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REVIEW ARTICLE OPEN ACCESS

State-of-the-Art Review of Vibration-Based Health Monitoring of Piles

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Vibration-based health monitoring (VHM) has emerged as a promising technique for assessing the integrity of deep foundations by interpreting variations in dynamic response governed by soil–pile interaction. This review presents the theoretical background of foundation failure mechanisms, sensing technologies, and numerical approaches that underpin VHM for pile foundations, with emphasis on recent advances in fiber-optic sensing, piezoceramic transducers, and acoustic emission measurement. Developments in optimal sensor placement, high-rate data acquisition, and advanced signal-processing techniques including time- and frequency-domain analysis and machine-learning-based interpretation are examined in relation to their capability to identify damage mechanisms such as cracking, scouring, buckling, degradation of bearing capacity and shaft resistance, and post-earthquake damage. A critical evaluation of physical model tests, field studies, and numerical investigations highlights the strong influence of pile geometry, embedment depth, material type, excitation method, and sensor configuration on the sensitivity of vibration-based indicators. While VHM has demonstrated strong potential during installation and under controlled monitoring conditions, its application to existing and aging foundations, particularly deeply embedded and large-diameter piles, remains limited. The findings underscore the need for unified VHM protocols, scalable and nonintrusive sensing strategies, and field-validated diagnostic indicators that explicitly account for soil–pile interaction to support reliable long-term performance assessment of pile foundations, especially for postdisaster damage evaluation.

1 | Introduction

Pile foundations are essential load-bearing components used in a wide range of civil infrastructure systems, including bridges, high-rise buildings, port facilities, wind turbines, transmission towers, power plants, and many other heavily loaded critical structures. Their performance directly influences overall structural safety and serviceability, making structural integrity assessment a critical engineering priority. Throughout their service life, piles are exposed to severe mechanical, environmental, and

geohazard-induced conditions including scour, corrosion, cyclic loading, and seismic excitation that can progressively modify their structural capacity and soil–pile interaction (SPI). The influence of scour on the dynamic behavior of bridge foundations is illustrated by the work of Foti and Sabia [1] and Kariyawasam et al. [2], while Melchers [3] provides insights into long-term steel degradation under corrosive environments. Seismic effects on pile response form an integral component of geotechnical earthquake engineering [4], and the interaction between scour

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and corrosion on deep foundation performance is examined in recent numerical studies [5].

Numerous postearthquake investigations have shown that pile damages can lead to excessive settlement, reduced bearing capacity, and even catastrophic superstructure failure during major earthquakes and ground movement events [6–9]. Similar vulnerabilities have been observed in infrastructure supported on piles in liquefiable soils [8–10]. These outcomes collectively underscore the urgent need for reliable monitoring techniques capable of detecting both structural damage and changes in SPI.

Conventional nondestructive testing (NDT) techniques such as low-strain pile integrity testing (PIT), cross-hole sonic logging, thermal integrity profiling, and gamma–gamma density logging remain standard practice during construction and rehabilitation phases [11–17]. These methods form the core of deep foundation integrity evaluation recommended by Engineers and are governed by widely used standards including ASTM D5882 [11] for low-strain integrity testing, ASTM D6760 [12] for cross-hole sonic logging, and ASTM D7949 [13] for thermal integrity profiling. Although effective for identifying major sectional anomalies, these techniques generally require direct access to the pile head or embedded instrumentation and therefore provide only discrete snapshots of foundation condition. Their diagnostic capability is further reduced for long piles ($L/D > 30$), large-diameter drilled shafts, and pile groups, particularly when foundations are embedded in spatially variable or liquefiable soils [18, 19]. As a result, conventional NDT methods often struggle to capture progressive or deeply embedded deterioration, highlighting the need for complementary monitoring strategies.

Vibration-based health monitoring (VHM) has therefore emerged as a powerful complementary approach for continuous or periodic condition assessment. By interpreting dynamic characteristics such as natural frequencies, modal curvature, and impedance, the VHM can detect changes attributable to cracking, debonding, scour progression, soil degradation, or stiffness loss induced by seismic events [2, 20–25].

Rapid advances in sensing technologies have expanded the feasibility and precision of VHM. Piezoceramic transducers

(PZT) facilitate high-frequency stress-wave interrogation [26–29], while FBG sensors and distributed fiber-optic sensing (DFOS) systems enable depth-resolved strain measurements and detection of SPI changes, cracking, or toe anomalies [30–33]. Wireless and MEMS-based sensor networks have further supported scalable field deployment [34]. Parallel advancements in signal processing such as wavelet transforms, Hilbert–Huang transforms (HHTs), operational modal analysis (OMA), and frequency-response-based techniques have improved feature extraction under noisy, nonstationary conditions [35–38]. Machine learning (ML) and deep learning (DL) approaches now enhance diagnostic automation through pattern recognition, environmental normalization, and high-dimensional data fusion [39–42].

Despite these advances, widespread adoption of VHM remains limited by challenges in calibration, environmental compensation, numerical model updating, and standardization. This review synthesizes theoretical foundations, sensing and DAQ technologies, numerical modeling techniques, and field applications that collectively define the state of the art in VHM for deep foundations. It further identifies key research gaps that must be addressed to advance VHM toward standardized practice and broader implementation.

2 | Damage Mechanisms in Pile Foundations

Pile foundations deteriorate through interacting structural, material, and construction-related mechanisms (Figure 1), each contributing distinctive changes in stiffness, mass distribution, damping, and SPI parameters that directly influence vibration response and thus VHM detectability. Understanding these mechanisms is essential for interpreting dynamic signatures associated with pile degradation.

Structural damage (Figure 1(a), I–III) arises when service or extreme loads exceed the axial, flexural, or shear capacities of the pile. High axial compression can induce crushing or local toe damage, while lateral or combined loading promotes flexural cracking and yielding, as well as global buckling, particularly near the pile head or other regions of elevated bending demand [43]. Driving-induced impacts introduce initial defects such as

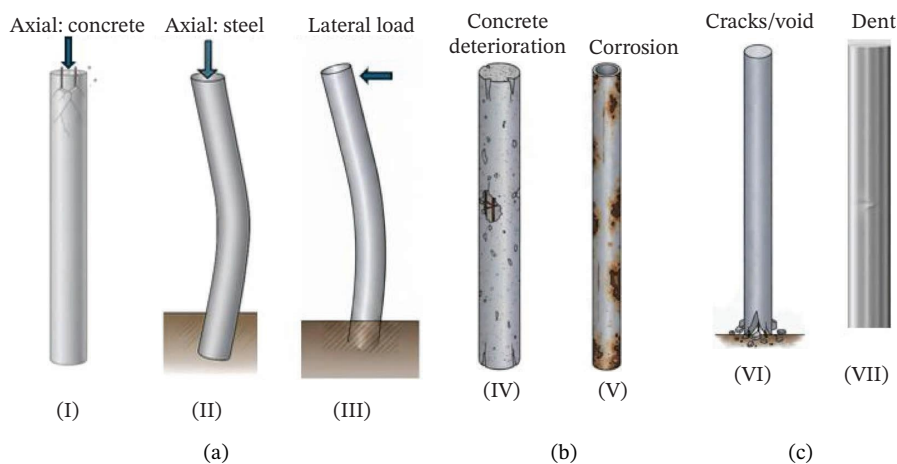


FIGURE 1 | Classification of pile damage mechanisms: (a) structural damage caused by compression, tension, and bending; (b) material degradation including concrete deterioration and corrosion; and (c) installation-related defects such as cracks, voids, and dents.

internal cracking in concrete or localized yielding in steel piles, which can propagate under cyclic loading [44].

During seismic excitation, liquefaction reduces lateral confinement, increasing effective slenderness and predisposing piles to bending instability [9]. Centrifuge and full-scale observations indicate that bending initiates within the liquefied zone and may transition to global buckling as unsupported length increases [45]. These degradation processes reduce axial and lateral stiffness, degrade energy dissipation characteristics, and compromise load-transfer efficiency [46], making them critical targets for VHM.

Material degradation mechanisms ((Figure 1(b), IV–V)) alter the pile's mechanical properties and accelerate stiffness loss. Steel piles are particularly susceptible to electrochemical corrosion in chloride-rich or oxygenated marine environments, leading to section loss and reduced load-carrying capacity [3, 47]. Reinforced concrete piles experience deterioration due to chloride-induced reinforcement corrosion, sulfate attack, alkali-silica reaction, and leaching, all of which promote cracking, spalling, microstructural weakening, and bond degradation [48, 49].

Environmental cycles such as wetting-drying or freeze-thaw further exacerbate deterioration. In seismic or laterally deforming soils, increased bending and shear demands accelerate cracking, corrosion progression, and interface degradation [7, 50]. Scour may expose deeper pile segments, enhancing corrosion rates and cyclic fatigue effects [1]. These processes produce measurable dynamic signatures, including stiffness reduction, increased damping, and altered curvature profiles.

Construction-induced defects (Figure 1(c), VI–VII) frequently act as initiators of long-term deterioration. Common anomalies include concrete segregation, necking, voids, inclusions, and misalignment in cast-in-place piles, as well as weld defects, dents, and geometric imperfections in steel piles [51]. These irregularities distort stress distributions, introduce eccentricity, and create localized stress concentrations that can precipitate premature cracking or buckling [35]. Postinstallation soil disturbances—such as heave or reconsolidation—further alter shaft friction and end-bearing resistance, compounding the impact of initial flaws. Under repeated cyclic or seismic loading, these defects may propagate, leading to significant stiffness degradation or loss of bearing capacity [52].

3 | VHM of Piles: Past Studies and Relevant Formulations

VHM of piles has evolved markedly over the past 2 decades, from early frequency- and impulse-based approaches to advanced distributed sensing, guided-wave methods, and ML-assisted diagnostics. This section reviews key studies on pile dynamics, sensing strategies, and defect characterization and summarizes the theoretical formulations underpinning modern VHM.

3.1 | Past Studies

A diverse body of experimental, numerical, and field research has investigated the dynamic response of piles subjected to structural defects, soil degradation, or boundary-condition changes [1, 20–23, 25, 53–71]. Further, Table 1 provides a consolidated listing of major contributions, demonstrating the wide variability

in materials, geometries, sensing systems, and analytical methods used across studies.

Initial VHM studies primarily employed accelerometers and low-strain excitation to estimate global dynamic characteristics such as natural frequencies, amplitude, and strains [1, 20–23, 67, 68]. While effective for detecting large stiffness losses, these global indicators lacked sensitivity to localized anomalies such as cracks, necking, bulging, voids, or soil-pile debonding [20–23, 71]. Numerical and experimental studies confirmed that low-frequency modes tend to mask high-gradient local defects [20–23, 71].

To address these limitations, contemporary VHM research increasingly employs high-resolution and multimodal sensing systems capable of capturing fine-scale dynamic response that traditional accelerometer-based approaches cannot resolve. PZT transducers enable both guided-wave interrogation and high-frequency damage detection, allowing identification of cracks, debonding, and impedance changes along the pile shaft [26, 28, 29, 63, 64]. FBG sensors provide quasi-distributed strain measurements with high accuracy, making them effective for monitoring toe-soil interaction, bending behavior, and strain localization in embedded pile segments [31, 33, 50, 82]. DFOS technologies based on Brillouin or Rayleigh backscattering extend this capability to full-length, millimetre-scale strain resolution, enabling continuous profiling of SPI, scour effects, and progressive deterioration [74–76, 78, 83, 84]. Additional platforms such as acoustic emission (AE) systems capture transient energy releases associated with microfracture activity [42, 85], while PVDF film sensors offer lightweight and flexible high-frequency response suitable for laboratory-scale studies [86]. Increasingly, researchers are integrating these technologies into hybrid sensing networks, which combine optical, piezoelectric, acoustic, and inertial measurements to establish multispectral and multiphysics diagnostic signatures, thereby enhancing the reliability and resolution of VHM systems.

Parallel advancements in numerical modeling and computation have enabled detailed simulation of wave propagation, modal behavior, and SPI under damaged conditions. Studies by Meng et al. [56], Liao et al. [25], and Xu et al. [59, 60] demonstrate effective integration of numerical analysis for interpreting sensor response and designing experimental protocols.

ML contributions have accelerated in recent years. Abdeljaber et al. [39] and Wu et al. [58] showed that artificial neural networks, convolutional neural networks (CNNs), and feature-learning algorithms can classify damage states and extract sensitive vibration features, including under operational and environmental variability [40]. Spencer et al. [87] and Das et al. [88, 89] further demonstrated the effectiveness of ML/DL for integrating large sensor datasets, enabling automated structural health monitoring (SHM) workflows. Moreover, the integration of advanced sensing and ML provides comprehensive damage prediction capabilities, including optimization of sensor placement for improved detectability [90–94].

Figures 2, 3, and 4 illustrate the multidisciplinary growth of VHM research, the predominance of concrete piles in experimental programs, and the geometric heterogeneity of test specimens. The lack of standardization in geometry, boundary conditions, or loading protocols presents challenges for cross-study comparison

TABLE 1 | Representative studies on vibration-based health monitoring (VHM) of pile foundations.

Sl.	Authors	Mat.	L/D	L (m)	Sensors	Monitoring objective
1	Davis and Dunn [65]	RC	—	~10–20	ACC	Integrity
2	Rausche and Goble [72]	RC	—	—	PIT	Integrity
3	Rausche et al. [17]	RC	—	—	PIT	Integrity
4	Rausche et al. [73]	RC	—	—	PIT	Comparison
5	Chow et al. [66]	RC	~20–30	~20–40	PIT, ACC	3D Effect
6	Ni et al. [18]	RC	—	—	PIT	Integrity
7	Klar et al. [74]	RC	~25	~18	DFOS	Strain monitoring
8	Bennett et al. [30]	RC	~20–30	~15–25	DFOS	Strain monitoring
9	Glisic et al. [50]	RC	~29	~35	OF	Load response
10	Lu et al. [75]	RC	~20	~12–20	DFOS	Field monitoring
11	Wang et al. [29]	RC	~24	~3.7	PZT	Damage detection
12	Feng et al. [26, 28]	RC	—	—	PZT	Damage detection
13	Hong et al. [32]	RC	~30	~20	OF	Axial response
14	Kou et al. [33]	T/RC/AL	~14	~1.0	FBG	Stress monitoring
15	Monsberger et al. [76]	ST	~25	~25	DFOS	Field monitoring
16	Wang et al. [77]	RC	~34	~42	DFOS	Integrity profiling
17	Zheng et al. [78]	RC	~43	~52	DFOS	Offshore monitoring
18	Zhu et al. [63, 64]	RC	~38	~1.5	PZT	Bond condition
19	Prendergast [79]	ST	~12.6	~1.26	ACC, PMT	Scour monitoring
20	Prendergast and Gavin [80]	ST	~15	~1.0	ACC	Scour monitoring
21	Zarafshan et al. [61]	RC	~20–30	~10–20	FBG	Scour monitoring
22	Foti and Sabia [1]	RC	~25	~15	ACC	Dynamic response
23	Dackermann et al. [49]	T/RC	~12	~3.0	ACC, ML	Damage detection
24	Gelman and Kırılancı [24]	RC	~28	~10	NA, OMA	Frequency change
25	Liu et al. [69]	ST	—	—	NA	Wave propagation
26	Pasqual and Kormann [70]	RC	—	—	NA	Integrity analysis
27	Ma et al. [55]	RC	~50	~40	NA	Damage imaging
28	Wu et al. [58]	RC	~40	~20	ACC, ML	Damage detection
29	Jiang et al. [38]	RC	—	—	NA	Damage imaging
30	Ying et al. [81]	RC	~1.25	~1.0	PZT, FBG	Axial monitoring

Note: ST = steel; AL = aluminum; T = timber; COMP = composite. ACC = accelerometer; PZT = piezoelectric transducer. (All dimensions are in meter).

Abbreviations: DFOS = distributed fiber-optic sensing, FBG = fiber Bragg grating, ML = machine learning, NA = numerical analysis, OMA = operational modal analysis, PIT = pile integrity test, PMT = physical model test, RC = reinforced concrete.

and highlights the need for scaling effects and more universal interpretive strategies [20–23, 37, 91, 95].

Concrete piles dominate the literature, comprising nearly 70% of reported investigations, consistent with their widespread use in civil infrastructure [50, 53, 83]. Steel, aluminum, timber, and composite piles are represented mainly in laboratory studies [86, 96]. Reported pile lengths span from small-scale specimens less than 1 m to full-scale foundations exceeding 70 m [76, 78].

3.2 | Relevant Formulations

VHM interprets changes in the dynamic response of pile–soil systems to infer deterioration in structural or geotechnical components. A pile behaves as a continuous beam embedded in a deformable and dissipative soil medium, where flexural stiffness, mass distribution, boundary conditions, and soil restraint collectively govern the measured response. Damage mechanisms

such as cracking, section loss, corrosion, scour, toe–soil decoupling, or liquefaction-induced softening alter these governing parameters, resulting in observable changes in modal properties, deformation patterns, wave propagation characteristics, and energy transmission behavior [71, 97].

3.2.1 | Beam-on-Elastic-Foundation

The classical Winkler foundation model represents the soil as a set of independent linear springs, in which the foundation reaction is proportional to the local beam deflection, leading to the governing equation (1)

$$EI \frac{d^4 w}{dx^4} + kw = q(x), \quad (1)$$

where $w(x, t)$ is the transverse beam deflection, E is the Young's modulus of the beam material, I is the second moment of area, k is the Winkler foundation modulus representing normal soil

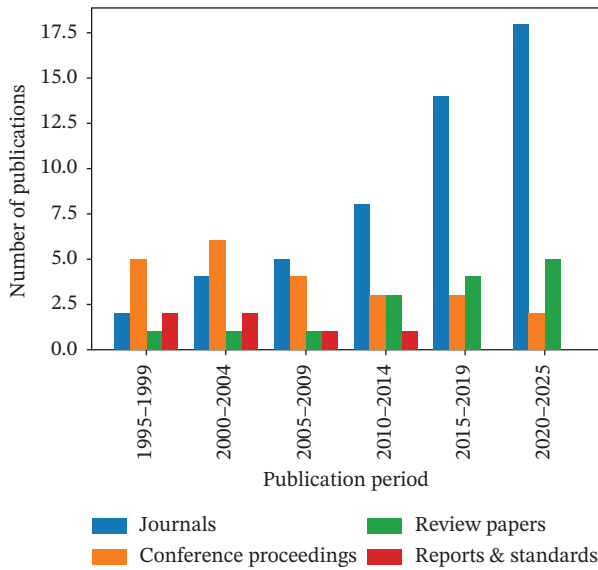


FIGURE 2 | Contributions to the field of vibration-based health monitoring (VHM) of piles.

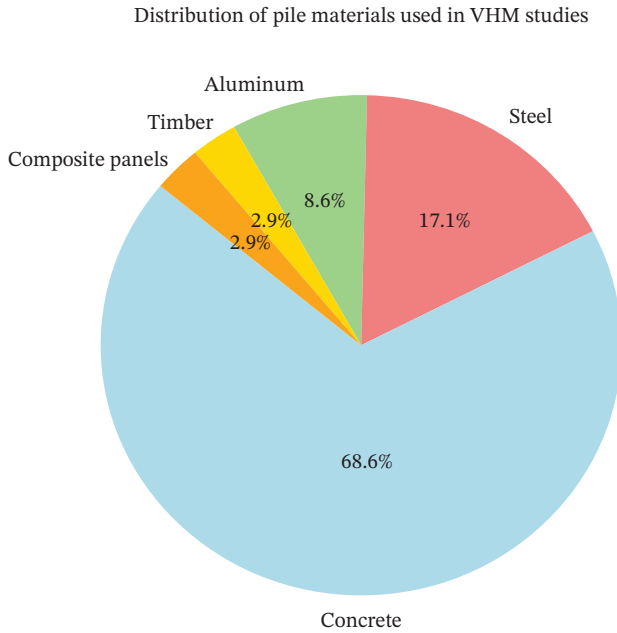


FIGURE 3 | Pile material used for VHM studies.

stiffness per unit length, x is the beam axis, and $q(x)$ is the applied load per unit length [98, 99]. Since the Winkler model neglects soil continuity, the Pasternak foundation model introduces shear interaction between adjacent soil springs, yielding (equation (2))

$$EI \frac{d^4 w}{dx^4} + kw - G_p \frac{d^2 w}{dx^2} = q(x), \quad (2)$$

where G_p is the Pasternak shear parameter accounting for lateral soil interaction [97]. The Vlasov foundation model is derived from elastic continuum theory by assuming a depth-dependent soil displacement field, resulting in foundation stiffness parameters directly related to soil elastic modulus and layer thickness [100]. The Kerr foundation model further extends this

concept by introducing multiple spring layers and an intermediate shear layer to represent depth-dependent stiffness and soil stratification [101]. For vibration and seismic applications, dynamic beam-on-elastic-foundation models incorporate inertia and damping effects, leading to

$$EI \frac{d^4 w}{dx^4} + kw - G_p \frac{d^2 w}{dx^2} + m \frac{\partial^2 w}{\partial t^2} + c \frac{\partial w}{\partial t} = q(x, t), \quad (3)$$

where m is the mass per unit length of the beam–foundation system, c is the damping coefficient, t is time, and $q(x, t)$ is the time-dependent external load, enabling realistic analysis of dynamic and seismic soil–structure interaction [102].

3.2.2 | Modal Curvature as a Damage Indicator

For a linear system, the dynamic response can be decomposed into vibration modes. The curvature associated with the i -th mode shape $\phi_i(x)$ is defined as (equation (4))

$$\kappa_i(x) = \frac{d^2 \phi_i(x)}{dx^2}, \quad (4)$$

which is directly proportional to bending strain and therefore highly sensitive to local stiffness variations. Since curvature amplifies spatial gradients in deformation, localized damage such as cracking, necking, or material degradation produces pronounced changes in curvature distribution. Consequently, modal curvature provides a physically meaningful feature for detecting and localizing damage in piles within a vibration-based monitoring framework [23, 57, 103].

3.2.3 | Wave-Based Interpretation and Impedance Mismatch

Dynamic excitation also induces stress-wave propagation along the pile, allowing the system to be interpreted as a one-dimensional waveguide. For axial wave motion, the governing equation is equation (5).

$$\frac{\partial^2 u(x, t)}{(\partial t^2)} = c^2 \frac{\partial^2 u(x, t)}{\partial x^2}, \quad (5)$$

where $u(x, t)$ is the axial displacement and $c = \sqrt{E/\rho}$ is the wave velocity, with E denoting Young's modulus and ρ the material density. The axial impedance of the pile is defined as in equation (6a)

$$Z = \frac{EA}{c}, \quad (6a)$$

where A is the cross-sectional area. Structural or geotechnical defects introduce impedance discontinuities along the pile, leading to partial wave reflection and transmission. The reflection coefficient at a defect is given by equation (6b)

$$R = \frac{Z_d - Z_0}{Z_d + Z_0}, \quad (6b)$$

where Z_0 and Z_d denote the impedances of the intact and damaged sections, respectively. Cracks, toe voids, and pile–soil debonding produce characteristic reflection signatures that influence the frequency content and amplitude of the measured response, forming the basis of stress-wave-based and active sensing approaches [26, 38, 104].

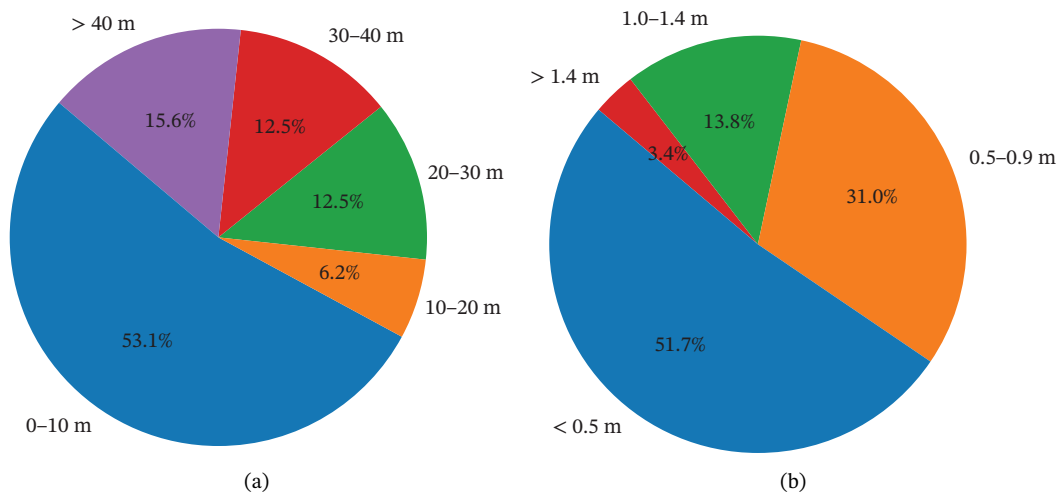


FIGURE 4 | Pile dimension used in past studies (a) length and (b) diameter.

3.2.4 | Frequency Response and Energy-Based Indicators

The combined effects of SPI, modal behavior, and wave propagation are commonly examined using frequency-domain representations. The frequency response function (FRF) is defined as

$$H(\omega) = \frac{X(\omega)}{F(\omega)}, \quad (7)$$

where $F(\omega)$ is the applied excitation and $X(\omega)$ is the measured response at angular frequency ω . Changes in stiffness, damping, or boundary conditions manifest in FRFs as shifts in resonant frequencies, variations in modal amplitudes, and increased energy dissipation [77, 105]. From an energy perspective, damage modifies the ability of the pile-soil system to transmit and store vibrational energy, resulting in increased attenuation and redistribution of response energy across frequency bands. These frequency- and energy-based characteristics provide physically interpretable indicators for vibration-based damage monitoring without reliance on purely empirical damage indices.

4 | Advancement in VHM

This section presents recent advances in sensors, sensor placement, data acquisition (DAQ) and processing, the application of ML and artificial intelligence, as well as the use of numerical analysis, are discussed, with emphasis on their current developments.

4.1 | Advanced Sensor Technologies

VHM has advanced significantly over the past 2 decades, enabling more reliable and noninvasive evaluation of pile foundations. These developments encompass sensing technologies, DAQ systems, signal processing techniques, and numerical methods [20–23, 53, 87, 95]. Based on the compiled dataset in Table 1 and a few other studies, Figure 5(a) summarizes the distribution of sensors adopted in previous studies. Accelerometers remain the most widely used sensing devices due to their robustness, low cost, and direct applicability to modal- and vibration-based assessment methods [20–23, 25, 67, 68].

Statistical trends in Figure 5(b) indicate that accelerometers account for approximately 38% of sensor deployments, followed by PZT transducers (~19%) and FBG sensors (~16%). Other sensing platforms include PIT instrumentation [11, 17, 18, 66, 73], polyvinylidene fluoride (PVDF) films [86], tactile transducers [49], and DFOS systems [74–76, 78, 83, 84], which appear less frequently overall, although DFOS usage has increased rapidly in recent field applications [76, 78, 84].

While Figure 5 summarizes the prevalence of sensor usage in previous studies, sensor selection in VHM is governed not only by adoption frequency but also by sensing capability and diagnostic objectives. Figure 6 provides a comparative overview of commonly used sensor technologies, highlighting their complementary roles in global vibration monitoring, localized damage detection, SPI assessment, and long-term field deployment. This comparison establishes a structured framework for interpreting the sensor-specific studies discussed in the following sections.

Early VHM implementations relied primarily on accelerometers and geophones to capture low-strain vibration responses, particularly for identifying global stiffness changes and modal parameter variations in piles [25, 67, 68]. While these point-based sensors are robust and cost-effective, their sensitivity to localized defects—such as cracking, section loss, or deep-seated damage along the pile shaft—is limited [22, 71]. In addition, accelerometer-based measurements can be adversely affected by environmental noise and provide only discrete information, offering limited insight into the spatial distribution of SPI effects [34, 37].

To address these limitations, recent research has increasingly adopted high-resolution sensing technologies capable of detecting localized stiffness degradation, impedance discontinuities, and high-frequency stress-wave phenomena. PZT transducers are widely employed in both active (wave excitation) and passive (response sensing) configurations, enabling identification of cracks, toe-soil separation, and debonding through wave scattering, reflection, and impedance contrast mechanisms [26, 28, 29, 63, 64]. AE sensors further complement PZT-based approaches by capturing transient microfracture events associated with material degradation and progressive damage [42, 85].

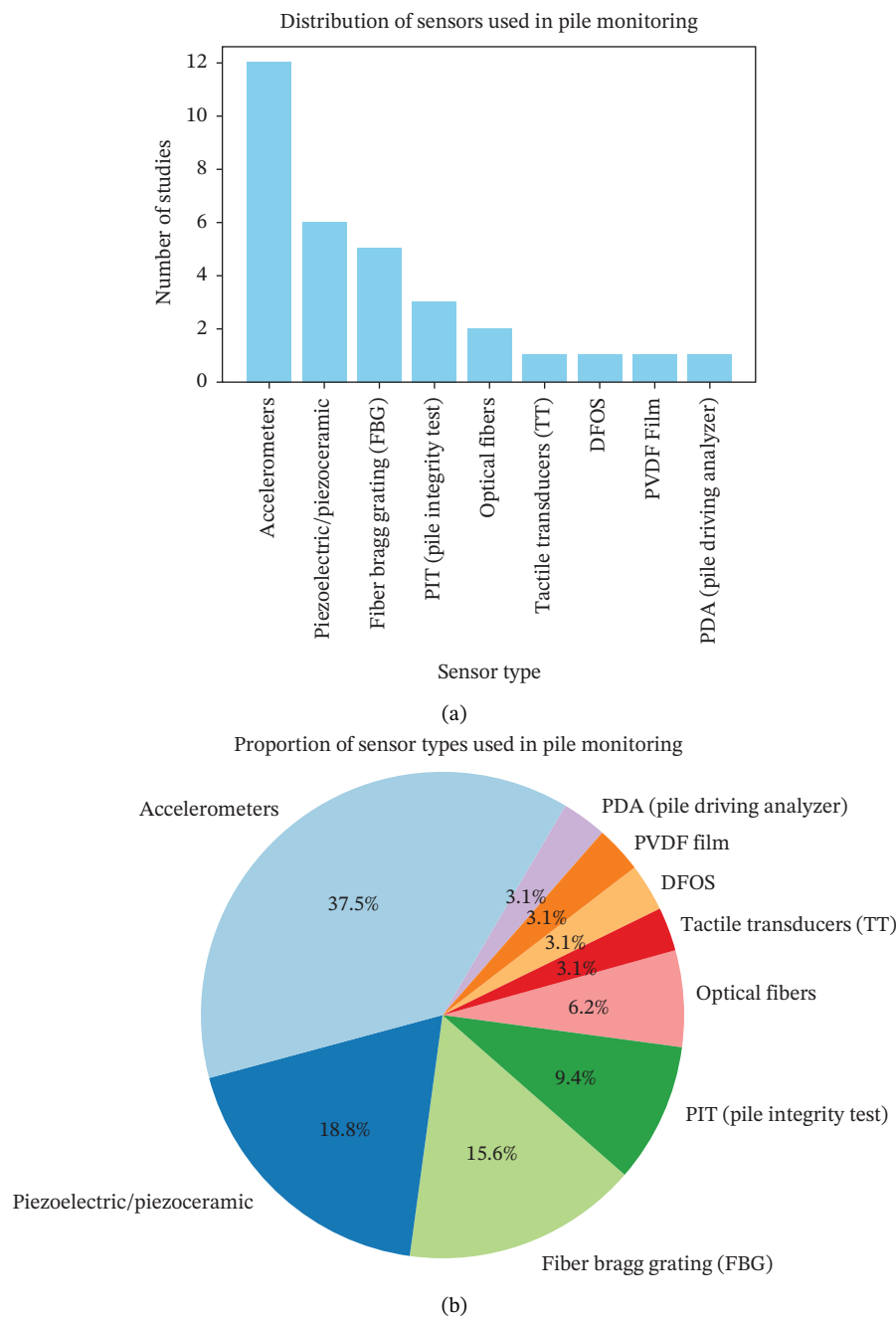


FIGURE 5 | (a) Distribution of sensors adopted in vibration-based health monitoring (VHM) of piles and (b) percentage statistics of sensor usage in previous studies.

Fiber-optic sensing technologies provide an alternative and increasingly powerful monitoring paradigm. FBG sensors offer quasi-distributed, high-precision strain measurements along instrumented sections of piles, facilitating detection of curvature anomalies, neutral-axis shifts, and localized stiffness loss [31, 33, 82]. DFOS systems—based on Brillouin or Rayleigh scattering—extend these capabilities to full pile length, enabling continuous strain profiling under operational loading, seismic excitation, or scour-induced soil loss [76, 78, 84]. These systems offer exceptional durability and performance in harsh environments, making them particularly attractive for long-term geotechnical monitoring.

PVDF films, commonly used in laboratory-scale investigations, provide lightweight and flexible transducers capable of capturing high-frequency strain variations [86]. MEMS-based sensors introduce compact, multiparametric measurement capabilities, allowing simultaneous monitoring of acceleration, inclination, pore pressure, and temperature, often within wireless sensor networks (WSNs) [34].

4.2 | Optimal Sensor Placement (OSP)

Because SPI strongly modulates measurable response, OSP plays a crucial role in ensuring diagnostic sensitivity and minimizing

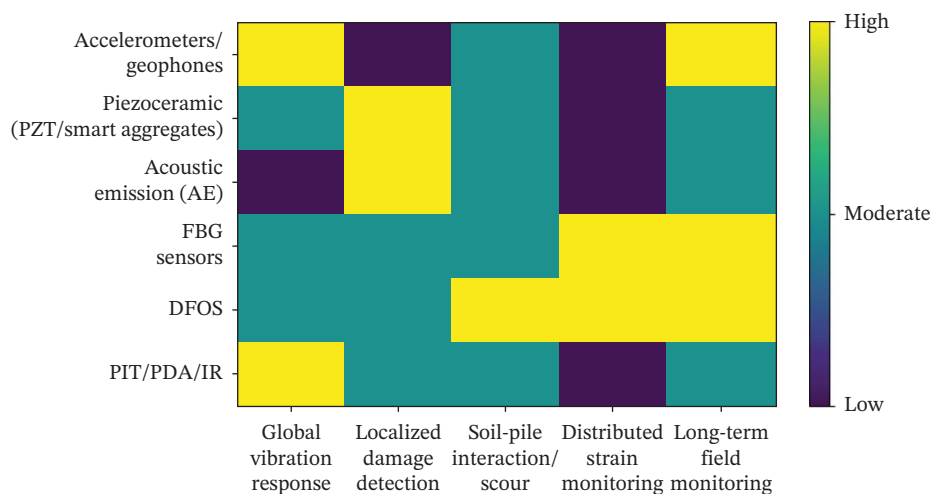


FIGURE 6 | Comparison of commonly used sensors in vibration-based health monitoring of piles based on their monitoring capability and application scope.

uncertainty. Classical OSP approaches include the Effective Independence method [92], D-optimality, and modal assurance criterion-based optimization, which target improved observability of desired vibration modes. OSP approaches, including effective independence and metaheuristic optimization, also enhance damage detectability by positioning sensors at locations of high modal curvature, strain energy, or wave-reflection sensitivity [94]. Dense sensing platforms such as FBG arrays, DFOS, and PZT networks increasingly use WSNs and edge processing to manage large data volumes and support real-time diagnostics [34]. Multisensor systems require precise temporal synchronization using GPS or network protocols to ensure phase consistency essential for modal, wave-based, and interferometric analyses [37].

More recently, metaheuristic algorithms, including genetic algorithms, particle swarm optimization, and hybrid evolutionary strategies, have been adopted to accommodate nonlinear SPI, multiple objectives, and high-dimensional search spaces [90, 93]. These methods can strategically position accelerometers, PZT patches, or FBG arrays at locations of high modal curvature, strain-energy density, or wave-reflection sensitivity, thereby enhancing the detectability of cracks, toe anomalies, or debonding zones.

For dense sensing systems such as DFOS or distributed PZT clusters, OSP frameworks ensure efficient data representation, limit redundancy, and enable cost-effective deployment. In WSNs, OSP is equally critical for minimizing communication overhead and enabling edge-based processing [34].

4.3 | DAQ and Signal Processing

Modern DAQ systems record analog outputs from accelerometers, PZT transducers, FBGs, and DFOS with high accuracy [34]. Sampling rates typically 50–100 kHz are required to preserve high-frequency stress-wave components associated with defects, impedance mismatches, and soil-pile debonding [28, 63, 64]. High-resolution 16–24 bit A/D converters improve sensitivity to weak reflections and low-amplitude vibrations in long or deteriorated piles. Signal conditioning reduce gain control, impedance matching, and antialias filtering reduce electronic and environmental noise, ensuring accurate digitization [37].

Signal processing extracts damage-sensitive features from recorded responses. Time-domain methods—root-mean-square (RMS), kurtosis, autoregressive (AR), and AR moving average (ARMA) models—enable anomaly detection but are sensitive to nonstationary conditions [37]. Frequency-domain approaches remain fundamental for estimating natural frequencies, damping, and spectral energy distribution, which change with stiffness degradation and soil softening [22, 35]. Given the transient and nonlinear nature of SPI, time-frequency analyses provide superior performance. The short-time Fourier transform (STFT) offers joint temporal-spectral resolution, while continuous wavelet transforms (CWT), discrete wavelet transform (DWT), and wavelet packet transform (WPT) effectively identify abrupt stiffness changes, crack initiation, and wave-scattering signatures [35, 36]. The HHT and empirical mode decomposition (EMD) are particularly effective for nonlinear phenomena such as breathing cracks or progressive debonding [38]. Modal-based methods including OMA and Stochastic Subspace Identification (SSI) estimate modal parameters under ambient excitation. Derived indicators such as modal curvature and flexibility remain highly sensitive to localized stiffness loss [71].

4.4 | ML and DL Techniques

ML has broadened the scope of VHM by enabling automated interpretation of high-dimensional vibration, strain, and wave-based signals. Classical ML algorithms—such as Support Vector Machines, Random Forests, and k-Nearest Neighbours—have demonstrated strong performance in damage classification and anomaly detection when paired with carefully engineered modal or time-frequency features [40, 49, 106].

DL methods further enhance diagnostic capability by learning representative features directly from raw sensor input. CNNs excel in capturing spatial patterns in FRFs or spectrograms [39, 96]. Recurrent neural networks (RNNs) and long short-term memory architectures model temporally evolving responses and are highly suited for long-term VHM datasets [47]. Autoencoders and variational autoencoders (VAEs) support unsupervised anomaly detection when baseline damaged-state data are unavailable.

Recently explored architectures including transformers, graph neural networks, and physics-informed neural networks offer promising avenues for modeling spatially distributed SSI effects and environmental variability. However, challenges remain regarding dataset size, generalizability, and field implementation [40, 87].

4.5 | Numerical Modeling

Numerical modeling forms the analytical backbone of VHM because it enables controlled simulation of SPI, damage evolution, and dynamic response across a wide range of spatial and temporal scales. Among available modeling strategies, finite element modeling (FEM) remains the most widely adopted due to its ability to incorporate nonlinear soil behavior, detailed material deterioration mechanisms, and wave-propagation effects in a unified framework [46, 55, 56, 107, 108]. For concrete piles, deterioration is often represented using concrete damage plasticity (CDP), smeared cracking, or cohesive-zone models, which capture tensile cracking, compressive softening, stiffness reduction, and progressive section loss [55, 60]. Steel piles are typically modeled using elastoplasticity with kinematic or isotropic hardening, enabling representation of yielding, buckling, low-cycle fatigue, and corrosion-induced wall thinning [44, 45, 76].

Because pile dynamics are strongly governed by the surrounding soil, accurate modeling of SPI is essential. Contemporary VHM-oriented numerical models employ several strategies to represent interfacial behavior: interface elements with nonlinear shear and normal stiffness capture slipping, gapping, and soil–pile debonding [56, 63, 64], allowing simulation of partial or full loss of contact under cyclic or seismic loading. Contact algorithms simulate separation–reclosure cycles that contribute to nonlinear damping and wave distortion. *t*–*z* and *p*–*y* springs, or more advanced constitutive soil models, represent degradation of shaft friction, lateral stiffness loss, and liquefaction-induced softening. Fully coupled soil continua allow simulation of pore-pressure buildup, lateral spreading, or scour-induced loss of confinement [59, 67].

Beyond FEM, boundary element methods (BEM) and hybrid FE–BE formulations provide computationally efficient solutions for simulating far-field wave propagation and radiation damping [102]. Spectral element methods (SEM) and finite-difference time-domain (FDTD) schemes offer high accuracy for modeling guided-wave propagation and stress-wave reflections arising from cracks, necking, toe anomalies, or stiffness discontinuities [55, 69, 109].

5 | Applications of VHM in Foundations

The present applications reviewed here show that VHM can be tailored to specific performance and safety challenges in deep foundations. Although all methods rely on interpreting dynamic response characteristics, each use case such as scour detection, capacity evaluation, buckling assessment, and damage identification exhibits distinct diagnostic indicators. By targeting

problem-specific dynamic features, VHM provides actionable insights that strengthen broader SHM frameworks.

5.1 | Scour Monitoring

Scour reduces the effective embedded length and lateral confinement of piles, causing measurable changes in their dynamic response. Experimental and numerical investigations have consistently shown that the first bending natural frequency decreases with progressive scour, reflecting loss of soil stiffness and reduced boundary restraint [1, 54, 61, 67]. Prendergast [79], Zhan et al. [67], and others [61, 80] demonstrated through field and vibration-monitoring studies that scour induces distinct curvature anomalies, with inflection points forming at the scour boundary due to compromised SPI.

Stress-wave diagnostic behavior also changes under scour. Reduced stiffness leads to delayed and attenuated toe reflections in impact-based testing [66, 70, 110], while DFOS captures localized increases in strain curvature along scour-affected regions [76, 78, 84]. These depth-resolved strain gradients provide real-time identification of scour effects even in deep foundations where direct inspection is not feasible. Overall, VHM methods offer reliable scour detection through a combination of modal-frequency analysis, curvature evaluation, and wave-propagation monitoring [54, 57, 67].

5.2 | Bearing Capacity and Shaft Resistance Monitoring

Dynamic-response techniques serve as powerful tools for assessing shaft friction and end-bearing resistance in deep foundations. High-strain PDA testing remains widely used for estimating mobilized resistance through stress-wave propagation and impedance matching [17, 48, 72, 111, 112]. Low-strain impulse-response and mobility analyses provide complementary insights [18, 66, 73].

Finite-element studies by Meng et al. [56] and experimental investigations validated that degradation in soil–pile bonding or shaft friction manifests as reductions in dynamic stiffness and changes in damping characteristics [63, 64, 66]. These influence both low-frequency mobility and high-frequency reflection patterns. Alterations in toe-reflection amplitude under low-strain excitation further correlate with end-bearing condition, enabling VHM systems to capture capacity loss or recovery without requiring conventional static load tests [73, 112]. Thus, VHM provides a practical, noninvasive pathway for monitoring bearing performance throughout a pile’s service life.

5.3 | Buckling Monitoring

Buckling vulnerability in slender or partially unsupported piles is effectively reflected in their vibration characteristics. As axial load approaches critical values or lateral confinement decreases, the pile’s flexural stiffness drops, resulting in measurable reductions in the first bending natural frequency [43, 44]. Modal curvature responds even more sensitively, showing localized curvature amplification near the onset of instability [71].

Advanced sensing systems enhance this capability by capturing evolving strain patterns. Kou et al. [33], Soga and Luo [84], and Pelecanos & Soga [113] demonstrated that fiber-optic sensing embedded along piles provides high-resolution measurements of axial stress redistribution that may precede flexural instability. Zhu et al. [63, 64] further showed that dynamic excitation can reveal nonlinear signatures associated with pile–soil debonding and bonding degradation, including waveform distortion and response modulation, which may serve as early indicators of instability-related damage. These patterns closely resemble the distorted impulse-response functions observed in defective pile waveforms. Taken together, VHM offers a powerful framework for detecting prebuckling behavior in deep foundations under combined axial and lateral demands.

5.4 | Localized Damage and Crack Monitoring

Wave-based VHM methods, particularly low-strain PIT and impulse-response (IR) testing, are highly sensitive to localized defects such as necking, bulging, cracking, voids, and section loss [18, 66, 73, 110]. The time-domain velocity trace presented in the first figure demonstrates classic diagnostic behavior: after the incident wave, a negative-phase reflection indicates necking due to reduced impedance, whereas a positive-phase reflection indicates bulging from localized stiffness increase. These polarity differences have been validated experimentally and numerically by Rausche et al. [73], Chow et al. [66], and Pasqual and Kormann [70]. The arrival times allow direct depth calculation for the defect and pile toe, respectively, while reflection amplitude scales with defect severity.

Frequency-domain mobility analysis strengthens these observations. Defects introduce additional resonant peaks or modify the spacing of existing ones. Modern studies have shown that swept-frequency excitation and advanced processing can enhance detectability of subtle defects, with defective piles showing early secondary peaks, phase distortion, and altered toe-reflection characteristics [24, 38]. Modern sensing approaches such as DFOS and PZT-based active sensing extend this capability by detecting high-frequency scattering, localized response disturbances, and nonlinear defect signatures [29, 63, 64, 76, 78, 83]. These combined indicators yield a highly robust framework for identifying and characterizing localized damage in deep foundations.

5.5 | Postearthquake-Induced Damage and Soil Degradation Monitoring

Seismic loading induces complex deterioration in both pile structures and surrounding soils, producing clear shifts in dynamic response parameters. Natural frequencies typically decrease after significant shaking due to structural cracking or soil softening, while damping ratios increase as soils enter nonlinear or partially liquefied states [4, 9]. Such changes can be captured through ambient vibration surveys, impulse-response tests, or real-time monitoring systems.

Gelman and Kırılancık [24] provided a quantitative correlation framework showing that damage severity correlates strongly with reductions in natural frequency and increases in damping and peak acceleration sensitivity. Although not related to scour, their findings confirm the reliability of frequency- and damping-based VHM indicators for general structural deterioration. Wave-

propagation analysis also reveals seismic-induced degradation; reductions in wave speed and weakened toe-reflection signatures associated with interface debonding or soil softening have been demonstrated through numerical and experimental studies [63, 64, 114]. For foundations without preinstalled sensors, portable accelerometers and impact-based methods allow rapid postevent evaluation [65, 73]. Together, these findings highlight VHM as an effective mechanism for postearthquake assessment, enabling rapid detection of hidden damage in pile-supported structures.

6 | Discussion on SHM Techniques

A wide spectrum of SHM and NDT methods are available for assessing the integrity of deep foundations, each offering distinct diagnostic capabilities, operational requirements, and limitations. Most established methods, such as low-strain integrity testing (ASTM D5882, 11), cross-hole sonic logging (ASTM D6760, 12), thermal integrity profiling (ASTM D7949, 13), and gamma-gamma density logging, have been extensively applied during construction and rehabilitation phases to verify material continuity, detect major anomalies, and assess construction quality [14–16, 115]. These code-recognized procedures reliably identify defects such as voids, inclusions, necking, segregation, or poor concrete zones. However, their reliance on direct access to the pile head, embedded access tubes, or preinstalled instrumentation restricts their applicability for long-term assessment once the structure is operational.

In contrast, VHM offers a fundamentally different capability by evaluating the global dynamic behavior of the combined pile–soil system rather than solely assessing internal material continuity. Dynamic parameters including natural frequencies, damping ratios, modal curvatures, frequency-response characteristics, and wave-propagation signatures are sensitive to both structural and geotechnical degradation. Thus, changes in soil stiffness, loss of lateral confinement, scour-induced exposure, cracking, or interface debonding can be detected indirectly through shifts in vibration response [1, 2, 69, 116]. Because VHM can be applied under ambient, operational, or low-strain excitation, it is uniquely suited for repeated measurements, temporal trend analysis, and long-term monitoring in buried or inaccessible environments.

Nevertheless, vibration-based methods face challenges related to environmental and operational variability, including temperature changes, hydrological cycles, and fluctuations in operational loads. These effects may mask or mimic damage-induced changes, necessitating careful normalization, environmental filtering, or the integration of ML-based compensation schemes [39, 40, 96, 117–119]. Additionally, while VHM excels in detecting global stiffness changes or boundary-condition shifts, its ability to identify certain localized defects—such as small voids or reinforcement-level flaws—may remain limited without complementary high-resolution sensing systems (e.g., PZT, DFOS, FBG).

The diagnostic capability of vibration-based parameters is underscored by the correlation analysis derived from Kırılancık and Gelman [24] and illustrated in Figure 7. The strong negative correlation between damage level and natural frequency (-0.65) aligns with the well-established principle that stiffness

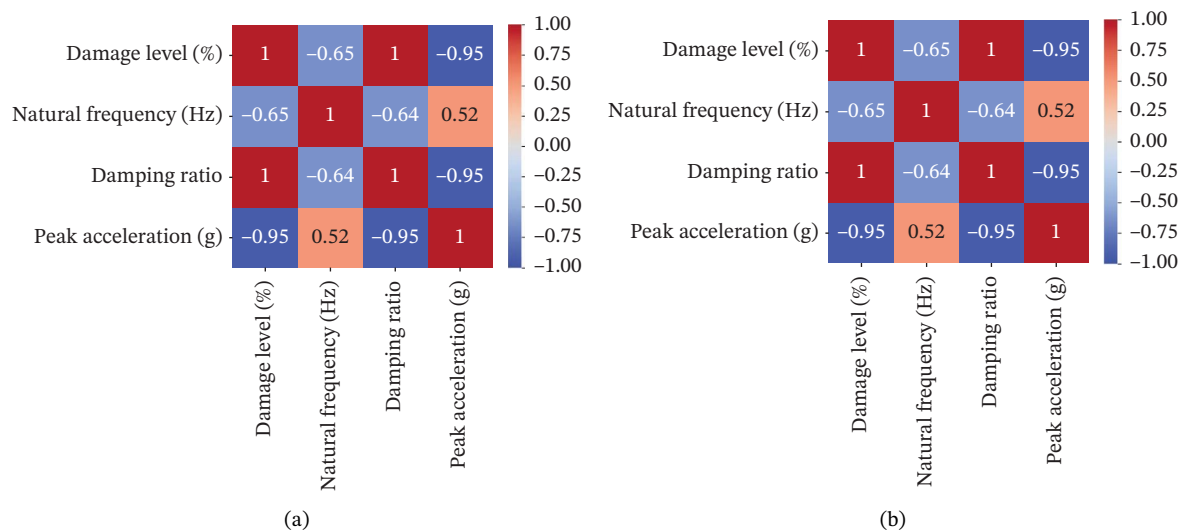


FIGURE 7 | Correlation of key vibration-based parameters and damage level for FRF-CFB and wave-speed analyses. (a) FRF-CFB values for different modes. (b) Wave-speed for piles.

reduction—whether due to structural cracking, scour, or soil degradation—produces modal frequency drops. The positive correlation with damping ratio (1.00) reflects increased energy dissipation associated with cracking, interface softening, or nonlinear soil response. The strong inverse correlation with peak acceleration (−0.95) further indicates diminished vibrational amplitude as damage severity increases. Importantly, these trends appear consistently across both FRF curve-fitting methods and wave-speed-based evaluations, demonstrating the robustness of dynamic indicators for SHM of deep foundations.

7 | Conclusions

This review has integrated the theoretical foundations, sensing technologies, analytical models, and application domains that define VHM for deep foundations, with particular emphasis on the role of SPI in governing measurable dynamic response. The collective evidence demonstrates that VHM offers a robust, noninvasive means to detect structural deterioration, soil–pile stiffness changes, toe and shaft anomalies, and localized defects that conventional NDT methods often overlook, especially in long, deeply embedded, or inaccessible piles.

Across applications including scour assessment, axial capacity and shaft resistance monitoring, buckling detection, post-earthquake degradation, and crack identification dynamic features such as natural frequency, modal curvature, peak acceleration, and impedance variations consistently emerge as reliable markers of deterioration. Importantly, the reviewed studies indicate that the sensitivity of these indicators depends strongly on pile geometry, embedment depth, boundary conditions, and excitation characteristics, underscoring the need to interpret vibration signatures within an SPI framework rather than as purely structural responses.

Despite significant advancements in sensing technologies and analytical methods, major barriers remain for the widespread field adoption of VHM in pile foundations. While many sensing approaches—such as embedded PZT and fiber-optic systems—can be efficiently deployed during the construction phase of

new piles, their application to existing and aging foundations, particularly large-diameter piles and offshore monopiles, remains challenging due to accessibility constraints, retrofit limitations, sensor survivability, and reduced signal quality. Moreover, most reported VHM implementations are still laboratory- or pilot-scale, and the performance of these techniques under realistic environmental and operational variability has not been sufficiently explored. The lack of standardized testing protocols, robust environmental normalization strategies, and practically calibrated diagnostic thresholds continues to limit the transition of VHM from research-oriented studies to routine field deployment.

To advance VHM toward reliable field application, priority needs include (i) establishing dynamic reference baselines that explicitly account for SPI and site variability; (ii) developing calibrated relationships between specific damage mechanisms and measurable vibration signatures; (iii) creating nonintrusive sensing solutions suitable for existing foundations; (iv) integrating soil–pile dynamic interaction explicitly into diagnostic and numerical models; and (v) building hybrid NDT–VHM frameworks that enable cross-validation with established integrity testing methods [120–131].

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. S. Foti and D. Sabia, "Influence of Foundation Scour on the Dynamic Response of an Existing Bridge," *Journal of Bridge Engineering* 16, no. 2 (2011): 295–304, [https://doi.org/10.1061/\(ASCE\)BE.1943-5592.0000146](https://doi.org/10.1061/(ASCE)BE.1943-5592.0000146).
2. K. D. Kariyawasam, R. Campbell, G. Madabhushi, S. K. Haigh, and J. P. Talbot, "Assessment of Bridge Natural Frequency as an Indicator of Scour Using Centrifuge Modelling," *Journal of Civil Structural Health Monitoring* 10, no. 5 (2020): 861–881, <https://doi.org/10.1007/s13349-020-00420-5>.
3. R. E. Melchers, "Long-Term Corrosion of Cast Irons and Steel in Marine and Atmospheric Environments," *Corrosion Science* 68 (2013): 186–194, <https://doi.org/10.1016/j.corsci.2012.11.014>.
4. S. L. Kramer and J. P. Stewart, *Geotechnical Earthquake Engineering* (Boca Raton, FL: CRC Press, 2024).
5. S. Niu, Z. Liu, A. Guo, and S. Xu, "Modeling and Investigation of Long-Term Performance of HIGH-RISe Pile Cap Structures Under Scour and Corrosion," *Journal of Marine Science and Engineering* 13, no. 1 (2025): 11, <https://creativecommons.org/licenses/by/4.0/>, <https://doi.org/10.3390/jmse13030450>.
6. H. Muguruma, M. Nishiyama, and F. Watanabe, "Lessons Learned from the Kobe earthquake—A Japanese Perspective," *PCI Journal* 40, no. 4 (1995): 28–42, <https://doi.org/10.15554/pcij.07011995.28.42>.
7. K. Ishihara, "Geotechnical Aspects of the 1995 Kobe Earthquake (Terzaghi Oration)," in *Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering* (Hamburg, Germany, 1997), 2047–2074.
8. K. Ishihara and M. Cubrinovsky, "Case Studies of Pile Foundations Undergoing Lateral Spreading in Liquefied Deposits," in *Proceedings of the 5th International Conference on Case Histories in Geotechnical Engineering* (New York, NY, April 2004).
9. K. Tokimatsu and Y. Asaka, "Effects of Liquefaction-Induced Ground Displacements on Pile Performance in the 1995 Hyogoken-Nambu Earthquake," *Soils and Foundations* 38, no. Special (1998): 163–177, https://doi.org/10.3208/sandf.38.Special_163.
10. M. H. Fansuri, M. Chang, and R. Kusumawardani, "A Case Study on Buckling Stability of Piles in Liquefiable Ground for a coal-fired Power Station in Indonesia," in *Innovative Solutions for Soil-Structure Interaction (Geomeast 2019)*, ed. H. El-Naggar, et al. (Springer, 2019), 88–106, https://doi.org/10.1007/978-3-030-34252-4_8.
11. Astm D5882, *Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations* (ASTM International).
12. Astm D6760, *Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing* (ASTM International).
13. Astm D7949, *Standard Test Method for Thermal Integrity Profiling of Concrete Deep Foundations* (ASTM International).
14. M. Hajali and C. Abishdid, "Cross-Hole Sonic Logging and Frequency Tomography Analysis of Drilled Shaft Foundations to Better Evaluate Anomalies Locations," *DFI Journal* 8, no. 1 (2014): 27–38, <https://doi.org/10.1179/tbc14z.0000000001>.
15. G. Mullins, "Thermal Integrity Profiling of Drilled Shafts," *DFI Journal* 4, no. 2 (2010): 54–64, <https://doi.org/10.1179/dfi.2010.010>.
16. W. M. Camp, D. W. Holley, and G. J. Canivan, "Crosshole Sonic Logging of South Carolina Drilled Shafts: A Five-Year Summary," in *Contemporary Issues in Deep Foundations* (ASCE, 2007), 1–11, [https://doi.org/10.1061/40902\(221\)2](https://doi.org/10.1061/40902(221)2).
17. F. Rausche, G. Likins, and M. Hussein, "Pile Integrity by Low and High Strain Impacts," in *Proceedings of the 3rd International Conference on Application of Stress-Wave Theory to Piles* (Ottawa, Canada, 1988), 44–55.
18. S. H. Ni, L. Lehmann, J. J. Charng, and K. F. Lo, "Low-Strain Integrity Testing of Drilled Piles with High Slenderness Ratio," *Computers and Geotechnics* 33, no. 6-7 (2006): 283–293, <https://doi.org/10.1016/j.compgeo.2006.08.001>.
19. Y. Zhang, H. Ji, L. Zhang, M. H. El Naggar, and W. Wu, "Identification of Bored Pile Defects Utilizing Torsional Low Strain Integrity Test: Theoretical Basis and Numerical Analysis," *Journal of Rock Mechanics and Geotechnical Engineering* 17, no. 5 (2025): 3035–3053, <https://doi.org/10.1016/j.jrmge.2024.08.005>.
20. S. W. Doebling, C. R. Farrar, and M. B. Prime, "A Summary Review of Vibration-Based Damage Identification Methods," *The Shock and Vibration Digest* 30, no. 2 (1998): 91–105, <https://doi.org/10.1177/058310249803000201>.
21. S. W. Doebling, C. R. Farrar, M. B. Prime, and D. Shevitz, "Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics: A Literature Review," *Los Alamos National Lab Report LA-13070-MS* (1996): <https://doi.org/10.2172/249299>.
22. W. Fan and P. Qiao, "Vibration-Based Damage Identification Methods: A Review and Comparative Study," *Structural Health Monitoring* 10, no. 1 (2011): 83–111, <https://doi.org/10.1177/1475921710365419>.
23. G. Boscato, L. Zanotti Fragonara, A. Cecchi, E. Reccia, and D. Baraldi, "Structural Health Monitoring Through Vibration-based Approaches," *Shock and Vibration* 2019, no. 1 (2019): 2380616, <https://doi.org/10.1155/2019/2380616>.
24. L. Gelman and A. S. Kirlangic, "Novel Vibration Structural Health Monitoring Technology for Deep Foundation Piles by Non-Stationary Higher Order Frequency Response Function," *Structural Control and Health Monitoring* 27, no. 6 (2020): e2526, <https://doi.org/10.1002/stc.2526>.
25. K. W. Liao, M. Y. Cheng, Y. F. Chiu, and J. H. Lee, "Preliminary Bridge Health Evaluation Using Pier Vibration Frequency," *Construction and Building Materials* 102 (2016): 552–563, <https://doi.org/10.1016/j.conbuildmat.2015.11.011>.
26. Q. Feng, H. Xiao, Q. Kong, Y. Liang, and G. Song, "Damage Detection of Concrete Piles Using Piezoceramic Passive Sensing," *J Vibroeng* 18, no. 2 (2016): 801–812, <https://doi.org/10.21595/jve.2016.16631>.
27. Q. Feng, Q. Kong, L. Huo, and G. Song, "Crack Detection and Leakage Monitoring on Reinforced Concrete Pipe," *Smart Materials and Structures* 24, no. 11 (2015): 115020, <https://doi.org/10.1088/0964-1726/24/11/115020>.
28. Q. Feng, Q. Kong, and G. Song, "Damage Detection of Concrete Piles Subject to Typical Damage Types Based on Stress Wave Measurement Using Embedded Smart Aggregates Transducers," *Measurement* 88 (2016): 345–352, <https://doi.org/10.1016/j.measurement.2016.01.042>.
29. R. L. Wang, H. Gu, Y. L. Mo, S. Yan, and B. Xie, "Proof-Of-Concept Study of Damage Detection in Concrete Piles Using Embedded Piezoceramics," *Smart Materials and Structures* 22, no. 4 (2013): 042001, <https://doi.org/10.1088/0964-1726/22/4/042001>.
30. P. J. Bennett, A. Klar, T. E. B. Vorster, et al., "Distributed Optical Fibre Strain Sensing in Piles," in *Proceedings of the International Conference on Re-use of Foundations for Urban Sites (EP73)* (Garston, UK, 2006), 105–114.
31. P. Doherty, D. Igoe, G. Murphy, et al., "Field Validation of Fibre Bragg Grating Sensors for Measuring Strain on Driven Steel Piles,"

- Geotechnique Letters* 5, no. 2 (2015): 74–79, <https://doi.org/10.1680/geolett.14.00120>.
32. Y. Hong, Y. F. Zhang, and L. Q. Liu, “Application of Distributed Optical Fiber Sensors for Monitoring the Mechanical Performance of Driven Piles,” *Measurement* 88 (2016): 186–193, <https://doi.org/10.1016/j.measurement.2016.03.052>.
33. H. L. Kou, H. Jing, N. Zhou, Y. Huang, and Z. Li, “Feasibility of Bare Optical Fibre Bragg Grating Sensing in Inner Wall Axial Stress Measurement Along Open-Ended Pipe Piles in Sand,” *Structural Control and Health Monitoring* 29, no. 1 (2022): e2920, <https://doi.org/10.1002/stc.2920>.
34. J. P. Lynch, “An Overview of Wireless Structural Health Monitoring for Civil Structures,” *Philos Trans R Soc A* 365, no. 1851 (2007): 345–372, <https://doi.org/10.1098/rsta.2006.1932>.
35. M. Ruzzene, A. Fasana, L. Garibaldi, and B. Piombo, “Natural Frequencies and Dampings Identification Using Wavelet Transform: Application to Real Data,” *Mechanical Systems and Signal Processing* 11, no. 2 (1997): 207–218, <https://doi.org/10.1006/mssp.1996.0078>.
36. W. J. Staszewski, “Identification of Damping in MDOF Systems Using time-scale Decomposition,” *Journal of Sound and Vibration* 203, no. 2 (1997): 283–305, <https://doi.org/10.1006/jsvi.1996.0864>.
37. J. S. Bendat and A. G. Piersol, *Random Data: Analysis and Measurement Procedures*, 4th ed. (Wiley, 2011).
38. Z. Jiang, Z. Wang, F. Kan, Y. Zhang, and R. Gorgin, “Low-Strain Damage Imaging Detection Experiment for Model Pile Integrity Based on the Hilbert–Huang Transform,” *Structural Durability & Health Monitoring* 17, no. 6 (2023): 557, <https://doi.org/10.32604/sdhm.2023.042393>.
39. O. Abdeljaber, O. Avci, S. Kiranyaz, M. Gabbouj, and D. J. Inman, “Real-Time Vibration-based Structural Damage Detection Using One-Dimensional Convolutional Neural Networks,” *Journal of Sound and Vibration* 388 (2017): 154–170, <https://doi.org/10.1016/j.jsv.2016.10.043>.
40. E. Figueiredo, G. Park, C. R. Farrar, K. Worden, and J. Figueiras, “Machine Learning Algorithms for Damage Detection Under Operational and Environmental Variability,” *Structural Health Monitoring* 10, no. 6 (2011): 559–572, <https://doi.org/10.1177/1475921710388971>.
41. D. M. Cui, W. Yan, X. Q. Wang, and L. M. Lu, “Towards Intelligent Interpretation of Low Strain Pile Integrity Testing Results Using Machine Learning Techniques,” *Sensors* 17, no. 11 (2017): 2443, <https://doi.org/10.3390/s17112443>.
42. A. Jierula, T. M. Oh, S. Wang, J. H. Lee, H. Kim, and J. W. Lee, “Detection of Damage Locations and Damage Steps in Pile Foundations Using Acoustic Emissions with Deep Learning Technology,” *Frontiers of Structural and Civil Engineering* 15, no. 2 (2021): 318–332, <https://doi.org/10.1007/s11709-021-0715-y>.
43. S. Bhattacharya and M. Bolton, “Buckling of Piles During Earthquake Liquefaction,” in *Proceedings of the 13th World Conference on Earthquake Engineering* (Vancouver, Canada, 2004).
44. F. W. D. Liam, “A Study of Piles During Earthquakes: Issues of Design and Analysis,” *Bulletin of Earthquake Engineering* 3, no. 2 (2005): 141–234, <https://doi.org/10.1007/s10518-005-1241-3>.
45. R. E. Melchers, “Modeling of Marine Immersion Corrosion for Mild and Low-Alloy Steels—Part 1: Phenomenological Model,” *Corrosion* 59, no. 4 (2003): 319–334, <https://doi.org/10.5006/1.3277564>.
46. Z. Li, “Experimental and Numerical Study of Deep Foundations Under Seismic Loading: Vertical Piles and Inclined Piles,” (France: Ecole Centrale de Nantes, 2014), <https://hal-emse.ccsd.cnrs.fr/EC-NANTES/te1-01095508v1> PhD Dissertation.
47. N. H. Notash and R. Dabiri, “Real-Time Seismic Health Monitoring of a Single Pile in Layered Sandy Soils Using Wavelet Analysis,” *Geotechnical & Geological Engineering* 43, no. 8 (2025): 466, <https://doi.org/10.1007/s10706-025-03486-4>.
48. F. Rausche, C. Alvarez, and G. E. Likins, “Dynamic Loading Tests: a State of the Art of Prevention and Detection of Deep Foundation Failures,” in *Proceedings of the 3rd Bolivian International Conference on Deep Foundations* (2017), 177–197.
49. U. Dackermann, Y. Yu, E. Niederleithinger, J. Li, and H. Wiggenshauser, “Condition Assessment of Foundation Piles and Utility Poles Based on Guided Wave Propagation Using a Network of Tactile Transducers and Support Vector Machines,” *Sensors* 17, no. 12 (2017): 2938, <https://doi.org/10.3390/s17122938>.
50. D. Glisic, D. Inaudi, and C. Nan, “Pile Monitoring With Fibre Optic Sensors During Axial Compression, Pullout, and Flexure,” *Transportation Research Record* 1808, no. 1 (2002): 11–20, <https://doi.org/10.3141/1808-02>.
51. H. Gu, G. Song, H. Dhonde, Y. L. Mo, and S. Yan, “Concrete Early-Age Strength Monitoring Using Embedded Piezoelectric Transducers,” *Smart Materials and Structures* 15, no. 6 (2006): 1837–1845, <https://doi.org/10.1088/0964-1726/15/6/038>.
52. L. L. Guan, Y. G. Chen, and R. P. Liao, “Accuracy Analysis for 3D Photogrammetric Measurement for Deep Foundation Pit Deformation,” *KSCE Journal of Civil Engineering* 27, no. 2 (2023): 577–589, <https://doi.org/10.1007/s12205-022-1543-x>.
53. P. Qiu, L. Yang, Y. Xie, X. Liu, and Z. Chen, “Pile Integrity Testing Using Non-Destructive Testing Techniques and Artificial Intelligence: a Review,” *Applied Sciences* 15, no. 15 (2025): 8580, <https://doi.org/10.3390/app15158580>.
54. T. Bao and Z. Liu, “Vibration-Based Bridge Scour Detection: A Review,” *Structural Control and Health Monitoring* 24, no. 7 (2017): e1937, <https://doi.org/10.1002/stc.1937>.
55. L. Ma, Z. Duan, W. Guo, and Y. Ren, “Numerical Studies on Low-Strain Integrity Testing of cast-in-place Pile,” *Front Built Environ* 10 (2024): 1330580, <https://doi.org/10.3389/fbuil.2024.1330580>.
56. K. Meng, C. Cui, Z. Liang, H. Li, and H. Pei, “A New Approach for Longitudinal Vibration of a large-diameter Floating Pipe Pile in viscoelastic Soil Considering the Three-Dimensional Wave Effects,” *Computers and Geotechnics* 128 (2020): 103840, <https://doi.org/10.1016/j.compgeo.2020.103840>.
57. T. Bao and Z. Liu, “Bridge Scour Characteristic Curve for Natural Frequency-Based Bridge Scour Monitoring Using Simulation-based Optimization,” *Structural Control and Health Monitoring* 28, no. 8 (2021): e2773, <https://doi.org/10.1002/stc.2773>.
58. J. Wu, M. H. El Naggar, and K. Wang, “Pile Damage Detection Using Machine Learning With the Multipoint Traveling Wave Decomposition Method,” *Sensors* 23, no. 19 (2023): 8308, <https://doi.org/10.3390/s23198308>.
59. Y. Xu, G. Nikitas, T. Zhang, et al., “Support Condition Monitoring of Offshore Wind Turbines Using Model Updating Techniques,” *Structural Health Monitoring* 19, no. 4 (2020): 1017–1031, <https://doi.org/10.1177/1475921719875628>.
60. X. Xu, X. Di, Y. Zheng, A. Liu, C. Hou, and X. Lan, “Dynamic Response Characteristics and Pile Damage Identification of High-Piled Wharves Under Dynamic Loading,” *Applied Sciences* 14, no. 20 (2024): 9250, <https://doi.org/10.3390/app14209250>.
61. A. Zarafshan, A. Iranmanesh, and F. Ansari, “Vibration-Based Method and Sensor for Monitoring of Bridge Scour,” *Journal of Bridge Engineering* 17, no. 6 (2012): 829–838, [https://doi.org/10.1061/\(ASCE\)BE.1943-5592.0000362](https://doi.org/10.1061/(ASCE)BE.1943-5592.0000362).
62. X. Zhang, W. Yao, B. Chen, and D. Liu, “Damage Identification of Piles Based on Vibration Characteristics,” *Science World Journal* 2014 (2014): 150516–150518, <https://doi.org/10.1155/2014/150516>.
63. D. Zhu, S. Tian, H. Yan, and Z. Wang, “A Feasibility Study on Monitoring Pile-Soil Bonding Condition Using Piezoceramic Transducer

- and Horizontal Impact,” *Journal of Sensors* 2021, no. 1 (2021): 5575854, <https://doi.org/10.1155/2021/5575854>.
64. D. Zhu, L. Wang, and Z. Wang, “Study on Pile-Soil Bonding Condition Based on Transient Shock Response Using Piezoceramic Sensors,” *Journal of Low Frequency Noise, Vibration and Active Control* 43, no. 1 (2024): 358–370, <https://doi.org/10.1177/14613484231193270>.
65. G. Davis and C. S. Dunn, “From Theory to Field Experience With the Non-Destructive Vibration Testing of Piles,” *Proceedings-Institution of Civil Engineers* 57, no. 2 (1974): 571–593, <https://doi.org/10.1680/iicep.1974.3895>.
66. Y. K. Chow, K. K. Phoon, W. F. Chow, and K. Y. Wong, “Low Strain Integrity Testing of Piles: Three-Dimensional Effects,” *Journal of Geotechnical and Geoenvironmental Engineering* 129, no. 11 (2003): 1057–1068, [https://doi.org/10.1061/\(ASCE\)1090-0241\(2003\)129:11\(1057\)](https://doi.org/10.1061/(ASCE)1090-0241(2003)129:11(1057)).
67. J. Zhan, Y. Wang, F. Zhang, and K. Liu, “Scour Depth Evaluation of Highway Bridge Piers Using Vibration Measurements and Finite Element Model Updating,” *Engineering Structures* 253 (2022): 113815, <https://doi.org/10.1016/j.engstruct.2021.113815>.
68. W. Weijtjens, T. Verbelen, E. Capello, and C. Devriendt, “Vibration-Based Structural Health Monitoring of the Substructures of Five Offshore Wind Turbines,” *Procedia Engineering* 199 (2017): 2294–2299, <https://doi.org/10.1016/j.proeng.2017.09.187>.
69. X. Ding, H. Liu, J. Liu, and Y. Chen, “Wave Propagation in a Pipe Pile for low-strain Integrity Testing,” *Journal of Engineering Mechanics* 137, no. 9 (2011): 598–609, [https://doi.org/10.1061/\(ASCE\)EM.1943-7889.0000263](https://doi.org/10.1061/(ASCE)EM.1943-7889.0000263).
70. R. P. S. Pasqual and A. C. M. Kormann, “Low Strain Integrity Tests in Piles–1-D and 3-D Numerical Modeling and Comparisons With Results Obtained in the Field,” *Multiple Sclerosis J* 2, no. 3 (2019): 1–8, <https://doi.org/10.33837/msj.v2i3.878>.
71. K. Pandey, M. Biswas, and M. M. Samman, “Damage Detection From Changes in Curvature Mode Shapes,” *Journal of Sound and Vibration* 145, no. 2 (1991): 321–332, [https://doi.org/10.1016/0022-460X\(91\)90595-B](https://doi.org/10.1016/0022-460X(91)90595-B).
72. F. Rausche and G. G. Goble, “Determination of Pile Damage by Top Measurements,” *ASTM STP* 670 (1979): 500–506.
73. F. Rausche, S. H. Renkung, and G. E. Likins, “Comparison of Pulse Echo and Transient Response Pile Integrity Test Methods,” *Transportation Research Record* 1331 (1991): 21–27.
74. A. Klar, P. J. Bennett, K. Soga, et al., “Distributed Strain Measurement for Pile Foundations,” *Proceedings of the ICE-Geotechnical Engineering* 159, no. 3 (2006): 135–144, <https://doi.org/10.1680/geng.2006.159.3.135>.
75. Y. Lu, B. Shi, G. Q. Wei, S. E. Chen, and D. Zhang, “Application of a Distributed Optical Fiber Sensing Technique in Monitoring the Stress of Precast Piles,” *Smart Materials and Structures* 21, no. 11 (2012): 115011, <https://doi.org/10.1088/0964-1726/21/11/115011>.
76. C. M. Monsberger, W. Lienhart, and M. Hayden, “Distributed Fiber Optic Sensing Along Driven Ductile Piles: Design, Sensor Installation and Monitoring Benefits,” *Journal of Civil Structural Health Monitoring* 10, no. 4 (2020): 627–637, <https://doi.org/10.1007/s13349-020-00406-3>.
77. J. Wang, H. Zhu, D. Tan, et al., “Thermal Integrity Profiling of Cast-In-Situ Piles in Sand Using Fiber-Optic Distributed Temperature Sensing,” *Journal of Rock Mechanics and Geotechnical Engineering* 15, no. 12 (2023): 3244–3255, <https://doi.org/10.1016/j.jrmge.2023.02.028>.
78. X. Zheng, B. Shi, H. H. Zhu, et al., “Performance Monitoring of Offshore PHC Pipe Pile Using BOFDA-based Distributed Fiber-optic Sensing System,” *Geomech Eng* 24 (2021): 337–348, <https://doi.org/10.12989/gae.2021.24.4.337>.
79. L. J. Prendergast, “Monitoring of Scour Around Structures Using Changes in Natural Frequency of Vibration of Foundation piles—A Field Investigation,” (School of Civil, Structural and Environmental Engineering, University College Dublin, Ireland, 2015), PhD Dissertation.
80. L. J. Prendergast and K. Gavin, “Monitoring of Scour Critical Bridges Using Changes in the Natural Frequency of Vibration of Foundation piles—A Field Investigation,” in *Proceedings of the Transport Research Arena* (Paris, 2014).
81. H. Ying, Z. Liu, J. Wang, et al., “Experimental Study on Axial Compression Monitoring of Pile Foundation Based on Sensor-Enabled Piezoelectric Geocable,” *Smart Materials and Structures* 32, no. 11 (2023): 115003, <https://doi.org/10.1088/1361-665X/acfad7>.
82. C. Y. Hong, Y. F. Zhang, M. X. Zhang, L. M. G. Leung, and L. Q. Liu, “Application of FBG Sensors for Geotechnical Health Monitoring, a Review of Sensor Design, Implementation Methods and Packaging Techniques,” *Sensors and Actuators A: Physical* 244 (2016): 184–197, <https://doi.org/10.1016/j.sna.2016.04.033>.
83. L. Kechavarzi, L. Pelecanos, N. De Battista, and K. Soga, “Distributed Fibre Optic Sensing for Monitoring Reinforced Concrete Piles,” *Geotechnical Engineering Journal of the SEAGS & AGSSEA* 50, no. 2 (2019): 43–51, <https://doi.org/10.14456/seagi.2019.40>.
84. K. Soga and L. Luo, “Distributed Fiber Optics Sensors for Civil Engineering Infrastructure Sensing,” *Journal of Structural Integrity and Maintenance* 3, no. 1 (2018): 1–21, <https://doi.org/10.1080/24705314.2018.1426138>.
85. M. J. Kim, H. Kim, J. W. Lee, and T. M. Oh, “Assessment of Foundation Damage During Earthquakes Using Acoustic Emission Monitoring: An Experimental Study on the Shaking Table Test,” *Soils and Foundations* 64, no. 6 (2024): 101473, <https://doi.org/10.1016/j.sandf.2024.101473>.
86. E. Guzmán, J. Cugnoni, and T. Gmür, “Monitoring of Composite Structures Using a Network of Integrated PVDF Film Transducers,” *Smart Materials and Structures* 24, no. 5 (2015): 055017, <https://doi.org/10.1088/0964-1726/24/5/055017>.
87. B. F. Spencer, Jr, S. H. Sim, R. E. Kim, and H. Yoon, “Advances in Artificial Intelligence for Structural Health Monitoring: A Comprehensive Review,” *KSCE Journal of Civil Engineering* 29, no. 3 (2025): 100203, <https://doi.org/10.1016/j.kscej.2025.100203>.
88. K. Das, C. K. Leung, and K. T. Wan, “Application of Deep Convolutional Neural Networks for Automated and Rapid Identification and Computation of Crack Statistics of Thin Cracks in Strain Hardening Cementitious Composites (Shccs),” *Cement and Concrete Composites* 122 (2021): 104159, <https://doi.org/10.1016/j.cemconcomp.2021.104159>.
89. K. Das, D. Suthar, and C. K. Leung, “Machine Learning-Based Crack Mode Classification From Unlabeled Acoustic Emission Waveform Features,” *Cement and Concrete Research* 121 (2019): 42–57, <https://doi.org/10.1016/j.cemconres.2019.03.001>.
90. J. B. Su, S. L. Luan, L. M. Zhang, R. H. Zhu, and W. G. Qin, “Partitioned Genetic Algorithm Strategy for Optimal Sensor Placement Based on Structure Features of a High-Piled Wharf,” *Structural Control and Health Monitoring* 26, no. 1 (2018): e2289, <https://doi.org/10.1002/stc.2289>.
91. S. Hassani and U. Dackermann, “A Systematic Review of Optimization Algorithms for Structural Health Monitoring and Optimal Sensor Placement,” *Sensors* 23, no. 6 (2023): 3293, <https://doi.org/10.3390/s23063293>.
92. C. Kammer, “Sensor Placement for On-Orbit Modal Identification and Correlation of Large Space Structures,” *Journal of Guidance, Control, and Dynamics* 14, no. 2 (1991): 251–259, <https://doi.org/10.2514/3.20635>.
93. K. H. Tong, N. Bakhary, A. B. H. Kueh, and A. Y. Yassin, “Optimal Sensor Placement for Mode Shapes Using Improved Simulated Annealing,” *Smart Structures and Systems* 13, no. 3 (2014): 389–406, <https://doi.org/10.12989/sss.2014.13.3.389>.
94. C. Papadimitriou, “Optimal Sensor Placement Methodology for Parametric Identification of Structural Systems,” *Journal of Sound and Vibration* 278, no. 4–5 (2004): 923–947, <https://doi.org/10.1016/j.jsv.2003.10.063>.

95. B. Gunes and O. Gunes, "Structural Health Monitoring and Damage Assessment Part I: A Critical Review of Approaches and Methods," *International Journal of the Physical Sciences* 8, no. 34 (2013): 1694–1702.
96. M. Azimi, A. D. Eslamlou, and G. Pekcan, "Data-Driven Structural Health Monitoring and Damage Detection Through Deep Learning: State-of-the-Art Review," *Sensors* 20, no. 10 (2020): 2778, <https://doi.org/10.3390/s20102778>.
97. P. L. Pasternak, "On a New Method of Analysis of an Elastic Foundation by Means of Two Foundation Constants. Moscow," (1954), (in Russian).
98. E. Winkler, *Die Lehre Von Der Elastizität Und Festigkeit* (Prague, 1867).
99. M. Hetényi, *Beams on Elastic Foundation* (University of Michigan Press, 1946).
100. V. Z. Vlasov and N. N. Leont'ev, *Beams, Plates and Shells on Elastic Foundations* (Israel Program for Scientific Translations, 1966).
101. A. D. Kerr, "Elastic and Viscoelastic Foundation Models," *Journal of Applied Mechanics* 31, no. 3 (1964): 491–498, <https://doi.org/10.1115/1.3629667>.
102. J. P. Wolf, *Dynamic Soil–Structure Interaction* (Englewood Cliffs, NJ: Prentice Hall, 1985).
103. J. Wu, N. Hu, Y. Dong, and Q. Zhang, "Monitoring Dynamic Characteristics of the 600-m+ Shanghai Tower During Two Consecutive Typhoons," *Structural Control and Health Monitoring* 28, no. 2 (2021): e2666, <https://doi.org/10.1002/stc.2666>.
104. H. Y. Chai, K. K. Phoon, and D. J. Zhang, "Effects of the Source on Wave Propagation in Pile Integrity Testing," *Journal of Geotechnical and Geoenvironmental Engineering* 136, no. 9 (2010): 1200–1208, [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000272](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000272).
105. S. Webster and W. Teferra, "Pile Damage Assessments Using the Pile Driving Analyzer," in *Proceedings of the 5th International Conference on Application of Stress-Wave Theory to Piles* (1996).
106. J. M. Nichols, S. T. Trickey, and M. Seaver, "Damage Detection Using Multivariate Recurrence Quantification Analysis," *Mechanical Systems and Signal Processing* 20, no. 2 (2006): 421–437, <https://doi.org/10.1016/j.ymssp.2004.08.007>.
107. A. Ioakim and L. J. Prendergast, "Two-Stage Method to Estimate the Embedded Length of Foundation Piles Using FRF-based Model Updating," *Mechanical Systems and Signal Processing* 184 (2024): 111445, <https://doi.org/10.1016/j.ymssp.2023.110445>.
108. A. Ioakim, S. Greš, M. Döhler, L. J. Prendergast, and E. Chatzi, "An Indirect data-driven model-updating Framework to Estimate Soil–Pile Interaction Parameters Using Output-Only Data," *Engineering Structures* 328 (2025): 119699, <https://doi.org/10.1016/j.engstruct.2025.119699>.
109. J. Fischer, C. Missal, M. Breustedt, and J. Stahlmann, "Numerical Simulation of Low-Strain Integrity Tests on Model Piles," in *Proceedings of the 7th European Conference on Numerical Methods in Geotechnical Engineering* (Trondheim, Norway, 2010), 655–660.
110. E. Loseva, I. Lozovsky, and R. Zhostkov, "Identifying Small Defects in Cast-In-Place Piles Using Low Strain Integrity Testing," *Indian Geotechnical Journal* 52, no. 2 (2022): 270–279, <https://doi.org/10.1007/s40098-021-00583-y>.
111. G. Likins and F. Rausche, "Pile Damage Prevention and Assessment Using Dynamic Monitoring and the Beta Method," in *From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering* (Honoring Roy E. Olson, 2014), 428–442.
112. G. Likins and F. Rausche, "Correlation of CAPWAP With Static Load Tests," in *Proceedings of the 7th International Conference on Application of Stress-Wave Theory to Piles* (2004), 153–165.
113. L. Pelecanos and K. Soga, "Innovative Structural Health Monitoring of Foundation Piles Using Distributed Fibre Optic Sensing," in *Proceedings of the International Conference on Structural Engineering Construction Management (ICSECM)* (Kandy, Sri Lanka, 2017).
114. X. Liu, M. H. El Naggar, K. Wang, and W. Wu, "Theoretical Analysis of Three-Dimensional Effect in Pile Integrity Test," *Computers and Geotechnics* 127 (2020): 103765, <https://doi.org/10.1016/j.compgeo.2020.103765>.
115. W. F. Starke, M. C. Janes, and B. H. Fellenius, "Accuracy and Reliability of Low Strain Integrity Testing," in *Proceeding of the 3rd International Conference on Application of Stress Wave Theory to Piles* (May 1988), 19–32.
116. Y. He, J. P. Yang, and J. Yu, "Surrogate-Assisted Finite Element Model Updating for Detecting Scour Depths in a Continuous Bridge," *Journal of Computer Science* 69 (2023): 101996, <https://doi.org/10.1016/j.jocs.2023.101996>.
117. W.-J. Yan, L.-F. Mei, J. Mo, C. Papadimitriou, and K. V. Yuen, "Navigating Uncertainties in Machine Learning for Structural Dynamics: a Comprehensive Review of Probabilistic and Non-Probabilistic Approaches in Forward and Inverse Problems," (2024), <https://arxiv.org/abs/2408.08629>.
118. Y. Zhang and X. Liang, "Domain Adaptation in Structural Health Monitoring of Civil Infrastructure: a Systematic Review," (2025), <https://arxiv.org/abs/2512.18780>.
119. N. Bao, T. Zhang, R. Huang, S. Biswal, and J. Su, "A Deep Transfer Learning Network for Structural Condition Identification with Limited Real-World Training Data," (2023), <https://arxiv.org/abs/2307.15249>.
120. M. Mahissi, W. Cai, X. Zhang, et al., "A Novel Method for Fishing Boat Vibration Sensing Using an FBG-based Warning Sign Pile Accelerometer," *IEEE Sensors Journal* 24, no. 6 (2024): 7963–7974, <https://ieeexplore.ieee.org/document/10424423>, <https://doi.org/10.1109/jsen.2024.3361214>.
121. Y. Sugimura and M. B. Karkee, "Nature of Damage to Pile Foundation of Buildings in Recent Earthquakes and Some Proposals for Seismic Design," in *Proceedings of the 2nd US–Japan Workshop* (2001), 16.
122. X. Zhang, P. Wang, and J. C. Xing, *Optimal Placement of Sensor for Health Monitoring of high-piled Wharf Structures* (Port Waterw Eng, 2013), 80–84.
123. G. Song, H. Gu, Y. L. Mo, and R. Wang, "Health Monitoring of Concrete Piles Using Piezoceramic-based Smart Aggregates," in *Proceedings of SPIE International Society for Optical Engineering* (2010), 76500X, <https://doi.org/10.1117/12.847827>.
124. K. Worden and G. Manson, "The Application of Machine Learning to Structural Health Monitoring," *Philosophical Transactions of the Royal Society A* 365, no. 1851 (2007): 515–537, <https://doi.org/10.1098/rsta.2006.1938>.
125. P. S. Addison and J. F. Watson, "Wavelet Analysis for Low-Strain Integrity Testing of Foundation Piles," in *Proceedings of the 5th International Conference on Inspection, Appraisal, Repairs and Maintenance of Buildings and Structures* (Singapore, 1997), 15–16.
126. X. Wang, F. Yu, and F. Liang, "A Review of Bridge Scour: Mechanism, Estimation, Monitoring, and Countermeasures," *Natural Hazards* 87, no. 3 (2017): 1881–1906, <https://doi.org/10.1007/s11069-017-2842-2>.
127. Y. K. Chow, K. K. Phoon, W. F. Chow, and K. Y. Wong, "Closure to Low Strain Integrity Testing of Piles: Three-Dimensional Effects," *Journal of Geotechnical and Geoenvironmental Engineering* 131, no. 2 (2005): 270, [https://doi.org/10.1061/\(ASCE\)1090-0241\(2005\)131:2\(270.1](https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(270.1)
128. J. Kordjazi, J. T. Coe, and S. Mahvelati, "Advances in Stress-Wave Nondestructive Testing Methods for Evaluation of Deep Foundations,"

DFI Journal 12, no. 2 (2018): 108–121, <https://doi.org/10.1080/19375247.2018.1562598>.

129. C. Rausche, C. Alvarez, and G. E. Likins, “Dynamic Loading Tests: Prevention and Detection of Deep Foundation Failures,” in *Proceedings of the 3rd Bolivian International Conference on Deep Foundations* (2017), 177–197.

130. X. Wei, Q. Wang, and J. Wang, “Damage Patterns and Failure Mechanisms of Bridge Pile Foundation Under Earthquake,” in *Proceedings of the 14th World Conference on Earthquake Engineering* (Beijing, China, 2008).

131. I. Bayane, J. Leander, and R. Karoumi, “An Unsupervised Machine Learning Approach for Real-Time Damage Detection in Bridges,” *Engineering Structures* 308 (2024): 117971, <https://doi.org/10.1016/j.engstruct.2024.117971>.