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A Review of Bridge Scour Monitoring Techniques

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Abstract

The high profile failure of the Malahide Viaduct, in Dublin, Ireland which is a part of the EU TEN-T network of critical transport links was caused by foundation scour. In a study of five hundred bridge failures that occurred in the United States between 1989 and 2000, flooding and scour were the cause of 53% of the recorded failures (Wardhana and Hadipriono 2003). Scour is a common soil-structure interaction problem. In light of current changes in climate, increased frequency of flooding, coupled with the increased magnitude of these flood events, will lead to a higher risk of bridge failure occurring. Monitoring scour is of paramount importance to ensure the continued safe operation of the aging bridge asset network. Most monitoring regimes are based on using expensive underwater instrumentation that can often be subject to damage during times of flooding, when scour risk is at its highest. This paper presents a critical review of existing scour monitoring equipment and methodologies with a particular focus on those that use the dynamic response of the structure to indicate the existence and severity of the scour phenomenon affecting the structure. A sensitivity study on a recently developed monitoring method is also undertaken.

Keywords: Scour; Dynamics; Monitoring; Instruments; Bridge Failure

1.0 Introduction to Scour

Scour of foundations is the number one cause of bridge collapse in the United States (Melville and Coleman 2000; Briaud et al. 2001 and 2005). During the last 30 years 600 bridges have failed due to scour problems (Shirole and Holt 1991; Briaud et al. 1999) causing major operating disruption and financial losses (De Falco and Mele 2002). In the US the average cost for flood damage repair of highways is estimated at $50 million per year (Lagasse et al. 1995). During a single flood event in the upper Mississippi and lower Missouri river basins which occurred in 1993, at least 22 of the 28 bridges that failed were due to scour. The associated repair costs were more than $8,000,000 (Kamojjala et al. 1994).

Scour can be defined as the excavation and removal of material from the bed and banks of streams as a result of the erosive action of flowing water (Hamill 1999). Scour occurs in three main forms; namely General scour, Contraction scour and Local scour. General scour occurs naturally in river channels and includes the aggradation and degradation of the river bed that may occur as a result of changes in the hydraulic parameters governing the channel form such as changes in the flow rate or changes in the quantity of sediment in the channel (Forde et al. 1999). It relates to the evolution of the waterway and is associated with the progression of scour and filling, in the absence of obstacles (Federico et al. 2003). Contraction scour occurs as a result of the reduction in the channel's cross-sectional area that arises due to the construction of structures such as bridge piers and abutments. It manifests itself as an increase in flow velocity and resulting bed shear stresses, caused by a reduction in the channel's cross-sectional area at the location of a bridge. The increased shear stresses can overcome the channel bed's threshold shear stress and mobilize the sediments (Briaud et al. 1999). Finally, Local scour occurs around individual bridge piers and abutments. Downward flow is induced at the upstream end of bridge piers leading to very localized erosion in the direct vicinity of the structure (Hamill 1999), See Figure 1. Horseshoe vortices develop due to the separation of the flow at the edge of the scour hole upstream of the pier and result in pushing the down-flow inside the scour hole closer to the pier. Horseshoe vortices are a result of initial scouring and not the primary cause of scour. Furthermore, separation of the flow at the sides of the pier result in wake vortices (Heidarpour

et al. 2010). Local scour depends on the balance between streambed erosion and sediment deposition. Clear-water scour is the term given to describe the situation when no sediments are delivered by the river whereas live-bed scour describes the situation where an interaction exists between sediment transport and the scour process (Brandimarte et al. 2006). The presence of live-bed conditions leads to smaller ultimate scour depths than in clear-water conditions.

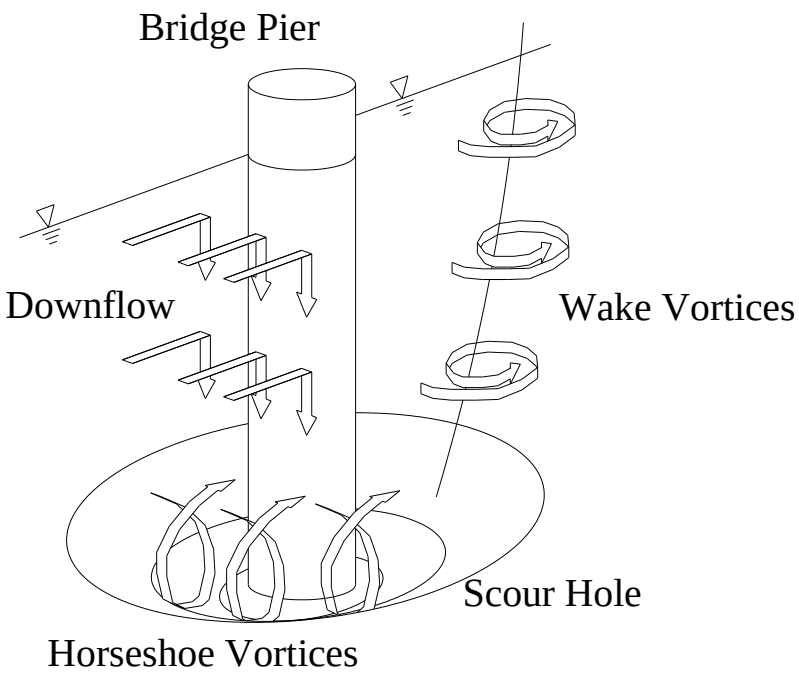

Figure 1 Schematic of the Scour Process

Scour poses obvious problems to the stability of bridge structures. Current practice dictates that the depth of scour is determined by the addition of the individual scour depths caused by the aforementioned mechanisms (general, contraction and local scour) (Briaud et al. 2005). This is the most critical design case. The scour hole generated has the effect of reducing the stiffness of foundation systems and can cause bridge piers to fail without warning. Notable bridge failures due to scour in Europe, include the failure of the Sava bridge in Zagreb and the collapse of the Malahide viaduct in Dublin, (See Figure 2).

(a)

(b)

Figure 2 Failure of bridges due to scour, (a) Sava Bridge, Zagreb and (b) Malahide Viaduct, Dublin. Both bridges failed in 2009

Scour can be combatted in a number of ways. At the bridge design stage, it is possible to allow for scour mitigation by providing both hydraulic and structural countermeasures (NCHRP 2009).

Hydraulic countermeasures involve the prevention of rapid flow expansion or contraction caused by sudden induced changes in flow direction that would occur due to blunt pier faces obstructing the flow. These sudden flow changes can lead to the creation of the vortices responsible for the occurrence of scour. They can be prevented by maintaining larger bridge openings at the design stage and also by streamlining pier geometries (May et al. 2002). It is imperative to maintain clear openings by removing debris such as fallen trees and other objects that can often become lodged in bridge openings, obstructing the flow. However, it is noteworthy that maintaining large bridge openings and streamlined pier faces can often be a futile exercise as natural changes in channel deposition and erosion upstream of a bridge can often change the angle of flow relative to the alignment of a bridge and cause these hydraulic problems to occur. Structural countermeasures can be implemented at the design stage by ensuring spread footings are located below maximum design scour depths, or as remediation by adding rock-armour and rip-rap to the base of piers and abutments. This countermeasure is limited by uncertainties in predicted design scour depth obtained using formulas such as the Colorado State University (CSU) formula (Bolduc et al. 2008) formulated in the Hydraulic Engineering Circular (HEC-18) design code (Arneson et al. 2012). It can also only be implemented on new structures, since many existing structures have unknown foundation depths. More information on the uncertainties in bridge scour depth estimation is available in (Johnson and Dock 1998).

A more effective and economically viable method of combatting scour is to monitor its evolution over time and implement remediation works as they are required (Briaud et al. 2011). The most widespread monitoring scheme in place as part of any national bridge asset management framework is to undertake visual inspections. These types of inspections are commonplace in engineering and are used to detect structural anomalies such as cracking and other damage (Sohn et al. 2004). With regard to scour, visual inspections involve the use of divers to inspect the condition of foundation elements and to measure the depth of scour using basic instrumentation (Avent and Alawady 2005). Two particular disadvantages associated with this inspection method include the fact that inspections cannot be carried out during times of flooding, when the risk of scour is highest, and the maximum depth of scour may not be recorded as scour holes tend to fill in as flood waters subside (Lin et al. 2010; Foti

and Sabia 2011). The fact that scour holes tend to refill can be dangerous and misleading as the true extent of the scour problem may be missed in the inspection. A more effective alternative is to use fixed or discrete scour depth recording instrumentation. A number of instruments have been developed that can monitor the depth of scour around bridge piers and abutments. Some of these sensing instruments are discussed in section 2.

2.0 Scour Monitoring using Depth-Measuring Instrumentation

Given the importance of the problem of scour, a range of instrumentation has been developed to monitor scour-hole development. These instruments can be broadly categorized as follows: Single-Use Devices, Pulse or Radar Devices, Buried or Driven rod systems, Sound-Wave Devices, Fibre-Bragg Grating Devices and Electrical Conductivity Devices. These are detailed separately in the following sub-sections.

2.1 Single-Use Devices

Single-use devices consist of float-out devices and tethered buried switches (NCHRP 2009; Briaud et al. 2011) that can detect scour at their location of installation. These devices are installed vertically in the riverbed, near a pier or abutment of scour interest, and work on the principle that when the depth of scour reaches the installation depth of the device, they simply float out of the soil. When the device changes from a vertical orientation to a horizontal one (upon floating out) an electrical switch triggers, which can indicate to a data acquisition system that the device is no longer in the ground and that the scour depth has reached its elevation. Tethered Buried Switches typically have three status indicators; “in position”, “floated out” and “not operational” (Briaud et al. 2011). Although these are very simple mechanical devices, they have a number of distinct disadvantages. They require expensive installation, have only a single use before they must be re-installed and can only indicate that the scour depth has reached the position of the device. As a result, they give no further information on maximum scour depth reached. Tethered Buried Switches must also be directly hard-wired to a data acquisition system and as such are susceptible to debris damage. Float-out devices have a finite

amount of stored power, which means they have to be replaced eventually as part of normal maintenance procedures. However, Float-out devices and Tethered Buried Switches are otherwise reliable pieces of equipment, due to their inherent simplicity, and can adequately indicate when the depth of scour has reached their installation depth.

2.2 Pulse or Radar Devices

Pulse or radar devices utilize radar signals or electromagnetic pulses to determine changes in the material properties that occur when a signal is propagated through a changing physical medium (Forde et al. 1999). This typically occurs at a water-sediment interface and thus this type of device can detect a depth of scour at a particular location. Time-Domain Reflectometry (TDR) is one method that uses changes in the dielectric permittivity constants between materials to determine a depth of scour at a particular location (Yu 2009). This method was originally developed by electrical engineers who were interested in detecting discontinuities along power and communication lines (Yankielun and Zabilansky 1999). Measuring probes are installed into the soil at a location of scour interest and a fast-rising step impulse is sent down a tube which determines the interface between the water and the soil, and hence the depth of scour. They operate based on the principle that when the propagating wave reaches an area where the dielectric permittivity changes (e.g. the water-sediment interface), a portion of the energy is reflected back to the receiver. They can therefore be used to observe the variation of scour depth with time (Hussein 2012). The method requires long probes to be installed into the riverbed at the location of interest, which can prove expensive and time consuming. The measurement accuracy is affected by varying temperature in the channel, with relative errors of the order of 5% being reported in some studies (Fisher et al. 2013). However, monitoring the channel temperature in addition to the TDR waveform can mitigate this effect.

A second method that uses pulse or radar technology to detect scour is Ground-Penetrating Radar (GPR) (Forde et al. 1999; Anderson et al. 2007). This method uses radar pulses to determine the water-sediment interface and hence the depth of scour. The device works using similar principles to the TDR arrangement described previously but does not require probes to be installed into the

stratum. Instead, a floating GPR transmitter is pulled along the water surface thus obtaining a geophysical profile of the riverbed as it passes. It operates by sending out high frequency electromagnetic waves which are partially reflected as they pass through different media, thus building up a geophysical map of the subterranean lithology (Anderson et al. 2007). A disadvantage of this method is that it requires manual operation and cannot be used during times of heavy-flood flow when scour is often at its highest risk of occurring. Furthermore, it can only give information on the depth of scour present at a certain location at its time of deployment and as a result cannot be used as a continuous monitoring solution. However, the method is easy to implement and can provide very accurate information about the sub-surface ground conditions.

2.3 Fibre-Bragg Grating (FBG)

Fibre-Bragg Grating sensors are a form of Piezo-electric device (Sohn et al. 2004). These types of sensor operate based on the concept of measuring strain along embedded cantilever rods to generate electrical signals, which can indicate the progression of scour along the rod. It has been found that the shift of the Bragg wavelength has a linear relationship to the applied strain in the axial direction (Lin et al. 2006). An embedded rod that becomes partially exposed due to scour will become subject to hydrodynamic forces from the flow of water that induce bending in the exposed rod. This bending allows the strain sensors to detect that the rod is free. If a number of strain gauges are positioned along a rod, the progression of scour may be monitored. These devices perform particularly well at monitoring the change in scour depth with time at their installed location and are relatively cheap to fabricate. The resolution, however, depends on the spacing of the sensor array along the rod and it can also be highly sensitive to vibrations of the support structure used, with vibrations occurring due to flowing water or traffic excitation from the bridge. Some reviews of the efficacy of the approach report that there is little difference between buried and exposed sensors as a result of this phenomenon (May et al. 2002).

2.4 Driven or Buried Rod Devices

Buried or driven rod systems include such systems as the Magnetic Sliding Collar, the "Scubamouse", the Wallingford "Tell-Tail" Device and Mercury Tip Switches. These instruments work on the principle of a manual or automated gravity-based physical probe that rests on the streambed and moves downward as scour develops. The gravity sensor is usually positioned around a buried or driven rod system in the streambed. It must be sufficiently large to prevent penetrating into the streambed while in a static state. A remote sensing element is typically used to detect the change in depth of the gravity sensor. In the case of a Magnetic Sliding Collar (MSC), the location of the collar relative to its original position is determined by the closure of magnetic switches along the structurally rigid rod. As the streambed erodes, the sensor moves along the rod and its magnetic nature causes these switches to close. The data can be manually or automatically read. In the case of automatic reading, flexible cables can be attached to the system, which convey magnetic switch closures back to a data acquisition unit. This device provides a relatively straightforward method to monitor scour depth progression; however there are a number of disadvantages. In the manual readout mode, the sensor requires infrastructure in the form of metal tubing that can be susceptible to damage from debris impacts, particularly during times of heavy flood flow. Scour depths can only be detected in the direct vicinity of the device so a number of devices may be required to capture the true (global) effect of scour. The device uses a gravity sensor and as such, it remains at the lowest depth of scour after each flood event (NCHRP 2009). This means it may have to be reset which can be costly and time-consuming and provides no information on scour hole re-filling.

The "Scubamouse" works in a very similar way to the Magnetic Sliding Collar, except in this case the location of the collar is determined by sliding a radioactive sensing element into the supporting steel tube, which locates the collar. The Wallingford "Tell-Tail" Device (De Falco and Mele 2002) consists of a set of omni-directional motion sensors mounted on "tails" and connected to a rod that can be buried in the ground at a range of depths. This device works on the principle that the motion sensors detect bed movements as scour reaches the depth of embedment of the sensor. It can be connected to a data acquisition system and thus provides a relatively straightforward mechanism to detect scour.

Mercury tip switches can be used on a driven or buried rod to detect scour. This works on the principle that when a steel pipe is augured into the ground, switches located along the shaft fold up against the pipe, thus closing the circuit. If the streambed material is eroded away, the switches open thus breaking the circuit. Due to its simplicity, this device provides a robust way to detect scour local to the sensor installation area. Decreasing the sensor switch array spacing allows the accuracy to be improved. Disadvantages associated with this instrument include the fact that mercury is used in the sensor, which can prove hazardous to the environment if released (NCHRP 2009). Also, the sensor cannot indicate that scour hole re-filling has occurred because the switches cannot close again once opened. It can, however, provide a good estimate of the maximum scour depth developed.

Zarafshan et al. (2012) developed a driven rod system that uses changes in the natural frequency of the rod to detect the presence of scour. The rod is fitted with a strain-sensor that can detect dynamic strains along the rod in real time. The system works on the principle that the natural frequency of a cantilevered rod is inversely proportional to its length. As scour occurs, the rod becomes exposed and its cantilevered length increases. The strain sensing element on the rod measures the dynamic strain, which is converted to the frequency domain using spectral analysis tools such as the Fast Fourier Transform (FFT). The change in frequency is correlated to a depth of scour by developing a Winkler-based numerical model of the soil-rod system and choosing an appropriate coefficient of subgrade reaction (Dutta and Roy 2002). The system allows for self-calibration, where the natural frequency measured at installation is used to choose an appropriate subgrade modulus for the system. This allows the scour depth to be correlated directly to the observed change in frequency caused by scour. The system works reasonably well at the real time monitoring of scour but is limited in that it can only detect scour local to the sensor and it requires installation into the streambed, which can be labour intensive and expensive. A similar device has recently been developed that also uses a vibration-based method to detect scour using a partially buried pipe installed upstream of a river bridge pier or abutment (Fisher et al. 2013). The device consists of a series of sensors located along the pipe. These sensors are each equipped with a flexible disk chosen such that it will respond (by vibrating) to the dynamic pressure present as a result of the highly turbulent flow. These are referred to as vibration-

based turbulent pressure sensors (VTP). The device works on the principle that the vibrations of the VTPs can be measured by an accelerometer in the time-domain. The energy content is determined as the mean squared signal from each sensor and is proportional to the vibrational energy of each VTP. By monitoring the energy content of an array of these sensors along the pipe, it can be shown that the energy content of the sensors exposed to the flow can be one to two orders of magnitude greater than that of sensors located in the sediment thus allowing for scour to be directly measured. This device has been shown to be unaffected by turbid flow conditions, which have been noted to affect other instrument types and it also works very well, even in cases where the flow is misaligned to the order of 90° to the sensors' orientation (Fisher et al. 2013). The device provides a simple mechanism to detect scour and has been shown to be reliable and robust in harsh hydraulic environments.

2.5 Sound Wave Devices

A number of devices have been developed that use sound waves to monitor the progression of scour holes. They work on the same principle as devices that use electromagnetic waves, in that waves are reflected from materials of different densities thus establishing the location of the water-sediment interface. One example, Sonic fathometers (Nassif et al. 2002; Fisher et al. 2013) can be mounted on bridge piers just below the level of the water stage. They then build up continuous profiles of the streambed by emitting sonic pulses from a pulse generator, which travel through the medium to the water-sediment interface. In doing so, the device can detect and monitor the depth of scour over time. The device can, however, only be operated within certain depth tolerances and is susceptible to interference from entrained air present in highly turbulent flow. In addition, where the bed topography is variable, this type of sensor only measures the shallowest depth. Therefore, the beam width at the bed with respect to the scour hole may significantly affect the accuracy of the scour depth measurements (Fisher et al. 2013).

Reflection Seismic Profilers also utilize sound waves to monitor and detect scour (Anderson et al. 2007). This device typically employs a coupled acoustic source transducer and receiver transducer that are placed immediately below the water surface. As the system is towed manually across the

water surface, the source transducer produces short period pulsed acoustic signals at regular time or distance intervals. The high frequency seismic pulse propagates through the water column and into the subterranean sediments below. This device can build up profiles of the streambed as some of the acoustic energy is reflected back to the receiver when the water-sediment interface is encountered. By combining the signals from multiple locations and using estimated seismic interval velocities, the time-depth profile can be converted into a depth profile. Some disadvantages of the system include; noise with variable streambeds leading to the crossing-over of signals, both the source and receiver need to be submerged meaning that data cannot be obtained continuously over sand bars and the device also requires significant manual input, which may make it unsuitable as a viable monitoring regime in a lot of cases. If used correctly, however, it can provide a very accurate map of the channel sub-features.

Echo Sounders work in a very similar manner to Reflection Seismic Profilers and can be used to determine scour hole depths (Anderson et al. 2007). The only major difference is that they emit higher frequency acoustic source pulses and due to the rapid attenuation of the high frequency pulsed acoustic energy, relatively little signal is transmitted into or reflected from within the sub-bottom sediment. A time-depth profile is generated by plotting traces from adjacent source and receiver locations. Using estimated seismic interval velocities, these plots may be converted to depth plots. The only disadvantage of this system over Reflection Seismic Profilers is that no information about previously filled in scour holes can be obtained since the high frequency waves cannot penetrate into the sub-bottom strata.

2.6 Electrical Conductivity Devices

Devices of this type use the differences in the electrical conductivity of various media to determine the location of the water-sediment interface. They work on the principle of measuring an electrical current between two probes. If the material between the probes changes, the ability for a current to be drawn will also change. This phenomenon can be used to indicate the presence and depth of scour. An example of a device that uses this technology is Electrical Conductivity Probe (Anderson et al. 2007).

A schematic showing the deployment of some of the instrumentation described in section 2 is shown in Figure 3. Most of the instrumentation described has the disadvantage of either requiring underwater installation, which can be costly, or can only be used discretely as part of routine inspections. These are notable disadvantages. Monitoring the dynamic response of the structure itself to the occurrence of scour has gained significant interest in recent times and is described in more detail in section 3.

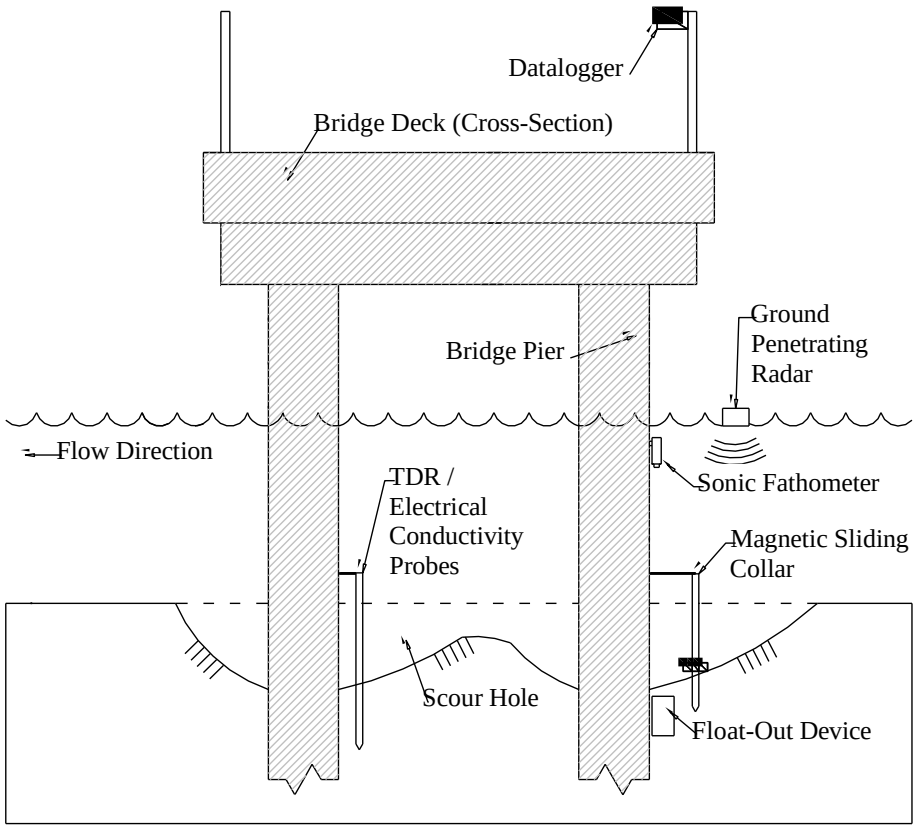

Figure 3 Scour monitoring instrumentation

3.0 Scour Monitoring using Changes in Structural Dynamic Properties

To date scour monitoring has mostly used underwater instrumentation that measures the progression of scour depths with time. Limited research has been undertaken to consider the effect that scour has on the response of the bridge structure itself. Some of the instruments developed to measure the response of a bridge structure to scour include Tiltmeters and Accelerometers. Tiltmeters, also known

as Inclinometers, measure the relative rotation of a structural element and as such can be used to detect differential settlement, which can occur as a result of the scour process. The only major disadvantage of the device is that it does not give a direct indication of scour depth. Devices capable of measuring structural distress directly, are more likely to be successful in allowing engineers to implement the necessary repair schemes on critical structures, prior to the occurrence of failure.

Accelerometers allow for the measurement of the structural response particularly to a change in boundary conditions. The soil-structure interaction process is complex during scour (Foti and Sabia 2011), however, removal of material from under (or around) the foundation during scour will cause increased stress and consequently reduced stiffness in the remaining soil, see Figure 4. Since the frequency of vibration of the structure depends on the system stiffness, observing changes in vibration frequencies is a potential method for damage identification and health monitoring. The natural frequency of the bridge pier-foundation system can be determined from accelerometers placed on the structure using spectral analysis tools such as Fast Fourier Transforms (FFTs) or Frequency Domain Decomposition (FDD) (Brincker et al. 2001) among many other methods. A number of authors have investigated the feasibility of using dynamic measurements to detect the presence of scour. These methods usually comprise the use of accelerometers to detect modal properties such as natural frequency in concert with the development of reference numerical models.

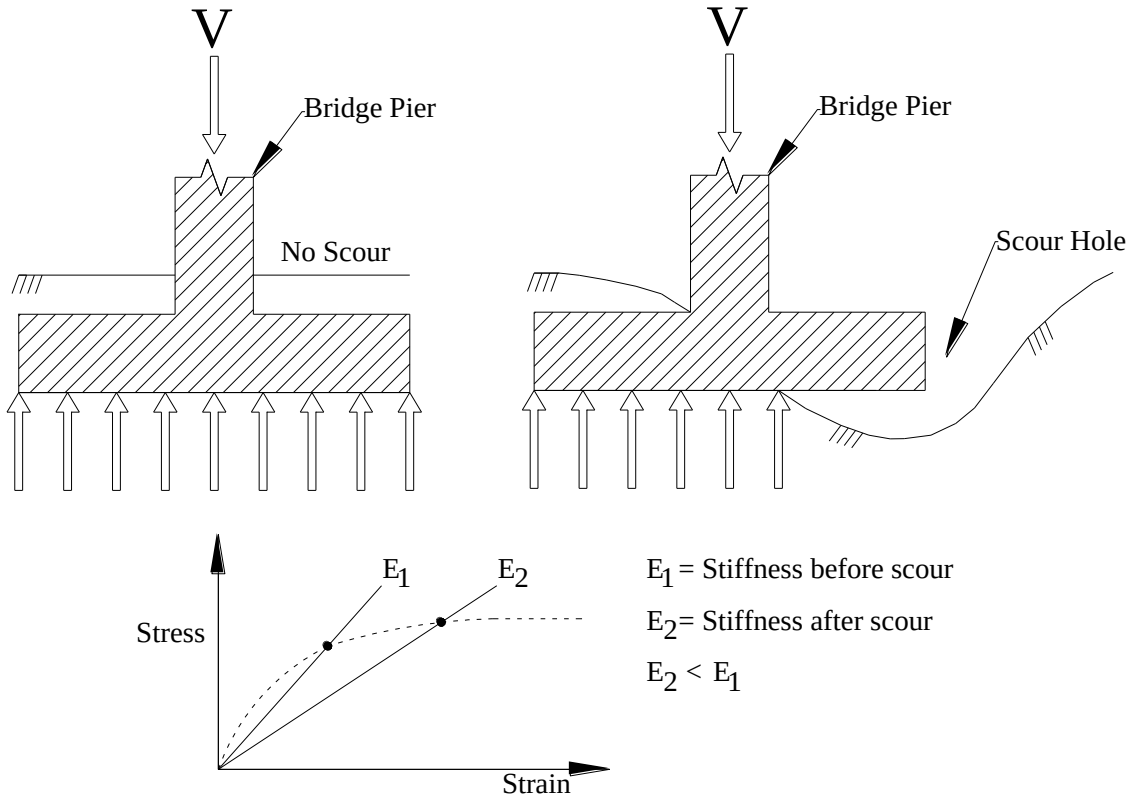

Figure 1 Reduction in Stiffness caused by Scour

Foti and Sabia (2011) describe a full-scale investigation that was undertaken on a bridge in Northern Italy which had been adversely affected by scour during a flood in 2000. The bridge, located in Turin, contained five spans each 30 m long, and was supported by four large concrete piers. The original foundation system of each of the four piers comprised a mat of 24 piles with diameters of 600 mm and lengths of 15 m. In the 1980s as part of a scour protection regime, a series of 55 piles with diameters of 400 mm and lengths of 8 m were placed around the perimeter of each foundation mat. Scour affected the foundations continuously over time. When originally constructed, the riverbed was at the same level as the top of the foundation mat. As time progressed, the top 2 m to 3 m of the piles became exposed (with pier no. 2 on the bridge developing a 6 m deep scour hole) leaving this portion of the foundation without lateral restraint. In response to this, a continuous monitoring regime was implemented which involved the collection of topographical measurements to detect the rotations of the piers as well as the installation of a permanent inclinometer on the critical pier. The worst affected

pier continued to settle consistently and in March 2004, was noted to have settlements of 16 mm and 44 mm on either side of the pier. The movement of the other piers was very limited in contrast.

A replacement scheme for the critical pier was agreed and a dynamic survey was undertaken before and after the replacement of the pier by analyzing traffic-induced vibrations. The survey involved using a method that defines a mathematical model capable of linking the theoretical response of a dynamic system to the time-history measurements from the system. A vector extension of the Auto-Regressive Moving Average (ARMA) technique (Juang 1994) was used to estimate the modal response using signals acquired from a number of accelerometers distributed along the bridge spans. For the bridge spans, a total of six modes were identified, with modes 1 and 3 showing the most significant differences before and after the retrofit. This data is summarized in Table 1.

Table 1. Modal Analysis of Bridge Spans before and after retrofitting.

Span	**1**	**2**	**3**	**4**	**5**
Mode 1 Before (Hz)	4.7	4.5	4.7	4.7	4.9
Mode 1 After (Hz)	4.7	4.4	4.4	4.7	4.7

In the survey performed before rehabilitation, the second span, which was supported by Pier P2, exhibited the lowest frequency and had an anomalous mode shape when compared to the other spans. In the retrofitted case, the natural frequencies of span 1, 4 and 5 were identical whilst the frequencies of span 2 and 3 were lower. This was because the rehabilitation scheme for Pier P2 involved placing a beam spanning between the new structural supports, on which the original bridge spans would now rest. This new construction resulted in a lower structural stiffness than the original mass pier construction.

The damaged pier itself was analyzed by observing the asymmetric dynamic response of the foundation system using accelerometers placed along a line parallel to the direction of flow. The asymmetry is expected due to the rotation of the foundation caused by uneven support conditions. Modal analysis is less useful with the expected rigid body motion of the mass pier. The covariance

matrix of the measured acceleration signals was used to detect the presence of scour, but cannot be used to quantify its extent due to the effect of external load intensity on the magnitude of the covariance. However, it was expected that the variation in covariance along the element would give an indication of the presence of scour. The retrofitted pier was also tested. A simplified numerical model of the bridge was developed to act as a sensitivity analysis in determining the parameters of interest for scour monitoring and to assess the effects of load position and severity of scour on the dynamic response of the bridge structure. A modal analysis conducted in the numerical model before and after scouring showed only moderate differences in natural frequencies and mode shapes and as such, indicated that experimental accuracy would not be sufficient to detect variations in soil-structure interaction induced by scour. This was mainly because the pier behaved as a rigid body. However, a load applied on the same side of the model as the scour hole did have a different effect than a load applied on the opposite side (This load models the effect of traffic moving in different directions along the bridge deck). This was confirmed by the experimental measurements with Pier P2 showing a marked asymmetry when compared to the other piers. The results of this analysis are shown in Figure 5, which presents a plot of the diagonal term of the covariance matrix obtained for each pier prior to retrofitting. Three repetitions are shown on each plot. Pier P2 shows both larger magnitude variance values than other piers as well as significant asymmetry. Pier P3 also showed high variance magnitudes. This was the other central pier and as such was more likely to have been affected by erosion.

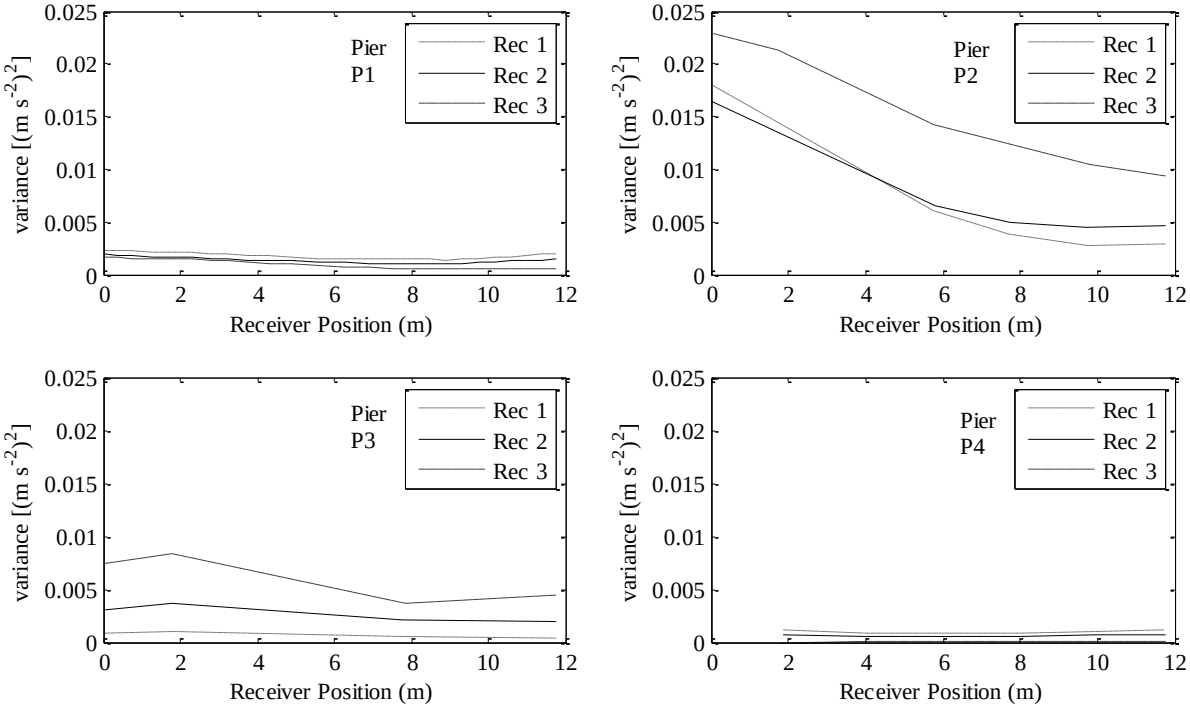

Figure 5 Dynamic response of piers before retrofitting for traffic on the upstream side of the carriageway; the results for three different records are shown (Foti and Sabia 2011).

The research concluded that the analyses presented can be used to highlight the difference in behaviour of a single pier compared to others, or to monitor the evolution of scour if repeated over time. The purpose of the research was not to determine the actual extent of scour, however, as the methods developed are not suited to this purpose. Detecting the actual depth of scour would be a useful addition to the analysis developed by (Foti and Sabia 2011).

Briaud et al. (2011) present a laboratory and field investigation undertaken to study the effectiveness of various instruments, including accelerometers, at monitoring scour. A model-scale bridge was constructed in a large hydraulic flume at Haynes Coastal Engineering Laboratory, Texas A&M University. Two foundations types were tested, shallow and deep, as these are the most common foundations used on bridges. The research involved the construction of the two types of bridges in the flume and instrumenting them with various scour monitoring devices. Devices tested included Float out devices, Sonar sensors, Water Stage measurement devices, Accelerometers and Tiltmeters. The

study involved increasing the velocity of water in the flume in a controlled manner to induce scour gradually. The acceleration response of the structure was obtained by impacting various pre-determined points on the deck with a rubber hammer to simulate excitation that would occur due to traffic loading. This acceleration was picked up by accelerometers placed on the bridge pier. The accelerations in three directions were analyzed; namely the flow direction, the traffic direction and the vertical direction. Two different methods were used to analyze the effect of scour on the acceleration responses measured. Firstly, Fast Fourier Transforms (FFTs) were used to obtain the frequency content of the measured acceleration responses. Secondly, the ratio of the Root Mean Square (RMS) values of the acceleration measured in two different directions was investigated as a parameter to measure scour. This is shown in Eq. (1) for the flow and traffic directions. The vertical direction was also measured.

$$\frac{a_x}{a_y} = \frac{\sqrt{\dfrac{a_{x1}^2 + a_{x2}^2 + \ldots + a_{xn}^2}{n}}}{\sqrt{\dfrac{a_{y1}^2 + a_{y2}^2 + \ldots + a_{yn}^2}{n}}} \tag{1}$$

where a_x is the RMS value of the measured acceleration in the flow direction and a_y is the measured acceleration in the traffic direction.

The frequency response in the direction of flow showed the highest sensitivity to the occurrence of scour in both the shallow and deep foundation laboratory trials. The results from the shallow foundation trial are shown in Figure 6 (a). This figure charts the change in frequency for the first, second and third mode of vibration of the structure against time. After 4.5 hours in the hydraulic experiment, a notable drop in frequency was observed in all three modes corresponding to the depth of scour reaching the bottom of the installed column. The higher modes exhibited relatively larger drops in natural frequency at this point than the fundamental mode. At the same time, the ratio of the RMS values of acceleration in the flow-traffic direction and traffic-vertical direction showed a significant change in relative magnitude. This is shown as an increase in the RMS ratios at the 4.5 hour mark in Figure 6 (b).

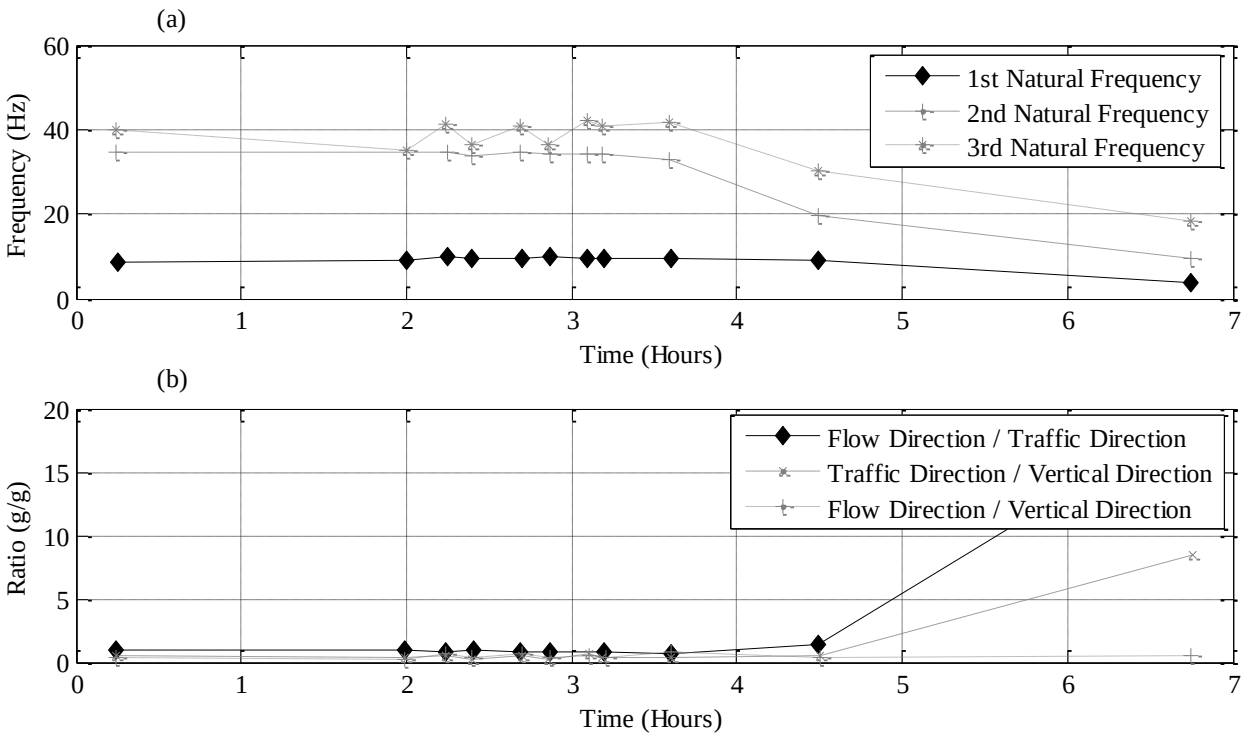

Figure 6. Laboratory results shallow foundation. (a) variation in first, second and third natural frequency in flow direction for shallow bridge foundation; (b) Change in the ratio of RMS acceleration values for three different directional combinations (Briaud et al. 2011).

Similar results were obtained for the deep foundation trial. The study concluded that accelerometers placed on bridge piers showed significant potential at detecting the presence of scour at laboratory scale for both the shallow and deep foundation types. The sensitive parameters identified were changes to the natural frequency and ratio of RMS values of acceleration. This was particularly true for the case of vibration in the flow direction, which showed that the methods seemed promising.

The laboratory trials were compared to reference numerical models generated using the commercial software LS-DYNA in order to quantify critical conditions required for bridge failure so that suitable warning criteria can be specified. The ratio of RMS acceleration values and natural frequency are investigated in these analyses. Different scour depths are modeled in the analysis and the effect on the structure is obtained. Eigenvalue analyses are conducted such that the numerical and experimental natural frequencies can be compared and transient dynamic analyses are conducted such that the ratio of RMS acceleration values for the numerical and experimental trials can be compared. The results of

the analyses for the shallow experiment reported good agreement between both parameters being obtained. Due to the sudden failure of the deep experiment during the experimental scour trial, a full numerical comparison was not possible, thus results could only partially be compared. The laboratory trial concluded that Accelerometers along with Tiltmeters and Sonar can be used to predict bridge failure. The FFT approach as well as the RMS approach was shown to be effective to analyze the accelerometer data as they showed significant changes when the scour depth reached the bottom of the column.

Following the success of the laboratory trail, a full-scale field investigation on two different bridges was conducted (Briaud et al. 2011). One of the bridges tested was the US59 Bridge, which is 111 m long with three spans. This bridge had been subject to remediation works over its life span because of scour problems. The field-scale deployment for scour monitoring involved testing the various instruments from the laboratory investigation such as Accelerometers, Tiltmeters, Float-out devices, water-stage sensors and Tethered Buried Switches. The scour monitoring regime was implemented and initially showed promise. However, the accelerometers did not give satisfactory results as in the laboratory trials. Low excitation due to the traffic loading, low signal to noise ratios, the high energy required to transmit accelerometer data and harsh weather conditions which led to failures of the solar re-charge system for the data storage were some of the reasons given for the lack of success at field deployment. It was concluded overall that using accelerometers to detect and monitor bridge scour showed potential, but would require much more research and resources to conclusively achieve results.

Hussein (2012) published a study which involved assessing the effect of scour on the supports of a model-scale bridge. The research initially considered a finite-element numerical model that was used to assess the effect of scour on various aspects of the bridge's dynamic response. The numerical model was created in SAP2000 v12.0.2 with the bridge supports modeled as piles that extended from the base to the deck and were fully-fixed at the base. Scour was modeled as an increase in the effective length of these piles. Eigenvalue analyses were performed to extract the dynamic

characteristics of the structure. It was concluded from these analyses that vertical mode shapes of the structure were insensitive to scour due to the limited effect of the pile's axial stiffness on the dynamic response of the superstructure (Elsaid and Seracino 2014). However, the horizontally displaced mode shapes showed significant sensitivity to the progression of scour, due to the reduction in the flexural stiffness of the bridge piles with increasing effective length. This is in agreement with the laboratory study reported by Briaud et al. (2011). Other damage indicators, namely; mode shape curvature, flexibility-based deflection and curvature were also assessed in the finite-element environment to investigate their applicability to detecting scour. Results from the numerical analyses indicated that these methods not only showed promise at detecting scour but also showed that it may be possible to quantify the extent of scour.

Following on from the numerical investigation, an experimental regime was undertaken to assess the applicability of the methods on a real structural frame (Hussein 2012; Elsaid and Seracino 2014). The test regime involved impacting the structure in the vertical and horizontal direction and measuring its dynamic response using accelerometers placed on the web of steel girders. Frequency Response Functions (FRFs) were developed to obtain the natural frequency for each case, which show the ratio of the output response to the input stimulus. In this case, the input stimulus is the time-history of forces over the strike duration and the output response is the acceleration readings from the accelerometers. Three different scour scenarios were modeled; symmetrical scour, unsymmetrical scour and braced piles (representing the case of scour that exposes the pier's foundation or a ground beam connecting the two piles). As in the finite-element investigation, scour was modeled simply as increasing the effective length of piles, which are fixed at the base to the laboratory floor. For the unsymmetrical case, the shorter pile was fixed to a concrete block, in order to keep the steel frame level. The experimental investigation verified the numerical prediction in that vertically displaced mode shapes were deemed insensitive to scour with little differences being recorded in the FRFs before and after scour. For the horizontal impact assessment, the first, third and fifth mode shapes showed the most sensitivity to scour with a decrease in natural frequency being obtained as scour depth increased, See Figure 7. The first and third mode shapes showed a decrease in frequency and

the fifth mode shape showed an initial increase in frequency. The second and fourth mode shapes were deemed insensitive to scour based on the geometry of the system under investigation.

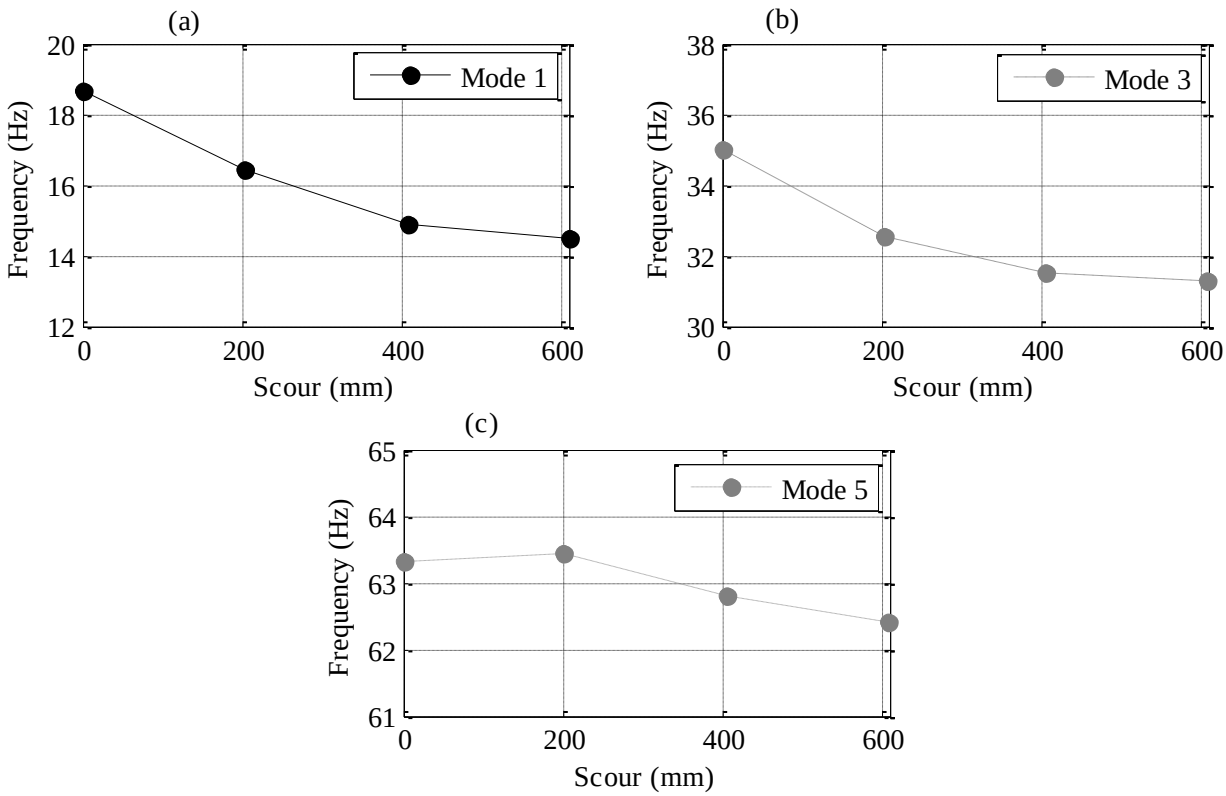

Figure 7 Relationship between scour level and natural frequencies (a) first, (b) third and (c) fifth horizontally displaced mode shape [converted from inches] (Hussein 2012).

In addition to the horizontally displaced mode shapes showing sensitivity to the progression of scour, the three damage indicators (mode shape curvature, flexibility-based deflection and curvature) were also investigated to study their effectiveness at detecting scour. Results indicated that the three damage indicators were able to identify the exact location of scour for the symmetrical scour cases and the scour zone for the unsymmetrical and braced scour cases. The change in flexibility-based deflection was capable of determining the extent of scour as well as its location. Although the laboratory investigation showed promise, the scour modeling was greatly simplified in that no treatment of soil-structure interaction was considered and this would have a significant effect on the dynamic response of the structural supports.

A recent investigation by Prendergast et al. (2013) details the development of a method to detect and monitor the presence of scour by observing the change in the dynamic response of a pile foundation to progressive scour. This research which builds on the findings of Briaud et al. (2011) and Hussein (2012) and includes explicit treatment of soil-structure interaction. The method allows for direct estimation of scour depth based on an observed value of natural frequency of vibration by creating reference numerical models capable of analysing the combined stiffness of the soil-structure system. Both laboratory and field trials were undertaken to verify the method. In the laboratory investigation a 1.26 m long pile was installed in a sand box to an initial embedment depth of just over 490 mm (See Figure 8). Sand was incrementally removed from around the pile in 50 mm lifts, See Figure 8. Before each excavation the top of the pile was subjected to an impulse load and the resulting acceleration response was measured using an accelerometer placed at the top of the pile. The time-history acceleration responses obtained at each scour depth were converted to the frequency domain by applying Fourier transforms in MATLAB. The natural frequencies obtained as the scour depth progressed are shown in Figure 9.

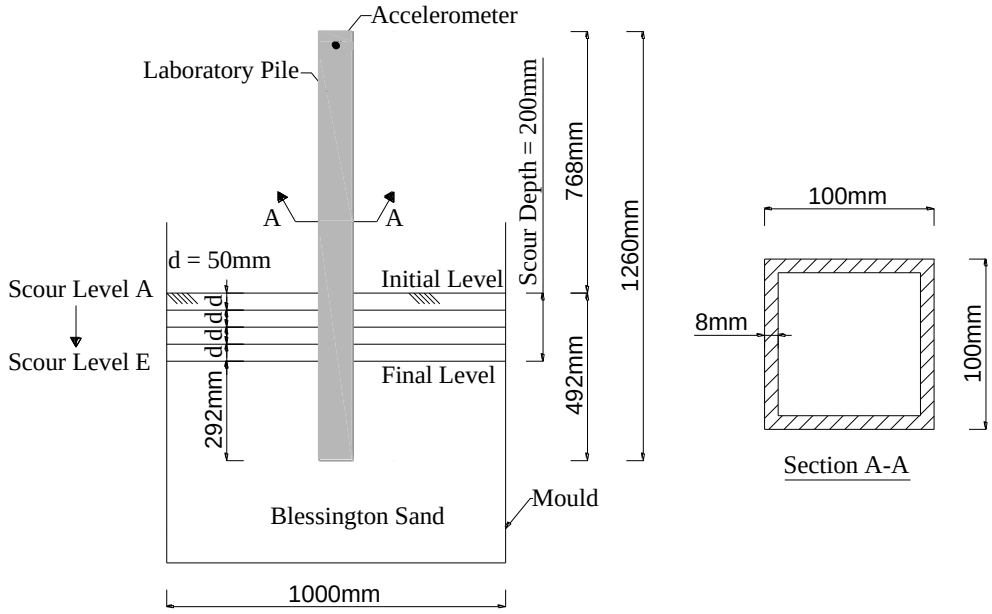

Figure 8. Laboratory Schematic (Prendergast et al. 2013).

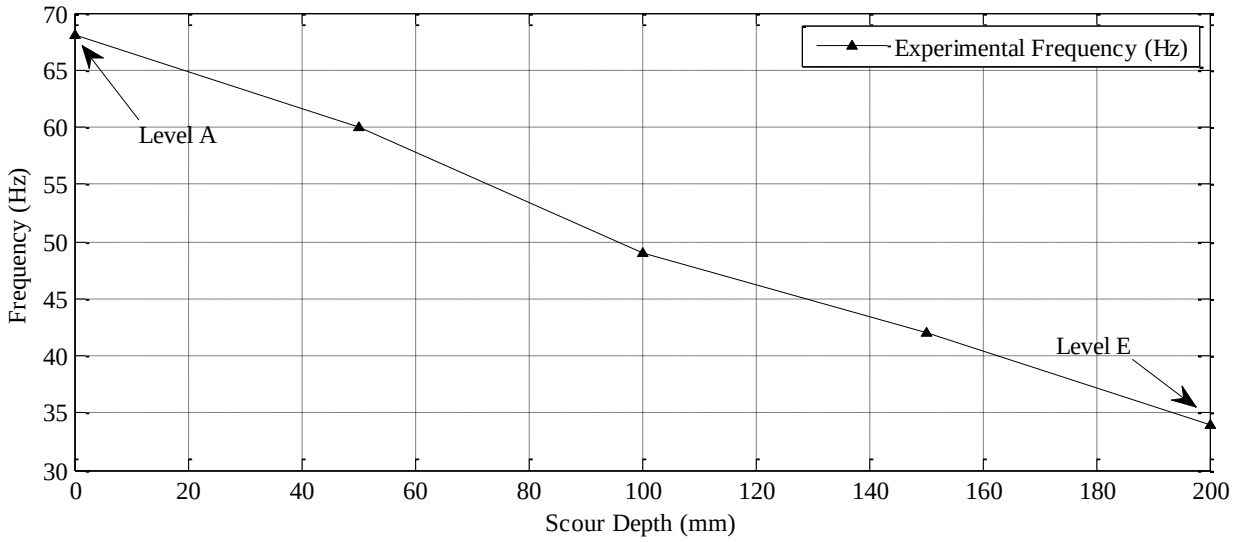

Figure 9. Frequency Change with Scour (Prendergast et al. 2013).

The results indicate that significant frequency changes were detectable with a reduction in frequency being recorded over the 200 mm total excavation of sand (from level A to E). Whilst a reduction in frequency is expected to be observed as the effective length of the structure increased, the results of the laboratory analysis were used to calibrate a numerical model (which included the soil stiffness) that would be capable of tracking the change in frequency with scour. A spring-beam numerical model was developed that modeled the pile as a beam on an elastic foundation (Dutta and Roy 2002;

Ashford and Juirnarongrit 2003), known as the Winkler hypothesis. The pile was modeled as a beam supported by linear-elastic springs using the elemental stiffness and mass matrices defined in (Kwon and Bang 2000). These matrices were altered slightly to account for the lateral stiffness contribution from the soil. Scour was modeled by removing springs from the model corresponding to an increase in scour depth (or effective length). Eigenvalue analyses were undertaken in the model to obtain the natural frequency of the system for each scour depth. By incrementing the stiffness value attributed to the springs in the model, it was possible to obtain a very good match with the laboratory experimental data for frequency response against scour depth.

The promising results from the laboratory calibration study led to a field investigation on a full-scale pile which was driven in dense sand at a test location outside Dublin city, Ireland. The pile had a diameter of 0.34 m and a depth of embedment of 6.5 m prior to the start of the scour test. The test procedure was similar to that followed in the laboratory, with sand being removed in increments of 0.5 m from around the pile. A modal hammer was used to apply the lateral excitation and a series of accelerometers located along the pile shaft measured the acceleration response at each excavation depth. These accelerations were then processed using Fourier transforms in MATLAB to obtain the frequency content at each scour depth. The spring stiffness values for the model were derived from site-specific soil stiffness parameters. These soil-stiffness parameters were determined from in-situ geophysical tests such as the Multi-Channel Analysis of Surface Waves (MASW), See (Donohue et al. 2004) to determine shear wave velocity measurements and Cone Penetration Tests (CPT) to determine a profile of cone tip resistance with depth. Scour was modeled by removing springs from the numerical model and performing an eigenvalue analysis to determine the change in frequency with increasing scour depth. Very good matches were obtained between the experimentally varying natural frequencies with increasing scour depth and those calculated using the numerical models. This is shown in Figure 10, which includes a theoretical estimation of the natural frequency of a free cantilever which is shown as an upper bound to the measured frequency response. As is evident from the plot, a very good match is observed between the experimentally measured variation in natural frequency and that predicted using numerical models encompassing the small-strain stiffness of the

soil, namely the Numerical (CPT) and Numerical (Shear Wave) frequencies. Also shown in the plot is the frequency predicted using spring stiffness values prescribed by offshore pile lateral loading design codes, the American Petroleum Institute (API) (API 2007), as well as the frequency predicted by an equivalent rigid cantilever. The purpose of the cantilever is to show that the results of the analysis are in line with expectations since all frequencies are lower than their cantilever equivalent, at each depth. The research concluded that if accurate assessments of the small-strain stiffness of the soil could be obtained for a particular site, then the level of scour could be determined by simply observing the natural frequency of the pile using accelerometers placed on the exposed potion of the pile shaft.

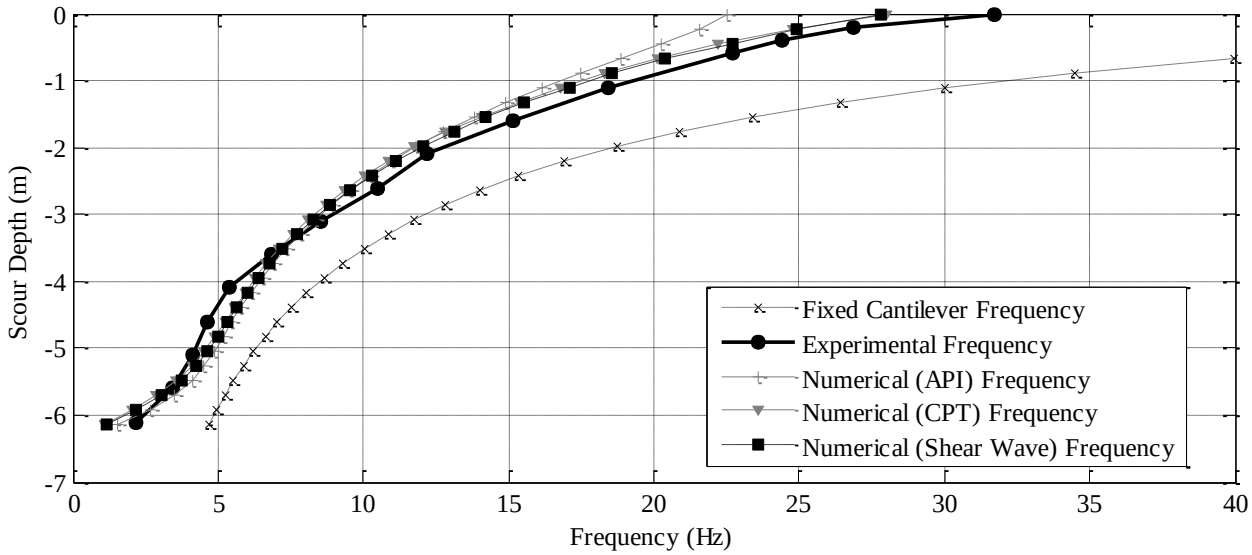

Figure 10. Change in Frequency with Scour Depth (Prendergast et al. 2013).

4.0 Sensitivity Study

A sensitivity study is presented in order to investigate whether the approach developed by Prendergast et al. (2013), outlined in the previous section, could be applicable to full-scale bridge monitoring. A simplified numerical model of a bridge pier-foundation system was developed comprising an embedded pile, a pile cap interface, a cylindrical bridge column to represent the pier and a pinned/fixed connection to model the boundary condition with the deck superstructure. The bridge pier was restrained laterally at the top using either a pinned of a fixed connection. In one case it is free to rotate about the pin and in the second, no rotation is allowed. The purpose of this modeling

approach is to attempt to encompass the behaviour of the bridge deck-pier boundary connection without considering a full deck-pier bridge model. The mass of the deck has no effect on the dynamic response of the pier in this model as only the connection type governs the response. This simplified modeling approach is used to obtain a reasonable estimate of the change in frequency of the bridge pier-foundation system to progressive scour and to assess the applicability of the method to detecting scour on real structures. The range of bridge pier diameters and lengths which were investigated in this sensitivity study are outlined in Table 2. The pile cap mass is lumped at the interface node between the bridge pile and the pier.

Table 2. Parametric analysis.

Parameter	**Value**
Diameters tested (m)	1 m, 1.5 m
Pier lengths considered (m)	5 m, 10 m, 15 m
Scour depth considered (m)	0 m – 3 m
Pile cap dimensions (m)	2 m x 2 m x 1 m
Pile cap mass (kg)	9600 kg
Pile diameter (m)	0.34 m
Pile penetration (m)	6.57 m
Pile material	Steel (ρ = 7850 kg m^{-3})
Pier material	Concrete (ρ = 2400 kg m^{-3})

The soil stiffness was obtained using the same values as presented in (Prendergast et al. 2013) from the shear wave velocity measurements measured in dense sand. The pile length and geometry was fixed for the purpose of consistency while the other parameters were varied. The results of this analysis are presented in Figure 11 as a percentage change in natural frequency with reference to the zero scour frequency response. This allows a window of expected frequency shift magnitudes to be ascertained for the given geometries considered.

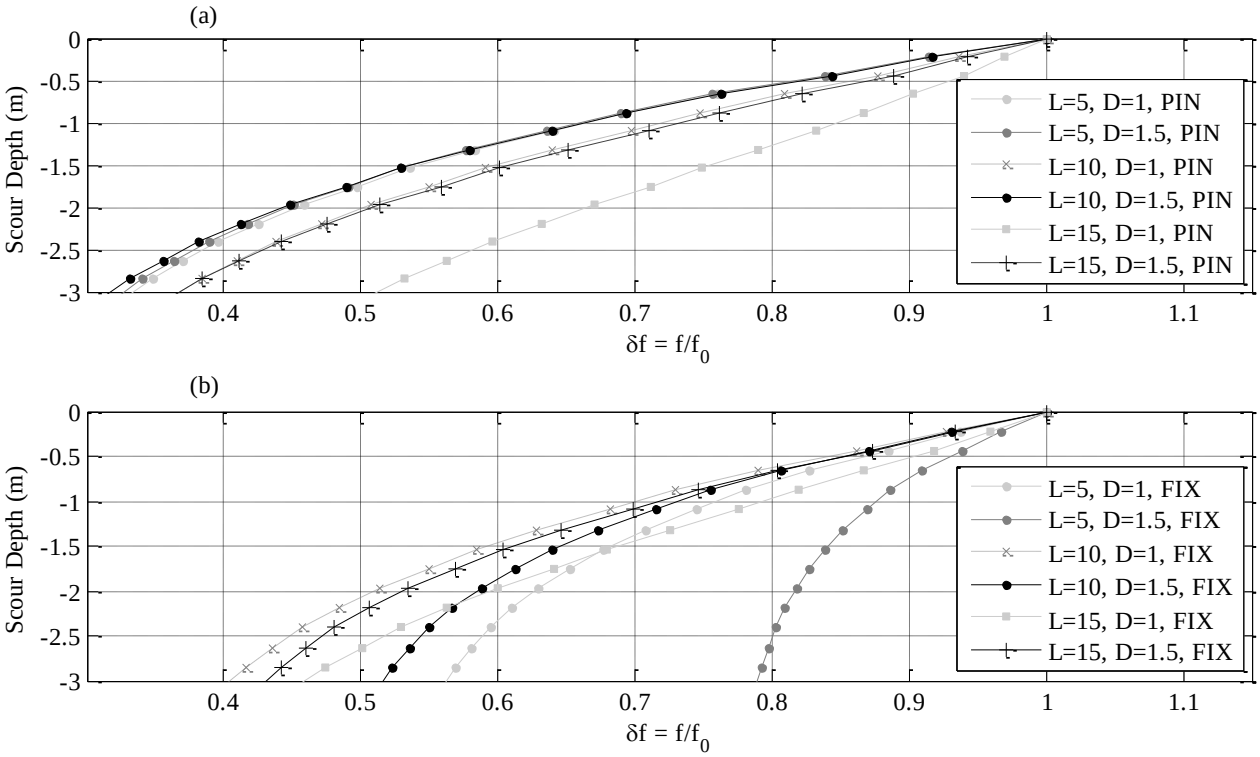

Figure 11 Frequency change sensitivity study for 3 m scour depth. (a) pinned connection with deck assumed; (b) fixed connection with deck assumed as boundary conditions with superstructure.

The results of the analysis were quite sensitive to the boundary condition assumed and the geometry considered with changes in frequency over a 3 m scour depth ranging from 50% to 69% for the pinned connection and 21% to 60% for the fixed connection. The purpose of this analysis was not to determine exact frequency shifts corresponding to a real life bridge but merely to assess if adequate frequency shifts were observed when a full bridge pier and connection with a bridge deck is considered. This is important since this was not directly considered in the work of (Prendergast et al. 2013). From the analysis, it is clear that scour has a significant effect on the dynamic response of a bridge pier-pile foundation system for the given geometries and structural fixities considered.

5.0 Conclusions

Traditional scour monitoring instrumentation often requires expensive installation and maintenance and can also be susceptible to debris damage during flooding. Often, the interpretation of data from these instruments can also be time consuming and difficult. There is much on-going research into the use of the structural dynamic response to detect and measure the depth of scour around structures. The research is paving the way for low-maintenance non-intrusive structural health monitoring to detect and monitor scour development. The advantages of dynamic measurements over traditional scour depth measuring instrumentation are the ease of installation above the waterline and the low maintenance required. Frequency shifts offer potential to detect the loss of stiffness associated with scour and as a result, to detect the effect that this loss of stiffness has on the structure of interest. This aspect is often missed by instruments installed in the stream bed, as the global effect of scour may not be observed unless a high density of instruments are used around scour critical areas. There is still significant room to improve dynamic measurement systems. Some of these difficulties associated with these methods include issues such as the high volume of acceleration data required to obtain sensible information (Briaud et al. 2011), the high power requirements for data acquisition systems as well as other effects. The issue of environmental effects on the measured natural frequency is also a factor worth considering (Sohn 2007). In time, improvements in technology will mitigate some of these issues and more reliable dynamic based scour monitoring instrumentation may be developed.

The work of (Prendergast et al. 2013) was developed in this paper for the purpose of a sensitivity study assessing the applicability of the approach to full-scale monitoring of scour. A simplified bridge pier-foundation model was created that modeled the boundary condition with the deck as a pin and a fully-fixed connection. The purpose of this was to assess a reasonable range of expected frequency magnitude shifts that could be obtained for a range of different bridges. The analysis concludes that the method developed in (Prendergast et al. 2013) is very applicable to full scale bridge monitoring with significant frequency shifts occurring for a range of geometries and boundary conditions.

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