Bridge Scour Detection using Vehicle Acceleration Measurements

Eugene J. OBrien[1], Abdollah Malekjafarian[1], Paul C. Fitzgerald[1]

[1]School of Civil Engineering, University College Dublin, Ireland

email: eugene.obrien@ucd.ie, abdollah.malekjafarian@ucd.ie, paul.fitzgerald.3@ucdconnect.ie

ABSTRACT: Bridge scour is a serious issue concerning bridge condition and can have adverse consequences if undetected. It is the most common cause of bridge collapse today. One method of assessing the issue is through the use of visual inspections but this has drawback in that often an underwater inspection may have to be carried out. This makes it an expensive solution. Human objectivity leads to inconsistencies in the approach also and this is an issue. A sensor-based approach is a suitable alternative due to these reasons. The use of vehicle acceleration measurements to detect scour is analysed in this paper. The continuous wavelet transform is used to decompose the accelerations into time and frequency information. It is found that the location of the pier under which the scour is present can be identified using this method.

KEY WORDS: Bridge Scour; Continuous Wavelet Transform; Vehicle Accelerations.

1 INTRODUCTION

Bridge scour is the erosion of soil around the foundation of a bridge and is the most common cause of bridge collapse in the United States [1]. The Malahide Viaduct collapsed in Ireland due to scour in 2009 [2]. Having a reliable scour detection scheme is imperative to ensure the continued safety of a bridge. Visual inspection methods have previously being used to make a bridge scour assessment, but the method has issues in that visibility is limited underwater and access is not convenient. Moreover, a scour hole may in fact have been deeper during a flood and will have infilled somewhat after the flood. A reduction in mechanical strength is a consequence of this and this issue cannot be detected visually [3]. Instrumentation has also been used and these devices generally monitor the depth of a scour hole. A float-out device is one example of these devices. It is installed in the riverbed and it simply floats to the surface when a pre-defined scour depth has been reached. Prendergast and Gavin carry out a more detailed review of current methods being used to detect scour [4].

Vibration-based approaches have long been used to detect bridge damage [5-7]. The reduction in bending stiffness due to damage affects the bridge modes of vibration and changes in these vibration modes can be used as means to monitor its condition. Recently, the same approach has been used in the scour monitoring field [8-10]. The removal of soil around a bridge foundation results in a loss of support stiffness. This loss of stiffness can be detected by installing sensors on a pier and monitoring changes in frequency of vibration. A downside of this approach is that many sensors may need to be installed depending on the number of bridge spans and a source of sensor power is also required.

A drive-by approach to detect bridge scour is investigated here. Drive-by uses vibration data from sensors installed on a passing vehicle and is hence an indirect approach. An application to monitor scour of a railway bridge is investigated here. In this paper, a train carriage is represented by a simplified two degree of freedom model. Accelerations from the degree of freedom representing the train bogie are analysed using the Continuous Wavelet Transform (CWT). Wavelet choice is an important aspect in this approach. Reda-Taha et al. [11] review wavelet choices previously used for structural health monitoring approaches. The 'Mexican Hat' wavelet is used in this paper. Scour is detected by calculating the differences in the CWT coefficients between a healthy and scoured case.

2 MODEL

A numerical vehicle bridge interaction (VBI) is modelled using finite element (FE) method in this study. A schematic of the dynamic model used is shown in Figure 1. There are three main parts in the model: the vehicle, bridge and the supports (which are resting on a spring representing the vertical stiffness provided by the foundation) and all components are coupled. There also exists a rail profile (FRA Class 4). Before the bridge, a 50 m approach is used. This is used to ensure that vehicle transient effects are removed before the vehicle arrives on the bridge.
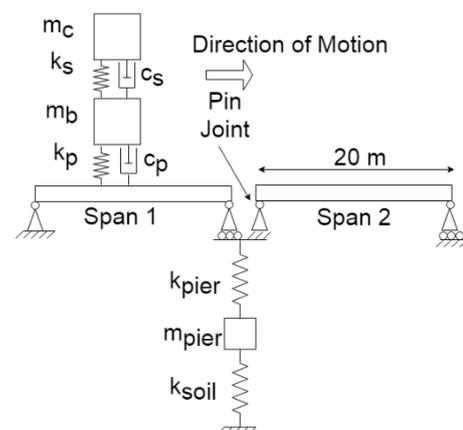

Figure 1. Model Schematic.

Table 1. Vehicle properties (based on [12]).

Property	Value	Unit
m_c	18,426	kg
m_b	3,910	kg
k_p	5.6	MN/m
k_s	2	MN/m
c_p	58.8	kNs/m
c_s	60	kNs/m

A train is modelled using a simplified two degree-of-freedom quarter car. Two masses are used and these represent the bogie mass (m_b) and half of the carriage mass (m_c). Primary and secondary suspension stiffness and damping are represented respectively by k_p, c_p, k_s and c_s. The parameters used here are represented in Table 1. The vehicle model has carriage and bogie bounce frequencies of 1.07 Hz and 6.55 Hz, respectively.

The bridge is 40 m in length and has two 20 m spans. The spans are modelled as a beam. Each span is simply supported and has a depth and width of 1 m and 4 m, respectively. Twenty 1 m long elements are used in the finite element model of the beam. Three per cent Rayleigh damping is also added to the bridge model. The second moment of area, Young's Modulus and density of each beam are chosen to be 0.33 m⁴, 35×10⁹ N/m² and 2400 kg/m³ respectively. The bridge pier has dimensions 7 m (height), 2.5 m (depth) and 1 m (width), respectively. The start and end of the bridge in this study cannot deflect have pin and roller supports. The density of the piers is the same as the bridge, making the mass of each pier 42,000 kg. The value of the spring underneath each pier (k_{soil}) is chosen to be 344 MN/m. It represents the vertical stiffness provided by a shallow pad foundation of length and width of 4 m and 2 m, respectively and is based on a paper by Adhikary et al. [13].

Scour is represented as a loss of stiffness in the value of k_{soil} under the pier. A 30% loss in stiffness is used in this study. Figure 2 shows how the first mode shape of the bridge structure and substructure system changes with scour and a significant change is visible.
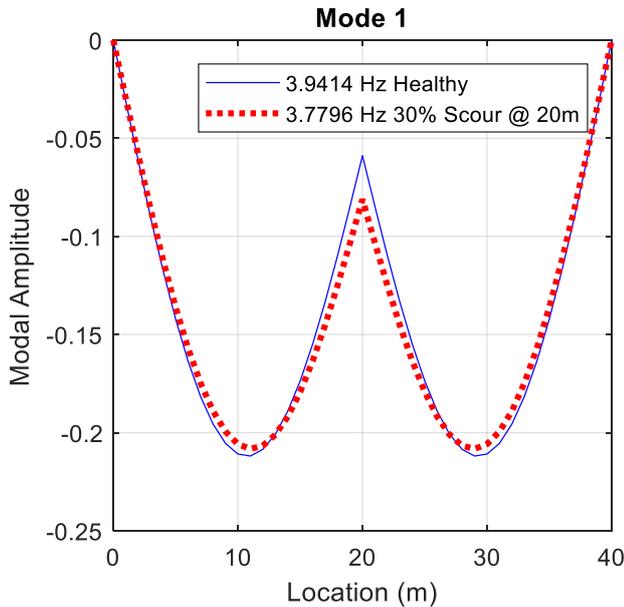
Figure 2. First mode shape – bridge deck deflection

3 WAVELET THEORY

The CWT of a signal, $f(t)$, is defined as the sum over all time of $f(t)$, multiplied by scaled and translated versions of a base wavelet, $\varphi(t)$. The base wavelet is a zero mean and it also only has a finite time duration. A real or complex valued wavelet can be chosen. In this study, a real Mexican hat wavelet is used. The Mexican hat wavelet used is defined as

$$\varphi(t) = \frac{2}{\sqrt{3}} \pi^{-1/4} \left(1 - t^2\right) e^{-t^2/2} \tag{1}$$
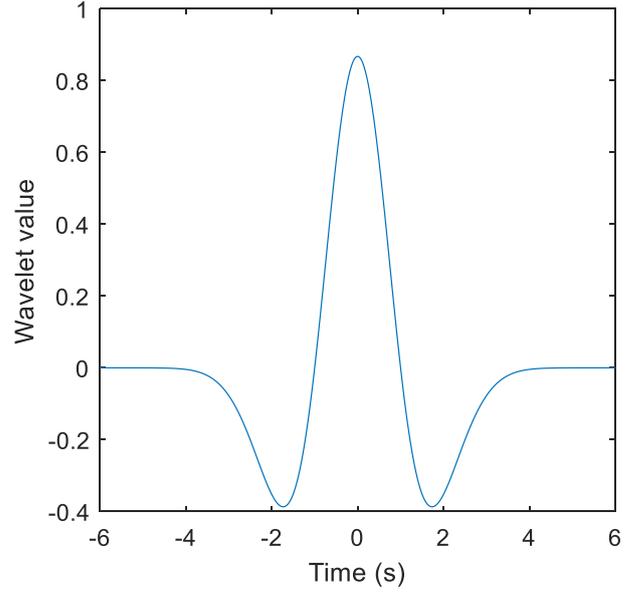
and is represented graphically in Figure 3 [14].

Figure 3. Mexican Hat Wavelet

In the CWT, the base wavelet is modified using the parameters, *scale* (s) and *position* (p) to create a range of analysing wavelets, β, defined as,

$$\beta(s, p, t) = \frac{1}{\sqrt{s}} \varphi\left(\frac{t-p}{s}\right) \tag{2}$$

The square root of the scale term in equation (2) is necessary for energy normalisation purposes. The output of the CWT are coefficients, C, which may be defined as,

$$C(s,t) = \int_{-\infty}^{+\infty} f(t)\beta(s, p, t)\mathrm{d}t \tag{3}$$

The coefficients, C, are an indication of the correlation between the analysing wavelet and the particular area in the signal. The scale of the wavelet can be related to a pseudo frequency, F_s defined as:

$$F_s = \frac{F_c}{s\Delta} \tag{4}$$

where F_c is the centre frequency of the wavelet in Hz and Δ is the sampling frequency. Hence, the wavelet coefficients give

an indication of the particular frequencies present in a signal at a given point in time. In this study, the coefficients are compared between healthy and scoured situations. It is found that by subtracting the two, it is possible to detect scour.

4 RESULTS

Here, a 30% loss of stiffness in implemented. Figure 4 shows the accelerations of the bogie degree of freedom for the healthy and scoured case. It is plotted against distance on bridge for clarity and it is clear that the scour is having an effect on the amplitude of the acceleration signal.
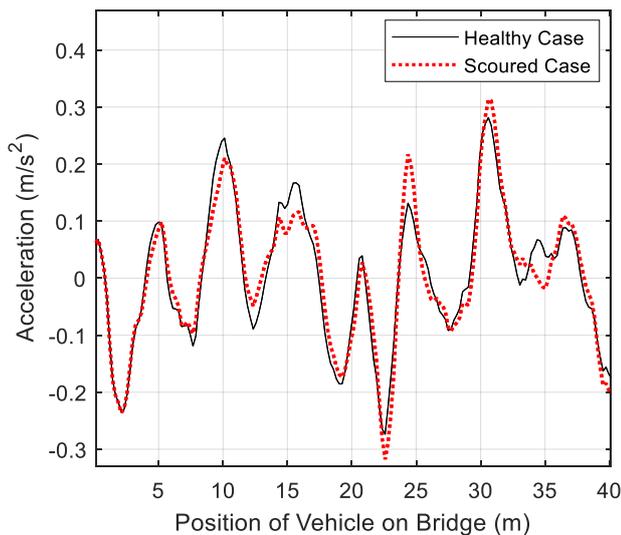

Figure 4. Bogie Accelerations for healthy and scoured case
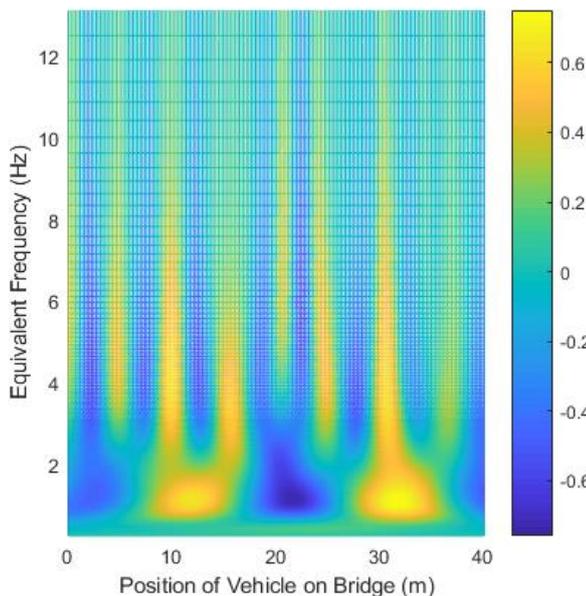

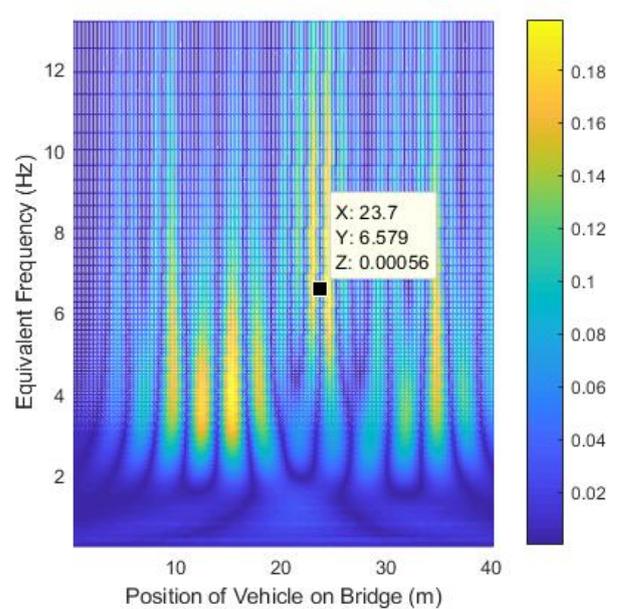Figure 5. Wavelet coefficients of scoured acceleration signal

Figure 6. Absolute value of healthy coefficients minus scour coefficients

Figure 5 presents the wavelet coefficients of the acceleration for the scoured case. There is no clear signs of issues or abnormalities from this figure. However, if the coefficients are obtained for both a healthy case and then a scoured case, and then subtracted, the effect of scour can be detected. Figure 6 shows the absolute value of the differences.

From Figure 6, the coefficients are showing the greatest changes in the regions at around 4 Hz and the in the range of about 6 Hz to 8 Hz. The large differences in around the 4 Hz point can be attributed to the vehicle picking up changes in the bridge first mode shape (shown in Figure 2) – which has the largest modal amplitude in the midspan of the bridge spans. In Figure 6, the large differences in around the 4 Hz mark are happening roughly at the centre points of the two spans (10 m and 30 m point).

The second frequency range showing high values in Figure 6 may be attributed to the change in excitation that the vehicle experiences due to the effect of scour. The bogie bounce frequency in this study is 6.55 Hz (approximately shown in Figure 6). In the scoured case, the vehicle is experiencing a different apparent profile and hence, a different excitation is experienced. This change is mostly detected around the vehicle bogie bounce frequency.

5 CONCLUSION

This study has shown how bridge scour may be detected by analysing the acceleration of a passing vehicle. By subtracting the wavelet coefficients between a healthy and scoured case, it is possible to detect the presence of scour. A more detailed analysis needs to be carried out however in order to see if the method works in practice. Vehicle variations (speed, mass etc.) also need to be accounted for.

REFERENCES

[1] J.-L. Briaud, H.-C. Chen, Y. Li, P. Nurtjahyo, J. Wang, SRICOS-EFA method for contraction scour in fine-grained soils, Journal of geotechnical and geoenvironmental engineering 131(10) (2005) 1283-1294.

[2] B. Maddison, Scour failure of bridges, Proceedings of the Institution of Civil Engineers-Forensic Engineering 165(1) (2012) 39-52.

[3] L.J. Prendergast, D. Hester, K. Gavin, Determining the presence of scour around bridge foundations using vehicle-induced vibrations, Journal of Bridge Engineering 21(10) (2016) 04016065.

[4] L.J. Prendergast, K. Gavin, A review of bridge scour monitoring techniques, Journal of Rock Mechanics and Geotechnical Engineering 6(2) (2014) 138-149.

[5] S. Das, P. Saha, S. Patro, Vibration-based damage detection techniques used for health monitoring of structures: a review, Journal of Civil Structural Health Monitoring 6(3) (2016) 477-507.

[6] W. Fan, P. Qiao, Vibration-based damage identification methods: a review and comparative study, Structural Health Monitoring 10(1) (2011) 83-111.

[7] X. Zhu, S.-S. Law, Structural health monitoring based on vehicle-bridge interaction: Accomplishments and challenges, Advances in Structural Engineering 18(12) (2015) 1999-2015.

[8] J.-L. Briaud, S. Hurlebaus, K.-A. Chang, C. Yao, H. Sharma, O.-Y. Yu, C. Darby, B.E. Hunt, G.R. Price, Realtime monitoring of bridge scour using remote monitoring technology, Texas Transportation Institute, Texas A&M University System (2011).

[9] A. Elsaid, R. Seracino, Rapid assessment of foundation scour using the dynamic features of bridge superstructure, Construction and Building Materials 50 (2014) 42-49.

[10] L.J. Prendergast, D. Hester, K. Gavin, J. O'sullivan, An investigation of the changes in the natural frequency of a pile affected by scour, Journal of Sound and Vibration 332(25) (2013) 6685-6702.

[11] M.R. Taha, A. Noureldin, J. Lucero, T. Baca, Wavelet transform for structural health monitoring: a compendium of uses and features, Structural Health Monitoring 5(3) (2006) 267-295.

[12] E.J. OBrien, P. Quirke, C. Bowe, D. Cantero, Determination of railway track longitudinal profile using measured inertial response of an in-service railway vehicle, Structural Health Monitoring (2017) 1475921717744479.

[13] S. Adhikary, Y. Singh, D. Paul, Modelling of soil-foundation-structure system, Soil Dyn. Earthquake Eng 61 (2014) 13-28.

[14] I. Daubechies, Ten lectures on wavelets, Siam1992.