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REVIEW **Open Access**

A review of bridge scour monitoring techniques and developments in vibration based scour monitoring for bridge foundations

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Abstract

Scour is the gradual erosion of the sediment around a bridge foundation and is one of the leading causes of bridge failure. This erosion is caused by turbulence and sediment transport mechanisms and worsens during high-water flow, such as flooding. A severely scoured bridge is a safety concern for commuters. Monitoring systems are sometimes used to provide indications of the scour extent. Most scour monitoring systems require underwater installation, which is inherently difficult to implement for existing structures. Data obtained from such systems may not necessarily be accurate due to factors such as site temperature fluctuations, or the presence of large debris in the channel causing faulty readings during times of high flooding. Inaccuracy in this data is a problem because it could display erroneous results, leading to a false sense of security. Researchers worldwide are exploring vibration-based techniques to monitor scour to overcome this challenge. These techniques can possibly monitor scour without any underwater installation and may be more efficient than the traditional underwater technologies currently implemented. This review piece aims to present a summary of the several types of scour monitoring techniques traditionally used to monitor scour of bridge structures and the advancement in technology for existing monitoring techniques based on the vibration characteristics of bridges. The importance of monitoring scour progression focused on vibration-based techniques will be discussed as well as providing a fair appraisal of these techniques. This review piece shows evidence through laboratory and field experiments that monitoring a structure based on vibrational changes due to scour is possible, and with the advances in technology over the most recent decade, it is now possible to design cost-effective and accurate scour monitoring systems for future field implemented structural health monitoring projects. This evidence is relevant to future researchers for the implementation of prospective bridge vibration-based systems.

Keywords: Scour, Monitoring, Vibration bridge structures

1 Introduction

Bridge scour refers to the removal of sediment from around a structure's foundation because of the erosive action of fast flowing water (Kariyawasam et al. 2020). Scour of foundations is the number one cause of bridge collapse in the United States (Prendergast and Gavin 2014a). Approximately 60% of bridge failures in the United States are caused by scour (Prendergast and Gavin 2014a; Wardhana and Hadipriono 2003). These failures result in significant losses (Kamojjala et al. 1997) and disrupt a variety of road connections and transportation routes (Pizarro et al. 2020). Scour causes a decrease in the soil's elevation corresponding to the bridge foundation and causes problems with the bridge's stiffness and strength (Fitzgerald et al. 2019). Figure 1 below shows a decrease in soil's elevation around a bridge pile.

The severity of scour on a bridge pile or pier is a combination of the amount of energy that flows, the amount of sediment transported, and the dynamic characteristics of the structure itself (Gotvald 2003). Typically, bridges will be subjected to two types of scour: local scour and global scour. Local scour is known as the local lowering of the bed level, which corresponds to the general level of the stream or river channel (Kariyawasam et al. 2020). Local scour depends on factors such as the amount of sediment displaced and the erosion at the base of the stream or river (Prendergast and Gavin 2014a). Global scour refers to an overall general lowering of the base soil level over a broad area (Kariyawasam et al. 2020). Global scour occurs naturally in streams or river passages. It includes the deterioration of the riverbed that may arise because of changes in the velocity and flow of water or changes in the amount of sediment in the stream or river passageway (Forde et al. 1999). Local Scouring is primary caused by the downflow of fast flowing water against an individual pier in which the erosive action of the horseshoe vortices remove sediment around the foundation (Zhao 2022; Chavan et al. 2022; Wu et al. 2020). Due to these hydrodynamic interactions, removal and ejection of sediment happens, thus forming a depression around the pier known as scour. Figure 2 below illustrates the hydrodynamic interactions between the pier and the streambed which initiates the process of scouring (Zhao 2022).

Bridge failures caused by local and global scour produce large financial losses (Kamojjala et al. 1997). In the United States, the average cost for flood damages and

Fig. 1 Scour damage on bridge pile

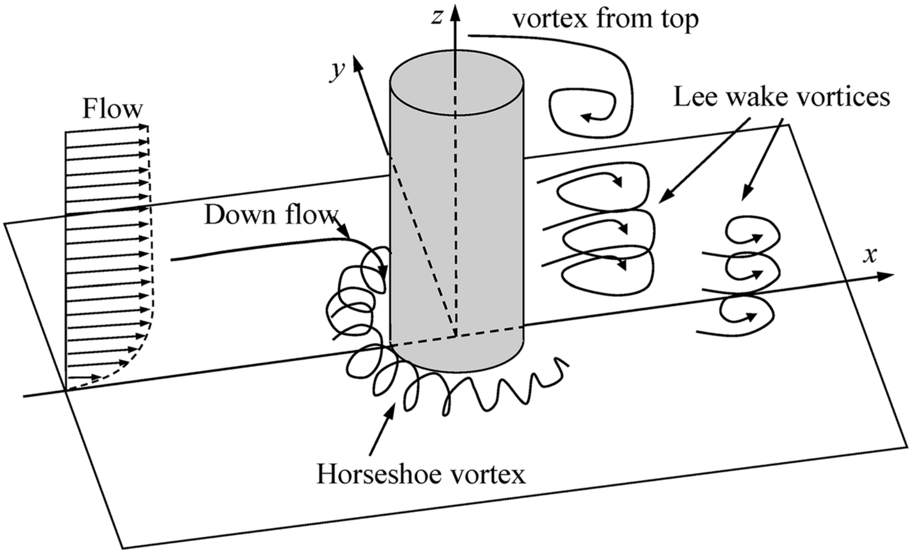


Fig. 2 Scouring process on bridge pier. Figure adapted from Reference (Zhao 2022) with permission from MDPI

the repair of bridges due to these damages are estimated at higher than $50 million per year (Shinoda et al. 2008). Combating and monitoring scour provides an opportunity to take countermeasures that will increase the overall safety and usability of bridge structures over time; and decrease costs related to bridge repairs and cost of transportation impacts due to bridge failures. Additionally, it helps transportation agencies with time-crucial maintenance decisions for critically scoured bridges.

Countermeasures and monitoring of scours can be done in several ways and is most effective when considered during the design of bridges. When a bridge is initially being designed, it is possible to combat scour by providing both structural supports and hydraulic supports (Hunt 2009). Structural countermeasures involve the addition of ripraps to the base of the bridge or piers during the initial design stages by ensuring that the spread footings are located below the maximum scour depths that the structure could be subjective to (Prendergast and Gavin 2014a). Figure 3 below shows riprap being utilized to protect the bridge pier foundation from scouring.

Hydraulic supports involve providing resistance to the rapid flow of water caused by changes in the flow direction, such as keeping large bridge openings during the initial design of the bridge and using pier geometries that could minimize debris buildup (May et al. 2002). The hydraulic countermeasures mitigate conditions that create vortices which are mainly responsible for the development of scour (Prendergast and Gavin 2014a). Monitoring scour for existing bridges includes the use of sonar and water level sensors, magnetic sliding collars, and float-out devices in conjunction with data loggers for real-time data transmission.

In order to economically mitigate the consequences of scour, it is more effective to implement remediation and rehabilitation works as necessary and in a timely manner so that the scour does not progress to cause structure instability (Briaud et al. 2011). Therefore, scour monitoring and observation are considered one of the most

Fig. 3 Riprap protection on bridge pier

Fig. 4 Visual Bridge Inspection for structural damage

cost-effective ways to combat scour. Currently, the most widespread monitoring scheme is to undertake visual inspections of bridges. Visual inspections allow for structural damage such as cracks and other structural damages to be detected (Sohn et al. 2003). Figure 4 below shows visual inspections being conducted on a bridge.

The problem with visual inspections and obtaining manual measurements of scour is that they cannot be completed during flooding. Flooding generates high turbulence within the stream which is when the risk of scour is the greatest. Once the water subsides and the in-stream velocity reduces, the greatest depth of the scour holes may not be correctly measured due to sediment deposition (Lin et al. 2010). Scour evaluations via instrumentation or by divers after sediment redeposition may provide an inaccurate representation of scour.

Preliminary Scour depth estimation can be accomplished using empirical equations, depending on the specific conditions of the bridge and the flow of water (Gaudio et al. 2010). An example of awidely used equation to determine scouring under the erosive action of moving water is the Colorado State University equation shown below (US Department of Transportation 2012).

$$\frac{Ys}{b} = 2K1K2K3K4\left[\left(\frac{h}{b}\right)^{0.35} Fr^{0.43}\right] \tag{1}$$

Where,

Ys = scour depth

b = pier width

h = depth of flow

Fr = Froude number

$K1$ = correction for pier shape

$K2$ = correction for attack angle of approach flow

$K3$ = correction for bed form

$K4$ = correction for armoring

Equation 1 above is suitable for determining scour depths in a variety of scenarios involving narrow and intermediate piers (Mohamed et al. 2006). There are other empirical equations available to estimate scour depths (Gaudio et al. 2010; Namaee et al. 2018; Kiraga et al. 2020; Khassaf and Ahmed 2021; Hamidifar et al. 2019; Das et al. 2021) such as the Froehlich Equation andSimplified Chinese Equation (Chase and Holnbeck 2004), but they will not be discussed in this article to maintain the tight scope of this manuscript. Despite the availability of empirical equations, some researchers have found that these equations may not be accurate (Alemi and Maia 2018; Sajjadi et al. 2018) due to the fact that they are derived under simplified and controlled laboratory studies (Saha et al. 2018). Because of this reason, these empirical equations will serve as a tool for initial bridge design, but its use may be limited for field monitoring purposes.An alternative approach to manual measurement to combat scour is using scour depth monitoring devices that can monitor the depth of the scour around a bridge. A wide range of devices has been developed and implemented on bridges and abutments to monitor scour and its development over time (Kariyawasam et al. 2020; Prendergast and Gavin 2014a; Pizarro et al. 2020; Gotvald 2003; Forde et al. 1999; Hunt 2009; May et al. 2002; Briaud et al. 2011; Sohn et al. 2003; Lin et al. 2010; Boujia et al. 2018; Lan et al. 2021; Yao et al. 2010; Kariyawasam et al. 2019; Lin et al. 2021; Yang et al. 2021; Fujino 2018; Lin and Chang 2017; Hashimoto et al. 2020; Bao and Liu 2017; Jeary et al. 1988; Ko et al. 2010a; Akib et al. 2010; Whelan et al. 2009; Funderburk et al. 2022; Zhan et al. 2022; Cheng et al. 2022). These devices can range from single use devices, such as float out devices, to other types of devices, such as buried rod devices, sound-wave devices, and electrical conductivity probes (Prendergast and Gavin 2014a; Maroni et al. 2020). Some of these devices are shown below in Fig. 5 (Maroni et al. 2020).

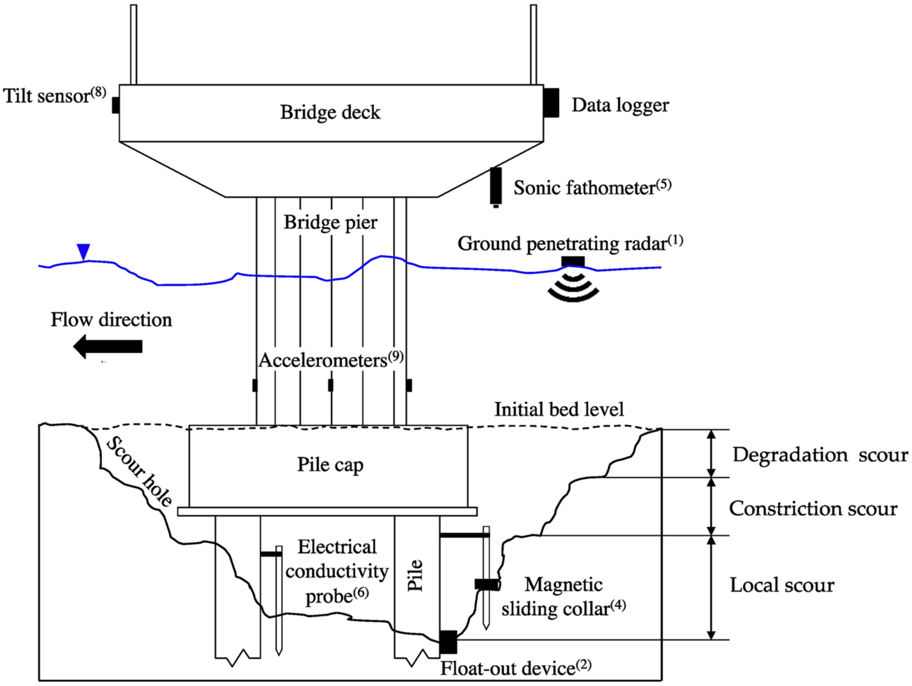


Fig. 5 Devices used to monitor scouring and its progression over time. Figure adapted from Reference (Maroni et al. 2020) with permission from MDPI

These devices are installed underwater, making them expensive to implement and prone to damage since they are subject to harsh conditions during a flood. Since it is not the scope of the paper to review all available measuring techniques, discussions of these devices will be left out of the manuscript. Instead, this manuscript's aim will focus on the vibration-based technique, thought to be more current than other techniques used to monitor scour. It should also be made clear that this manuscript does not promote any individual scour monitoring products and does not discredit any techniques used for scour monitoring in the past, but simply reviews the advantages, progression, and advancements for the vibration-based scour monitoring technique.

2 Scour monitoring using vibration-based techniques

Traditional scour monitoring devices are based on monitoring the size and depth of the scour hole over time using underwater sensors. Scour monitoring using vibration-based techniques is a recent development. This technique is based on the premise that scour causes a reduction in stiffness, which in turn causes structural characteristics changes that can be captured using commercial sensors such as the accelerometer. Accelerometers are devices that measure the acceleration due to excitation from kinetic motion (Varanis et al. 2018). This excitation can then be converted to vibration characteristics and is often used on structures like bridges for health monitoring. Data gathered regarding the vibration can be used to correlate with the scour extent (Prendergast and Gavin 2014b).

The basis of the vibration-based technique lies in the fact that the vibration characteristics of a bridge will change with the change of stiffness (Bao and Liu 2017).

Formation of scour directly removes soil and in turn changes the stiffness of the pier. The change in stiffness thus affects the modal characteristics of the structure such as the natural frequencies, mode shapes and damping ratios which may be observable from the accelerometer data, by modal identification techniques (Ko et al. 2010b). This theory was tested by some of the pioneers of the vibration-based technique (Fujino 2018; Lin and Chang 2017; Jeary et al. 1988; Fujimoto et al. 1988; Ko et al. 2010a; Akib et al. 2010; Whelan et al. 2009; Masui and Suzuki 2009) and have since taken off and used by others (Kariyawasam et al. 2020; Fitzgerald et al. 2019; Shinoda et al. 2008; Briaud et al. 2011; Boujia et al. 2018; Yao et al. 2010; Kariyawasam et al. 2019; Prendergast and Gavin 2014b; Lin et al. 2021; Keyaki and Suzuki n.d.; Fisher et al. 2013; Zhang et al. 2019; Lin et al. 2013; Tubaldi et al. 2022; Samusev et al. 2019). One pioneer example is of The Disaster Prevention Research Laboratory creating an advanced system for evaluating the soundness of bridge substructures to detect scouring and monitor the condition of piers. The system can detect vibrations caused by trains, as well as changes in inclination. The laboratory has conducted long-term field tests using a prototype vibration sensor and used the test results to determine the necessary sensor specifications. The laboratory also analyzed field captured measurement data and confirmed that it is effective in detecting scouring and changes in natural frequency (Masui and Suzuki 2009).

Generally, the relationship of the predominant natural frequency and the stiffness of a bridge can be represented in Eq. 2 below as

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

Where f_n, k and m represent the predominant natural frequency, stiffnes and mass respectively (Bao and Liu 2017). This equation shows the proportionality and relationship between the square root of stiffness with the predominant natural frequency. Since accelerometers were used to determine the vibration characteristics, it is necessary to post-process the raw data to observe the vibration characteristics such as the predominant natural frequency, f_n as shown in the equation above. Examples of techniques that may be used to process the accelerometer data include but are not limited to the Peak Picking Method (Naderpour and Fakharian 2016) and the Enhanced Frequency-Domain Decomposition (Bayraktar et al. 2015).

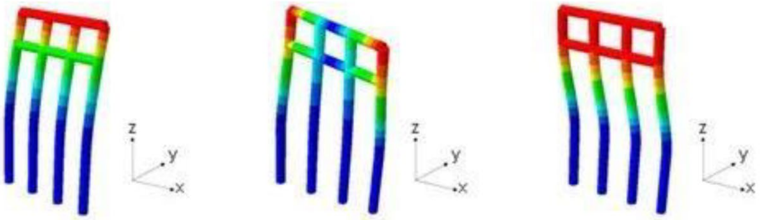
There are different approaches to monitoring bridge scour based on vibration characteristics. These approaches range from monitoring the frequency of a rod sensor inserted in the soil next to the pier (Boujia et al. 2018; Funderburk et al. 2022; Zarafshan et al. 2011), to directly monitoring the frequency of the bridge or the abutment itself (Fitzgerald et al. 2019; Gotvald 2003; Briaud et al. 2011; Lan et al. 2021; Kariyawasam et al. 2019; Prendergast and Gavin 2014b; Fujino 2018; Lin and Chang 2017; Hashimoto et al. 2020; Bao and Liu 2017; Ko et al. 2010a; Zhan et al. 2022; Cheng et al. 2022; Saidin et al. 2022). Monitoring the frequency of a rod sensor inserted in the soil next to the pier is one technique in which the vibration responses of embedded rods help estimate the current scour depth. This method is based on the hypothesis that the vibration frequency of the rods will decrease with the increase of the exposed length of the rods (Boujia et al. 2017). To investigate the effect of scour on the changes in natural frequency, laboratory tests were performed, and the results obtained are discussed in "Lab experiments" section. The outcome of these tests shows a reduction in frequency when scour is present.

Monitoring the frequency of a bridge or an abutment is another technique in which the vibration characteristics are based on various indicators that change over time. These indicators include modal frequencies, modal shape, modal shape curvatures, frequency variation rates, modal assurance, structural deflection, and other indicators (Lan et al. 2021). One of the most important indicators in vibration-based scour monitoring is a bridge's modal frequency, which can be obtained through modal analysis. Modal analysis is defined as the process of determining the characteristics of a system, such as natural frequencies and using them to create a model for the system's behavior (Fu and He 2001). The disadvantage of only analyzing the modal frequency in vibration-based monitoring is that the scour process occurs over an extended period which causes the characteristics of the bridge frequency to change very slowly. This implies that the changes in the bridge frequency will be very low when only analyzing the modal frequency. Another problem when only analyzing the modal frequency in vibration-based monitoring is that external environmental factors such as changes in temperature, windspeed, vehicular movements, and such can influence the frequency of the bridge. These factors can lead to inaccuracies in bridge frequency measurements and can be mistaken for changes in structural characteristics (Lan et al. 2021).Another critical parameter in the modal analysis in helping determine the amount of scour present is the changes in a bridge's modal shapes. The modal shape of a bridge is defined as a specific pattern of vibration carried out by a system at a particular frequency. Taking a bridge structure's characteristics and then finding the displacement values that change under different mode shapes makes it possible to find the displacement changes in the three orthogonal dimensions for both scour-free and scour-critical critical cases. As a result, these values can then be compared, and changes in parameters due to scour can be found, as shown in Fig. 6 (Hashimoto et al. 2020).

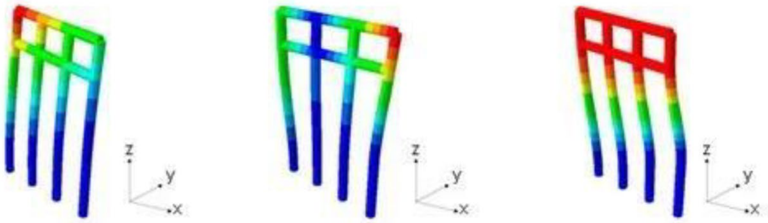
The modal shape is an essential indicator of scour since it is more sensitive to scour than the modal frequency and is not affected by external weather conditions (Lan et al. 2021). The damage to the bridge or abutment can be inferred by observing changes in the modal shape (Hashimoto et al. 2020).

Damage to a bridge results in a decrease in its natural frequency due to reduced overall stiffness, a change in modal shape due to stiffness redistribution caused by defects, and an increase in damping resulting from the formation of cracks (Ko et al. 2010b). The current problem with only analyzing the modal shapes in vibration-based monitoring is that it has only been experimentally verified in the laboratory. Hence, its effectiveness in the field is unknown.

Monitoring scours using a single parameter has its pros and cons. Vibration-based techniques are adapting to monitor multiple important indicators at once. They include newer indicators being researched, such as deriving a structure's flexibility matrix, horizontally-displaced mode shapes and analysis of the damping ratio (Lan et al. 2021; Elsaid and Seracino 2014; Xiong and Cai 2022). Including more indicators will help vibration-based monitoring techniques better quantify the amount of scour below the surface, allowing remediation actions to be conducted when necessary.



(**a**) Scouring-free case (**left**: 1st mode, **center**: 2nd mode, **right**: 3rd mode)



(**b**) Scouring case (**left**: 1st mode, **center**: 2nd mode, **right**: 3rd mode)

Fig. 6 Mode shapes for a simulated pier model under scour-free and scour cases. Figure adapted from Reference (Hashimoto et al. 2020) with permission from MDPI

Most vibration-based scour monitoring studies and techniques mentioned above were carried out in the laboratory or field experiments. The results obtained from these studies show promise for future applications to better quantify scours underwater. To further bring to light the recent development of the vibration-based technique for scour monitoring, the following sections will discuss the work done by different authors and research groups, both in the laboratory and the field. "Lab experiments" section will first highlight the contributions and significance of studies done in the laboratory setting. "Field experiments" section details contributions in scour monitoring done in the field.

2.1 Lab experiments

Many bridge scour detection studies were done in the laboratory. These studies mainly use natural frequency to characterize scours. In 2008, M. Shinoda et al. (Shinoda et al. 2008) conducted a laboratory study using a vibration-based technique. This is significant because the authors concluded that river degradation indicated that scour-induced damage was the main reason for the frequency decrease and that this frequency variation can be captured using accelerometers. This study evaluated the changes in the frequency of a bridge from river degradation by flooding. This laboratory experiment had accelerometers attached to the top of the bridge, and vibrations were induced by an iron ball. The iron ball actuation was designed to have minimal contact with the bridge to avoid additional induced vibrations. The vibration frequencies captured were analyzed to find the bridge's natural frequency. This test showed that there are decreases in frequency of the pier when river degradation is present and an increased change in frequency when reinforcements were added (Shinoda et al. 2008). These findings help show a correlation between both scour and natural frequency reduction and that these changes can be captured.

Following Shinoda 2008's work, in 2010, C. Yao et al. (Yao et al. 2010) conducted a laboratory study using a vibration-based technique. This study is significant because the authors continued to see that the frequencies decreased as scour depth increased and that the sensors were able to capture these changes. This study employed multiple sensors at a shallow foundation bridge model. To simulate the real structure, concrete columns were embedded into sand inside a flume to simulate a shallow foundation. Different sensors were placed on the model to record the data such as accelerometers, tilt sensors, float-out devices, sonar sensors, etc. A hammer was used as the excitation source to induce vibrations for the model and this model was placed in a flume. The flume was filled with water, and vibration was generated by a flow in which different flow velocities were implemented. The experimental results showed that natural frequency decreased with time as soon as a scour hole was present, and with the scour present, a change in frequencies of 50% to 60% was discovered (Yao et al. 2010).

In 2014, Elsaid et al. (Elsaid and Seracino 2014) conducted a laboratory experiment using a vibration-based method. This study is significant because frequency changes of greater than 20% were observed when analyzing horizontally displaced mode shapes for scour detection and prevention, In this study, an idealized bridge was studied numerically and experimentally under four different levels of scour. Numerical simulations were used to examine the impact of scour on the bridge's dynamic characteristics, while the experimental testing was used to develop a scour detection technique. The mode shape curvature and dynamic flexibility were evaluated as a new method of scour detection. Their numerical study involves an idealized structure representing a two-span continuous bridge where scouring of different depths including 1.3, 1.5 and 1.7 m respectively were used. Modal analysis was then performed, and the results of the modal analysis were categorized according into vertically displaced mode shapes and horizontally displaced mode shapes. It was observed that the horizontally displaced mode shapes are sensitive to scour and changes of more than 20% were observed which confirms the numerical simulation outcomes in this laboratory study (Elsaid and Seracino 2014).

Four years after Elsaid's work, Boujia et al. in 2018 (Boujia et al. 2018) conducted a laboratory study using a vibration-based technique. This study is significant because the authors shows a clear reduction in frequency when scour is present, and this frequency can be captured using accelerometers. This study was conducted using aluminum rods of different lengths and geometries embedded in dry and saturated soils to investigate the effect of the variation of the embedded length when the exposed length is kept fixed. Scour was simulated by progressively increasing the exposed length of the rods by 5 cm [about 1.97 in] and an impact was generated which was captured by an accelerometer for analysis. This data was analyzed using Fast Fourier Transform. Results from their analysis showed that by monitoring the frequency of a rod sensor embedded around the pier, the variation of the natural frequency changes ranges from 47% to 55% when scour is present (Boujia et al. 2018).

Just 1 year later in 2019, Fitzgerald, Paul C et al. (Fitzgerald et al. 2019) conducted a laboratory study using a vibration-based technique. This study is significant because the results show that frequency shifts due to changes in scour were recognized. These included a 5.3% decrease in frequency for the 44.9% reduction in the stiffness scour test and a 2.8% decrease in frequency for the 24.5% reduction in the stiffness scour test. This study was conducted by first creating a laboratory scaled bridge. This scaled bridge was designed with four simply supported spans and contained three piers that were supported on springs. Four parallel springs were used at each pier to provide vertical stability, and bearings were used at each end of each span to create pinned, and roller supports. Four springs of different stiffnesses were used to model scour, and each was tested individually to model various levels of scour. An experimental vehicle model was used as a bridge exciter to capture the vibration characteristics under each of the four different spring stiffness values. A total of seven accelerometers were used at three pier locations and four midspan locations to capture the vibration data. Reduction in frequencies obtained through vibrational changes was related to the changes of spring stiffness representing higher levels of scour being introduced to their model. This model showed that not only were there decreases in frequency when scour worsened, but accelerometers could also capture these decreases in frequency. The results also showed that frequency shifts in all modes tested are detectable (Fitzgerald et al. 2019).

Based on the discoveries made in the previous research conducted in the 2000s and 2010s, respectively, Kariyawasam K. et al., in 2020 (Kariyawasam et al. 2020) conducted a laboratory study using a vibration-based technique. This study is significant because it shows the potential for changes in natural frequency to be an indicator of local and global scour. This study is based on full-scale bridges and was conducted by scaling down four different bridge piers from 1/60th to 1/40th of their actual size and modeling them using aluminum alloy. These models were inserted into sand inside a centrifuge container since the centrifuge replicates full-scale stress fields within small scale models for testing and since sand is generally used in centrifuge modeling tests. An actuator and modal hammer were used as the excitation sources so that the ten accelerometers that were placed along the model could capture the vibrations under different levels of local and global scour. The accelerometer data showed that based on one of the methods of vibration monitoring, the frequency of the bridge or the abutment itself, the fundamental natural frequency of certain types of bridges could change by more than 16% due to local scour and more than 40% due to global scour when analyzed with accelerometers (Kariyawasam et al. 2020). Based off the laboratory experiments mentioned, the vibration technique is a promising approach because of the safety, economic feasibility, accuracy, convenience, and low cost of implementation for continuous monitoring of scour around piers and abutments.

2.2 Field experiments

Apart from experimental work done in laboratory settings, field studies of vibration-based scour monitoring and bridge scour detection using the natural frequency have been carried out by some research groups around the world (Briaud et al. 2011; Kariyawasam et al. 2019; Prendergast and Gavin 2014b; Lin et al. 2021; Ko et al. 2010b; Ting Bao et al. 2017).

In 2010, Ko, Y. Y. et. al (Ko et al. 2010b) conducted a field study using vibration-based methods. This field study is significant since it shows a correlation between scouring and natural frequency changes in two real world bridge experiments. This study examined the impact of foundation exposure on the vibration characteristics of bridge superstructures. Field measurements were obtained from two highway bridges in Taiwan that had experienced scouring, in order to determine the effect of foundation exposure on the vibration behavior of the bridges. A finite element model was also created for those bridges so that they could examine the impact of scouring-related foundation exposure on the vibration behavior of the two bridge superstructures. Modal analysis was then conducted to extract the fundamental frequencies and three foundation exposure conditions were used in this study which included zero exposure, 2.5m exposure, and 5m exposure respectively. In the field, sensors were physically deployed on the cap beam of the tested piers. To compare the vibration characteristics of bridge superstructures at varying levels of foundation exposure, simultaneous field vibration measurements were taken using sensors at a severely exposed foundation and a slightly exposed foundation section of the Wensui Bridge. An averaged Fourier spectrum of the vibration of the severely exposed and slightly exposed foundations sections was conducted. It was found from the analysis from the sensors that since the severe foundation exposure reduced its lateral stiffness, a lower predominant frequency and larger amplitude of the vibration was exhibited (Ko et al. 2010b). Similar results were obtained from the Hsichou Bridge. It was concluded that the predominant frequencies of the bridges were lowered significantly when the foundation was more severely exposed (Ko et al. 2010b).

One year later, Briaud J.L. et al. (Briaud et al. 2011) conducted a field study using a vibration-based technique. This study is significant because it was concluded from this test that using accelerometers for monitoring bridge scour in the field has exciting potential. Still, it requires further research, time, and resources to achieve results in the field. This field study was conducted by setting up two large-scale lab experiments. One experiment is the simulation of a bridge with a shallow foundation, and the other is the simulation of a bridge with a deep foundation. A series of instruments were installed on the simulated bridge to monitor the performance of the bridge due to scour. Accelerometers were used in both the shallow and deep foundation experiments, and a hammer was used as the excitation source. It was found that the starting of the scour hole and its development can be monitored by frequency domain analysis. It was also found that the change in the natural frequencies due to the progress of scour hole is due to the decrease in the stiffness of the foundation caused by the removal of soil around the foundation (Briaud et al. 2011). Following this successful lab experiment, two individual monitoring systems were designed and installed on two bridges in Texas. Real-time data was collected and transmitted to a computer server at Texas A&M University, which can be accessed remotely. The remote system was implemented with $+-2\,g$ accelerometers collected every 10 minutes at a frequency of 80hz and was able to capture vibration data for multiple days before losing connection with the host. It was then fixed and captured vibrational data for multiple weeks before power demand became a problem due to transmitting large amounts of data.

Three years after Briaud's (Briaud et al. 2011) publication,, Prendergast L.J. et al. (Prendergast and Gavin 2014b) published a field study using a vibration-based technique in 2014. This field study is significant because the test results showed a correlation between the amount of scour and natural frequency. The results concluded that placing accelerometers on a bridge pile should be capable of tracking the changes in the scour depth In the publication Prendergast L.J. et al. (Prendergast and Gavin 2014b) demonstrated a reduction in observed frequency as scour depth changes.

The researchers started this study by installing an open-ended steel pile driven into a dense sand test bed to a depth of 6.5 m below the initial ground level. Four accelerometers were placed along the exposed portion of the pile shaft. These accelerometers were programmed into a datalogger, where a scan rate of 1000 Hz was implemented. The pile head was excited using a modal hammer, and a range of predetermined scour depths was set at 0.5 m spacing along the pile shaft. An excavator was used to remove the sand around the pile shaft before each test was undertaken. Each test comprised of impacting the pile head with the modal hammer and measuring the resulting acceleration response with the accelerometers. This was accomplished at each predetermined scour depth. Once the acceleration response was obtained for each depth of scour, the frequency was obtained by passing the time-domain acceleration signal through a Fourier transform using the analysis tool in MATLAB. After analysis of the data, this experimental field test showed a direct correlation and pronounced changes between the natural frequency and the amount of scour loss at the pile.

During the same year, in 2014, Lin Y.B. et al. (Lin et al. 2021) conducted a field study in the similar topic. This field study is significant because this scour monitoring system produced results in which the measurements of total scour-depth evolution based off vibrations can provide predictive information of scour-depth variations for early warning in bridge failure. This study started with the researcher's implementation of a scour monitoring system using accelerometers installed on the bridge pier in the mainstream of the Da-Chia River. With five vibration-based MEMS sensors, the scour monitoring system was designed for measuring the bridge scour-depth variations. The sensors were packed in a waterproof stainless-steel ball to embed into the riverbed to resist the harsh environment during flooding for long-term operational purposes. These sensors were tested in the laboratory for durability and reliability before being deployed in the field. A flood event that occurred on May 19th, 2014, was used as the excitation source for the vibration data to be captured and analyzed. The scour monitoring data in the scour and deposition processes were recorded and analyzed. A maximum scour depth of 1.5 m was recorded from one of the accelerometer's vibration readings after the highest flood peak discharge regarding the original riverbed elevation. The data showed that it is possible to measure scour depth using accelerometers during flooding for predictive maintenance.

In 2018, Kariyawasam K. et al. (Kariyawasam et al. 2019) conducted a field study using a vibration-based technique. This field study is significant because the team concluded an apparent reduction in modal amplitude as gathered by the accelerometers and that the mode shape and spectral density changes observed may have an enormous potential for vibration-based scour detection alongside natural frequency. This study was conducted and trialed on the Baildon Bridge in Bradford, UK during scour repair in 2018. This bridge was instrumented with 10 wired accelerometers to measure and capture vibrational changes due to scour. The researchers analyzed the vibration frequency changes of the bridge with scour and after adding support to the bridge. Based on this analysis, they saw changes in mode shape due to scour and during scour repair.

Based on the field experiments mentioned, the vibration technique shows promise in real-world systems for continuously monitoring scour around piers and abutments.

3 The progression and advancements in technology for vibration-based techniques

Over the years, technology for vibration-based health monitoring of bridges has become a more useful, economical, and environmentally friendly way of monitoring the structure for damage below the surface. This is because the traditional techniques to monitor scour require underwater installation and are subject to damage during flooding compared to sensors that can be installed above water which can monitor scour below the surface accurately. Monitoring scour using vibration-based techniques has become the mainstream alternative method over the last few years. There are two main reasons for the rapid progression of using this technique. Firstly, they are easy to install and operate and can be used during floods. Secondly, they offer real-time monitoring capabilities. The vibration frequency methods are also important because the frequency domain properties of a structure are stable, and even if the structure is subjected to different loading conditions, the properties extracted are similar. They only depend on the structure itself (Yang et al. 2021).

Vibration-based monitoring of structures started in the 1940s and 1950s with the monitoring of frequency changes due to different wind intensities at the Empire State Building in New York City, USA (Fujino 2018; Rathbun 1940). The structure was attached with multiple meters and cameras and the data collected and published during this decade was a monumental achievement at the time for helping set the foundation for building health monitoring. During the 1960s and 1970s, large-scale research programs on monitoring the difference in intensity of induced vibrations of structures were executed in North America and Europe. Offshore structure monitoring and structural response due to vibrations research were completed, and automatic systems that measure scour depth around a bridge pier were conducted in four different states in the USA (Fujino 2018; Hopkins et al. 1975; Davenport 1975). During the 1980s and 1990s, monitoring the structural integrity of buildings and bridges through vibrations began to receive more attention, and the installation of monitoring systems in bridges across the USA, as well as vibration-based scour monitoring at marine structures is studied (Fujino 2018; Jeary et al. 1988; Fujimoto et al. 1988). During the 2000s and 2010s, scour evaluation of bridge foundations using vibration measurements and structure behavior monitoring, as well as real-time monitoring of scour research, were conducted (Lin and Chang 2017; Ko et al. 2010a; Akib et al. 2010; Whelan et al. 2009). For example, the vehicle response-based scour detection is a vibration-based technique that is used to detect scouring indirectly and has contributed to the increase in interest of utilizing vibration-based methods over the last decades. This technique is used to detect and monitor erosion using vibration of the passage of vehicles on bridges. This method also uses accelerometers to detect and measure the vibrations caused by vehicles (Zhang et al. 2022). The data collected from these sensors can then be analyzed to determine the normal and danger ranges of scouring at the specific location (Masui and Suzuki 2009). This information can be used to identify occurrence of scour, and to monitor changes in the scour over time.

The model updating-based evaluation method couples a numerical model of a bridge with field collected data and is also an example of structural behavioral monitoring that emerged recently. The intent of this method is to produce a more representative numerical model (Roulund et al. 2005) that could be used in conjunction with the field data for scour estimation in moving water (Zhan et al. 2022). With the most current optimized model parameters, the numerical model can be used to simulate the bridge under various flow conditions and also predict the potential for scouring. This method is considered a powerful tool as it continuously improves the numerical model and allows for more realistic prediction of scouring. Because of this, swift remediation actions can be performed when necessary and thus improving the safety and longevity of the bridge (Huang et al. 2009).

In the present decade, advancements in machine learning techniques have also infiltrated into the area of scour prediction (Khosravi et al. 2021), and structure health monitoring considering environmental variables and other structural modes research is being conducted (Zheng et al. 2020; Funderburk et al. 2022; Zhan et al. 2022; Cheng et al. 2022).

The trends in Figure 7 show an increase in the interest and use of vibration-based scour methods, such as changes in modal properties of determining the scour of bridges over the past decades. There has been more than a 150% increase in the exploration and application of vibration-based scour methods between the 2000s and 2020s. This method has gained more traction and attention during the last decades. This is due to not having to implement the system under the water compared to traditional methods, the ease of maintenance once they are installed, and the required precision is now available for the sensors used in these systems based on technological advances over these decades.

The figure below shows the prices per unit sold by manufacturers for devices typically used in scour monitoring systems, not including installation costs.

Most of these traditional devices shown are costly because of the added costs of installing them underwater. The accelerometers shown in Fig. 8 are being researched as an alternative to monitor scour compared to the traditional methods and since they are installed above the surface (Gotvald 2003; Briaud et al. 2011; Lin et al. 2010; Kariyawasam et al. 2019; Prendergast and Gavin 2014b; Lin et al. 2021; Lin and Chang 2017; Avendano et al. 2021; Ko et al. 2010a; Cheng et al. 2022; Varanis et al. 2018) the installation costs are lower compared to the other scour monitoring devices shown. Vibration-based monitoring and vibration-based scour monitoring has been studied extensively

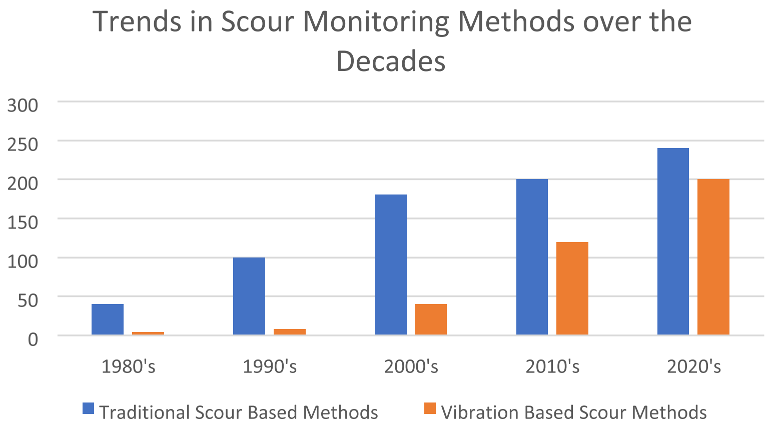


Fig. 7 Trends in Scour monitoring methods over the past decades based on cited literature

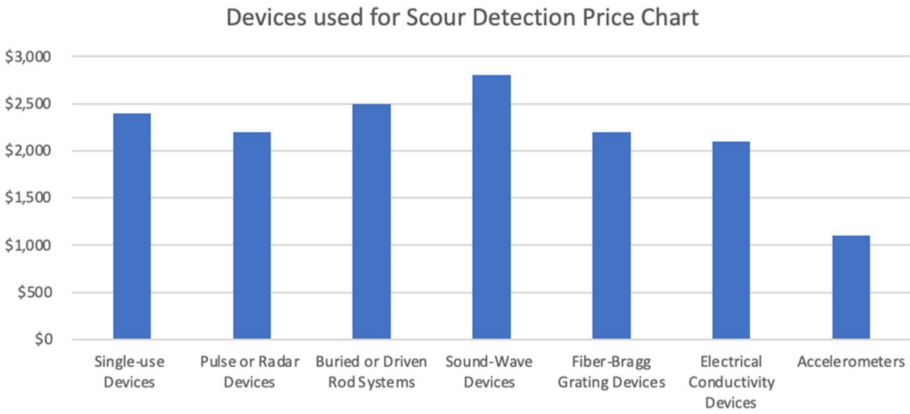
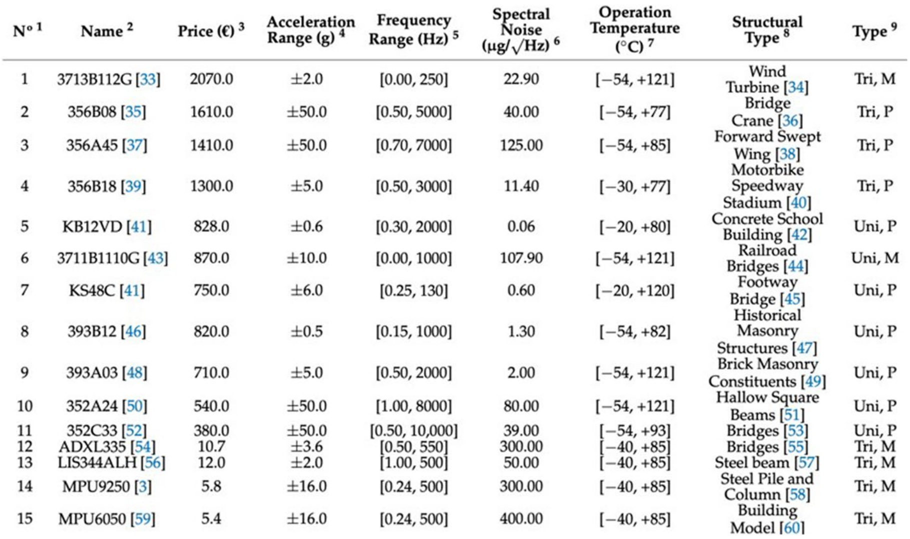


Fig. 8 Price chart per unit for devices used to monitor scour



N° [1]	Name [2]	Price (€) [3]	Acceleration Range (g) [4]	Frequency Range (Hz) [5]	Spectral Noise $(\mu g/\sqrt{Hz})$ [6]	Operation Temperature (°C) [7]	Structural Type [8]	Type [9]
1	3713B112G [33]	2070.0	±2.0	[0.00, 250]	22.90	[−54, +121]	Wind Turbine [34]	Tri, M
2	356B08 [35]	1610.0	±50.0	[0.50, 5000]	40.00	[−54, +77]	Bridge Crane [36]	Tri, P
3	356A45 [37]	1410.0	±50.0	[0.70, 7000]	125.00	[−54, +85]	Forward Swept Wing [38]	Tri, P
4	356B18 [39]	1300.0	±5.0	[0.50, 3000]	11.40	[−30, +77]	Motorbike Speedway Stadium [40]	Tri, P
5	KB12VD [41]	828.0	±0.6	[0.30, 2000]	0.06	[−20, +80]	Concrete School Building [42]	Uni, P
6	3711B1110G [43]	870.0	±10.0	[0.00, 1000]	107.90	[−54, +121]	Railroad Bridges [44]	Uni, M
7	KS48C [41]	750.0	±6.0	[0.25, 130]	0.60	[−20, +120]	Footway Bridge [45]	Uni, P
8	393B12 [46]	820.0	±0.5	[0.15, 1000]	1.30	[−54, +82]	Historical Masonry Structures [47]	Uni, P
9	393A03 [48]	710.0	±5.0	[0.50, 2000]	2.00	[−54, +121]	Brick Masonry Constituents [49]	Uni, P
10	352A24 [50]	540.0	±50.0	[1.00, 8000]	80.00	[−54, +121]	Hallow Square Beams [51]	Uni, P
11	352C33 [52]	380.0	±50.0	[0.50, 10,000]	39.00	[−54, +93]	Bridges [53]	Uni, P
12	ADXL335 [54]	10.7	±3.6	[0.50, 550]	300.00	[−40, +85]	Bridges [55]	Tri, M
13	LIS344ALH [56]	12.0	±2.0	[1.00, 500]	50.00	[−40, +85]	Steel beam [57]	Tri, M
14	MPU9250 [3]	5.8	±16.0	[0.24, 500]	300.00	[−40, +85]	Steel Pile and Column [58]	Tri, M
15	MPU6050 [59]	5.4	±16.0	[0.24, 500]	400.00	[−40, +85]	Building Model [60]	Tri, M

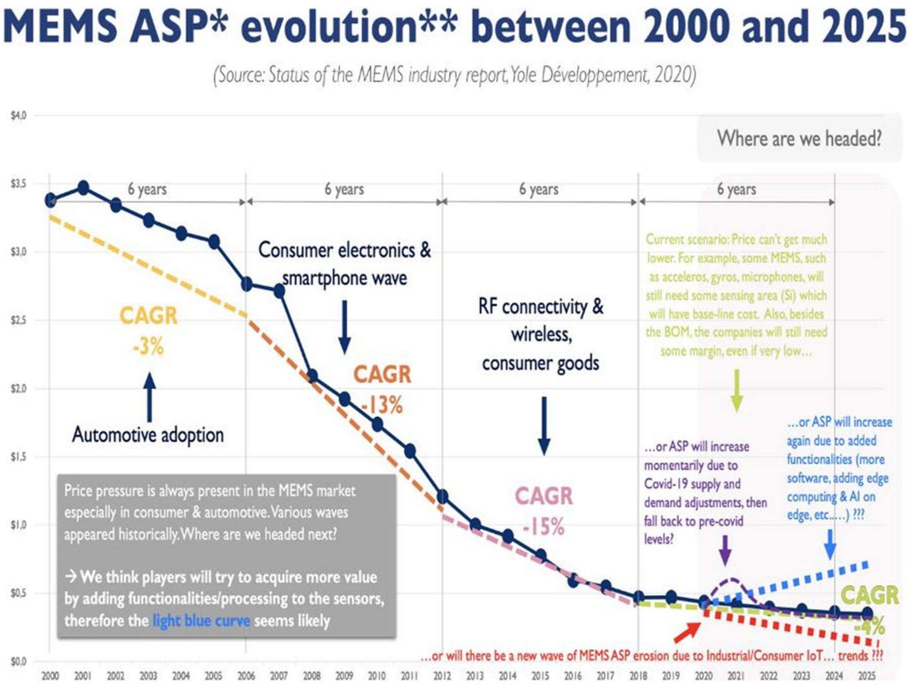
Fig. 9 Prices for different accelerometers used in structural health monitoring systems. Figure adapted from Reference (Komarizadehasl et al. 2021) with permission from MDPI

over the past decades as shown in Fig. 2 and the research of scour in laboratory experiments and field collected data demonstrated a reduction in a bridge's frequency. Current research is converging to real-world vibration-based implemented systems with the required accuracy, reliability, and economic costs of accelerometers used in these systems, and the installation costs of these systems are lower than the traditional methods currently used. Figure 9 below compares the prices of accelerometers used in different structural health monitoring systems and shows newer accelerometers are comparably as accurate in range and sensitivity as others while being almost 400% cheaper in price (Komarizadehasl et al. 2021).

Over the decades, there has also been a significant decrease in the price of these technologies. Figure 10 below shows the lowered costs of Micro Electronic Mechanical Systems [MEMS] accelerometers over the last 25 years (Développement 2021).

These decreases in prices and increases in the accuracy of accelerometers are helping researchers develop precise and cost-effective vibration-based systems for future field implementation projects.

In the recent decade, more advancements to vibration based monitoring have been noted and this progress includes advancements such as machine learning techniques coupled with instrumentation to understand changes due to temperature, as well as studies that includes analysis of multiple bridge factors to prevent showing incorrect data readings and helping obtain more accurate results (Lin and Chen 2020). The accelerometers' sensitivity to detect vibrations is also becoming more efficient in filtering out noise and sampling the correct low frequencies that naturally occur in bridges to help detect even the smallest variations. The previous problems of high-volume acceleration data and high-power requirements required for accurate output information of vibrational data are also being corrected and verified through newer accelerometers and sensors. There have also been progress in optimal sensor placement on bridges through enhancements in the modal assurance criterion and optimal sensor placement algorithms. The Modal Assurance Criterion is a statistical indicator that allows users to compare measured vibration mode shapes (Pastor et al. 2012). The correlation between mode shapes can help determine the best location to place the sensors. Optimal Sensor Placement is a method to improve the number of sensors and their positions (Avendano et al. 2021). Newer Optimal Sensor Placement algorithms are being used to optimize sensor placement since it is well-known that sensors must be placed at critical locations to obtain the most useful information (Yang et al. 2018). Even though there are advancements in the Modal Assurance Criterion and Optimal Sensor Placement methods respectively, different bridge types are considered differently and therefore the positions of the sensors


MEMS ASP* evolution** between 2000 and 2025

(Source: Status of the MEMS industry report, Yole Développement, 2020)

Price pressure is always present in the MEMS market especially in consumer & automotive. Various waves appeared historically. Where are we headed next?

→ We think players will try to acquire more value by adding functionalities/processing to the sensors, therefore the light blue curve seems likely

Current scenario: Price can't get much lower. For example, some MEMS, such as acceleros, gyros, microphones, will still need some sensing area (Si) which will have base-line cost. Also, besides the BOM, the companies will still need some margin, even if very low…

…or ASP will increase momentarily due to Covid-19 supply and demand adjustments, then fall back to pre-covid levels?

…or ASP will increase again due to added functionalities (more software, adding edge computing & AI on edge, etc.….) ???

…or will there be a new wave of MEMS ASP erosion due to Industrial/Consumer IoT… trends ???

Fig. 10 Average selling prices for MEMS Technology in the last 25 years. Figure adapted from Reference (Développement 2021) with permission from Yole Développement on the bridge to capture vibrational data changes should be determined by laboratory experiments and testing (Lan et al. 2021).

4 Conclusions

Scour monitoring has rapidly advanced throughout the years. Vibration-based monitoring of structures started in the 1940's and 1950's with the monitoring of frequency changes due to wind at the Empire State Building in New York City, which was a major first step in building health monitoring. In the 1960's and 1970's, large research programs on monitoring vibrations of structures were conducted in North America and Europe, including studies on offshore structure monitoring and scour depth measurements around bridge piers. In the 1980's and 1990's, monitoring structural integrity through vibrations received more attention and vibration-based scour monitoring at marine structures were studied. In the 2000's and 2010's, research on scour evaluation of bridge foundations using vibration measurements, real-time monitoring of scour and structural behavior monitoring were conducted. Currently, researchers are exploring ways to improve past scour techniques using machine learning, as well as studying structure health monitoring that considers environmental variables and other structural modes.

Vibration-based techniques have their advantages and disadvantages. Advantages include lower implementation costs since the systems will be installed overwater, less difficulty compared to the traditionally used underwater sensors, and easy data processing capabilities. The systems can also work on complicated bridge types. Disadvantages include excessive amounts of accelerometer data needed to see frequency changes over time, power requirements for the vibration-based systems, reliability of transmitted data, and how environmental effects will influence the natural frequency. Over time these systems should be able to correct some of the disadvantages listed, leading to a future of structural health monitoring systems which will monitor precisely and contribute to safe and reliable bridge scour detection.

The current research shows a correlation between the amount of scour and bridge frequency but has been limited to lab experiments because there is limited research conducted in the field due to observational difficulties and because the scour process occurs over a long period of time. The advancements in algorithms for data analysis, advancements in accelerometer sensitivity and technology as well as lowered costs of these technologies, and machine learning advancements are coming to the point where systems can be field implemented and gather the correct data unobtrusively and monitor the scour changes over time accurately based on vibrations and frequency changes. The creation of more precise simulations of soil-structure interactions is one important aspect to address in the near future. Addressing this will increase the precision and dependability of scour prediction. Additional study is also required to comprehend how environmental variables like wind and temperature affect bridge vibrations and to create strategies for mitigating these impacts.

In terms of hardware used for vibration-based monitoring as mentioned in "The progression and advancements in technology for vibration-based techniques" section, as the cost of sensors becomes more cost effective, it is natural that accelerometers can be used alongside other types of sensors to monitor for scour. Future work in vibration based scour monitoring may include multi-sensor system will allow for more parameters that influence the evolution of scour to be gathered and analyzed. In terms of data analysis, machine learning, and artificial intelligence are being developed to enhance the effectiveness of vibration-based scour detection (Bonakdari et al. 2020), including scouring detection, categorization, and prediction. These methods will continue to improve and be more widely utilized. Finally, it's important to note that the development of low-cost and easy-to-deploy sensors will be crucial to make vibration-based scour detection more accessible and practical for bridge engineers and maintenance staff.

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Authors' contributions
AK: Wrote the manuscript with support and input from all the authors. TY: Conceived the original idea of the manuscript, helped supervise the research, and was a major contributor to the formation of this manuscript. MO: Assisted with collection of data used in the manuscript. MA: Assisted with collection of data used in the manuscript. JY: Assisted with collection of data used in the manuscript. DG: Assisted with collection of data used in the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing or conflicts of interest.

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