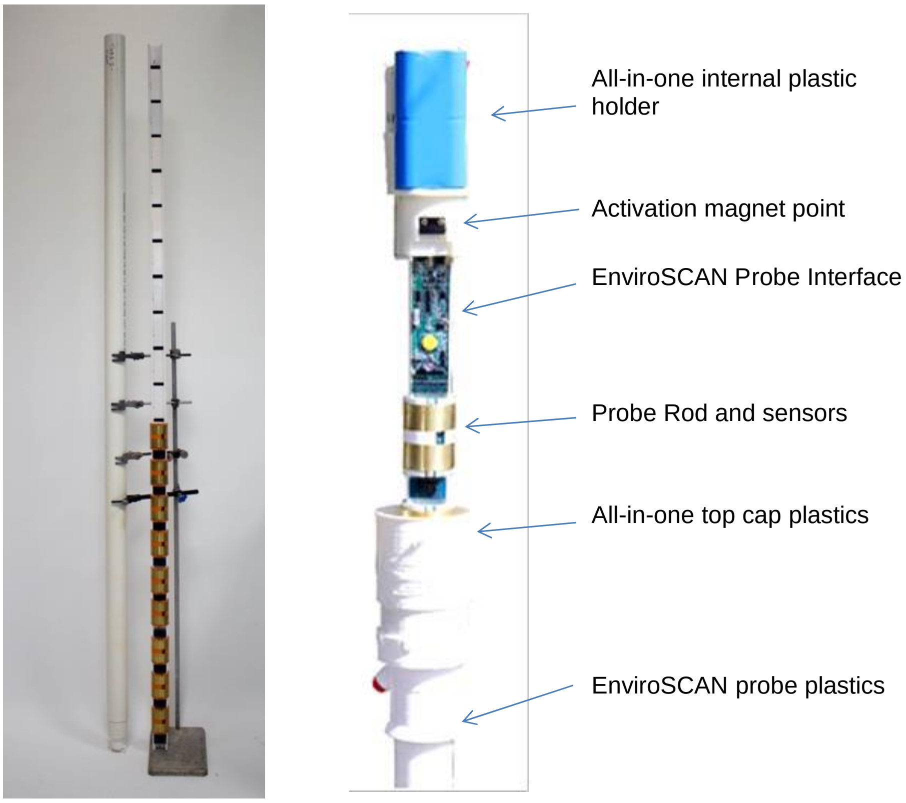
- Electrical conductivity devices are another example of instrument developed and tested for measuring scour at bridge pier only in the laboratory.

### 3.3.1 *Dielectric probes*

<u>EnviroSCAN from Sentek Technologies, Australia (supplied by Soil Moisture Sense in the UK)</u>

EnviroSCAN probe (Figure 12a), developed by Sentek sensor technologies [74] and provided by Soil Moisture Sense in the UK, is an example of dielectric probes that consists of a plastic rod equipped with capacitive sensors, representing one of the techniques available for measuring electromagnetic properties of the soil.

Figure 12b shows the components of the scour probe, which includes a battery, an electronic board (which is the EnviroSCAN Probe Interface), a GPRS modem, and the electromagnetic sensors. The probe has an extended access tube made of plastic which protects the components of the probe (as shown in Figure 12a) from water damage and debris when it is installed in wet environments for monitoring purposes. Table 2 reports some of the specifications of the EnviroSCAN probe from Sentek sensor technologies website.



(a) (b)

*Figure 12. (a) The EnviroSCAN probe; (b) Probe's components [75].*

The probe consists of a plastic rod equipped with multiple sensors, installed every 10 cm along the rod height. Therefore, the monitoring system has a resolution of 10 cm. The standard version is 50-cm long and is equipped with maximum 5 sensors, but the seller also offers bespoke versions of the probe with a customisable length of the plastic rod. However, the EnviroSCAN probe is supplied with a maximum of 16 sensors, regardless the length of the rod, because its mainboard has 16 channels. Therefore, being the sensors removable, their arrangement is customisable since the plastic rod has several slots (at 10 cm to each other) where to insert a sensor. This feature makes the probe very versatile because different configurations can be achieved, such as a probe with 1.60-meter-long monitoring part with 10-cm resolution (i.e., 16 sensors installed without empty slots among them) or with a 3.20-meter-long monitoring part with 20-cm resolution (i.e., an empty slot after each sensor). The more extended is the monitoring part, the lower is the resolution of the system.

Considering the smallest resolution of the system (i.e., 10 cm), the precision of the scour measurement provided by the monitoring system can be found by expressing it as a uniform distribution centred in zero and spanning between -5cm and +5cm. The standard deviation $\sigma_D$ (i.e., representing the precision of the scour measurement) of this distribution of probability is equal to:

$$\square\sigma_D = \frac{1}{\sqrt{12}}\left(b-a\right) = \frac{10}{\sqrt{12}} = 2.88\,\text{cm}, \tag{1}$$

where *a* and *b* are the bounds of the uniform distribution.

*Table 2. Specification of the EnviroSCAN probe*

| | |
|---|---|
| **Maximum sensors per standard probe** | 16 |
| **Current drain** | |
| **Sampling** | 100 mA |
| **Standby** | 66 mA |
| **Sleep mode** | 250 µA |
| **Temperature range** | –20 to 75 °C |
| **Temperature effect** | ±3% 5˚C to 35˚C |
| **Sphere of influence** | 99% of the reading is taken within a 14 cm radius from the outside of the access tube |
| **Sensor diameter** | 50.5 mm |
| **Access tube diameter** | 56.5 mm |
| **Probe length (standard version)** | 50 cm (20 inches) |

### *3.3.2 Time domain reflectometry system*

TDR200 from Campbell Scientific (UK)

Campbell Scientific, a designer and manufacturer of sensors and data acquisition systems with branches spread worldwide (the headquarter is in the Utah State, USA), commercialises the TDR200 Time-Domain Reflectometer (Figure 13). The TDR200 is a pulse generator, sampler and analog-to-digital converter device and, in turn, is the core of the TDR system. As mentioned above, TDR systems are able to determine soil properties such as the volumetric water content, bulk electrical conductivity or even more specific electromagnetic measurement (e.g., soil permittivity). The TDR200 generates an electromagnetic pulse that is sent to the TDR probes (Figure 14) for soil properties measurements. A complete TDR200-based system includes the TDR200, SDM8X50 multiplexers, data logger, power supply, enclosures, and probes. Table 3 reports some of the specifications of the TDR200 Time-Domain Reflectometer from Campbell Scientific website.

*Table 3. Specification of the TDR200*

| | | |
|---|---|---|
| **Power supply** | Unregulated 12 VDC (9.6 to 16 VDC), 150 mA maximum, USB powered (5 VDC) | |
| **Current drain** | | |
| **During measurement** | 120 mA | |
| **Sleep mode** | 1 mA | |
| **Temperature range** | –40 to 85 °C | |
| **Waveform sampling** | 20 to 10112 waveform values over chosen length | |
| | **Distance** | **Time (one-way travel)** |
| **Range** | 0 to 3800 m | 0 to 27.75 μs |
| **Resolution** | 1.35 mm | < 4.4 ps |

*Figure 13. TDR200 Time-Domain Reflectometer [76]*

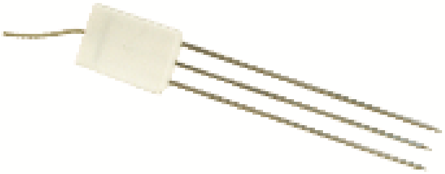


*Figure 14. An example of soil TDR probe* [76]

The TDR systems are generally used to measure properties of soil and the detection of scour is only a consequence of this measure. Therefore, datasheets found on the sellers' website only provide metrology parameters (e.g., range, resolution or precision) related to the measured quantity, such as distance or time as depicted above. However, some of the contributions in the literature that study the feasibility of TDR technology in the detection of scour depth suggest that a precision in the order of 1 cm [46], [77].

SoilVUE10 from Campbell Scientific (UK)

Campbell Scientific also supplies the SoilVUETM10 (Figure 15) that is a soil water content profile sensor based on TDR technology (e.g., Campbell TrueWave$^{\text{TM}}$). The probe consists of a rod with sensors along its length thus allowing to make multiple measurements of soil moisture, electrical conductivity, dielectric permittivity, and temperature. The embedded TDR technology generates an electromagnetic pulse that is applied to the helical wave guides. The two-way travel time of the pulse allows for calculating the dielectric permittivity of the surrounding media. The device comes in two version: a 0.5m option with 6 points of measurement (i.e., 6 sensors), depicted in Figure 15, and a 1m option with 9 points of measurement (i.e., the 3 more points are at 60 cm, 75 cm and 100 cm, respectively).

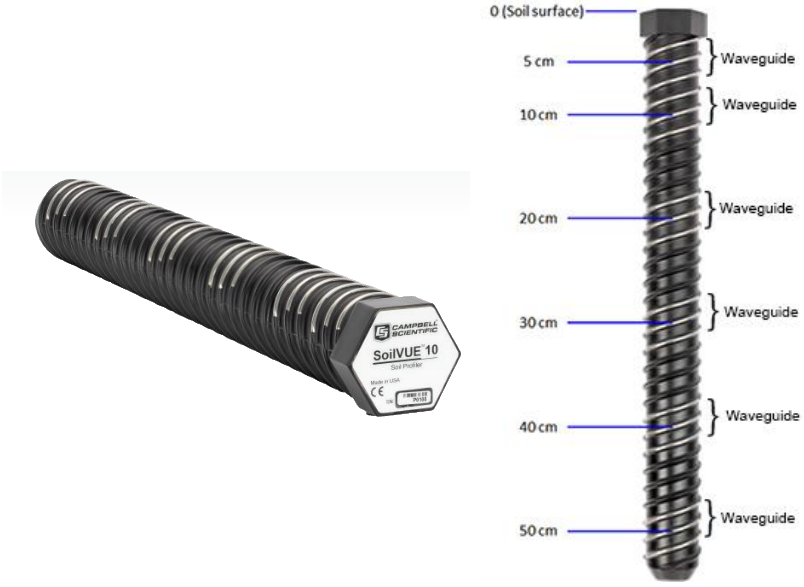


*Figure 15. SoilVUE$^{TM}$ 10 probe [76]*

Table 4 reports some of the specifications of the SoilVUE$^{TM}$ 10 probe from Campbell Scientific website.

*Table 4. Specification of the SoilVUE$^{TM}$ 10 probe*

| | |
|---|---|
| **Power supply** | 12 VDC |
| **Current drain** | |
| **During measurement** | ~64 mA |
| **Sleep mode** | ~1.5 mA |
| **Electrical Conductivity** | |
| **Range** | 0 to 10 dS/m |
| **Accuracy** | ±2% (0 to 2.5 dS/m) and ±5% (full range) |
| **Permittivity** | |
| **Range** | 1 to 80 |
| **Accuracy** | ±1 permittivity unit (between 4 and 42 permittivity) |
| **Volumetric water content** | |
| **Accuracy** | ±1.5% typical with most soils |
| **Soil temperature** | |
| **Accuracy** | ± 0.15°C (between -30° and +40°C) |

As with the EnviroSCAN probe, the sensors in the SoilVUE$^{TM}$ 10 probe are placed every 10 cm or more (except the first one). Therefore, the precision of the scour measurement can be assumed equal to 2.88 cm.

### 3.3.3 *Sound wave devices*

3D Profiling Sonar Model 2001-SMS from Marine Electronics

The 3D Profiling Sonar Model 2001-SMS, supplied by Marine Electronics, is designed to gather high resolution bathymetry data by operating long term on fixed structures. The sonar unit is light and portable (the diameter is only 90 mm) and it can be installed on a bridge pier, dam wall or offshore windfarm (Figure 16a). Despite its small dimension, the 3D profiling sonar is extremely resistant since it can be manufactured in Stainless Steel or Titanium or PEEK / Hard Anodised Aluminium.

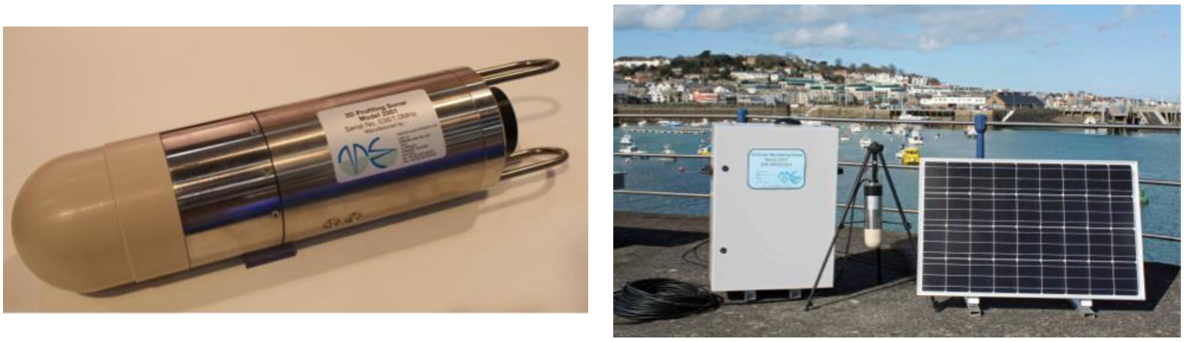

(a) (b)

*Figure 16. (a) 90mm sonar unit; (b) sonar head, 4G / battery control Box, Solar panel [78].*

The system provides the bathymetry by determining a time in µsec from the start of the transmit pulse to the rising edge of the sound echo. In order to provide the most precise measure, it uses data from embedded conductivity, temperature and pressure transducers to calculate an accurate value for the velocity of sound in the water at the sonar head. It also includes tilt sensors providing attitude correction so that the 3D surface data is orientated correctly allowing features such as scour to be precisely quantified.

Marine Electronics declare a range resolution <1 mm in the specification for their 3D Profiling Sonar Model 2001-SMS.

RiverSurveyor M9 from SonTek

The RiverSurveyor M9 is an Acoustic Doppler Current Profiler (ACDP) which relies on a total of 9 transducers shown in Figure 17, of which 5 are active at any point in time. The central 0.5 MHz transducer stays always active because it pings a vertical acoustic beam, whereas the device automatically actives one of two sets of diagonal sounding beams. The 3 MHz set of beams (i.e., the smaller) is operated for sounding depths up to around 5 m, whilst the larger 1 MHz set of beams is used for depths greater than this. These sets of beams are tilted 25-degrees to the vertical, in a Janus formation.

The ACDP outputs data to the native RiverSurveyor Live data-logging software, developed by SonTek as well, which allows the boat path to be traced in real time and the latest depth sounding to be read. The coordinates of the boat are also recorded, and the RiverSurveyor Live software also corrects for pitch and roll.

*Figure 17. RiverSurveyor M9 [79].*

This device can be deployed in dynamic settings as well as in the common fixed installations. For instance, The University of Southampton has recently fitted a SonTek RiverSurveyor M9 ADCP to the “ARC-boat” (Figure 18a), an unmanned, remote-controlled boat from manufacturer HR Wallingford [80]. The ARC-boat relies on sonar to record the bathymetry (depth) of riverbeds at high resolution, and, additionally, on a GPS receiver (Leica GS14 RTK-GPS) to obtain accurate global coordinates for all data points recorded by the ADCP’s sonar (Figure 18b). The boat has been tested in the field to study its potential in the assessment of bridge pier scour [81].

(a) (b)

*Figure 18. (a) ARC-boat [80]; (b) The ARC-boat fitted with SonTek M9 ADCP and Leica GS14 RTK-GPS [81].*

The study found that, when surveying natural riverbeds without large discontinuities, the accuracy of the data collected dynamically by M9 ADCP is less than the 1% declared in

SonTek's product brochure (the uncertainty is 15%). When surveying large bed discontinuities, the errors become even bigger.

### 3.3.4 Inclinometers

HCA528T - High Accuracy Current Output Dual-axis Inclinometer from StrainSense

The HCA528T, shown in Figure 19, is a high accuracy dual-axis inclinometer using the standard industry electronic interface 4-20mA and can be used in long-distance transmissions of up to 2000 metres. The product uses the latest MEMS technology, has precise temperature and non-linearity error correction, and highly accurate up to 0.003°. Table 5 reports some of the specifications of the HCA528T inclinometer from StrainSense website.

*Figure 19. High Accuracy Current Output Dual-axis Inclinometer [82]*

*Table 5. Specification of the HCA528T inclinometer*

| **Parameters** | **Conditions** | **HCA528T-10** | **HCA528T-30** | **Unit** |
|---|---|---|---|---|
| Measuring range | | ±10 | ±30 | ° |
| Measuring axis | | X, Y axis | X, Y axis | |
| Zero output | 0°Output | 12 | 12 | mA |
| Resolution | | 0.001 | 0.001 | ° |
| Absolute accuracy | | 0.005 | 0.01 | ° |
| Long term stability | | 0.01 | 0.02 | |
| Zero temperature coefficient | -40~85° | ±0.002 | ±0.002 | °/C |
| Sensitivity temperature coefficient | -40~85° | <50 | <50 | ppm |

MEMS Analogue Submersible Tilt Meter from GeoSense

Geosense® Submersible Tilt Meters are designed to measure tilt on submerged structures either on a vertical, inclined or horizontal surface (Figure 20). They consist of highly accurate MEMS sensors mounted in robust watertight stainless-steel housing which can be attached to the structure by bolting, bonding or welding. Each unit is individually calibrated to provide the ultimate in system accuracy and repeatability.

*Figure 20. MEMS Analogue Submersible Tilt Meter [83]*

Table 6 reports some of the specifications of the MEMS Analogue Submersible Tilt Meter from GeoSense website.

*Table 6. Specification of the MEMS Analogue Submersible Tilt Meter*

| **Models** | **SUTM-M 15-1-420** | **SUTM-M 15-2-420** |
|---|---|---|
| Range | ±15° | ±15° |
| Axis | Uniaxial | Biaxial |
| Signal Output | 4-20 mA | 4-20 mA |
| Accuracy | ±0.005°<br>±18 arc sec<br>±0.1mm/m<br>±0.017% FS | ±0.005°<br>±18 arc sec<br>±0.1mm/m<br>±0.017% FS |
| Resolution | 0.0019°<br>7 arc sec<br>0.033 mm/m<br>0.007% FS | 0.0019°<br>7 arc sec<br>0.033 mm/m<br>0.007% FS |
| Repeatability | ±0.002°<br>±7.2 arc sec<br>±0.03 mm/m<br>±0.007% FS | ±0.002°<br>±7.2 arc sec<br>±0.034 mm/m<br>±0.007% FS |
| Operating Temperature | -40 to +85°C | -40 to +85°C |

### *3.3.5 Accelerometers*

M-A550 QMEMS Accelerometer from Epson

The M-A550 is a small size device that is able to measure 3-axis acceleration with high accuracy and high stability and low power consumption. This sensor unit, based on Quartz technology (QMEMS), enables wide dynamic range acceleration and vibration sensing. The M-A550 comes in two variants: one using RS-422 for digital communication and the other using CANBus. The main difference is that the RS-422 variant allows recording time-synchronised data from multiple devices, with each sensor connected to the data logger via a separate cable. Whilst the CANBus variant only allows for collection of data from one sensor at a time in sequence (i.e., not time-synchronised). Along with acceleration measurements, tilt angle and tilt angular velocity are available as output measurement options. The accelerometer is packaged in a waterproof and dust-proof metallic case making it suitable for use in field and bridge applications. Table 7 reports some of the specifications of the M-A550 QMEMS Accelerometer from Epson website.

*Figure 21. M-A550 QMEMS Accelerometer [84]*

*Table 7. Specification of the M-A550 QMEMS Accelerometer*

| **Models** | **M-A550AC2x** | **M-A550AR2x** |
|---|---|---|
| High-resolution | 0.06 μG | 0.06 μG |
| Frequency range | 50 Hz | 100 Hz |
| Detection Range | ±5 G | ±5 G |
| Accuracy Range | ±1 G | ±1 G |
| Protocol | CANopen | RS-422 |
| Voltage supply | 9 to 30 V | 9 to 30 V |
| Power consumption | 24 mA typ (Vin=12 V) | 15 mA typ (Vin=12 V) |
| Operating Temperature | -20 to +70°C | -20 to +70°C |
| Waterproof, Dust-proof | IP67 | IP67 |

### *3.3.6 GPS/GNSS*

Displayce from Yet it moves!

DISPLAYCE is a solution for the automatic and continuous monitoring and early warning of surface deformations of ground, buildings and critical infrastructures. The architectural elements of DISPLAYCE consist of a network of GNSS (Global Navigation Satellite System) L1 receivers and a wireless data transmission system from one node to another. The GNSS L1 receivers are installed in the area subject to deformation and they allow continuously measuring the movements to which they are subjected. The DISPLAYCE sensors are based on GNSS U-BLOX NEO M8T modules able to acquire GPS and Galileo observables. Each node is able to save data on an internal memory.

*Figure 22. DISPLAYCE stations mounted on the ground in areas subject to landslide. In the photos the receiver and the battery housed in a cabinet with IP67 protection anchored to a pole through suitable fixing brackets [85].*

Table 8 reports the root mean square error of the estimates of the deflections along the three orthogonal directions as a function of the session length for DISPLAYCE. It can be observed that the maximum error in the horizontal direction is of the order of 1mm, for a session length of 12h or higher.

*Table 8. Root mean square (RMS) error of deflections for different session lengths*

| **Session length [h]** | **RMS U [mm]** | **RMS E [mm]** | **RMS N [mm]** |
|---|---|---|---|
| 24 | 3.2 | 0.7 | 0.7 |
| 12 | 3.8 | 0.7 | 1.0 |
| 6 | 3.9 | 1.0 | 1.2 |
| 3 | 5.0 | 1.5 | 1.9 |
| 1 | 7.5 | 2.5 | 3.5 |

Although a network of GNSS receivers has not used to monitoring scour at bridges yet, the values reported in Table 8 suggest that they may be considered in alternative to tiltmeters to detect bridge movements, even though they are characterized by a lower accuracy/resolution.

### 3.4 Comparison of scour monitoring methods

To be effective, bridge scour monitoring should provide continuous real-time data with a good resolution, especially during a peak flood event. Detecting the presence of redeposited soil can also deliver beneficial information about the foundation bearing capacity. Table 9 reviews the scour monitoring techniques based on the features that define their reliability and field of application. In particular, the table outlines the ability of the devices to provide continuous monitoring, their usefulness in identifying and monitoring the scour depth development during high flows, as well as their capability to track the refill (deposition) process. Furthermore, the scour measurement resolution of each sensor is highlighted, where "High" defines a resolution better than 10 cm whereas “Low” means “order of tens of cm”. This property is not directly quantifiable for the indirect scour monitoring devices because they only detect change in the structural response (e.g., pier inclination or changes in bridge's modal properties due to a certain level of scour), and typically recognised the presence of scour when it is so critical to affect the structural stability. The last column provides an estimation of costs for the deployment of the monitoring technique (i.e., including installation costs), where "High" indicates costs greater than £25,000, "Medium" defines the range £5,000–10,000 while "Low" means costs lower than £3,000.

*Table 9. Comparison of the advantages and disadvantages of scour monitoring techniques.*

| | Continuous monitoring | Measurement during extreme events | Scour depth resolution | Detection of refill | Costs |
|---|---|---|---|---|---|
| **Direct scour measurement devices** | | | | | |
| (1)Pulse or (2)radar devices | ✓ | ✓ | High | | Medium |
| (3)Single-use or float-out devices | | | Low | | Low/Medium |
| (4)Fiber–Bragg grating systems | ✓ | ✓ | Low | | High |
| (5)Sounding or driven rod systems | ✓ | ✓ | Medium | | Medium |
| (6)Sound wave devices | ✓ | | High | ✓ | High |
| (7)Electrical conductivity devices | ✓ | | High | ✓ | Medium |
| (8)Dielectric probes | ✓ | ✓ | High | ✓ | Medium |
| **Indirect scour measurement devices** | | | | | |
| (9)Tilt sensors | ✓ | ✓ | | | Low |
| (10)Accelerometers | ✓ | ✓ | | | Low |
| (11)GPS | ✓ | ✓ | | | Medium |
| (12)Satellite | ✓ | ✓ | | | Low |

In summary, few technologies are able to detect the depth of scour with a resolution better than 10 cm and at the same time are able to separate the redeposited soil and saturated soil. Among these, the dielectric probes are the only ones which allow for recording during an extreme event and thus can be used as an early warning system. The main drawback of these probes is that they provide only a localized measure of the scour depth, where they are installed. Thus, the optimal scour monitoring strategy should involve a combination of sensors. For example, sound wave devices could be used during bridge inspections or at more frequent intervals to evaluate the bathymetry of the riverbed, and scour probes could be used to achieve continuous measurements at critical locations. The information gained from sound wave devices could be extended to other locations using the methodology developed in Maroni et al. [86].

### 3.5 Bridge scour monitoring installations

Despite the development of the sensors mentioned above, practical applications aiming to monitor bridge scour in real-time are very limited because of accessibility issues under flood events, damage, their cost and their inherent imprecision. However, there are few examples of scour monitoring systems installation, especially for bridges that experienced significant scour in the past and were close to collapse. The following paragraphs review notable scour monitoring installations in the UK, a country whose bridges have been affected significantly by scour in recent years and where the use of scour monitoring sensors is increasing fast.

Cumbria, a non-metropolitan county in North West England, has been particularly battered by storms and flood events in the last decade. Following record daily rainfall for the UK in November 2009, 20 road bridges were damaged or destroyed, including the Northside bridge, which led to one death [16]. In December 2015, Cumbria was again hit by heavy flooding as a result of Storm Desmond (i.e., it broke the United Kingdom's 24-hour rainfall record, 341.4 mm of rain falling at Honister Pass in Cumbria [87], which affected more than 130 bridges. Pooley bridge was washed away, and one person died [17].

*Figure 23. Bridgecat technology for bridge inspection [89].*

In order to respond to the region of Cumbria proneness to flashing flood event and the consequences that these have on bridges, the Cumbria County Council, in partnership with Department of Transport and Gaist Solutions, developed the 'BridgeCat' technology to check flood-hit bridges for damage more quickly [88]. The system allows for monitoring and inspecting hard-to-reach areas of the bridge, including the underwater parts of piers without involving divers. The solution consists of vehicle featuring a hydraulic arm equipped with a mechanical scanning sonar, a high-resolution camera able to provide imagery of foundations beneath the water, and a digital altimeter measuring height off the riverbed (Figure 23).

The winter storms of 2015 resulted in serious damage/destruction to bridges across Scotland as well. This included the Lamington viaduct, which resulted in the closure of the West Coast mainline between Glasgow and London for nearly two months due to a scour failure at one of its piers [18]. Following the incident, scour countermeasures have been undertaken to increase the resistance of the bed to scour (i.e., rock armouring has been placed below the riverbed) and monitoring systems have been installed at the viaduct.

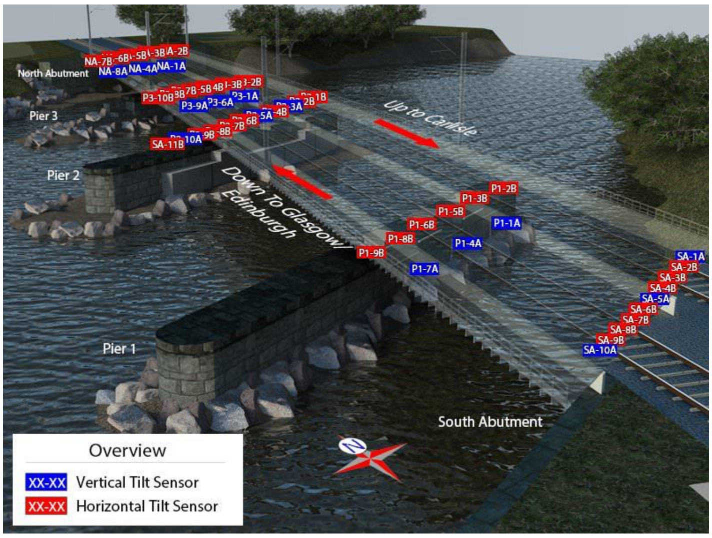


*Figure 24. Layout of the SHM system installed at the Lamington viaduct (courtesy of Network Rail).*

The first system measures the water level at the upstream region of the Lamington viaduct over time. The second is an SHM system consisting of a network of tilt sensors for detecting structure movement caused by scour. The monitoring system includes 48 inclinometers (i.e., 33 of them measure the inclination along the horizontal direction and 15 along the vertical direction) installed throughout the bridge covering both abutments and the three piers. A schematic layout of the SHM system is depicted in Figure 24. The instrumentation is able to measure very small movements, has a battery life of several years and uses wireless technology.

An additional scour monitoring system involving indirect measurement of scour has been presented in Kariyawasam et al. [90], where a vibration-based scour detection system was deployed for five months at the Baildon Bridge in Bradford, UK. The monitoring system consisted of ten 3-axis accelerometers installed on the two piers and the superstructure. The BridgeCat mobile inspection system described above was used to scan the riverbed before and after the installation of the sensors and it detected the presence of scour holes. Analysing data measured on-site through the frequency domain decomposition method, the authors showed the potential of alternative structural response parameter (i.e., spectral density and mode shape) as scour detection parameters, rather than using natural frequency alone.

An example of deployment of direct scour measurement devices is the pilot monitoring system installed at the A76 200 bridge in New Cumnock (i.e., 40 miles southern than Glasgow). The sensing system consists of two 4-meters-long dielectric probes that are equipped with electromagnetic sensors, designed to detect changes in the medium permittivity surrounding bridge foundations (Figure 25). The sensors buried in the riverbed can track the evolution of the scour depth, whereas the others placed within or above the running water of River Nith can be used to measure the water level, being able to discriminate the permittivity values between air and water. The electromagnetic sensors can also distinguish between saturated soil and deposited soil, which is useful to assess whether the scour hole has been refilled after the flood peak has receded.

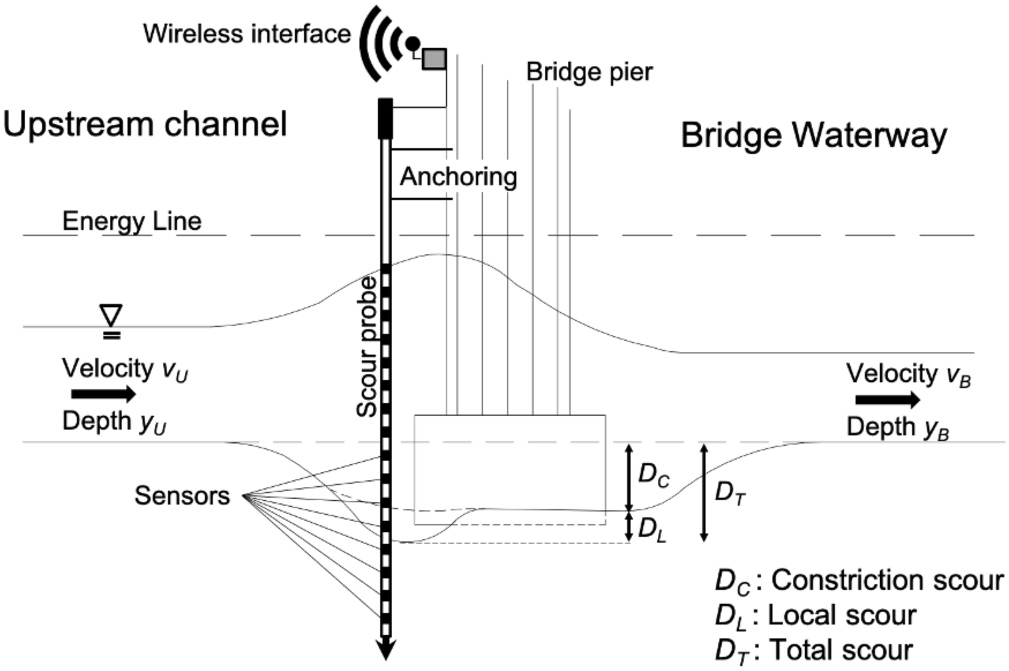


*Figure 25. Layout of the pilot scour monitoring system installed at the A76 200 bridge [62].*

One probe is installed on the upstream face of a pier of the A76 200 bridge to detect total scour (Figure 26a), whereas the other is installed in the centre of the river to detect degradation and constriction scour, and is connected to a pedestrian bridge, which is upstream to the bridge (Figure 26b).


(a) (b)

*Figure 26. (a) Dielectric probe for total scour at the pier; (b) dielectric probe for degradation and constriction scour [62].*

After a peak flood event, the probe installed in the middle of the channel measured 30 cm of scour, and the recorded data were consistent with the survey of the riverbed in vicinity of the probe carried out using a telescopic pole during a bridge inspection. This has proved the potential of the technology in providing continuous scour monitoring, even during extreme flood events, thus avoiding the deployment of divers for underwater examination.

# 4 Conclusions

This report presented a review of the bridge scour risk for road and railway bridges, current procedures for managing this risk implemented by transport agencies, and the various scour monitoring techniques available in the literature or deployed in bridges across UK and in particular in Scotland. The key findings from the review are the following:

- Scour, the erosion of sediment around bridge foundations due to flowing water, is recognised as one of the most common causes of bridge failures worldwide in the last century. The problem of scour is also exacerbated by climate change.
- Transport agencies' scour risk management relies on:
    (i) visual inspections at regular intervals to identify the bridges at risk of scour;
    (ii) bridge scour risk classifications through a scour vulnerability index;
    (iii) "visual" decision schemes for bridge closure under extreme events based on water level markers placed on the bridge upstream surface.

  Visual inspections are in general expensive and provide unreliable estimates of scour while triggering bridge closures according to flood level markers does not allow the direct control of scour risk under floods. Furthermore, the many uncertainties affecting the problem might lead to an overestimation of scour depths that might cause a misclassification of the bridge scour risk and result in unnecessary bridge closure. In essence, visual inspections and water levels are rough indicators of bridge scour risk.
- A wide range of techniques have been developed in the last decades for monitoring bridge scour; however, on-site campaigns aiming to continuously monitor real-time scour are still scarce due to accessibility issues under flood events, their cost, and their inherent imprecision.
- To be effective, bridge scour monitoring should provide continuous real-time data with a resolution better than 10 cm (especially during a peak flood event) and track the presence of redeposited soil. Among the range of scour detection techniques, the dielectric probes are the only ones presenting these three features altogether. However, they provide only a localised measure of the scour depth. Thus, the optimal scour monitoring strategy should involve a combination of sensors (e.g., sound wave devices and scour probes).

In conclusion, the analysis of the current literature has highlighted that scour risk management requires to be improved. Thus, there is a need of a system that, during and after an extreme weather event, is capable not only of monitoring the evolution of scour at bridge foundations, but also of providing transport operators with clear and precise information about scour and bridge state to support risk mitigation strategies and decision-making processes under flood events. For these reasons, quantifying the benefits of the different scour structural health monitoring techniques is essential for identifying optimal scour sensing strategies. To do so, a rational methodology will be proposed to quantify the effectiveness of the monitoring techniques identified in this report.

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