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Monitoring of scour critical bridges using changes in the natural frequency of vibration of foundation piles – A field investigation

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Abstract

The highly publicised failure of the Malahide Viaduct Railway Bridge in Ireland in 2009 was attributed to erosion of the supporting soils, commonly referred to as foundation scour. This is a widespread geotechnical-structural problem that has been identified as the main cause of failure of bridges in the United States. Monitoring scour is of significant importance to ensure the continued safe operation of the ageing bridge asset network. Most of the current monitoring regimes rely on expensive underwater instrumentation that is often subject to damage during times of flooding, when scour risk is at its highest. In this paper, a novel scour monitoring approach based on dynamic measurement techniques is described. The investigation involves the mounting of accelerometers on the structure of interest, which may be used as a non-intrusive monitoring scheme above the waterline. A significant advantage of this method over traditional scour monitoring approaches is that the structure itself is used to monitor the scour damage.

Keywords: Bridge Scour; Pile; Acceleration; Frequency; Structural Health Monitoring

Résumé

L'échec de haut niveau du pont de chemin de fer Viaduc de Malahide, en Irlande en 2009 a été attribué à l'érosion des sols à l'appui, communément appelés fondation affouillement. C'est un problème structurale répandu géotechnique-qui a été identifiée comme la principale cause de l'échec des ponts aux États-Unis. Le monitoring est d'une grande importance pour assurer la poursuite de l'exploitation sûre des vieux ponts. La plupart des régimes de surveillance actuels reposent sur des instruments sous-marin coûteux qui sont souvent soumis à des dommages en cas d'inondation. Dans cet article, une approche de surveillance basé sur des techniques de mesure dynamique est décrite. L'enquête comprend des accéléromètres de montage sur la structure d'intérêt, qui peut être utilisé comme un système de surveillance non intrusive en dessus de la ligne de flottaison. Un avantage important de cette méthode sur l'affouillement des méthodes de surveillance traditionnelles est que la structure elle-même est utilisée pour contrôler les dommages affouillement.

Mots-clé: affouillement de ponts; pile; accélération; fréquence ; surveillance de la santé structurelle.
Nomenclature

A  Cross-sectional area of pile (m²)
[D] System matrix
E  Young’s modulus of pile (kN m⁻²)
E₀ Small-strain Young’s modulus (kN m⁻²)
G₀ Small-strain shear modulus (kN m⁻²)
I  Moment of inertia of pile cross-section (m⁴)
[K] Global stiffness matrix
K  Modulus of subgrade reaction (kN m⁻²)
[M] Global mass matrix
ρ  Density of pile material (kg m⁻³)
v  Poisson ratio of soil

1. Introduction

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). There are three main divisions of scour: 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 (Forde et al., 1999). 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 localized erosion in the direct vicinity of the structure (Hamill, 1999). In terms of structural stability, it presents a widespread geotechnical-structural problem. In one study of 500 bridges in the United States, scour and other hydraulic phenomena have been identified as the main cause of failure in 53% of bridges (Wardhana & Hadipriono, 2003).

The depth of soil erosion (scour) around a bridge structure arises due to a combination of general, contraction and local scour. The scour hole that is generated can reduce the foundation stiffness significantly and lead to sudden collapse. The development of a scour hole cannot easily be prevented but may be combated using some simple scour mitigation measures. The best practice is to monitor its progression over time and implement remediation measures if required. Some common instruments for monitoring scour are briefly discussed in section 2.

2. Scour monitoring using fixed instruments

Scour monitoring takes many forms, from visual inspections to complex instrumentation capable of remotely sensing the depth of scour affecting a structure. Significant developments have been made recently into underwater instruments that aim to observe the change in scour depth over time (See Fig. 1(a)). These devices may be sub-divided into a number of categories, namely: single-use devices, sonic pulse and radar devices, buried and driven rod systems, sound-wave monitoring devices, and finally, devices based on changes in electrical conductivity. Some of these are discussed briefly herein.

Two types of typical single-use devices are float-out devices and tethered buried switches. These devices can be installed in the ground, near a bridge pier or abutment of scour interest. They can be programmed to remotely send signals to data-acquisition systems indicating their status, be it in position or floated out. They float out of the soil once the depth of scour reaches their installation depth, as they are no longer fixed in place once this occurs. Some notable disadvantages of this type of instrument are that they require re-installation upon floating out of position and can only indicate that the depth of scour has reached the position at which they are placed. For this reason, they are generally only used in easily accessible areas.

Sonic 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 medium. This typically occurs at a water-
sediment interface. This technology can thus indicate a change in bed elevation if used over time and hence a scour depth at a particular location. Time-domain Reflectometry (TDR) is one method that uses changes in the dielectric permittivity constants between soil and water to determine a depth of scour at a particular location (Yu, 2009). Measuring probes are installed into the soil at a location of scour interest and a step impulse is sent down a tube which determines the interface between the water and the soil, and hence the depth of scour. These devices may be used to observe the changing scour depth with time (Hussein, 2012). Ground-Penetrating Radar (GPR) uses radar pulses to determine the water-sediment interface. It involves floating a GPR transmitter along the water surface and obtaining a geophysical profile of the riverbed as it passes. 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. It is also not a remote sensor as it requires significant human input for correct operation.

Driven or buried rod systems used to detect the presence of scour include the Magnetic Sliding Collar, the “Scubamouse”, the Wallingford “Tell-Tail” device and Mercury Tip Switches. These instruments work using the principle of a gravity-based physical probe that rests on the streambed moving downward with increasing progression of scour depth. A remote sensing element is typically used to detect the level change of the gravity sensor, relative to a fixed rod placed in the soil. In the case of a magnetic sliding collar, the location of the collar relative to its original position is determined by the closure of magnetic switches along the structurally rigid rod. 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. Mercury tip switches work on the very basic principle that when a steel pipe is augured into the ground, switches located along the shaft fold up against the pipe, which closes the circuit. As streambed material is eroded away, the switches open iteratively which breaks the circuit and monitors the progression of scour. These instruments typically require re-installation and cannot detect the presence of infill – soil that enters the scour hole upon the subsidence of flood waters. They are quite adept at obtaining the deepest depth of scour reached.

Some of the aforementioned instruments are illustrated in Fig. 1.(a). Methods based on structural response measurement have come to the fore of research in recent times. Some of these methods are briefly discussed in section 3.

Fig. 1. (a) underwater scour instruments; (b) dynamic system measurement.
3. Scour monitoring using structural response measurement

Scour monitoring equipment has predominately focused on detecting the change in elevation of the bed level around structures using embedded instruments. Since scour causes a loss in foundation stiffness, methods that are capable of directly measuring this phenomenon are more likely to be able to assess the risk of structural failure. Monitoring the dynamic response of the structure is a relatively new area in terms of scour monitoring and has been investigated by some authors (See Fig. 1(b)). A full scale bridge investigation was undertaken in Northern Italy after a flood in 2000, which left one of the supporting bridge piers in a state of disrepair and had to be replaced (Foti & Sabia, 2011). A dynamic survey of the structure was conducted before and after the replacement of the pier to see if changes could be detected due to the scour that had occurred. By comparing the survey to reference numerical models developed using finite element software, it was concluded that the presence of scour was detectable but its extent was not. A laboratory investigation into the effectiveness of different scour monitoring equipment in the detection of scour was undertaken in Texas A&M Coastal Laboratories recently (Briaud et al., 2011). A scaled bridge with a central pier was constructed in a large hydraulic flume with two different foundation types, a shallow pad set-up and a deep piled foundation. Accelerometers were placed on the structure and the analysis showed that accelerometers showed promise as a method to detect scour. Impacts from a rubber hammer (to represent traffic) were used to excite the structure. However, a full-scale field implementation of the method did not prove as promising, with low excitation experienced due to traffic blamed as the reason for the low response rate, and large data transmission difficulties with the volume of acceleration data required for measurement.

4. Field investigation at UCD dense sand test site

This paper details the methods used to develop a methodology that allows for direct scour measurement based on an observed frequency response of foundation piles. It follows on from the work of Briaud et al. (2011) and Foti & Sabia (2011) detailed previously. A full scale field test to ascertain the effect of scour on the natural frequency of a driven pile was undertaken on a test pile at a test bed site in Blessington, outside Dublin city, Ireland. A numerical model was developed that is capable of predicting the frequency response of an embedded pile using springs to represent the lateral stiffness of the soil. This validated numerical model can be used to estimate the depth of scour around a structure using only the observed frequency response of the structure.

4.1. Field test

A full-scale test of the frequency response measurement of an installed pile was undertaken to establish the change in the natural frequency with the progression of scour. An open ended steel pile was driven into a dense sand test bed to a depth of 6.5 m below initial ground level. The pile had a total length of 8.76 m and a diameter of 0.340 m, with an annular thickness of 13 mm. It had a Young’s modulus (E) value of 2 x 10^11 N m^2. Four accelerometers were placed along the exposed portion of the pile shaft. These accelerometers were programed into a Campbell Scientific CR9000x datalogger, where a scan rate of 1000 Hz was implemented. The pile head was excited using a modal hammer, programmed to excite low frequency resonances (heavy hammer, soft tip) so that the fundamental mode would dominate the frequency spectrum (see (Dezi, Gara, & Roia, 2012) for more information on impact testing of piles). A range of predetermined scour depths were set at 0.5 m spacing along the pile shaft. An excavator was used to remove the sand from 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 undertaken at each predetermined scour depth. An image of the test in progress is shown in Fig. 2.
Once the acceleration response of the structure was obtained for each depth of scour, the frequency content of the signal was obtained by passing the time-domain acceleration signal through a Fourier transform using the analysis tool in MATLAB. A number of trials were undertaken at each depth and the frequency results were shown to be quite consistent. A profile of frequency response against depth of scour was created based on the experimental results.

### 4.2. Numerical modelling

In order to track the change in frequency and make a definitive link to the depth of scour around a pile, it is necessary to model the pile-soil dynamic interaction process. A finite-element model was developed using MATLAB. The structure of the pile was modelled using standard four degree of freedom (4-DOF) Euler-Bernoulli beam elements, the mass and stiffness matrices of which are given in (Tedesco et al., 1999). The embedded portion of the pile was modelled by attaching a lateral linear spring to one node of each beam element and using modified mass and stiffness matrices to account for this alteration.

Once the different elements have been specified in the model, it is necessary to assemble the global stiffness and mass matrices such that a dynamic analysis may be carried out. The assembly algorithm was extracted from (Kwon & Bang, 2000). A dynamic analysis is undertaken by specifying a system matrix \([D]\), which is a function of the global mass and stiffness matrices. This is shown in Eq. (1).

\[
[D] = [M]^{-1}[K] \tag{1}
\]

where \([D]\) = system matrix, \([M]\) = global mass matrix and \([K]\) = global stiffness matrix. The natural frequencies and mode shapes of the system can be obtained as the eigenvalues and eigenvectors of the system matrix. This is achieved using MATLAB’s inbuilt ‘eig’ function.

In order to model the system correctly, the system properties must be such that they match their real-life counterpart discussed in section 4.1. The properties of the pile are relatively straightforward to model as they are comprised of the standard structural parameters (E, I, A, \(\rho\)), all of which are easily obtained. The lateral stiffness coefficient for the springs, however, is where the difficulty lies. The primary geotechnical properties of the site are outlined in a subsequent Table 1 (Gavin et al., 2009; Gavin & Lehane, 2007). Since dynamic oscillations are relatively small, they impart very low strains in the soil mass surrounding the pile. As a result of this, the small-strain shear modulus \((G_0)\) is a particularly useful parameter in terms of dynamic soil-pile interaction modelling. The small-strain shear modulus for the test site is converted from shear wave velocity measurements, which are obtained using a relatively straightforward procedure known as the Multi-Channel Analysis of Surface Waves (MASW) (Donohue et al., 2004). A profile of the shear wave velocities and associated small-strain shear modulus is shown in Fig. 3.
Table 1. Site Properties

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<th>Value</th>
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<tr>
<td>Sand D₅₀ (mm)</td>
<td>0.1 mm – 0.15 mm</td>
</tr>
<tr>
<td>Fines Content</td>
<td>5% - 10%</td>
</tr>
<tr>
<td>Equilibrium Water Table (m BGL)</td>
<td>13 m</td>
</tr>
<tr>
<td>Bulk Density (Mg m⁻³)</td>
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<tr>
<td>Unit Weight (kN m⁻³)</td>
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</tr>
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<td>Constant Volume Friction Angle (°)</td>
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</tr>
<tr>
<td>Peak Friction Angle (°)</td>
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<tr>
<td>Specific Gravity</td>
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<td>e_max</td>
<td>0.73</td>
</tr>
<tr>
<td>e_min</td>
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Fig. 3. (a) shear wave velocity measurements from MASW; (b) G₀ profile (kPa) for test site.

Individual spring moduli are obtained for the numerical model by first converting the G₀ profile in Fig. 3.(b) to a Young’s modulus (E₀) profile for the site. This is achieved using the well-known relation shown in Eq. (2).

\[ E₀ = 2 \frac{G₀}{1+ν} \]  

Where ν is the small-strain Poisson ratio for the site. This E₀ profile can then be converted to a modulus of subgrade reaction (K) profile using the procedure outlined in (Ashford & Juin narongrit, 2003). The individual spring constants are obtained by multiplying the average K value at a given spring depth by the spring spacing. These are then applied to the model in MATLAB and form part of the global stiffness matrix for the combined system.

Scour is modeled by removing springs from the numerical model to simulate the effect of scour lowering the bed elevation level relative to the pile. At each spring removal phase, a new eigenvalue analysis is carried out to
obtain the natural frequency response of the pile. The results of both the field test and numerical modeling are presented in the next section.

5. Results & conclusions

In the field test, scour was induced using an excavator to remove sand from around a driven pile system. The dynamic response of the pile was obtained for a range of scour depths by impacting the pile head with a modal hammer and measuring the resulting acceleration using accelerometers installed along the exposed shaft. The frequency content was obtained using Fourier transforms on the time-domain signals and these are plotted against their corresponding scour depth. In the numerical modeling, a discretized beam model is created that aims to simulate the actual response of the field test. The pile is modeled using standard beam elements and the soil stiffness is modeled by attaching springs to the embedded beam sections. An eigenvalue analysis is undertaken on a defined system matrix to obtain the frequency response of the system. Scour is modeled by progressively removing springs from the model to correspond to a decrease in soil support level (model the action of the excavator). The results from both analyses are compared in the Fig. 4 below.

As is evident in Fig. 4, a very good match is observed between the experimental response and the numerical prediction. This plot shows the change in frequency obtained from the field investigation of the effect of scour and that predicted by a numerical model. Using the methods outlined in this paper to model the soil-structure interaction, it is possible to predict the depth of scour based on an observed frequency response. To this end, placing accelerometers on a bridge pile above the waterline should be capable of tracking the changes in the depth of scour, which will manifest itself as a reduction in observed frequency.

In a real-life scenario, the effect of the superstructure mass should also be taken into account as this will have a significant effect on the frequency response of the combined system. This paper, however, paves the way with the methods required to undertake such an analysis and is an improvement on traditional scour monitoring using fixed instrumentation.
Acknowledgements

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