



INFLUENCE OF MODE COUPLING ON PERCEIVED HEALTH OF SCOURED BRIDGES USING VIBRATION-BASED MONITORING

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Abstract

Scour at bridge foundations is a major cause of structural damage and failure, prompting extensive research and monitoring efforts in recent decades. Numerous monitoring techniques exist, from direct riverbed measurements to indirect methods based on structural response. However, real-world use of scour monitoring in bridge management remains limited and often does not meet expectations set by scientific research. Scour assessment in practice still relies mainly on hydraulic analysis, periodic visual inspections, and conservative design. Monitoring is usually reserved for high-risk locations, valuing robustness and ease of interpretation over measurement detail. Advanced methods, such as vibration- or acceleration-based techniques, are sensitive in controlled settings but are affected by environmental variability, structural stiffness, traffic, and modeling uncertainties in the field. Observations show these tools often respond clearly only when scour has already reached a structurally significant level, limiting their value as early-warning systems. Recent research has shown that relying solely on vibration-based methods may prove problematic as scour occurrence can fundamentally alter the boundary conditions of a structure, which can change the nature of dynamic responses. This paper investigates the potential for mode shape coupling to incorrectly suggest significant scour problems when only minor issues might exist, due to the dynamic behavior of the bridge changing for certain scour hole shapes.

Keywords: scour, vibration-based damage detection, structural health monitoring

1 Introduction

Scouring of bridge foundations, caused by adverse hydraulic actions due to flooding, is a leading cause of failure and collapse of ageing bridges [1–3]. Scour occurs in three main forms: i) general scour due to natural riverbed changes, ii) contraction scour due to flow constriction as it passes through bridge openings, and iii) local scour, caused by the presence of obstacles such as piers and footings in the flow. The result of scour formation is a reduction in the level of soil at or near bridge foundations, with resulting changes in bridge stiffness and capacity [4]. Scour can occur under moderate as well as severe flows, but tends to be exacerbated during flooding, when it is most difficult to safely assess structures.

Scour monitoring has mainly comprised physical divers inspecting the condition of bridge foundations, a practice that is expensive, labour-intensive, and dangerous during floods. This has necessitated the development of sensor-based approaches that can be categorised into two main approaches: (i) scour hole monitoring, and (ii) structural monitoring. The former involves the use of sensors such as magnetic sliding collars, time-domain reflectometry, or ground penetrating radar, which aims to ascertain the severity and extent of a scour hole affecting a critical bridge asset [5].

The main drawbacks of these approaches include that they typically only measure the depth of scour close to the installed sensor location – not necessarily that affecting nearby assets; they often require resetting after a major scour event; and they can be vulnerable to damage from river debris. These main issues have resulted in a concerted effort to develop methods that directly measure the structural responses using vibrations. Vibration-based structural health monitoring applied to detecting scour erosion comprises measuring the dynamic response of a structure and determining how changes in the dynamics resulting from scour occurrence at the foundation can be detected through key performance indicators such as natural frequency, mode shape, or modal curvature, among other approaches [6]. This approach is divided into online methods, where a sensor is placed directly on a structure [7]; or offline methods, where drive-by data is used from passing vehicles [8] or from UAVs [9]. The most common approach uses changes in natural frequency as a means to detect scour presence [10–12] but is typically limited in its ability to determine the extent of scour without adequate reference finite-element models for comparison.

One of the main barriers to effective scour characterisation using these approaches relates to how the shape of a scour hole affects the dynamic response. Most research has focussed only on the depth of scour affecting a foundation, however the shape (e.g. width, slope angle) has an influence on the remaining overburden, and correspondingly affects the stiffness of the remaining soil [13, 14]. Recent studies have suggested methods to account for scour hole shapes in developing reference models for scour (see [13]). When accounting for scour hole shape, the nature of how the structure responds under dynamic loading can change, altering the perception of a scour issue when using natural frequencies or mode shapes. This paper focuses on the issue of mode shape coupling, whereby the mode shapes of a bridge that are disparate and unique for the unscoured case, become coupled under certain combinations of scour hole depth and width. The ramifications for vibration-based structural health monitoring are briefly highlighted.

2 Numerical modelling of bridge

For the purpose of demonstrating the mode coupling effect, an example bridge is modelled in this paper, which comprises the hypothetical bridge model presented in Kosič et al. [13], a more detailed version of which is presented in Kosič et al. [15]. The model is inspired by a real structure - a girder bridge spanning the Kupa river in Croatia. The bridge comprises two main spans, each 48.6 m in length, supported on a central pier. The bridge is 12.4 m wide. The main properties are provided in table 1. The bridge pier is supported on a pile group comprising six piles, each 12 m long and 1 m in diameter, capped with a 1 m deep pilecap. The piles are assumed to be installed in a medium dense sand profile.

Table 1 Bridge properties

Element	Material	E [kN/m ²]
Deck	Steel	$2.1 \cdot 10^8$
Pier	Concrete	$3.1 \cdot 10^7$
Foundation	Concrete	$3.1 \cdot 10^7$

2.1 Structural modelling

The bridge is numerically modelled using OpenSees [16, 17], and a schematic is shown in figure 1, which presents the overall scheme, and the soil-structure interaction (SSI) framework. More details regarding the bridge can be found in the [13]. The global coordinate axis (X, Y, Z) is used to reference the directions regarding the modal behaviour of the bridge and a local coordinate axis is used for the SSI.

The SSI is modelled using a Winkler framework [18, 19], with distributed vertical and lateral springs denoting the soil resistances in each direction.

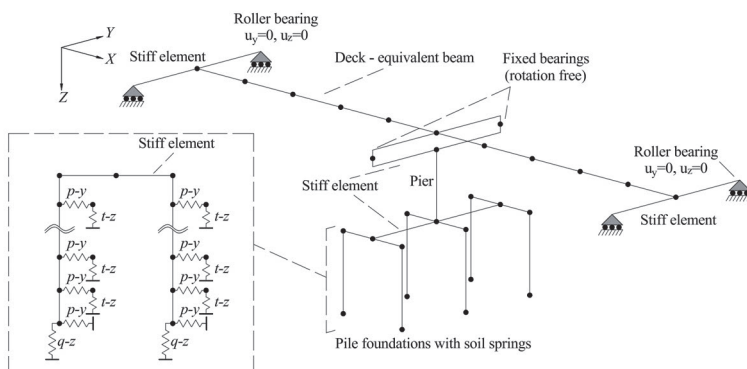


Figure 1 Numerical schematic of bridge (modified after [13])

The superstructure and pile foundations of the bridge are modelled using linear elastic Timoshenko beam-column elements, with mass and stiffness matrices available in Kwon and Bang [20]. The deck is modelled using a beam supported on bearings. The variation in the deck stiffness resulting from the changing thickness of the main girder flanges is incorporated using an array of discrete beam elements. The central pier is modelled using a similar approach.

2.2 Soil-structure interaction and scour modelling

The SSI model discussed above requires specification of parameters to characterise the response of the medium-dense sand in terms of stiffness and strength. The SSI springs comprise lateral load-displacement (p-y) springs, vertical shear stress-displacement (t-z) springs, and a vertical base resistance-displacement (q-z) spring. The load-displacement behaviour of each spring is characterised in OpenSees by implementing in-built models for p-y (PySimple1 [21]), t-z (TzSimple1 [22]), and q-z (QzSimple1 [23]) springs, respectively. To ensure these springs effectively represent the behaviour of medium-dense sand, the required inputs are the ultimate force values (P_u , T_u , Q_u) and the corresponding displacements at 50% of the ultimate force (y_{50} , z_{t50} , z_{q50}), which together define the non-linear load-displacement relationships in accordance with the predefined constitutive shapes of the corresponding OpenSees material models. For the p-y springs, P_u is defined as:

$$P_u = \bar{A}_s p_u \Delta z \quad (1)$$

where \bar{A}_s is the normalised resistance factor, p_u is the ultimate soil resistance per unit length, and Δz is the vertical spring spacing. The displacement at 50% of the ultimate load is calculated based on the API [24] hyperbolic load-displacement curve:

$$y_{50} = \frac{\bar{A}_s p_u}{k(z - d_s + z_{s,eff})} \operatorname{atanh}(0.5) \quad (2)$$

where k is the coefficient of subgrade reaction, k is the depth of the spring relative to the original ground level, d_s is the scour hole depth, $z_{s,eff}$ is the effective height of overburden above the scour hole to account for the scour hole shape, and D is the foundation diameter. For the t-z springs, T_u is defined as:

$$T_u = K \sigma'_v \tan(\delta) \pi D \Delta z \quad (3)$$

where $K = 1.0$ for full displacement piles, σ'_v is the vertical effective stress, and $\delta = 0.9 \phi'$ is the soil-pile interface friction angle. The displacement at 50% of the ultimate load (z_{z50}) is taken as 1.27 mm [25]. For the q-z spring, Q_u is defined as:

$$Q_u = \left[\sigma'_v N_q^* \right] \pi \frac{D^2}{4} \leq \left[0.5 p_a N_q^* \tan(\phi') \right] \pi \frac{D^2}{4} \quad (4)$$

where N_q^* is the bearing factor, and p_a is atmospheric pressure (assumed as 100 kPa). The displacement at 50% of the capacity (z_{z50}) is assumed as 12.5% of the pile ultimate displacement [26]. Scour is modelled by removing springs from the model and redistributing the stiffness and strength of the springs based on the shape of the scour hole that is generated (varying scour hole depth, widths, and angles of side slopes). The method derives an effective overburden height, $z_{s, eff}$ assumed to act uniformly over the base of a scour hole, to account for the wedge of soil that remains when a conical-shaped scour hole is generated. More details are provided in Kosič et al. [13]. The modal properties of the bridge are determined by solving the eigenvalue problem of the structural system. This procedure yields the natural frequencies and the corresponding mode shapes of the structure. The formulation is based on the mass and stiffness matrices of the bridge, from which the system matrix is assembled. The resulting eigenvalues represent the natural frequencies, while the associated eigenvectors describe the corresponding vibration modes of the bridge.

3 Analysis and results

The influence of varying the depth and width of a scour hole affecting the numerically modelled bridge is shown in figure 2. The plot shows the increase in modal period under scour ($T_{s,y}$) as a ratio of the unscoured modal period ($T_{0,y}$) in the flow (y) direction, where the slope angle is maintained constant at 30°.

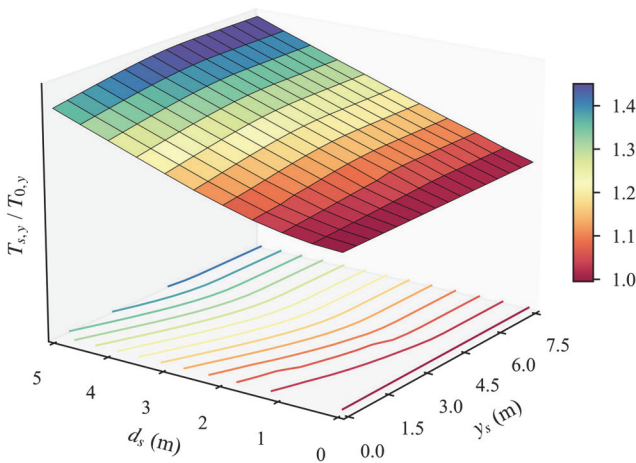


Figure 2 Impact of scour depth (d_s) and width (y_s) on relative increase of principal vibration periods in flow direction

The vibration period increases relative to the unscoured value for increases in scour depth (as expected), with an additional increase noted under increasing width of scour. The results plateau at larger scour hole depths for increased widths, i.e. the influence of scour width is less prominent when scour depth is also large, as seen for the case of 5 m scour in figure 2. By viewing the surface plot in figure 2 as a contour plot, the issue of mode coupling comes to light. Figure 3a shows the relative change in modal period for different scour-hole depths and widths. The ratio of modal periods increases smoothly with scour-hole width for all scour depths. Except for two specific conditions, $d_s = 1\text{ m}$ and $y_s = 3.5\text{ m}$ and $d_s = 1.5\text{ m}$ and $y_s = 1.5\text{ m}$. At these points, the non-smooth variation in period ratio suggests a fundamental change in the behavior of the bridge. For these cases, the transverse and vertical modes become coupled due to alignment of the periods, leading to the emergence of a coupled mode shape that does not occur under unscoured conditions. This interaction is further indicated by the drop in the MAC values in figure 3b for these specific conditions, suggesting that the observed modal changes may reflect mode coupling rather than a direct increase in scour severity alone.

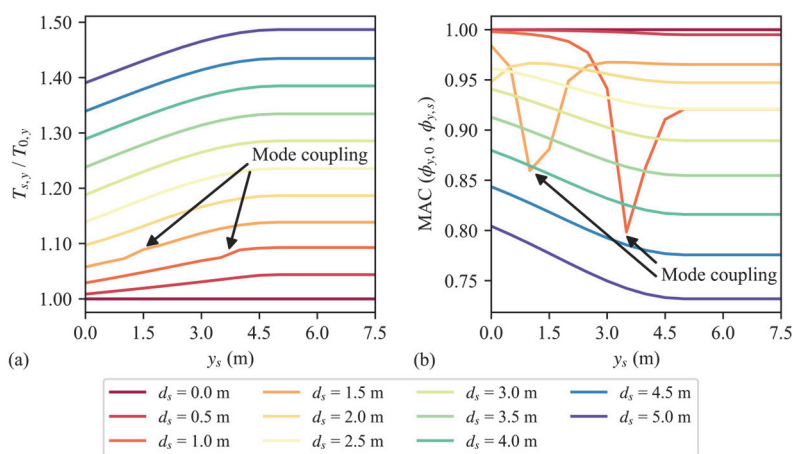


Figure 3 (a) Relative change of global vibration period and (b) MAC values in flow direction for different scour depths (d_s) and widths (y_s)

4 Conclusion

Scour of bridges is a leading cause of failure and remains a critical issue for asset managers. Vibration-based monitoring is a promising approach for scour detection. This paper demonstrates the issue of mode shape coupling, which can occur under certain combinations of scour hole shape parameters, resulting in the perception of a given scour severity affecting an asset, which may not be true. The issue occurs due to a fundamental change in the dynamic behaviour of a bridge for certain combinations of scour hole depth and width, which cause mode shapes to become coupled, potentially masking the true scour effect. The results suggest that using data-driven approaches without an underlying physics-based model can potentially lead to erroneous scour prediction using vibration-based measurements, underscoring the importance of combined data and model-based approaches. The issue is investigated numerically in this paper.

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