PhD Theses

The examination of wooden piles of lake-buildings

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Sopron

2025

Introduction

Wooden piles have long served as foundational supports for lake-based structures such as docks, piers, and bridges, relying on their high strength-to-weight ratio and elasticity to sustain environmental and mechanical loads (Bouras et al., 2010; Kromoser et al., 2024). Submerged piles face significant degradation risks—including biochemical decay, mechanical erosion, and physicochemical changes—that diminish critical properties like density and elastic modulus, thereby threatening stability and load-bearing capacity(Klaassen et al., 2016; Martín & López, 2023). Among failure modes, buckling under axial loads is especially critical for slender submerged piles exposed to cyclic aquatic forces (Hassan & Osama A.B, 2019; Vukelic et al., 2017).

The inherent heterogeneity of wood and challenges in in-situ assessment limit the practicality of traditional destructive testing methods (French et al., 2023; Liu et al., 2024; Rajagopalam & Prakash, 1975). Non-destructive testing (NDT) techniques, particularly ultrasonic testing, offer promising alternatives by enabling non-invasive evaluation of material integrity and detection of internal defects (Lian et al., 2024; Linpei, 2024; Xue et al., 2024). However, ultrasonic application in submerged wooden piles remains underexplored, with gaps in linking ultrasonic velocity measurements to mechanical properties and performance under dynamic loading.

A bibliometric analysis conducted as part of this research (Brougui et al., 2025) confirms these limitations, showing a predominant focus in the literature on terrestrial timber or lab-scale samples. Systematic studies on full-scale submerged piles are scarce, and complex interrelations among ultrasonic wave velocity, material degradation, buckling risk, and environmental parameters such as moisture and long-term aquatic exposure are yet insufficiently addressed.

To bridge these gaps, this study systematically investigates the relationships among ultrasonic wave velocity, dynamic modulus of elasticity, and critical buckling load in submerged timber piles. It integrates pile geometry, material degradation, and site-specific environmental conditions within a non-destructive evaluation framework that combines ultrasonic testing with three-dimensional finite element modeling in COMSOL Multiphysics, explicitly incorporating anisotropic wood behavior, soil–pile interactions, and submerged boundary conditions.

This combined experimental and computational approach aims to enhance structural assessment accuracy, establish robust indicators of pile stability, and guide maintenance and conservation strategies, ultimately supporting the extended service life of submerged timber infrastructure and the preservation of both modern constructions and heritage aquatic sites.

Research aim and objectives

This research aims to bridge existing knowledge gaps by developing an integrated framework that combines nondestructive ultrasonic testing, finite element modeling, and machine learning to evaluate the structural integrity and buckling behavior of submerged timber piles in Hévíz Lake, improving predictive reliability for structural monitoring and supporting sustainable management of aquatic heritage infrastructure.

The specific objectives are to:

- Assess the in-situ mechanical condition of submerged timber piles using ultrasonic non-destructive testing by measuring longitudinal wave velocity to detect stiffness loss and internal defects.
- Quantify dynamic modulus of elasticity (MOE) and critical buckling load from ultrasonic data using wave propagation theory and beam mechanics.

- Establish relationships between ultrasonic measurements, material properties, and structural performance.
- Integrate a quantitative risk classification framework linking ultrasonic wave velocity and dynamic modulus thresholds with stability categories—safe, at risk, critical—to precisely identify degradation and guide structural preservation.
- Construct three-dimensional finite element models incorporating anisotropic wood behavior, soil–pile interactions, and submerged boundary conditions to simulate pile response.
- Validate ultrasonic predictions with FEM simulations to reliably assess stress distribution, deformation, and buckling resistance under realistic submerged conditions.

Literature Review

This literature review synthesizes current scientific understanding of submerged timber piles, wood material behaviour, and non-destructive diagnostic approaches relevant to structural stability assessment. Fundamental concepts—including wood anatomy, density variation, moisture effects, and decay mechanisms—are examined to contextualize deterioration processes in aquatic environments. Research on timber piles in lake-building construction emphasizes their mechanical function, degradation pathways, and the critical influence of stiffness and buckling resistance on long-term performance.

A bibliometric analysis based on Scopus and Google Scholar further reveals substantial knowledge gaps in existing research. Most studies focus on terrestrial or laboratory-scale samples, whereas full-scale submerged piles remain largely unexamined. Limited work has explored the quantitative relationships among ultrasonic wave velocity, progressive material degradation, buckling resistance, and environmental drivers. In particular, the dynamic interaction between deterioration processes and buckling behaviour in submerged timber has not been experimentally or numerically characterized.

The bibliometric mapping also identifies two emerging research directions: (1) the integration of machine learning with ultrasonic measurements to improve the prediction of wood mechanical properties, and (2) the combined use of FEM validation and ultrasonic modeling to forecast failure mechanisms under variable environmental and loading conditions. These gaps and trends establish the scientific rationale for the integrated ultrasonic–FEM methodology developed in this dissertation.

Research Methodology

This research employs a comprehensive methodology combining non-destructive testing (NDT) and finite element modeling (FEM) to systematically evaluate the structural stability of submerged wooden piles supporting lakeside infrastructures in Hévíz, Hungary.

The methodology consists of two complementary approaches:

1. **Experimental Approach – Non-Destructive Testing and Structural Assessment:**

This approach employed two complementary ultrasonic test methodologies targeting distinct structural characterization objectives: dynamic modulus of elasticity (MOE) determination via ultrasonic wave velocity measurement, and pile length estimation through ultrasonic travel-time analysis. These parameters critically inform assessments of load-bearing capacity and buckling susceptibility of submerged wooden piles.

A representative subset of 40 piles was stratified from an initial population of 400 based on accessibility, structural significance, and degradation evidence, Advanced signal processing techniques and machine learning algorithms implemented in *MATLAB R2023a* were employed to enhance the accuracy of material property estimations under complex submerged conditions. The quantified parameters supported calculations of theoretical critical buckling loads, in-situ load-bearing assessments, and classification of pile conditions into risk categories (low, moderate, high).

1.1 Ultrasonic Wave Velocity Test (MOE Determination)

Longitudinal ultrasonic wave velocities were acquired using a *FAKOPP Microsecond Timer*, a time-of-flight instrument equipped with dual transducers.

Procedure:

- Sensors were mounted on the lateral surface of each pile at 80 cm spacing.
- Transmitter and receiver probes were positioned at a 45° angle.
- Acoustic pulses were initiated via metallic hammer strikes.
- Divers positioned the sensors underwater, while a surface team recorded travel times.
- Each pile underwent 3–5 repeated measurements to ensure reliability.

Environmental conditions: were recorded using a calibrated *Extech SDL500 temperature–humidity meter* and data logger installed 1.2 m above the water surface. The measured conditions were as follows:

- Air temperature: 5–8 °C
- Geothermal lake water temperature: 23–25 °C
- Relative humidity: 70–80%

1.2 Ultrasonic Travel-Time Test for Pile Length Measurement

This test focused on determining pile length, essential for evaluating buckling resistance and axial load capacity.

Instrumentation included *a FNIRSI 1014D digital oscilloscope* (100 MHz bandwidth, 1 GSa/s sampling rate) for high-resolution waveform acquisition, and 50 kHz piezoelectric longitudinal transducers (FNIRSI, Shenzhen, China) coupled with beeswax for stable acoustic contact and minimal signal attenuation.

<u>Procedure:</u>

- Pile locations were identified from structural drawings and accessed via the floor above.
- The transmitter was positioned on the pile head; the receiver was mounted laterally along the vertical axis.
- Longitudinal stress waves were generated by blunt steel hammer impacts.
- Time-of-flight data were analyzed to calculate pile length.
- Each pile was tested 3–5 times; trials compromised by noise or coupling issues were discarded and repeated.

2. Numerical Approach – Finite Element Modeling (FEM) and Validation:

FEM simulations using *COMSOL Multiphysics 6.0* were conducted to replicate the mechanical response of the piles under realistic boundary and loading conditions, including soil-pile interactions and submersion effects. FEM-derived critical buckling loads and deformation patterns were compared with ultrasonic-based estimates to validate experimental results. This comparison also refined the risk classification, offering detailed insights into internal stress distribution, deformation behavior, and potential failure mechanisms.

Results and Dissertation Theses

Thesis 1:Integrated Non-Destructive Evaluation Framework for Submerged Timber Piles

This research presents a novel, validated framework that integrates ultrasonic non-destructive testing (NDT), machine learning techniques for enhanced predictive accuracy, analytical buckling analysis using Euler–Bernoulli beam theory, and high-fidelity finite element modeling (FEM) to quantitatively assess the structural integrity and buckling behavior of submerged timber piles. This methodological approach addresses a critical gap in underwater timber infrastructure evaluation by enabling reliable in-situ diagnostics that holistically account for anisotropic wood properties, soil–pile interactions, and submerged boundary conditions under realistic environmental influences.

<u>Related Publications:</u>

Brougui, M., Andor, K., & Szabó, P. (2025). Finite Element Modeling of Submerged Timber Piles: Validation of Ultrasonic Non-Destructive Testing for Buckling Resistance. *Structural Health Monitoring Journal*, 19 p.
https://m2.mtmt.hu/api/publication/ 36450184

Brougui, M., Andor, K., & Szabó, P. (2025). Evaluation of Timber Mechanical Properties Through Non-Destructive Testing: A Bibliometric Analysis. *Buildings*, 15(13), 2192.
https://doi.org/10.3390/buildings15132192

Thesis 2: Ultrasonic-Based Prediction of Buckling Failure in Submerged Timber Piles

This thesis extends the well-established correlation between longitudinal ultrasonic wave velocity and the dynamic modulus of elasticity (MOE) by applying and validating it specifically in submerged timber piles exposed to thermal, mineral-rich aquatic environments—a context not previously examined in the literature ($r = 0.998$).

To assess the capability of ultrasonic measurements in predicting the buckling resistance of timber piles, ultrasonic velocity is integrated with geometric parameters to develop a predictive buckling-failure model, which accurately estimates critical buckling loads (R^2 = 0.943). This work provides the first field-validated link between ultrasonic measurements and buckling stability in full-scale, long-term submerged heritage piles, enabling early, non-destructive detection of stiffness loss and structural degradation.

Related Publications:

Brougui, M., Andor, K., & Szabó, P. (2025). Sensitivity of Buckling Resistance to Pile Length and Structural Imperfections in Submerged Timber Piles. *International Wood Products Journal*, 24 p. https://m2.mtmt.hu/api/publication/ 36450180

Thesis 3: Quantitative Analysis of Geometry and Material Property Interactions Governing Buckling Resistance in Submerged Timber Piles

This thesis quantitatively assesses the critical buckling load (P_{cr}) of submerged timber piles by integrating dynamic modulus of elasticity (MOE), derived from ultrasonic velocity measurements, within the classical Euler–Bernoulli beam framework. While the inverse correlation between pile length and buckling capacity ($r = -0.73$) is well-documented in classical column stability theory, this study provides the first comprehensive investigation—combining ultrasonic non-destructive testing, analytical modeling, and field validation—of heritage timber piles submerged in thermally and chemically complex aquatic environments. Notably, it demonstrates that environmentally driven variations in dynamic MOE critically modulate buckling resistance in intermediate-length piles (approximately 10–15 meters), where stiffness fluctuations significantly influence structural stability.in addition, The negligible difference between classical Euler–Bernoulli and Granholm-corrected beam models (0.05%) validates the adequacy of classical theory for slender submerged piles.

Related Publications:

Brougui, M., & Andor, K. (2024). Investigating the stability of wooden lake piles: The influence of dynamic MOE and pile length on buckling behavior. In *Wood 4 Sustainability: Processing, Construction, Products and Design* (pp. 161–174). Sopron University Press. ISBN 978-963-334-5412.

https://doi.org/10.35511/978-963-334-541-2-16

Thesis 4: Dual-Parameter Risk Classification Framework Enhancing Degradation Assessment of Submerged Timber Piles

This thesis identifies a critical limitation in the ASTM D2555 (2017) ultrasonic-based risk classification: elevated ultrasonic wave velocities can obscure subsurface defects and incipient decay that are not adequately reflected in stiffness reduction measurements alone. To overcome this challenge, a novel dual-parameter framework integrating ultrasonic wave velocity and dynamic modulus of elasticity (MOE) is proposed and validated.

The integrated approach reveals that transitional degradation states in submerged timber piles, characterized by asynchronous evolution of mechanical stiffness and internal defects, cannot be reliably identified by any single diagnostic parameter. By combining wave velocity and dynamic MOE indicators, the framework substantially enhances the sensitivity and accuracy of material degradation detection in submerged timber environments, where anisotropy, heterogeneity, and complex moisture dynamics affect degradation pathways.

Related Publications:

Brougui, M., Andor, K., & Szabó, P. (2025). Integrated Risk Classification and Buckling Resistance Prediction in Timber Piles Using Ultrasonic Wave Velocity and Dynamic Modulus of Elasticity, *JOURNAL OF NONDESTRUCTIVE EVALUATION,* 11 p. https://doi.org/10.21203/rs.3.rs-6813815/v1

Thesis 5: Validation of Ultrasonic-Based Assessment through Finite Element Modeling Incorporating Anisotropy and Environmental Boundary Conditions

This thesis validates ultrasonic-derived pile stiffness and buckling capacity estimates using orthotropic finite element models in

COMSOL Multiphysics, incorporating submerged and soil-embedded boundary conditions with realistic loading. The FEM simulations correlate strongly with ultrasonic predictions (correlation coefficient 0.9998; mean difference ~5%), confirming ultrasonic NDT reliability. FEM further reveals nonlinear buckling behaviors and pre-buckling displacements absent in analytical models, emphasizing the importance of integrating computational and experimental approaches for structural health monitoring of submerged timber piles.

Related Publications:

Brougui, M., Andor, K., & Szabó, P. (2025). Finite Element Modeling of Submerged Timber Piles: Validation of Ultrasonic Non-Destructive Testing for Buckling Resistance. *Structural Health Monitoring Journal*, 19 p.
https://m2.mtmt.hu/api/publication/ 36450184

Thesis 6: Nonlinear Finite Element Analysis of Pre-Buckling Lateral Instability in Submerged Timber Piles

This dissertation quantitatively demonstrates through nonlinear finite element modeling that submerged timber piles exhibit lateral instability initiation at a load factor of approximately $\lambda \approx 0.8$, significantly preceding classical ultrasonic-based buckling predictions ($\lambda = 1$). The onset of instability arises from nonlinear escalation in bending stresses and lateral displacements, driven by geometric imperfections, heterogeneous stiffness, and soil–structure interaction effects. These findings underscore the limitations of classical linear elastic theories and ultrasonic testing alone, highlighting the necessity of realistic FE simulations to capture complex pre-buckling behavior for accurate structural health assessment and failure prediction in marine timber infrastructure.

Related Publications:

Brougui, M., Andor, K., & Szabó, P. (2025). Finite Element Modeling of Submerged Timber Piles: Validation of Ultrasonic Non-Destructive Testing for Buckling Resistance. *Structural Health Monitoring Journal*, 19 p.
https://m2.mtmt.hu/api/publication/ 36450184

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