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2024

Wood 4 Sustainability

Processing, Construction, Products and Design

2024

Főszerkesztő: Dr. Csiha Csilla

Wood 4 Sustainability

Processing, Construction, Products and Design

2024



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Investigating the stability of wooden lake piles: the influence of dynamic MOE and pile length on buckling behavior

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ABSTRACT

This study investigates the stability of submerged wooden piles by examining the influence of the dynamic modulus of elasticity (MOE) and pile length on critical buckling load behavior—key parameters in the foundation design of aquatic structures. A non-destructive testing (NDT) approach was employed to assess the structural properties of 40 submerged wooden piles from lake-based structures in Hévíz Lake, Hungary, using FAKOPP acoustic measurements to determine dynamic MOE and a digital oscilloscope for waveform analysis and resonance frequency calculations. Euler's formula was used to compute the critical buckling load (P_{cr}), and statistical correlation analyses were conducted to assess the interaction between pile length, MOE, and buckling resistance. Results indicate that pile length is the primary determinant of buckling resistance, with longer piles exhibiting lower P_{cr} due to increased slenderness ratios. Shorter piles demonstrate higher buckling resistance, while MOE plays a secondary role, improving stiffness and stability, particularly in intermediate-length piles (10–15 m). Correlation analysis reveals a strong negative relationship ($r = -0.72$) between pile length and P_{cr} , whereas MOE exhibits a weaker positive correlation ($r = 0.40$) with buckling resistance. These findings underscore the importance of geometric and material properties in optimizing submerged wooden pile foundations for enhanced structural stability.

Keywords: wooden piles, dynamic MOE, Structural stability, nondestructive acoustic method, Hévíz Lake. Industry, innovation and infrastructure

1. Introduction

The utilization of wooden piles as integral structural components in various lake-based constructions has a well-documented history, attributable to the inherent versatility, natural abundance, and favorable mechanical properties of wood.

These piles have been employed to support a wide range of aquatic structures, from simple applications like piers and docks to more complex, high-load-bearing systems, including bridges and elevated platforms (Bouras et al., 2010; Kromoser et al., 2024;

Zhang et al., 2011). However, the performance and long-term stability of these wooden structures are significantly influenced by exposure to dynamic loads, including the weight of the superstructure and external environmental forces such as wind, wave impacts, and fluctuating water currents (Kotzamanis & Kalliontzis, 2023; Li et al., 2023; Yazdani et al., 2020).

This research focuses on wooden piles in lake-building structures located in Hévíz, Hungary, dating back to 1795. These structures face several challenges, including outdated construction methods, insufficient documentation, and historical damage, such as a conflagration in 1986 and pile failures. The stability of the wooden pile foundations, typically characterized by long wooden piles capped with concrete, is further complicated by the dynamics of piling, which continue until practical resistance is achieved, introducing additional uncertainties in foundation performance.

Among the various failure modes that can compromise structural integrity, buckling represents a significant risk for slender columns subjected to compressive loads. This phenomenon, characterized by axial compressive forces causing sudden lateral deformation, can lead to catastrophic structural failure. Buckling is particularly concerning for slender, load-bearing wooden piles subjected to cyclic or fluctuating loads, conditions prevalent in aquatic environments (Hassan, 2021; Kumar et al., 2015; Vukelic et al., 2017).

Two primary factors influence the buckling behavior of wooden piles: the dynamic modulus of elasticity (MOE) and the pile's geometric characteristics, particularly its length. The dynamic MOE quantifies the

material's stiffness under dynamic loading, reflecting how it responds to repetitive or impulsive forces (Chauhan & Sethy, 2016; Dahle et al., 2016; Giaccu et al., 2017). This property is vital for evaluating the performance of wooden piles in environments with fluctuating loads, such as aquatic settings. Generally, materials with higher dynamic MOE values demonstrate superior load-bearing capacity and stability, thus enhancing resilience against buckling risks (Budig & Mlote, 2022; Sharma & Bhandari, 2021; F. Wang & Sigmund, 2023). In addition to material properties, pile length is crucial for structural stability. According to Euler's buckling theory, longer piles require lower critical loads to buckle, creating an inverse relationship between length and stability (Bouchareb et al., 2022; Zheng et al., 2021).

Consequently, longer piles are more prone to buckling, highlighting the importance of balancing material selection and geometry in design. This study investigates the relationship between the dynamic modulus of elasticity (MOE) and pile length with the buckling behavior of wooden piles in lake-building structures in Hévíz, Hungary. Given the dynamic nature of aquatic environments, understanding how material properties and geometric constraints interact is crucial for optimizing structural stability. The objectives are: (i) to measure the dynamic MOE and lengths of wooden piles using nondestructive ultrasonic testing, alongside calculating the critical buckling load; (ii) to qualify the correlation between dynamic MOE and buckling resistance under dynamic loading; and (iii) to evaluate the effect of pile length on the critical buckling load.

2. Material and Method

2.1 Structural and Geotechnical Examinations

This study evaluated the stability of 40 wooden piles from a total of 400 supporting lake-based structures in Hévíz, Hungary, using nondestructive methods to determine the MOE and pile lengths as shown in Figure 1. The piles, typically made of spruce, larch, or oak, had diameters ranging from 20 to 29 cm and exhibited the presence of pith, as they were extracted from the central portions of whole trunks, capped with concrete (Figure 2).

The piles were driven into the lakebed of Hévíz Lake, consisting of a thin, rocky layer (0.3–1.4 m) overlying peat and transitioning to denser clay and sand layers.

The piles are submerged in the thermal waters, heated by geothermal energy with temperatures ranging from 33–36 °C in the summer to 23–25 °C in colder months. The water is rich in minerals, including sodium, potassium, magnesium, calcium, and sulphate with a pH of 7.14. Which can influence the wood's durability and potential degradation. These unique water characteristics must be considered when evaluating the stability of the submerged piles.

2.2 Dynamic Elastic Modulus Measurement

To assess the piles' mechanical properties, the Dynamic MOE was determined using a species-specific strength classification and calculated based on sound velocity and average density values, with wood species identified from core samples.

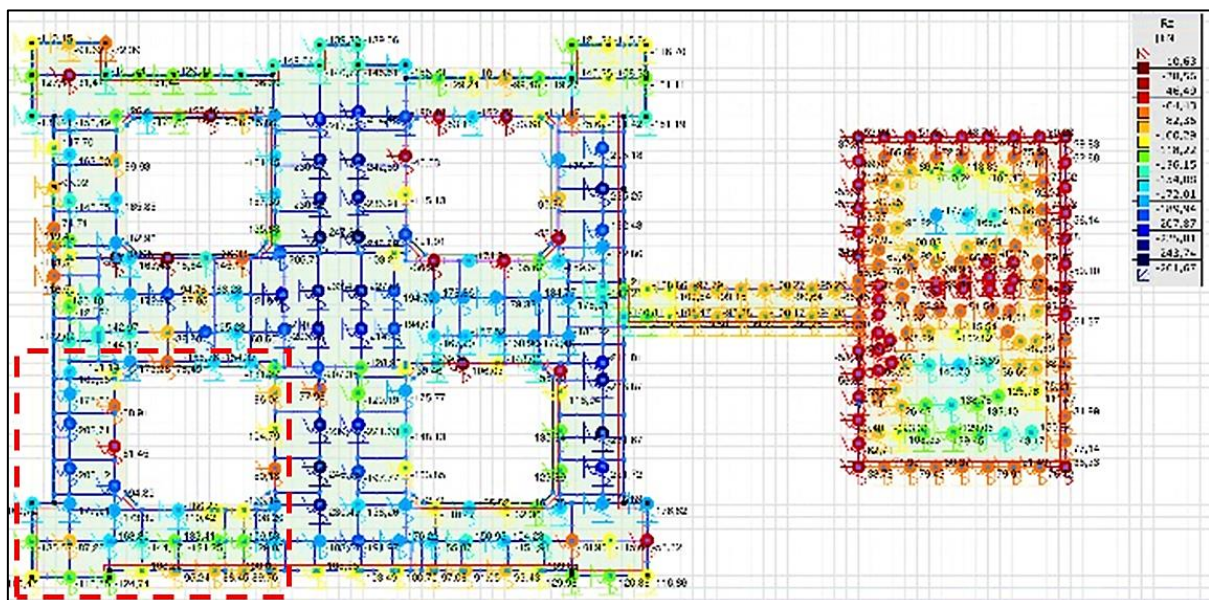


Figure 1. Structural Modeling of Submerged Wooden Piles in Hévíz Center, Emphasizing 40 Piles Under Evaluation

The 40 piles under evaluation were identified as spruce, with an average density of 470 kg/m^3 (Divós & Tanaka, 2005). Since direct density measurements were not possible, these average values were used. The relationship between sound velocity and density is expressed as:

$$E_{\text{din}} = c^2 \cdot \rho, \quad (1)$$

where: E_{din} - represents the dynamic elastic modulus [Pa]; c - is the sound propagation velocity in the wood [m/s]; and ρ - is the density [kg/m^3].

2.3 Sound Velocity Measurement

Sound velocity along the grain direction of the wooden piles was measured using a FAKOPP Microsecond Timer, consisting of two sensors and a time meter unit. Sound waves were generated by striking the wood with a hammer, and the travel time between the sensors (set 80 cm apart) was recorded in microseconds. Sound propagation velocity was calculated using the recorded time and known distance. Each

pile was tested 3 to 5 times to ensure accuracy.

2.3.1 In Situ Measurements with Divers

In situ measurements were conducted by divers at Hévíz Lake Spa, who positioned sensors along the submerged piles and generated sound waves by striking the "START" sensor with a hammer. A team on a boat recorded the propagation time, as shown in Figure 3. The diver also measured the pile diameter and inspected the surface for degradation to calculate the effective cross-sectional area. The sound velocity, combined with density values, was used to calculate the dynamic MOE, enabling pile classification according to the MSZ EN 338 standard.

2.4 Measurement Setup for Pile Length and critical buckling load Determination

Wooden pile lengths were measured using nondestructive acoustic testing with a FAKOPP device and oscilloscope.



Figure 2. The wooden pile submerged in Hévíz lake.



Figure 3. In situ diver-assisted sound velocity at Hévíz Lake.

Pile locations were identified from blueprints, and each pile was assessed individually. The FAKOPP sensor was stabilized with beeswax, and vibrations from a hammer strike were captured by the oscilloscope. The time-voltage signal was used to calculate pile length, with propagation velocity (c) based on the pile's material properties, using the following equation:

$$L_{\text{pile}} = c \cdot \frac{t}{2}, \quad (2)$$

where: L_{pile} – is the length of the pile [m]; c – is the sound wave velocity in the wood [m/s]; and t – is the measured round-trip travel time of the acoustic wave[s].

The critical buckling load (P_{cr}) was determined using the Euler-Bernoulli beam theory, as expressed by the equation:

$$P_{\text{cr}} = \frac{KEI}{L^2}, \quad (3)$$

where: P_{cr} – is critical buckling load [KN]; K – is a constant related to the boundary conditions. In our case, we have a simply Supported Pile ($K = 1$), E – is the dynamic modulus of elasticity [MPa], I – the moment of inertia the cross-section [m]; and L – is the pile length [m].

3. Results and Discussion

3.1 Establishing the Dynamic Modulus of Elasticity (MOE)

The dynamic Modulus of Elasticity (MOE) values, derived from ultrasonic velocity and wood density, ranged from 4727 MPa to 11186 MPa, with an average of 7777 Mpa, as presented in Table 1. A higher MOE indicates

better structural performance, enhancing load-bearing capacity and reducing the risk of failure, such as buckling under compressive forces. These values reflect the variability inherent in the material properties of wood, which are influenced by species, strength class, moisture content, and structural defects (e.g., knots, grain orientation).

3.1.1 Species-Specific Differences in Dynamic MOE

The dynamic MOE values were significantly influenced by the species and strength class of the wood. Specifically, piles classified as C14 exhibited an average dynamic MOE of 6580 MPa, whereas piles in the higher-strength class C22 displayed a significantly higher average dynamic MOE of 10620 MPa. Furthermore, the highest observed value, 11186 MPa, was recorded for a C27 pile. This variation is consistent with previous studies that have shown that the stiffness of wood, as represented by its dynamic MOE, is highly species-dependent. For instance, (Li et al., 2021; Y. Wang et al., 2018) found that denser species typically exhibit higher MOE values due to their structural characteristics, such as cell wall thickness and lignin content. In this study, the higher dynamic MOE values observed in the C22 and C27 strength classes can be attributed to the superior stiffness of these stronger wood types, which are less prone to buckling and deformation under load, making them more suitable for structural applications. This confirms findings from (Rais et al., 2020; Sharapov et al., 2019), who reported that denser woods like oak and beech have higher dynamic MOE compared to lighter softwoods such as pine.

Table 1. Summary of Dynamic MOE, ultrasonic velocity, Strength Classifications of Wooden Piles

Wooden piles	Time of flight (s)	Velocity (m/s)	MOE (MPa)	Strength Classes
1	0.000176	4551	8389	C16
2	0.000176	4539	8345	C16
3	0.000201	3981	6420	OUT
4	0.000185	4335	7612	C14
5	0.000199	4021	6548	OUT
6	0.000179	4471	8096	C16
7	0.000166	4818	9400	C18
8	0.000198	4038	6602	C14
9	0.000195	4097	6799	C14
10	0.000204	3925	6241	C14
11	0.000193	4144	6953	C14
12	0.000207	3871	6069	C14
13	0.000198	4038	6804	C14
14	0.000191	4181	7081	C14
15	0.000209	3823	5919	C14
16	0.000213	3751	5699	C14
17	0.000178	4497	8191	C16
18	0.000188	4257	7338	C14
19	0.000168	4766	9198	C18
20	0.000196	4072	6716	OUT
21	0.000173	4628	8675	C16
22	0.000174	4600	8570	C16
23	0.000162	4926	9827	C20
24	0.000169	4734	9078	C18
25	0.000155	5152	10751	C22
26	0.000198	4049	6641	C14
27	0.000160	4987	10072	C22
28	0.000234	3416	4727	OUT
29	0.000171	4688	8901	C16
30	0.000152	5255	11186	C27
31	0.000182	4393	7817	C14
32	0.000212	3767	5747	OUT
33	0.000173	4635	8702	C16
34	0.000160	5007	10155	C22
35	0.000188	4259	7346	C14
36	0.000171	4685	8890	C16
37	0.000183	4368	7727	C14
38	0.000168	4759	9150	C18
39	0.000196	4081	6744	C14
40	0.000209	3831	5943	OUT

3.2 Establishing Lengths of Wooden Piles and Assessing Critical Buckling Load

Based on Equations (2) and (3), the lengths and corresponding critical buckling loads of 40 wooden piles were both measured and computed. The pile lengths varied from 5.65 meters to 20.83 meters, with an average length of 10.2 meters. Pile length significantly influences buckling behavior, with longer piles exhibiting increased vulnerability to lateral instability under compressive forces. The calculated critical buckling loads (P_{cr}) ranged from 0.019 kN to a peak value of 0.247 kN, as shown in Figure 4.

3.3 Influence of Pile Length and Dynamic Modulus of Elasticity (MOE) on Critical Buckling Load

The analysis examines the relationship between the dynamic modulus of elasticity and pile length on the buckling load in Hevis wooden piles. As shown in Figure 5, a strong negative correlation between pile length and critical buckling load (P_{cr}), with a correlation coefficient of -0.72 in Graph A. This indicates that longer piles have reduced buckling resistance, consistent with structural stability principles.

Additionally, Figure 5 and Graph B show a positive correlation ($r = 0.40$) between the dynamic modulus of elasticity (MOE) and P_{cr} . While a higher MOE enhances stiffness and reduces deflection, its impact on buckling load is less significant than that of pile length, as buckling resistance depends more on geometry and length.

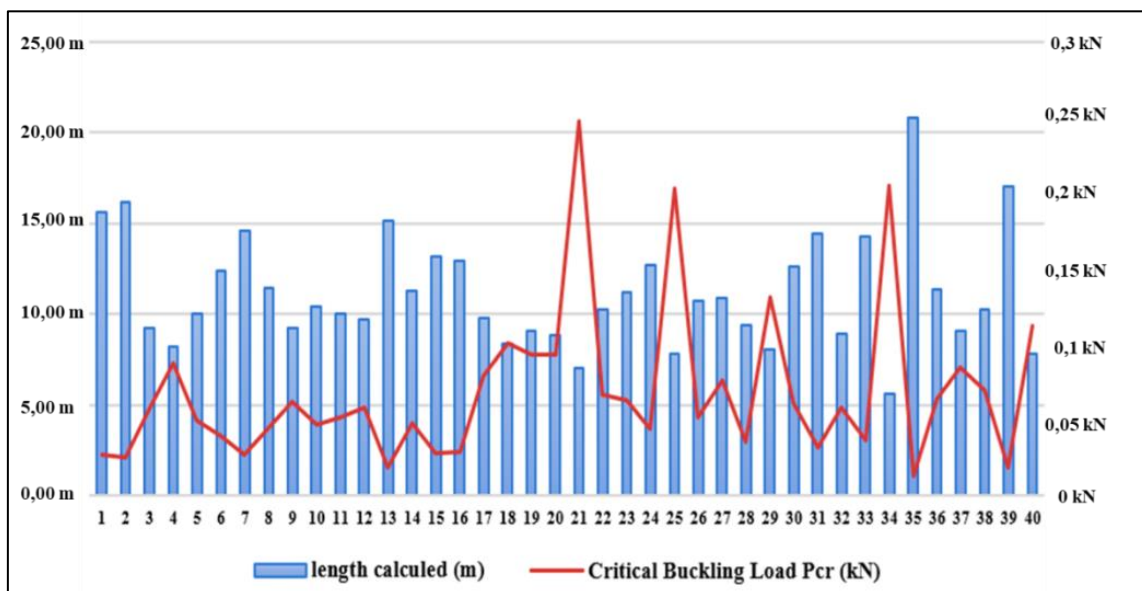


Figure 4. Pile length vs. critical buckling load across different pile samples

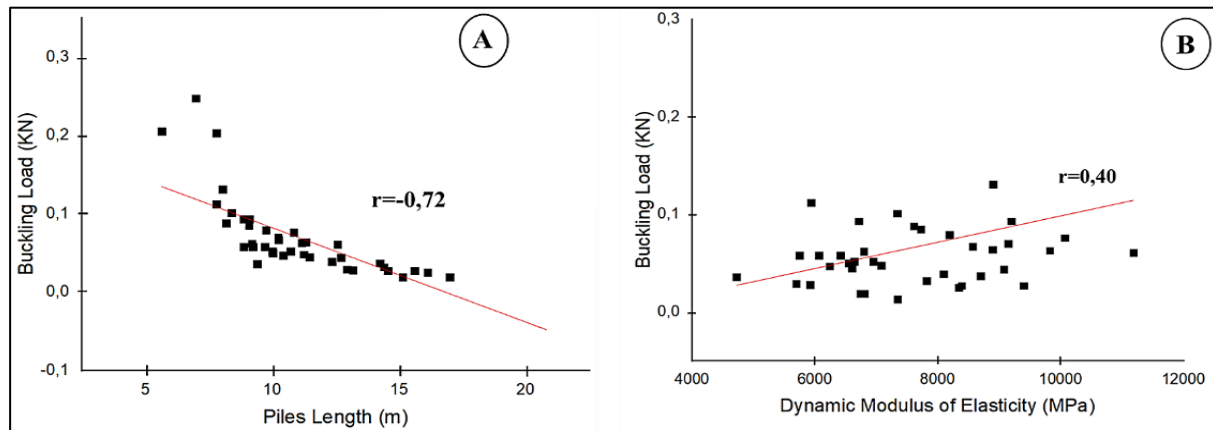


Figure 5. Relationship Between Pile Length and Dynamic Modulus of Elasticity on Critical Buckling Load

3.3.1 Higher Critical Buckling Loads in Shorter Piles

Shorter piles (e.g., 5.65 m and 6.99 m) demonstrate significantly higher critical buckling loads, with values of 0.205 kN and 0.247 kN, respectively (Figure 4), indicating enhanced stability and resistance to lateral deflections under compressive forces and buckling resistance. Shorter piles improve structural stability by reducing their effective length, which limits lateral deflection under compression. According to Euler's Buckling Theory, even minor reductions in pile length led to disproportionately higher critical buckling load, significantly enhancing stability. These shorter piles also exhibit increased stiffness, providing greater resistance to lateral deformations (Karampour et al., 2020; Tabarestani & Naghipour, 2022). Additionally, with lower slenderness ratios, shorter piles are less susceptible to higher-order buckling modes and instead experience simpler, lower-order buckling, improving axial stability as supported by Euler–Bernoulli beam theory and confirmed

by recent studies (e.g., (Fernández-Escobar et al., 2023; Giese et al., 2023; He et al., 2023; Jais et al., 2024).

3.3.2 Lower Critical Buckling Loads in Longer Piles

Longer piles (e.g., 20.83 m and 17.00 m) have significantly lower critical buckling loads (0.013 kN and 0.019 kN, respectively), As demonstrated in Figure 4. This reduction is due to increased flexibility and deflection potential, as longer piles are more prone to lateral displacements under axial loads, reducing their load-bearing capacity and buckling resistance, as noted by (Hassan, 2019).

3.3.3 Critical Buckling Loads for High-Dynamic MOE Pile

Piles with higher dynamic MOE values (e.g., 10751 MPa, 11186 MPa, and 9827 MPa) tend to exhibit lower critical buckling loads as shown in Figure 6. For instance, the pile with a dynamic MOE of 10751 MPa and a length of 7.81 m has a critical buckling load of 0.203 kN, while the pile with a dynamic

MOE of 11186 MPa and a length of 12.59 m shows a critical buckling load of 0.061 kN as shown in Figure 7. This suggests that pile length may influence buckling behavior more significantly than stiffness alone, aligning with studies by (Hasan, 2019; Moita et al., 2020).

While higher dynamic MOE is generally linked to greater bearing capacity and a theoretical increase in buckling resistance, the relationship between MOE and buckling load is complex.

In this study, the piles were driven into the lakebed of Hévíz Lake, where the soil consists of a thin, rocky layer (0.3–1.4 m) overlying peat, transitioning to denser clay and sand layers. These specific soil conditions, combined with the thermal waters of the lake, significantly impact pile performance. Additionally, the geothermal heating of the lake water, which ranges from 23 to 36 °C, and its mineral-rich composition (e.g., sodium, potassium,

magnesium, calcium), affect the wood's durability and performance. These unique site conditions—distinct from general water infrastructure environments—were carefully considered in the structural analysis of the piles. Moreover, dynamic loading conditions and potential soil liquefaction further influence pile stability, as demonstrated by Fenu et al. (2021) and Liu & Ma (2015).

3.3.4 Critical Buckling Loads for lower-Dynamic MOE Piles

Conversely, piles with lower dynamic MOE values (e.g., 4727 MPa for a 9.41 m pile) exhibit higher critical buckling loads compared to those with higher MOE. For instance, the 9.41 m pile with a dynamic MOE of 4727 MPa has a critical buckling load of 0.036 kN as shown in Figure 6. This implies that lower material stiffness increases flexibility, potentially reducing buckling at specific pile lengths, as described in the literature (Dyka & Klempka, 2023; Jawad & Albusoda, 2024).

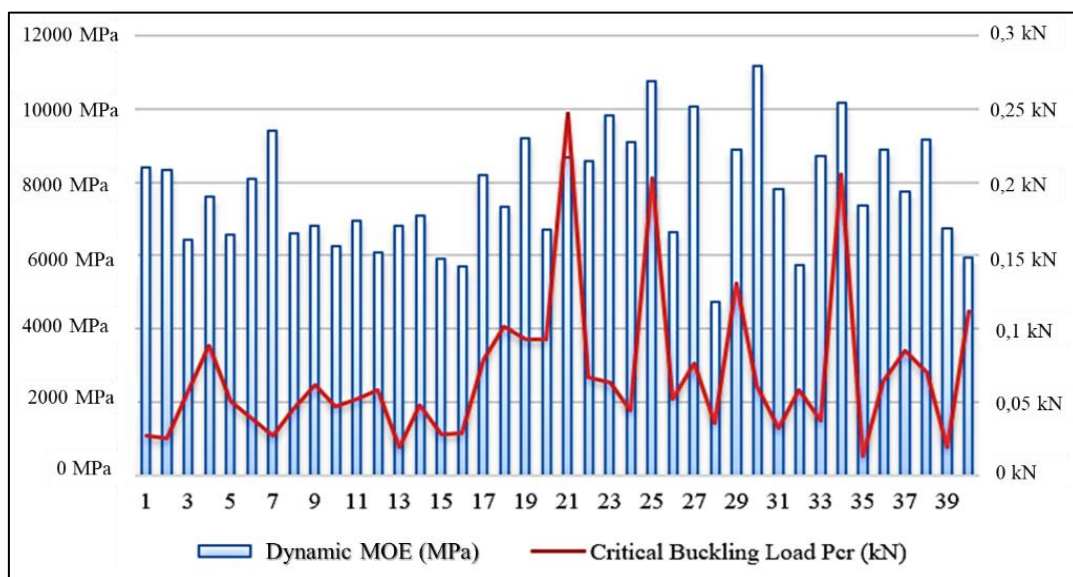


Figure 6. Dynamic MOE vs. critical buckling load across different pile samples

3.4 Combined Influence of Pile Length and Dynamic Modulus of Elasticity (MOE)

The data indicate that both pile length and the dynamic modulus of elasticity (MOE) influence the pile's buckling behavior. Pile length has a more direct and significant impact on the critical buckling load, while MOE serves as a secondary factor that refines the buckling response, especially for intermediate-length piles (approximately 10–15 m). In this range, piles with higher MOE values exhibit slightly higher buckling loads compared to those with lower MOE, suggesting that MOE enhances stiffness and resistance to buckling. However, this

difference diminishes in longer piles, where increasing MOE does not significantly improve buckling resistance. Conversely, for shorter piles (<10 m), the impact of MOE is more pronounced, with higher MOE values contributing to noticeably greater buckling loads.

Overall, while higher MOE reduces buckling risk, its influence is most effective when combined with optimal pile length and other structural considerations. As shown in Figure 7, piles with both shorter lengths and higher MOE values exhibit the strongest buckling resistance, whereas longer piles, even with high MOE, remain more vulnerable to buckling.

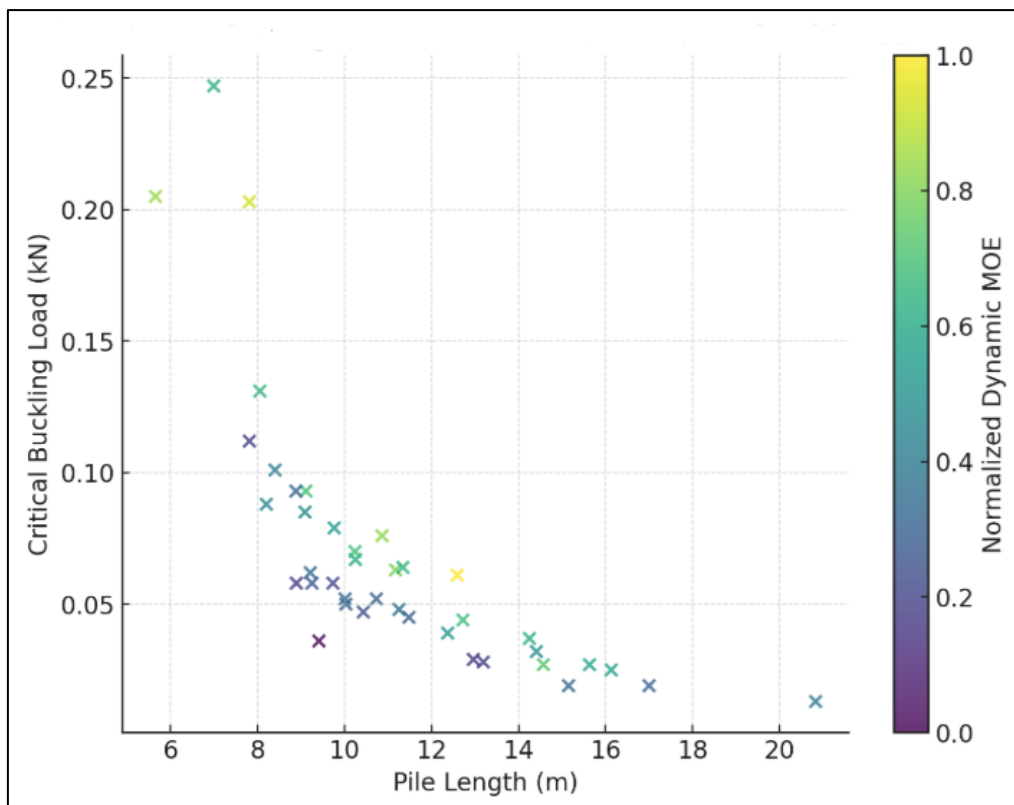


Figure 7. Effect of Pile Length and Dynamic Modulus of Elasticity (MOE) on Critical Buckling Load for Intermediate-Length Piles

4 Conclusions

This study examines the influence of dynamic modulus of elasticity (MOE) and pile length on the buckling behavior of submerged wooden piles at Hévíz Lake, Hungary. Both factors significantly affect stability, with pile length showing a strong correlation to critical buckling load: shorter piles exhibit higher stability due to their lower slenderness ratios, while longer piles are more prone to buckling under compressive forces. Dynamic MOE, though secondary, enhances stability by increasing stiffness, especially in denser woods like oak. Lower MOE values correlate with reduced structural performance, particularly in dynamic aquatic environments subjected to forces from currents and waves. Further

analysis indicates an interaction between pile length and MOE in modulating buckling behavior. For medium-length piles, increases in dynamic MOE result in a slight enhancement of critical buckling loads, highlighting a positive correlation between dynamic MOE and pile length in this range. However, for longer piles, the influence of dynamic MOE diminishes significantly, with pile length remaining the dominant factor controlling buckling loads. In conclusion, both pile length and MOE should be considered in the design of submerged wooden piles, with pile length prioritized to ensure stability under compressive forces, while dynamic MOE can refine buckling resistance.

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Author statements

Brougui Marwa – head of the research, data analysis, author.
Dr. Krisztián Andor – data collecting and analysis, editor.

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