Advances in Vibration-Based Scour Monitoring for Bridge Foundations

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Abstract. Scouring around bridge foundations is one of the main factors causing structural damage of bridges. Traditional scour monitoring techniques generally require a large number of sensing devices set up underwater, which is difficult to be implemented for actual bridges. To address this issue, scour monitoring technology based on structural vibrations is paid attention gradually, because this technique can work well with less equipment and can be free from the influence of the submerged environment. This study presents a systematic summary and analysis of the selection of scour indicators, sensor deployment principles and other related research involved in scour monitoring technology based on structural vibration. On this basis, the research status of the bridge scour monitoring method based on vehicle excitation is further summarized. Finally, the prospects for the application of vibration-based bridge foundation scour monitoring technology are presented, discussing the technologies that are currently missing and urgently needed for this monitoring method and the challenges faced today.

1. Introduction
Bridge failure or even collapse due to scour has become an increasingly serious problem. In the last 30 years, approximately 60% of bridge collapses in the USA have been associated with foundation scour [1]. In Colombia, over 24% of bridges have been damaged by the cumulative effect of scour, notably the Guadaus-Cabezas Bridge, which was damaged by scouring of its piers in July 2000, causing huge losses to the local economy [2]. China now has one million bridges of all types. Yi [3] collected a number of bridge collapses that occurred between 2000 and 2014, 30% of which were caused by scouring. In the first half of 2019 alone, a number of bridge scour accidents occurred in China, with serious consequences and huge impacts. Currently, however, the impact caused by scour on bridges cannot be accurately calculated by normal hydraulic and geotechnical analysis [4]. Therefore, the application of scour monitoring techniques to monitor the evolution of scour depth over time is of great importance to bridge engineering.

Traditional scour monitoring techniques like sonar, radar and sensor technology have shown significant shortcomings. Sonar technology is affected by the underwater environment resulting in low accuracy; radar technology has never performed well in brackish water environments and has a limited monitoring range; and sensing technology has complex signal interpretation. Traditional monitoring methods have been difficult to meet the needs of the population. In recent years, bridge foundation
scour monitoring technology based on structural vibration has attracted increasing attention. Compared to traditional techniques, it is independent of the underwater environment and only requires acceleration sensors or tiltmeters for scour depth measurement. As research progresses, it is now possible to achieve the accuracy required for practical projects. In the field of bridge foundation scour monitoring, this method is already dominating.

This paper provides an overview of the key issues in structural vibration-based scour monitoring technology, including the selection of scour indicators and the principles of sensor deployment, and adds a review of new techniques recently proposed for scour monitoring using vehicles as excitation sources and monitoring equipment. Finally, the shortcomings and problems of the existing research are summarised and analysed, and the development trends are clarified.

2. Scour monitoring indicators

2.1 Modal frequency

There are a variety of monitoring indicators that have been proposed in structural vibration based scour monitoring techniques. Luke J. Prendergast et al [4] concluded that scour monitoring can be carried out using the modal frequency, modal shape, modal shape curvature and covariance of acceleration signals of bridge structures. Based on this, Wen Xiong et al [5] added the use of frequency variation rate, modal assurance criterion, modal shape curvature and structural deflection as scour indicators for scour monitoring. However, at present, the modal frequency of the structure is still one of the most used indicators. When the foundation is subjected to the cumulative effect of water scour, changes in the foundation boundary conditions bring about changes in the stiffness of the structure and consequently affect the frequency of the structure. Therefore, the structural frequency is generally chosen directly to monitor scour.
However, there are two difficult problems with scour monitoring using structural frequency:

1. The sensitivity of structural frequency to scour is low. Scour is a long-term process and the boundary conditions of the foundation change very slowly, resulting in a lower sensitivity of structural frequency to scour, especially for cross-sea bridges [6] where the variation due to scour is smaller. Fabrizio Scozzese et al [7] obtained the variation of structural frequency versus scour depth through experimental simulations of scour collapse in a finite element model of a masonry arch bridge, as shown in the following table. Through the experiments he concluded that the change in frequency of the bridge structure is only more sensitive when the scour is particularly severe, and that the change in modal frequency is negligible when the scour is only on the outside of the foundation. Wen Xiong et al [5] verified this conclusion experimentally and concluded that frequency is generally only used as a qualitative estimate of scour.

Table 1. Frequency evolution due to scour depth progression

| Depth (m) | 1.0  | 2.0  | 3.0  | 4.0  | 5.0  | 6.0  | 7.0  |
|-----------|------|------|------|------|------|------|------|
| Frequency (Hz) | 6.455 | 6.453 | 6.445 | 6.428 | 6.357 | 5.077 | 3.431 |

To address these issues, Tzu-Kang Lin et al [8] proposed the use of fractal dimension (Ds) and topology (G) as scour indicators for scour monitoring. The fractal dimension (Ds) and topology (G) are the two main parameters of the modal signal obtained by Fourier transform, where the fractal dimension (Ds) is used as a proxy for the fundamental frequency of the structure and the topology (G) as a proxy for the vibration amplitude. Ds and G are highly sensitive to scour and provide a better indication of the variation of the vibration signal than direct estimates of the principal frequency and amplitude. Tzu-Kang Lin derived the range of values for the two main parameters and proposed an empirical formula for the scour safety factor (SF) for bridges through single column and full bridge experiments.

\[ SF = (Ds - 1)(\sqrt{G} + 1) + 0.3 \]  \( (1) \)
Tzu-Kang Lin has experimentally demonstrated that this formula is a good way of monitoring the critical conditions for scour damage to bridge foundations. In laboratory experiments, a bridge is considered to be in a safe condition when $SF \geq 1$; when $SF < 1$, it is on the verge of damage and collapses rapidly. The fractal dimension ($D_s$) and topology ($G$) are more sensitive to foundation scour, complementing some of the shortcomings of modal frequency as an indicator.

(2) The frequency of the structure is strongly influenced by the environment (temperature). Drastic changes in temperature affect the material properties as well as the boundary conditions of the structure. When the frequency changes it is generally difficult to distinguish whether it is due to scour or temperature. The problem of temperature is currently dealt with using statistical methods such as non-linear principal component analysis (NLPCA), artificial neural networks (ANN) and support vector machines (SVM) [9-12]. Wei Zheng et al [13] applied a probabilistic machine learning approach based on a Gaussian process model to understand the change in modal properties of the monitored bridge and the corresponding temperature measured by field sensors and thus mitigate the effects of temperature variations. There are many other methods to remove the effects of temperature, which are not listed here.

2.2 Modal shape

Compared to modal frequency, the modal shape has obvious advantages as a scour monitoring indicator. It is also one of the most used scour indicators as it is more sensitive to scour and is not affected by changes in other environmental conditions such as temperature. Damage to the bridge structure can be determined using significant changes in modes. A. Malekjafari et al [6] first introduced the concept of Modal Shape Ratio (MSR), which is the ratio of modal shaped amplitudes at two points on the overall structure of a bridge, as a new indicator of bridge scour. A. Malekjafari et al. found a 20% change in frequency and a 50% change in MSR in a 0-5m bridge foundation scour experiment, which shows that it is very sensitive to scour, but it has only been experimentally verified on a two-span bridge, so the specific application of MSR needs to be further tested. Using the same idea, Abdollah Malekjafari et al [14] proposed another new scour indicator, MNMS, which uses the relative variation of abutment amplitudes and uses frequency domain decomposition (FDD) to extract the first-order global amplitudes of multi-span bridges from acceleration measurements, and then tracks the relative variation of abutment amplitudes under scour action. The modal amplitude values of each pier are compared with the mean values of the remaining piers to form the normalised modal amplitude model (MNMS). Abdollah Malekjafari et al. went on to experimentally verify on a scaled-down model of a four-span bridge that scour locations could be accurately identified. However, the monitoring was not satisfactory when multiple piers were scoured. Therefore, such methods need to be further explored to meet practical engineering needs.

2.3 New indicators for scour monitoring

It is difficult to quantify the scour depth by simply applying the modal frequency or the modal shape. C. S. Cai et al [15] proposed a new bridge scour indicator for scour monitoring. Deriving the flexibility matrix ($D$) reflecting scouring by combining the two dynamic properties of natural frequency and modal shape. The deflection change parameter ($d$) is then defined as the change in the flexibility matrix due to scour and is further used as an indicator to identify the depth of scour. Once the dynamic characteristics ($d$) of the structure have been determined, the corresponding scour depth can be inferred from the early predicted relationship between $d$ and scour depth. Finally C. S. Cai illustrates the feasibility of the method based on actual field data. This method does not require any underwater instrumentation for long-term monitoring and is worth promoting.

In addition to the vibration pattern and frequency, the damping ratio of the structure is also a very important monitoring indicator. In the field of foundation scour monitoring, there are no relevant studies at home or abroad. In structural dynamics, damping is usually divided into viscous damping
and structural damping, which is very sensitive to changes in boundary conditions. Therefore, the use of structural damping to identify scour depth also shows good application prospects.

3. Principles of sensor arrangement

The correct installation of sensors on a bridge plays a vital role in providing us with a stable, effective bridge vibration signal. Traditional scour monitoring techniques generally require sensors to be installed underwater, and the sensing equipment is greatly affected by the underwater environment. The structural vibration-based scour monitoring technique presented in this paper allows the sensors to be placed on the superstructure of the bridge [14-16], and the sensors work independently of the underwater environment, which is important for the long-term safe operation of the scour monitoring system.

There is no clear answer to the question of where to install the sensors, as scholars both at home and abroad are divided. Luke J et al [4] used vehicles as excitation sources to generate moments at the top of bridge abutments and piers to cause transverse sway. He concluded that the top of the abutment was the best location to measure acceleration because the maximum transverse modal amplitude occurs at the bridge deck, and that installing sensors at the top of the abutment would help to identify the frequency and help to solve the signal-to-noise problem. Wen Xiong et al [16] gave several recommendations for the installation of sensors based on a cable-stayed bridge model:

(1) The sensor is to be placed in a position where it can be easily installed and measured.
(2) The location of the crests and troughs of low-order mode shapes, as these are sensitive to scouring.
(3) The quarter division point between the adjacent crest and trough of the selected mode shapes.
(4) The location of the point where there is a significant change in the modal shape to determine the curvature of the shape change.
(5) Location of scour-sensitive girder and tower sections in the vicinity of bridge piers.

This is a more detailed proposal for the deployment of sensors and the following diagrams are given for these recommendations.

![Arrangement of vertical acceleration sensors](image)

**Figure 3.** Arrangement of vertical acceleration sensors

No valid conclusions have been reached regarding the location of the transducers. In previous experiments, the dynamic response was usually obtained by sensors at the bridge deck, at the top of the piers or even at the bottom of the piers. There has been little research on where the effective or optimal location for sensor installation is, but such research is significant in that the optimal location...
can be a good guarantee of signal acquisition, and these issues can be addressed by experimental and numerical simulations to measure the dynamic response of bridge members at different locations [17].

4. Vibration scour monitoring based on vehicle sensing

Monitoring scour requires the study of multiple structural interactions, including vehicle-bridge interactions, bridge-wave interactions and foundation soil-bridge interactions. L. J. Prendergast et al [4,18] proposed a new vehicle-bridge-soil dynamic interaction model (VBSDI), which was used to simulate the effects of scour on the overall bridge. The dynamic signal output from the model is used to determine the modal parameters of the structure and the scour is identified by the variation of the parameters. VBSDI is the first numerical model to simulate scour and combines realistic vehicle loads with a foundation soil model, which is capable of outputting dynamic displacements, velocities and accelerations from multiple points on a bridge structure. In addition, the model is capable of outputting dynamic displacement, velocity and acceleration signals as the vehicle model passes over the bridge.

Firstly, soil-structure interactions are incorporated into the model by using the Winkler method. The soil is modelled as a discrete, mutually independent system of compact lateral springs. Furthermore, in the study of the vehicle-bridge interaction, the vehicle model has four degrees of freedom: the vertical displacement of the two axes ($y_1, y_2$), the body bounce ($y_b$), and the body pitch ($w_p$), and also includes the stiffness ($k$) of the suspension as well as the damping coefficient ($C$). The tyres are modelled as springs with stiffness. The specific schematic is as follows:

![Numerical model](image)

**Figure 4.** Numerical model

Chen et al [19], L.J. Prendergast et al [16,20] develop complete finite element models by updating the model properties to obtain modal data that match those of the actual structure. The numerical model is then used to update the scour depth around the piers until the predicted modal data matches the observed data. The use of numerical models to determine the actual scour around the actual piers is a successful application of vibration-based scour monitoring methods in practical engineering. In the vehicle-bridge-soil interaction model, the vehicle vibration response caused by scour is significant when scour is present. Therefore, Luke J. Prendergast et al [4,18] proposed to use the vibration response of a vehicle to identify foundation scour by installing acceleration sensors in a moving vehicle through a damaged bridge and using the sensor signals to identify the scour depth. X. Kong et al [21] also proposed the use of wave-excited lateral vibrations of bridges followed by vehicle
vibration signals to monitor scour. The method is still at a preliminary stage and there are still relatively few relevant studies, which could be put into research as a priority in the future.

5. Conclusions
By discussing the key issues involved in the selection of monitoring indicators and the optimal location of sensor installation in the bridge foundation scour monitoring technology based on structural vibration, the following conclusions are reached in this paper.

1) The selection of scour indicators focuses on the sensitivity of the indicators themselves to scour and the extent to which they are influenced by the environment. Traditional scour indicators such as modal frequency and modal shape are generally only used for qualitative analysis and it is difficult to obtain accurate scour depths through computational analysis. In the future, several indicators can be considered in combination or new ones can be developed for scour monitoring.

2) The question involving the optimum mounting position of the sensor has been unresolved in recent years. Different bridge types are considered differently and therefore the mounting position of the sensor should be determined by laboratory experiments according to the specific engineering situation. There is a lack of experiments on this issue, but in the future the principle of sensor mounting for different bridge types can be determined experimentally.

3) Scour monitoring using vehicles on bridges and the proposed numerical model for full bridges provide new directions for scour monitoring techniques based on structural vibrations, but there is currently little relevant research that could be a focus for future research.

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