Vibration based multi-piers bridges scour early detection

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ABSTRACT

Scour is a major cause of bridge collapse worldwide. Conventional techniques directly monitor the depth of soil near foundations. However, when scouring occurs, the holes can be filled with sediment, and so the scour cannot be detected by these methods. This paper presents an indirect, consequential method for an early and robust detection of bridge pier scour. Scour is detected using vibration analysis, by monitoring the dynamic response of the structure. The principle of the method is therefore to identify small variations in foundation stiffness from small variations in measured frequencies. The bridge and its piers are modeled by beams, and the foundations by springs, to obtain an expression for the sensitivity of frequencies to foundation stiffnesses. This expression is the result of a first-order perturbation calculation. Frequency variations are therefore expressed as linear combinations of the stiffness variations of the multiple foundations. This approach is tested on a digital model of 8-span bridge over the Loire River on the A85 motorway. The modelling assumptions of the bridge were validated using available ambient vibration measurements. Several scour scenarios were simulated by reducing the initial values of foundation stiffnesses. For the type under consideration in this paper, it was found out that the frequencies of the first out-of-plane modes of the bridge are sensitive to scour, depend little on the detailed functioning of the support. This method is effective because it is based on a robust inversion algorithm that prevents an amplification of the uncertainties in the variation of the measured frequencies. Foundation stiffness variations of 5% can be detected when the relative variation in useful frequencies is of the order of 1%. This level of variation is compatible with the uncertainty associated with the measurement chain and the operational modal analysis performed by professional software.

Keywords: Bridge scour foundations detection, Operational modal analysis of bridges, Ambient vibration monitoring, Robust inverse model

1. INTRODUCTION

Scour is the erosion of a riverbed caused by the action of water currents [1]. During this phenomenon, soil particles are progressively detached and carried away by the flow as sediments, creating holes around bridge piers and abutments [2]. Scour represents a major threat to the integrity of hydraulic infrastructures, being one of the main causes of bridge collapses worldwide [3]. Soil erosion around foundations weakens structures, reduces their load-bearing capacity, and can lead to critical structural failures. For instance, between 1966 and 2005, 58% of the 1,502 reported bridge failures in the United States were attributed to scour [4]. Similar incidents have been reported in Europe [5] [6]. These events highlight the dangers of bridges piers scour, and the need for rigorous monitoring to detect it early and mitigate associated risks.

Various traditional methods have been developed to detect scour, mainly relying on monitoring the level of the riverbed. These methods include floating sensors, sonar, radar systems and others [7]. While effective to some limits, they come with significant drawbacks [8]. Installation and maintenance can be expensive and complex, especially for devices that require submersion in water or drilling into the soil. In addition, these instruments are prone to degradation due to water flow and debris accumulation. Furthermore, sediment with poor mechanical properties can fill the scour holes, making direct detection methods less reliable.

The vibration-based method has recently been used to detect scoured piers by monitoring the dynamic behavior of the bridge rather than directly surveying the riverbed. This approach examines how scour influences the structure's dynamic parameters sensitive to foundation stiffness. Numerous studies have investigated the impact of scour depth on the bridge's modal characteristics, especially the eigenvalues and eigenmodes. Observing some variations in these values can be an indicator of scour. For example, the decrease of the natural frequencies might indicate that the scour depth is increasing [9]. Under the effect of forced vibrations induced by transverse percussion of the piers, the state of the Chikuma Bridge in Japan was assessed by comparing the natural frequencies and level of the riverbed between 1923 and 2007. Significant erosion of the riverbed was observed in the vicinity of one pier, resulting in a 40% reduction in its natural frequency [10]. The in-plane and out-of-plane frequencies of two bridges in Taiwan were measured under ambient vibrations, using accelerometers, for two distinct scour scenarios. For a scour of 3 meters, the first longitudinal and transverse frequencies of a pier decreased respectively by 6% and 25% [11].Similar results were obtained from laboratory experiments on a reduced-scale bridge model. The frequency of the first longitudinal mode decreases gradually as scouring progresses, simulated by sand removal around the piers [12]. Prendergast et al. [9] carried out an experimental test on a full-scale steel pile with a free length of 2.26 m and 6.5 m embedded in sand. Scour was induced in 12 stages by excavating a 0.5 m layer of soil around the pile at each step. At each scour level, an impulse force was applied at the pile head, and the first frequency was measured using an accelerometer. A progressive reduction in frequency was observed as the scour depth increased. For a scour depth of 2 m, corresponding to an 88% increase in the pile's free length, the frequency decreased by approximately 60%. Liao et al. [13] studied the effect of scour on frequencies and modal deformations by running simulations on a numerical model of a cable bridge. The soil around the piles is represented by a series of Winkler springs, which are progressively removed to model scour. The study shows that longitudinal and transverse vibration modes are sensitive to scour.

This article aims to detect as early as possible scour at several piers simultaneously using modal analysis. The second section of the paper details the methodology adopted, based on the detection of foundation stiffness losses from frequency variations. The third section introduces the expression of bridge frequencies sensitivity to stiffness losses affecting several piers. The fourth section presents the bridge under study and its numerical model, on which the method is applied. The fifth section presents the numerical and operational modal analysis, scour-sensitive modes and a digital twin of the process. The final part concludes the article and puts the main results into perspective.

2. METHODOLOGY

In this paper, a method is developed to detect scour by assessing its direct consequence on the bridge, which is the loss of stiffness at the foundations. Frequency is selected as the vibratory parameter for monitoring stiffness variations, as it is sensitive to this type of degradation. In this paper, the scour is defined as a reduction of the foundations stiffness, represented by elastic springs, in the two horizontal directions perpendicular to the piers [14]. A first-order perturbation approach is used to derive the sensitivity expression, Which relates frequency variations to losses in foundation stiffness. In this expression, the sensitivity matrix can be computed, and the vector of measured frequency variations is known as well. In order to identify the stiffness losses that have occurred, the Singular Value Decomposition (SVD) and least squares methods are used to solve the inverse problem. To ensure a robust inversion and limit the propagation of measurement uncertainties, the conditioning number of the sensitivity matrix is evaluated. If this number is high, the problem is regularized using the Truncated SVD. This step generates stable solutions that are little sensitive to perturbations.

3. FREQUENCY SENSITIVITY TO SCOUR

The eigenvalue problem for an elastic structure lying on a multiple located elastic foundation can be expressed as (1):

$$a_0(u, v) + \sum_{j=1}^{n} C_j \left((u, v) \right)_j = \lambda \, m(u, v) \tag{1}$$

where $a_0(u, v)$ and $m(u, v)$ are bilinear symmetric forms representing elastic strain energy and kinetic energy, respectively. The term $\sum C_j((u, v))_j$ accounts for the elastic deformation energy of the foundation, with C_j representing the stiffness of the jth foundation. To analyze the sensitivity of the system to small variations in foundation stiffness, the perturbations δC, $\delta \lambda$, and δu are introduced to (1). The perturbed equation is then (2):

$$a_0(u + \delta u, v) + \sum_{j=1}^{n} (C_j + \delta C_j) \left((u + \delta u, v) \right)_j = (\lambda + \delta \lambda) \, m(u + \delta u, v) \tag{2}$$

After applying a first-order approximation and in the case when modes are normalized with respect to the mass, the sensitivity of the eigenvalue to stiffness variation is expressed as (3)

$$\delta \lambda_i = \sum_{j=1}^{n} \delta C_j \left((u_i, u_i) \right)_j \tag{3}$$

In the case where the studied structure is a bridge with superficial foundations, the foundation is represented by a rotational spring with stiffness C (Figure 1). The bilinear form $((u_i, u_i))_j$ from (3) is equal to the rotations at the end of the jth pier for the ith mode, $(\theta_j(u_i))^2$. The sensitivity formula is then:

$$\delta \lambda_i = \sum_{j=1}^{n} \delta C_j \left(\theta_j(u_i) \right)^2 \tag{4}$$

The expression of the sensitivity of frequencies to stiffness loss is the following (5):

$$\frac{\delta f_i}{f_i} = \frac{1}{2} \frac{\delta \lambda_i}{\lambda_i} = \frac{1}{2} \sum_{j=1}^{n} \left(\frac{C_j}{f_i} \, \theta_j^2(u_i) \, \frac{\delta C_j}{C_j} \right) = \sum_{j=1}^{n} b_{ij} \frac{\delta C_j}{C_j} \tag{5}$$
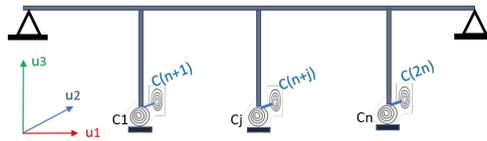
Figure 1: Schéma d'un pont à multipiles avec des ressorts de rotation

4. CASE STUDY: LANGEAIS BRIDGE

4.1. Description of the bridge and its digital model

The Langeais Bridge is a mixed-structure bridge with a total length of 601 meters, crossing the Loire River in France. It consists of 8 spans supported by 2 abutments and 7 circular piers with diameters of 3.5 m and heights varying between 9 m and 12 m. The deck section is composed of two steel girders topped with a 10.75 m wide reinforced concrete slab. The deck is connected to the piers through pot bearing devices. The bridge's foundations are shallow, with each pier resting on a rectangular caisson with heights ranging between 2.5 m and 6 m. Among the seven piers, four are submerged in water and are susceptible to scour. This bridge has been instrumented and monitored for a year. The Figure 2 shows the bridge with the positions of the real sensors fixed on its deck and the virtual ones used for simulations.

The numerical model of the Langeais Bridge was developed using CESAR, a finite element software [15]. The bridge was simplified into a 3D frame structure with a homogenized concrete deck section represented by 1D beam elements. The foundation stiffness in both transverse directions to the pier axis was modeled using rotational springs at the end of each pier, with stiffness values calculated using an empirical formula [16], using the properties of the soil and the foundation geometry. The bearings between the deck and piers were assumed to be rigid, permitting in-plane rotations and longitudinal sliding, except for the middle pier P4, which was fixed to the deck. Boundary conditions at the abutments were modeled as simple supports allowing sliding displacement.
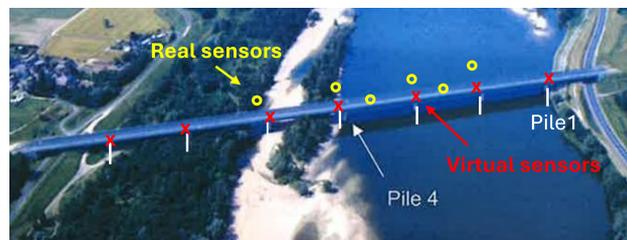

Figure 2: Langeais Bridge overview.

4.2. Scour detection using modal analysis

4.2.1. Vibration modes sensitive to scour

A uniform scour is modeled in the numerical model by reducing the initial stiffness of the springs attached to the bases of the piers immersed in the river by 10% in both transverse directions. The modal analysis of the damaged bridge model generates new frequency values. The Figure 3 shows the relative variations of the frequencies of the scoured model to the reference frequencies. By comparing the frequencies associated to the same vibrational modes in both studied cases, it can be seen that the vertical bending modes of the deck are insensitive to scour. However, the in-plane and out-of-plane vibration modes of the piers are affected by the changes of the foundation stiffness. For a 10% reduction in stiffness, the frequencies of in-plane pier vibration modes decrease by around 3%, and those of out-of-plane bridge modes by values ranging between 0.5% and 2.8%.

4.2.2. *Impact of connections type on the scour sensitive modes*

The actual functioning of the bearing devices between the bridge deck and the piers is uncertain. For instance, it is difficult to determine the conditions under which the longitudinal displacement is either mobilized or not. To address this problem uncertainty, the sensitivity of the frequencies of the vibration modes to scour is analyzed by considering different assumptions regarding the bearing devices than those taken in the reference model. The relative variations in frequencies following a 10% scour are presented in Figure 4 for the cases where the bearings are modeled as hinges and where the piers are rigidly connected to the deck.The results indicate that the in-plane sway modes of the piers are highly dependent on the bearing conditions. In the case of a bridge where longitudinal sliding and/or rotations are constrained at the connections, the in-plane frequencies become minimally sensitive to scour, or even completely insensitive. In contrast, regardless of the type of bearing devices, the mode shapes of the out-of-plane modes remain unchanged, and these modes retain the same frequency values across different connection types. Consequently, their sensitivity to scour is preserved. This study supports the exclusive use of out-of-plane modes for robust scour detection, as they are sensitive to scour while exhibiting negligible sensitivity to boundary conditions.
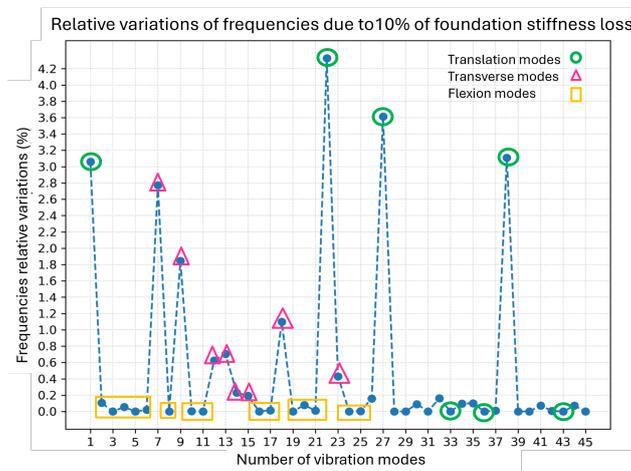
Figure 3: Frequencies relative variations caused by a 10% loss of foundations stiffness.
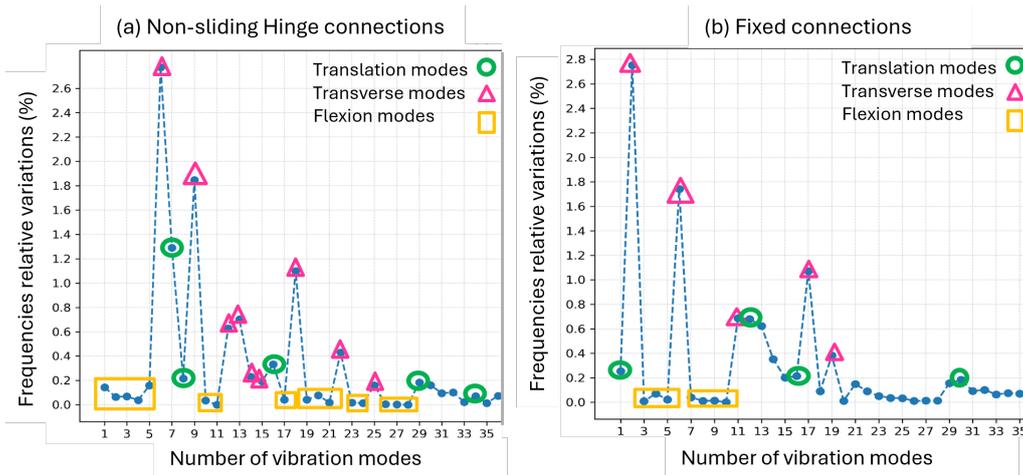
Figure 4: Impact of the connections type on the sensitivity of frequencies to scour.

4.2.3. Sensitivity matrix

The sensitivity matrix $\mathbf{A}$ is calculated using the sensitivity equation (5) and based only on the out-of-plane modes that are sensitive to scour (modes 7, 9, 12, 13, 18, and 23). For each sensitive mode, the rotations values in the X and Y directions are obtained from the reference numerical simulation of the bridge, prior to scour, at the nodes located at the base of the piers. The resulting sensitivity matrix $\mathbf{A}$ (6) consists of 4 columns, corresponding to the number of piers for which stiffness variations are to be determined, and 6 rows, representing the six out-of-plane modes sensitive to scour. The condition number of this sensitivity matrix is 6.08. To compute the relative stiffness losses $\frac{\delta \mathbf{C}}{\mathbf{C}}$, it is necessary to solve the linear system $\mathbf{A}\frac{\delta \mathbf{C}}{\mathbf{C}} = \frac{\delta \mathbf{f}}{\mathbf{f}}$ using the SVD method.

4.2.4. Simulated scour cases

To evaluate the early scour detection method and to avoid any inverse crime, a numerical dataset is created by simulating several scour scenarios on a bridge model that slightly differs from the reference model. Frequency variations between the non-scoured and scoured cases, derived from the perturbed model, form the vector of "measured" variables in the linear system. The sensitivity matrix $\mathbf{A}$ (6), used to solve the inverse problem, is computed from the reference model. By applying SVD and TSVD methods and restricting the solution space to positive values, the relative variations in stiffness loss are identified. The results, summarized in the Table 1, cover three scour scenarios: A uniform global scour (10% stiffness loss), a non-uniform global scour, and a local scour at pier 1. The calculated stiffness losses are close to the imposed values in the numerical model, with discrepancies under 1%, showing that the method effectively and accurately detects stiffness losses at multiple piers. SVD and TSVD methods give the same results, but TSVD results has lower sensitivity to measurement or model errors.

$$\mathbf{A} = \begin{bmatrix} 0.01 & 0.141 & 0.089 & 0.021 \\ 0.006 & 0.037 & 0.007 & 0.12 \\ 0.008 & 0.013 & 0.034 & 0.005 \\ 0.017 & 0.003 & 0.025 & 0.019 \\ 0.069 & 0.016 & 0.012 & 0.007 \\ 0.006 & 0.002 & 0.013 & 0.021 \end{bmatrix} \tag{6}$$

Table 1: Comparison between imposed and numerically calculated stiffness loss.

| Scour case | Piers | Relative stiffness loss (%) | | |
		Imposed	SVD	TSVD
Case 1	P1	10	10.87	11.1
	P2	10	10.77	11.63
	P3	10	9.88	8.61
	P4	10	10.86	10.71
Case 2	P1	8	8.5	8.22
	P2	5	5.33	4.31
	P3	2	1.61	3.12
	P4	10	10.73	10.91
Case 3	P1	10	10.63	10.65

5. VIRTUAL MODAL ANALYSIS

An eccentric traffic load on the deck induces out-of-plane vibrations. To reproduce this effect, a transverse force is applied to the deck of the bridge perturbed model, simulating vehicle passage. After a dynamic analysis of the finite element model, out-of-plane accelerations are extracted at the top of each pier for two cases: the initial model with no scour and the model with reduced foundation stiffness. The Figure 5 presents a sample of the virtual transverse acceleration time series at the pier P1.
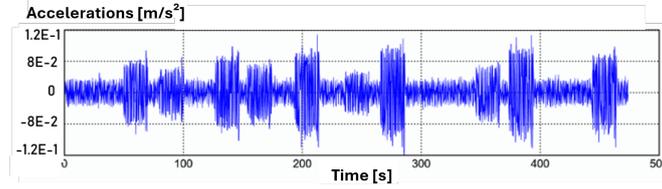

Figure 5: Transverse acceleration measurement on the pier P1.

Processing these virtual data with ARTeMIS software enables the extraction of the natural frequencies for both cases and the computation of the frequencies variations vector, which is sensitive to scour effects. Only frequency variations greater than 0.01 Hz are considered. By using the previously computed sensitivity matrix $\mathbf{A}$ and by applying the inverse method, stiffness losses are accurately identified at each pier immersed in water. The vector of relative frequency variations measured virtually and the vector of relative foundation stiffness reductions calculated are shown in (7). The discrepancy between the computed relative stiffness variation and the imposed value (10%) in the model remains below 1%. The synthesis of these data, which closely resemble real data, along with the application of the robust inverse method, constitutes the digital twin of the process, whereas a potential digital twin of the bridge under monitoring would take advantage of a continuous flow of real data in real time.

$$\frac{\delta f_p}{f_p} = \begin{pmatrix} \frac{\delta f_7}{f_7} \\ \frac{\delta f_9}{f_9} \\ \frac{\delta f_{12}}{f_{12}} \\ \frac{\delta f_{13}}{f_{13}} \\ \frac{\delta f_{18}}{f_{18}} \\ \frac{\delta f_{23}}{f_{23}} \end{pmatrix} = \begin{pmatrix} 2.767\ \% \\ 2.766\ \% \\ 0.629\ \% \\ 0.695\ \% \\ 1.117\ \% \\ 0.432\ \% \end{pmatrix} \implies \frac{\delta C}{C} = \begin{pmatrix} \frac{\delta C_1}{C_1} \\ \frac{\delta C_2}{C_2} \\ \frac{\delta C_3}{C_3} \\ \frac{\delta C_4}{C_4} \end{pmatrix} = \begin{pmatrix} 10.87\ \% \\ 10.80\ \% \\ 10.03\ \% \\ 10.86\ \% \end{pmatrix} \tag{7}$$

6. OPERATIONAL MODAL ANALYSIS

The processing of out-of-plane accelerations measured on the bridge using sensors (Figure 2) generates the spectrum shown in Figure 6. This spectrum reveals distinct peaks corresponding to the natural frequencies of the bridge's out-of-plane modes. However, the first peak is an artifact. To validate the digital model, simulated frequencies are compared with the measured ones. Results show a good match, with measured frequencies beeing slightly lower than the simulated ones. The 1st out-of-plane mode is 1.52 Hz in the measurements versus 1.74 Hz in the simulation. The operational frequencies for the 2nd and 3rd modes are 1.76 Hz and 2 Hz, respectively, while the simulated ones are 1.95 Hz and 2.22 Hz. These discrepancies of around 0.2 Hz suggest the bridge foundation stiffness was slightly overestimated in the model. Overall, the results validate the digital model and demonstrate that out-of-plane modes can be identified and tracked using operational measurements.
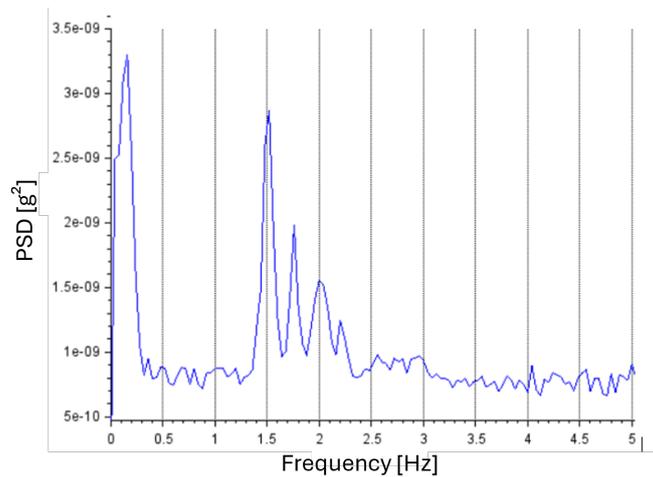
Figure 6: Measured transverse frequencies on the Langeais Bridge at the pier P2 in 2023.

7. CONCLUSION

In summary, this paper presents a method for the early scour detection at multiple bridge piers through modal analysis. The approach identifies small stiffness variations at the foundations by analyzing minor changes in the frequencies of transverse modes sensitive to scour, using a first-order sensitivity expression and solving an inverse problem by means of SVD and regularization techniques. The lack of knowledge about the behavior of bridge bearing devices does not affect the identification of stiffness losses, as the out-of-plane modes used in the analysis remain unaffected by boundary conditions. Virtual data were generated by applying the methodology to a numerical model of the bridge, simulating various scour scenarios, effectively creating a digital twin of the detection process. Additionally, operational measurements recorded on the bridge reveal the presence of out-of-plane modes, further validating the approach. Future research could focus on enhancing the measurement of transverse mode frequencies.

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