



MONITORING SCOUR AND SOIL–STRUCTURE INTERACTION IN PILE-SUPPORTED RAIL INFRASTRUCTURE USING VIBRATION-BASED DIGITAL TWINS

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Abstract

Pile foundations support many critical rail assets, including bridge and viaduct piers, abutments, transition structures, and retaining systems in weak or variable ground. For piled bridge substructures in particular, scour and erosion can reduce effective embedment and lateral resistance, while broader soil stiffness degradation alters soil–pile interaction (SPI). These changes lead to measurable shifts in modal properties and frequency-response characteristics, motivating vibration-based condition monitoring approaches. This contribution presents a vibration-driven digital-twin workflow to infer degradation in SPI from accessible dynamic measurements, supporting inspection and maintenance of pile-supported rail infrastructure. Two complementary model-updating methods are introduced. The first is an input–output Frequency Response Function (FRF)-based, two-stage iterative approach for laterally excited piles: the first vibration mode is used to estimate mobilized soil mass and stiffness, while a subsequent mode is exploited to estimate the effective embedded pile length, enabling the identification of scour-induced reductions in embedment and associated losses in soil mass and stiffness. The second method targets operational scenarios in which only response data are available. Output-only subspace identification is employed to extract modal parameters, including natural frequencies and mode shapes, together with their associated uncertainties. A stochastic evolutionary optimizer then updates a numerical pile–soil model, explicitly propagating measurement uncertainty into confidence bounds on the inferred SPI parameters. By tracking trends in updated stiffness, mobilized mass, and inferred embedment, the proposed methods provide practical indicators of scour progression and SPI degradation.

Keywords: digital twinning, rail infrastructure, model updating, operational modal analysis (OMA)

1 Introduction

Rail infrastructure is a critical component of national transportation networks, and the safety of rail bridges and viaducts is of paramount importance, particularly as many assets are ageing and heavily utilized. Conventional inspections remain essential but are episodic, labor-intensive, and often constrained by access and service disruption, limiting their ability to capture evolving structural behavior in real time [1]. Data-driven Structural Health Monitoring (SHM) and digital-twin approaches can therefore support engineers with continuous, objective performance information, complementing rather than replacing traditional practice [2]. However, for many rail bridge assets, performance is governed not only by superstructure condition but also by changes in support conditions and soil–structure interaction.

Pile foundations support many critical rail bridge substructures, and their dynamic response is strongly governed by SPI. The lateral stiffness, damping, mobilized soil mass, and boundary conditions at the foundation level directly influence modal properties and frequency-response characteristics, making accurate SPI modelling essential for interpretation of measured dynamics. Two principal modelling strategies are commonly adopted: direct continuum approaches, in which the soil domain is discretized using finite elements or finite differences to capture stress–strain behavior [3–5], and indirect substructure approaches, such as beam-on-foundation (Winkler-type) models, in which the pile is coupled to distributed springs and dashpots [6, 7]. While continuum models offer high fidelity, beam-on-foundation formulations are widely used in digital-twin applications because they are computationally efficient and amenable to calibration. However, key SPI parameters remain uncertain and may evolve due to scour, stiffness degradation, or changing boundary conditions. This motivates inverse/model-updating approaches in which measured dynamics are used to infer SPI parameters [8].

Scour around pile-supported substructures can reduce effective embedded length and lateral resistance, directly altering foundation stiffness and boundary conditions [9, 10]. As embedment decreases or soil stiffness degrades, measurable shifts occur in natural frequencies, mode shapes, and frequency-response functions (FRFs), motivating vibration-based monitoring strategies for soil–structure systems. In addition to geometric changes, the dynamic response is strongly influenced by the mobilized soil mass and the effective lateral stiffness participating in vibration. Variations in these parameters modify the system’s response, meaning that frequency shifts cannot be attributed to embedment loss alone without careful modelling [8, 11, 12]. Within system identification, two principal formulations are commonly used. When excitation is known or controlled, frequency-domain methods such as FRF-based identification enable direct updating in the frequency domain. In contrast, for in-service assets subjected to ambient or operational loads, output-only time-domain techniques are preferred, providing consistent estimates of natural frequencies, damping ratios, and mode shapes without measured inputs [13]. Many existing frameworks that use the guided wave theory for pile length estimation do not explicitly decouple embedded length from soil stiffness and mobilized mass [14, 15]. Building on this foundation, this paper presents two complementary model-updating frameworks previously developed for pile-supported systems. First, an input–output FRF-based two-stage method is employed, in which the first vibration mode is used to estimate mobilized soil mass and stiffness, while the second mode is leveraged to infer embedded length or scour depth. Second, an output-only framework combines stochastic subspace identification (SSI) with evolutionary optimization and uncertainty quantification, enabling the estimation of soil stiffness, mobilized mass, and embedment together with confidence bounds. This dual strategy provides physically interpretable indicators, namely stiffness, mass participation, and effective embedded length, that are directly suited to condition assessment and maintenance decision support for pile-supported rail assets.

2 Methodology

This paper employs two complementary optimization-based frameworks to estimate embedded pile length and key SPI parameters from vibration data, adapted from the deterministic FRF-based approach in [11] and the stochastic output-only approach in [16]. The unknowns are collected in:

$$\theta = \{L_1, w_m, w_k\} \quad (1)$$

where L_1 is the embedded length, and w_m and w_k scale the assumed distributions of mobilised soil mass and lateral soil stiffness, respectively. Parameter estimation is posed as an inverse problem:

$$\theta^* = \operatorname{argmin}_{\theta} \mathcal{L}(\theta) \quad (2)$$

with $\mathcal{L}(\theta)$ defined either in the FRF domain (input–output) or the modal domain (output-only).

2.1 Physics-based SPI model and data scenarios

Railway bridge piers are commonly supported by pile groups connected through a pile cap. For the purposes of demonstrating the proposed vibration-based monitoring framework, this study considers a single representative pile, allowing the key mechanisms of soil–structure interaction and parameter identification to be illustrated in a simplified lateral dynamic setting. The pile is represented by a linear Winkler-type beam–spring model for small-strain lateral dynamics. The pile is discretized with beam elements and coupled to distributed lateral springs and lumped masses along the embedded portion. A baseline stiffness profile is mapped to discrete springs and then scaled by w_k to reflect operating stiffness, while the lumped soil mass distribution is scaled by w_m to represent mobilization effects that strongly influence the first lateral mode. Two measurement scenarios are considered: (i) impact or controlled excitation, where the input and acceleration response are measured to form an FRF, and (ii) operational monitoring, where only acceleration outputs are available and modal properties are identified from response data.

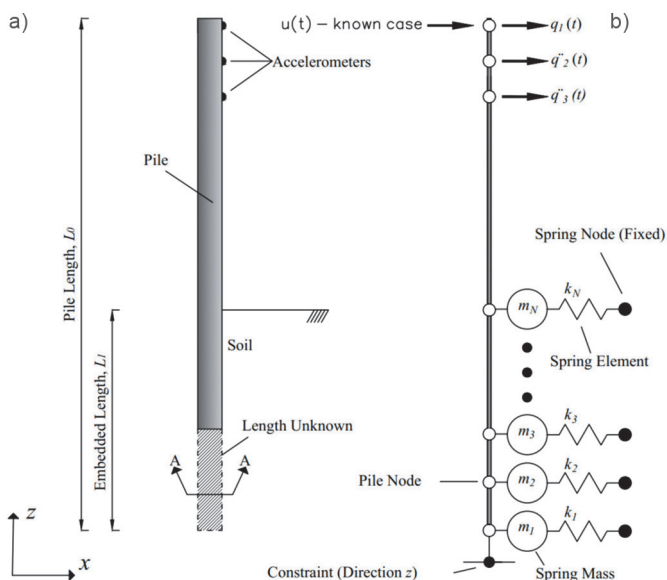


Figure 1 (a) Physical and (b) numerical beam-spring representation of the lateral soil-pile interaction model

2.2 Deterministic FRF-based updating (two-stage)

When the input force is known, an acceleration FRF at the pile head is computed and reduced to low-dimensional features (peak frequencies and amplitudes). A two-stage iterative strategy exploits two modes: stage 1 calibrates w_k and w_m for a fixed L_1 by matching the first FRF peak; stage 2 updates L_1 by matching a second-mode peak, using an efficient secant or linear-projection update. The process iterates until both first- and second-mode peak mismatches fall below tolerance, yielding θ^* . This approach is computationally efficient but requires measured excitation and clear peak separation. Full implementation details can be found in [11].

2.3 Stochastic output-only updating with SSI, UQ, and CMA-ES

Under unknown excitation, SSI is used to extract target modal frequencies and mode shapes from output-only data, together with estimation uncertainty. Model parameters are then inferred by minimizing a modal-domain objective combining relative frequency errors and mode-shape consistency (MAC), with acceptance guided by uncertainty bounds derived from the SSI estimates. Optimization is performed using CMA-ES, which is well suited to correlated parameters such as (L_1, w_k, w_m) . Convergence is declared when improvements saturate or when predicted modal quantities satisfy the uncertainty-informed criteria. Full implementation details are provided in [16].

3 Numerical analysis and case study

To benchmark the two updating frameworks, three synthetic target models are defined (table 1), representing increasing embedded pile lengths and including a case with variability in the small-strain shear modulus profile to reflect uncertainty in site characterization. Across all targets, the mobilization parameters are fixed at $w_m = 5$ and $w_k = 0.5$, while the pile length and soil-profile variability are varied to assess the recoverability of L_1 , w_m , and w_k under controlled conditions. The same target datasets are examined under two measurement scenarios: (i) an input–output impact-test setting, where the pile-head force is assumed measurable and frequency response functions (FRFs) are used for deterministic updating, and (ii) an output-only setting, where the excitation is treated as unknown and SSI-identified modal properties are used within the stochastic optimization framework.

Table 1 Configuration of target models used to generate the synthetic data

Target	w_m	w_k	r [m]	t_o [m]	L_1 [m]	L/D	Var. in G (Y/N)
1	5	0.5	0.5	0.025	20	20	N
2	5	0.5	0.5	0.025	25	25	N
3	5	0.5	0.5	0.025	30	30	Y

3.1 Deterministic FRF-based results

For the deterministic case, simulated force–acceleration data are used to construct pile-head FRFs, and the two-stage updating procedure is applied. For the 20 m target, the first and second modes of vibration are used, as these are sufficiently separated and can be identified reliably in the FRF. For the 25 m and 30 m targets, however, the first and second modes lie closer together, reducing the robustness of peak discrimination. In these cases, the first and third modes are instead used in the updating process, as they provide clearer modal separation and a more reliable basis for parameter correction.

The method alternates between calibrating w_m and w_k to match the first selected FRF peak and updating L_1 from the mismatch in the higher selected mode using a secant linear-projection step, until both modal features fall within tolerance. The results show stable convergence of L_1 , accompanied by coupled convergence of w_m and w_k , provided that the selected modal peaks remain distinguishable. Repeatability is quantified through Monte Carlo runs with random initialisations, showing low bias and relatively small dispersion in the recovered parameters (table 2).

Table 2 Monte Carlo results for the deterministic numerical analysis

Target	Target $\{w_m, w_k, L_1\}$	Mean $\{\hat{w}_m, \hat{w}_k, \hat{L}_1\}$	Std $\{\sigma_{w_m}, \sigma_{w_k}, \sigma_{L_1}\}$
1	{5, 0.5, 20}	{5.13, 0.51, 19.95}	{0.048, 0.004, 0.286}
2	{5, 0.5, 25}	{5.18, 0.52, 24.86}	{0.033, 0.003, 0.407}
3	{5, 0.5, 30}	{5.11, 0.51, 29.60}	{0.025, 0.002, 0.497}

3.2 Stochastic output-only results

For the output-only case, only acceleration responses are used. SSI is applied to multi-sensor time histories to estimate the modal frequencies and mode shapes, which are then used as targets in the CMA-ES optimization. As with the deterministic case, the selection of modes has an important influence on the quality of the inverse solution. For the 20 m target, the first three modes are used and lead to stable parameter recovery. For the 25 m target, using the same three modes results in a noticeably larger standard deviation in the recovered parameters, indicating reduced robustness of the modal information for longer piles. This behavior is attributed to the reduced sensitivity of the lower modes to changes in embedded length as pile length increases beyond the critical embedded length, such that changes in L_1 have a weaker influence on the corresponding modal properties. For the 30 m target, a fourth mode is therefore included in the objective function. This leads to a clearer and more stable convergence behavior, as the higher mode retains additional discriminatory information that improves identifiability of the updating parameters.

Tracking the best candidate per generation shows progressive correction of L_1 together with stabilization of w_m and w_k , reflecting the coupled nature of the inverse problem. The Monte Carlo statistics confirm this trend: although the 25 m case exhibits comparatively large variability when only three modes are used, the inclusion of an additional higher mode in the 30 m case substantially improves convergence and reduces parameter dispersion (table 3). Overall, the results support the suitability of SSI-driven updating when input forces are unavailable, while also highlighting the importance of mode-selection strategy as pile length increases and the lower modes become less sensitive to scour-related boundary-condition changes.

Table 3 Monte Carlo results for the stochastic numerical analysis

Target	Target $\{w_m, w_k, L_1\}$	Mean $\{\hat{w}_m, \hat{w}_k, \hat{L}_1\}$	Std $\{\sigma_{w_m}, \sigma_{w_k}, \sigma_{L_1}\}$
1	{5, 0.5, 20}	{5.04, 0.51, 20.35}	{0.525, 0.051, 0.340}
2	{5, 0.5, 25}	{5.52, 0.55, 24.85}	{1.056, 0.101, 1.071}
3	{5, 0.5, 30}	{4.99, 0.50, 30.46}	{0.176, 0.017, 0.176}

3.3 Field demonstration (output-only)

To demonstrate performance on real data, the stochastic framework is applied to field impact-test measurements reported in [7, 17], with the present analysis taken from [16]. The case study concerns an open-ended steel pile installed in dense sand, using recorded accelerations and SSI-extracted bending modes as optimization targets. An objective-function sweep indicates a minimum region close to the known total pile length, with a broader valley consistent with limited modal content and sparse instrumentation. Monte Carlo runs across representative impacts yield repeatable length estimates and consistent mobilization parameters, while indicating that richer modal content and improved sensor placement would further sharpen the optimization landscape and reduce uncertainty (table 4).

Table 4 Monte Carlo results for the stochastic field demonstration

Impact	Target L_0	Mean $\{\hat{w}_m, \hat{w}_k, \hat{L}_0\}$	Std $\{\sigma_{w_m}, \sigma_{w_k}, \sigma_{L_0}\}$
1	7.2	{6.35, 1.73, 7.80}	{2.320, 0.480, 0.480}
2	7.2	{6.18, 1.59, 7.70}	{3.170, 0.280, 0.560}
3	7.2	{6.40, 1.68, 7.80}	{2.650, 0.220, 0.550}

4 Conclusion

This paper presents a vibration-informed Digital Twin framework for pile foundations based on a Winkler-type soil–pile interaction model and an optimization-based inverse formulation. Two complementary updating strategies were investigated: a deterministic FRF-based approach for input–output testing and a stochastic output-only approach combining SSI-derived modal targets with CMA-ES optimization. Numerical studies on three synthetic configurations showed that both frameworks can recover embedded pile length and effective mobilization parameters governing lateral dynamic behavior. The deterministic method converges efficiently when input forces are measurable and modal peaks are clearly identifiable, whereas the stochastic approach enables output-only updating and remains robust under uncertainty in soil characterization, albeit at increased computational cost. Application to field impact-test data further demonstrated the practical feasibility of the output-only framework, yielding consistent parameter estimates across repeated excitations despite sparse instrumentation and limited modal content. Overall, the results support the use of vibration-based updating for tracking embedded length and soil mobilization in Digital Twin applications for pile-supported infrastructure, while highlighting the importance of sensor placement and excitation richness for reducing estimation uncertainty.

Future work will focus on extending the framework to pile groups and sheet pile walls, enabling application to more complex soil-structure systems.

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