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Bridge scour monitoring using accelerometers placed on bridge piers – a numerical investigation

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Abstract

Bridge scour has been identified as one of the leading causes of bridge failures in recent years, and caused the collapse of the Malahide Viaduct, a mainline railway bridge on the TEN-T network, in North Dublin in 2009. Scour is the term given to the removal of supporting soils from around foundations as a result of increased hydraulic stresses, a process exacerbated in times of heavy flooding. Scour is notoriously difficult to predict due to its dependence on many uncertain hydraulic parameters and difficulties in determining the exact condition of underwater foundations. This is a particular problem for rail bridges which may have been built more than 150 years ago. Protecting structures against scour generally involves relatively expensive installations that may not prove economically viable for widespread usage. Therefore, monitoring of scour-critical infrastructure is an attractive solution for infrastructure managers. The most common method for scour monitoring is to undertake visual inspections using divers to obtain the depth of scour around a foundation. This can prove time consuming and be particularly dangerous in times of heavy flooding, when scour is most critical. This paper charts the development of a new method of scour monitoring that uses the bridge structure itself to indicate the severity of the scour problem. Scour causes a reduction in foundation stiffness by removing soil from around foundation elements. This can manifest itself as a change in the natural frequency of bridge piers, due to the increase in effective length and reduction in soil stiffness. This paper presents a numerical examination of the effect of scour on the frequency response of a range of bridge pier geometries. The purpose is to show the effectiveness of the technique at remotely monitoring scour using accelerometers placed above the waterline.

Keywords: scour, vibration, accelerometer, frequency, Structural Health Monitoring (SHM)


1 Introduction to scour

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 [1], See Figure 1. Scour occurs in three main forms: 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 such as changes in the flow rate or changes in the quantity of sediment in the channel [2]. Contraction scour occurs in the general vicinity of channel obstructions, in this case, a bridge. 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. Finally, local scour occurs around individual bridge piers and abutments. It is caused by the generation of vortices as water accelerates around these obstructions. Downward flow is induced at the upstream end of bridge piers leading to very localized erosion in the direct vicinity of the structure [1].

Scour of foundations is the number one cause of bridge failures in the United States [3], [4], [5]. During the last 30 years, 600 bridges have failed due to scour problems [6], [7] resulting in significant operating disruption and financial losses. In one study investigating the causes of five hundred bridge failures that occurred between 1989 and 2000, scour and flooding were the cause of 53% of these failures [8]. Scour poses ongoing problems for bridges in operation and a balance between adequate protection and cost reduction must be undertaken with regard to protecting susceptible structures.

Figure 1. Scour process schematic [9]
1.1 Scour protection

It is possible to combat scour in a number of ways to mitigate its effect on vulnerable structures. At the design stage for a new bridge scheme, both hydraulic and structural countermeasures can be undertaken [10]. Hydraulic countermeasures involve the prevention of rapid flow expansion or contraction caused by sudden induced changes in flow direction as would occur at blunt or misaligned bridge pier faces. By streamlining pier faces and maintaining larger bridge openings at the design phase, these sudden flow direction changes can be prevented [11]. During the service life of a bridge, bridge openings should be routinely cleared of fallen trees and other debris so as to ensure flow continuity is not disrupted in the vicinity of bridge substructures. Structural countermeasures at a bridge design phase include ensuring that spread footings are located below the maximum expected design scour depth. This also applies to piled foundations by ensuring that adequate penetration of piles is achieved so that losses in shaft resistance due to loss of soil support does not have an overall implication for structural stability. These design countermeasures are limited by design uncertainties in scour depth estimation. These estimates can be based on formulae such as the Colorado State University (CSU) method [12] formulated in the Hydraulic Engineering Circular (HEC-18) design code [13]. Structural remediation works can also be carried out during the bridge service life and generally include the addition of rock-armour and rip-rap to the base of bridge piers and abutments.

1.2 Scour monitoring using depth measuring instrumentation

Many different devices have been developed over the years that aim to monitor the progression of scour depth with time at scour-critical locations. A full description of different scour monitoring systems is given in [9]. A brief synopsis of these devices is given herein. Devices range from simple float-out devices and radar measurement systems to driven mechanical systems and sound wave monitoring systems. These devices can either be permanently installed in the streambed at scour critical locations or used as part of routine maintenance inspections. The use of devices to monitor scour has gained potential in recent times due to an increase in the available technology and reliability of the measurements taken by these systems. These systems generally aim to monitor the change in scour depth at their installation locations. Figure 2 shows an overview schematic of these systems in place.
1.3 Scour monitoring using modal damage detection techniques

The use of modal damage detection techniques has gained significant research interest in recent years and has been used widely to detect damage such as cracking in bridge superstructures. The observation that changes in structural properties cause changes in natural frequencies was the impetus for using modal methods for damage identification and health monitoring [14]. These ideas can be transferred to the case of monitoring scour. Removal of material from under (or around) foundations during scour will cause increased stress and consequently reduced stiffness in the remaining soil. Since the frequency of vibration of structures depends on the system stiffness, observing changes in vibration frequencies is a potential method for damage identification and health monitoring [9]. Many authors have attempted to identify the presence and extent of scour around structures by observing changes in dynamic characteristics (see [15], [16], [17], [18]).

2 Field Investigation of the change in frequency of a bridge pile affected by scour

A field investigation into the effect of scour on the frequency response of a pile embedded in dense sand was undertaken by [15]. The current study builds on the results and methods from this study. The research involved placing accelerometers along the exposed portion of a 8.76 m long pile driven to an embedment depth of 6.5 m in dense sand. Sand was removed from around the pile in 0.5 m increments and the frequency response for each excavation depth
was obtained by impacting the pile with a modal hammer. The effect of increasing the scour depth on the natural frequency of the pile is shown in Figure 3. Also shown in this figure is the change in frequency of an equivalent cantilever clamped at the soil-air interface at each scour depth (i.e. for soil with infinite stiffness).

![Graph showing experimental and fixed cantilever frequencies with scour depth.](Figure 3. Experimental results of frequency change with scour [15].)

A numerical model was developed that was capable of tracking the change in frequency with scour of this experimental pile. The development of this model is described in the following section.

### 3 Numerical study on effect of scour on bridge pier frequency response

Following on from the investigation presented in [15], the effect of scour on the natural frequency response of a typical bridge pier-piled foundation is analysed with respect to ascertaining if feasible frequency changes can be obtained for measuring the presence of scour around a foundation element. A typical set-up is employed as is shown in Figure 4. For the connection with the superstructure, two scenarios are modelled: the first considers a pinned relationship between the pier and the deck, the second assumes full-fixity between the pier and deck. In reality, the stiffness of this boundary will be somewhere between these two extremes so both are analysed in order to ascertain if the changes in natural frequency which occur because of scour can be detected using the proposed method. The bridge pier length and diameter were varied in the parametric analysis to establish the envelope of expected frequency shifts for the two boundary conditions assumed.
Figure 4. Bridge pier scour model schematic. (a) Model schematic; (b) Numerical schematic

The numerical model involved using Euler-Bernoulli beam elements to construct a model of a bridge pier supported on a pile with a pile-cap at the interface. The beam elements contain four degrees of freedom and are available in [19]. The embedded portion of the pile is modelled using spring-beam elements, known as the Winkler hypothesis [20], which contain five degrees of freedom. The pile-cap is modelled as a lumped mass at the interface node. The modelling parameters are shown in Table 1.

Table 1. Model parameters

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<tr>
<td>Pier Diameters (m)</td>
<td>1, 1.5</td>
<td>Pile diameter (m)</td>
<td>0.34</td>
</tr>
<tr>
<td>Pier lengths (m)</td>
<td>5, 10, 15</td>
<td>Pile penetration (m)</td>
<td>6.57</td>
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<tr>
<td>Scour depths (m)</td>
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<td>Pile material</td>
<td>Steel (ρ=7850 kg/m$^3$)</td>
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<td>Pile-cap dimensions (m x m x m)</td>
<td>2 x 2 x 1</td>
<td>Pier material</td>
<td>Concrete (ρ=2400 kg/m$^3$)</td>
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<tr>
<td>Pile-cap mass (kg)</td>
<td>9600</td>
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The stiffness of the soil that is attributed to each spring in the model is derived from the work presented in [15], corresponding to field measurements from the University College Dublin test site at Blessington, Ireland. Scour is modelled as the removal of springs from the pile elements. An eigenvalue analysis is then performed within the model to obtain the natural frequencies. The results of the parametric analysis, plotted as relative changes in the natural frequency, \( f \) to the original natural frequency, \( f_0 \), are presented in Figure 5. The results suggest that for the range of parameters considered the natural frequency of the foundation-bridge system is sufficiently sensitive to scour to allow the method to be used in the field.

![Figure 5](image.png)

**Figure 5.** Change in frequency for bridge pier subjected to 3 m scour depth. (a) pinned connection assumed with deck; (b) fixed connection assumed with deck [9].

### 4 Conclusions

A numerical model was used to investigate whether a bridge monitoring scheme could be developed that uses changes in the natural frequency of a bridge to predict scour of foundations. The results from the analysis show that significant frequency changes can be obtained over the depth of scour of 3 m. The analysis is quite sensitive to the boundary conditions assumed with frequency changes ranging from 50% to 69% for the pinned boundary and 21% to 60% for the fixed boundary over the full scour depth. The purpose of this study was not to obtain realistic frequency changes but merely to ascertain if using accelerometers to detect scour is viable. The authors conclude that the results seem promising and a full-scale implementation of the technique will be carried out in the near future.
References