Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2281

Utility of microtremor array survey in offshore wind monopile design

Shubham Trivedi
Wood Thilsted Partners (formerly Arup), Japan, str@woodthilsted.com

Yuko Kawakami, Hitoshi Sasaki
Arup, Japan

ABSTRACT: Shear wave velocity (V_s) is a critical parameter in the design of offshore wind monopile foundations, influencing dynamic behavior and long-term performance. While PS logging provides accurate site-specific V_s measurements, its high cost and impracticality in deep waters necessitate alternative methods. Seismic CPT offers a viable alternative but remains expensive for large wind farms. Microtremor array surveys (MAS), a non-invasive geophysical technique widely used in seismic site characterization, have recently been applied in offshore environments. This study investigates the applicability of MAS in offshore wind foundation design by comparing MAS-derived V_s values with those obtained from PS logging, as well as from empirical correlations for standard penetration test (SPT) and cone penetration test (CPT). Field data from 21 monopile foundation locations at a recently developed offshore wind farm were analyzed. The accuracy of V_s estimations from MAS, SPT, and CPT was assessed by statistical comparison against PS logging results. A structural analysis of the coupled wind turbine–foundation system was further conducted to evaluate the impact of different Vs inputs on dynamic characteristics, ultimate limit state (ULS) behavior, and serviceability limit state (SLS) performance. The results demonstrate that MAS provides the highest correlation with PS logging across a wide V_s range, with relatively lower scatter compared to SPT and CPT-based correlations. Foundation response analysis indicates that MAS yields the closest agreement with PS-based predictions, particularly in estimating long-term rotation at the mudline. These findings suggest that MAS can serve as a cost-effective alternative to PS logging for offshore wind projects, providing reliable input for foundation design while minimizing environmental impact and survey costs.

KEYWORDS: Microtremor array survey, PS-logging, offshore wind, monopile foundations

1 INTRODUCTION

Shear wave velocity (V_s) or small-strain shear modulus (G_0) is a fundamental parameter in the design of offshore wind monopile foundations, where accurate characterization of soil stiffness is essential for predicting dynamic behavior and long-term performance. Monopile foundations, owing to their large diameter and relatively high stiffness compared to conventional pile foundations, exhibit a complex interaction with the surrounding soil, necessitating reliable in-situ measurements of V_s for robust geotechnical and structural design. V_s has traditionally been used in Japanese seismic design practice where it is used for site response and dynamic soil structure interaction analyses.

PS logging remains the most accurate method for direct measurement of V_s in offshore geotechnical investigations. However, its application is often constrained by high costs and logistical challenges, particularly at large water depths, where borehole instability further limits data acquisition. Seismic Cone Penetration Testing (SCPT) has been employed as a practical alternative, offering an integrated assessment of soil stratigraphy and shear wave velocity. However, in the context of large offshore wind farms, where extensive site investigations are required across numerous turbine locations, SCPT remains cost prohibitive.

Microtremor Array Survey (MAS) presents a non-invasive and cost-effective alternative for obtaining subsurface shear wave velocity profiles. This method has been extensively utilized in Japan for seismic hazard assessment and seismic design applications, demonstrating its efficiency in estimating surface wave dispersion characteristics. Recent studies have extended its applicability to offshore environments (Inoue et. al., 2022), prompting an investigation into its potential utility in offshore wind foundation design.

The present study evaluates the accuracy and applicability of MAS in offshore wind monopile foundation design by analyzing extensive survey data from a recent offshore wind farm. The accuracy of MAS-derived V_s values is assessed through comparison with conventional in-situ measurement methods, including PS logging, Standard Penetration Test (SPT), and Cone Penetration Test (CPT). Additionally, to elucidate the implications of shear wave velocity variability in foundation design, a comparative analysis of a coupled wind turbine–foundation system is conducted. This analysis encompasses three key aspects of foundation performance: eigenvalue analysis to characterize dynamic behavior and natural frequencies, extreme load case analysis to determine maximum bending moments, and serviceability limit state analysis to estimate accumulated permanent rotation at mudline under cyclic loading conditions. Through this investigation, the feasibility of MAS as a practical alternative to conventional methods is critically examined.

2 SITE INVESTIGATION AND DATA INTERPRETATION

2.1 *Site investigation*

This study utilizes site investigation data from Oga Katagami Akita Offshore Wind Farm in north-east Japan currently under development, where extensive geotechnical surveys were conducted at 21 turbine locations. The geological profile at the site is characterized by a surficial marine sand deposit, underlain by interbedded layers of sand and clay.

Four distinct in-situ measurement techniques were employed: PS logging, SPT, CPT, and MAS. While PS and MAS were conducted at all 21 locations, SPT and CPT investigations were performed at 15 and 11 locations, respectively, with five sites featuring data from all four methods as indicated in the turbine layout in Figure 1. Despite the comprehensive PS logging campaign, data availability was inconsistent due to borehole instability at shallow depths, which resulted in unreliable or missing V_s measurements at certain intervals.

2.2 *Data interpretation*

Shear wave velocity estimation from SPT and CPT was performed using established empirical correlations. The Ota and Goto (1978) and Imai and Tonouchi (1982) correlations were employed for SPT-based estimations (indicated as SPT-OG and SPT-IT respectively hereafter), while the Suzuki et al. (2003) and Robertson (2009) correlations were utilized for CPT-based estimations (indicated as CPT-SZ and CPT-RB respectively hereafter). In contrast, MAS-derived V_S profiles were obtained through inversion analysis of surface wave dispersion data, with complementary seismic surveys conducted to refine subsurface stratigraphy.

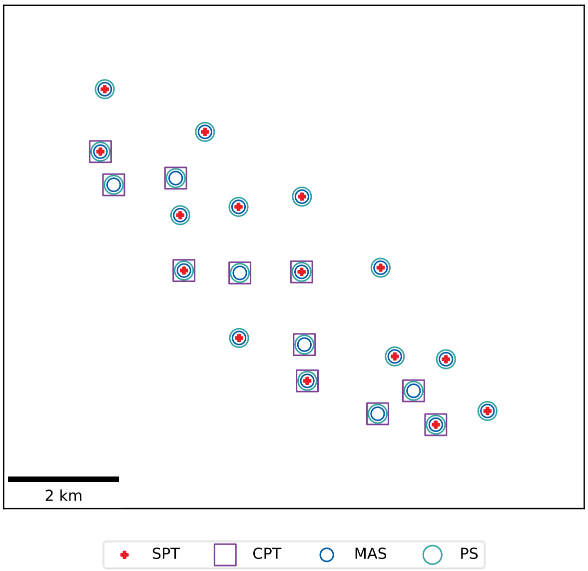

Figure 1. Layout of turbines and ground investigation performed at each position.

3 SHEAR WAVE VELOCITY COMPARISON

The accuracy of V_S derived from MAS, SPT, and CPT was evaluated by direct comparison with PS logging data, which is considered the most reliable benchmark. The comparative analysis encompassed five methods in total: MAS and two correlations each for CPT and SPT. The comparison results are summarized in Figure 3 to Figure 6, where V_S obtained from PS logging ($V_{S,PS}$) is plotted on the y-axis, and V_S obtained from the respective methods is plotted on the x-axis. Data points are differentiated by soil type, with sand represented in red and clay in purple. Pearson correlation coefficient (PCC) and concordance correlation coefficient (CCC) are also provided for each method to quantify the strength of correlation and the degree of agreement with PS logging. Correlation coefficients and number of data points in each dataset are also summarized in Table 1.

The results indicate that MAS exhibits the highest PCC and CCC among all the alternative methods, demonstrating strong agreement with PS logging across the full range of V_S. The scatter in MAS-derived V_S values is relatively consistent, whereas larger discrepancies are observed in SPT- and CPT-based correlations, particularly at higher velocities. Both SPT-based correlations exhibit a general trend of overestimating V_S, with the Ota and Goto correlation specifically underestimating V_S in sand layers where V_S is below 150 m/s. The CPT-based correlations show lower correlation coefficients, likely due to the limited number of available data points. The Suzuki correlation tends to underestimate V_S in clay layers at velocities smaller than 150 m/s, while the Robertson correlation exhibits a tendency to overestimate V_S in both sand and clay at velocities larger than 300 m/s.

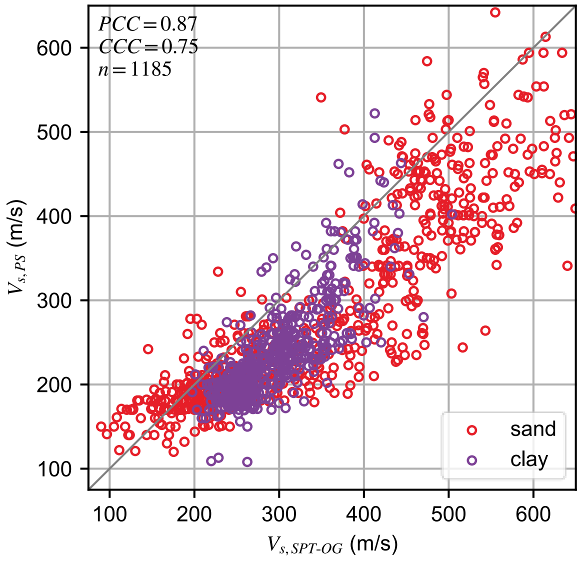

Figure 2. Correlation between PS logging data and SPT-OG.

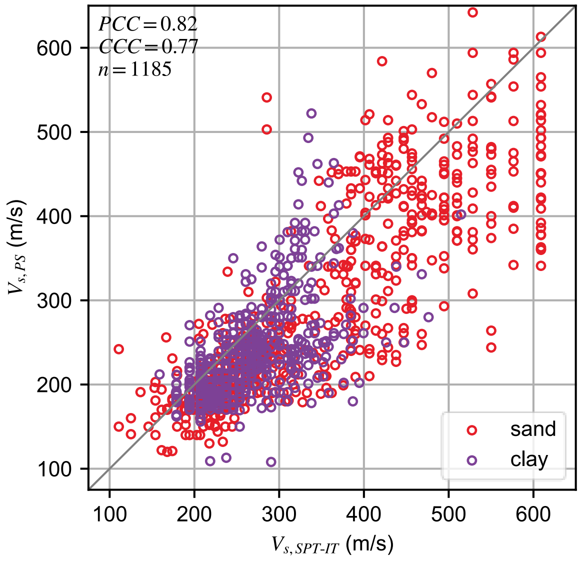

Figure 3. Correlation between PS logging data and SPT-IT.

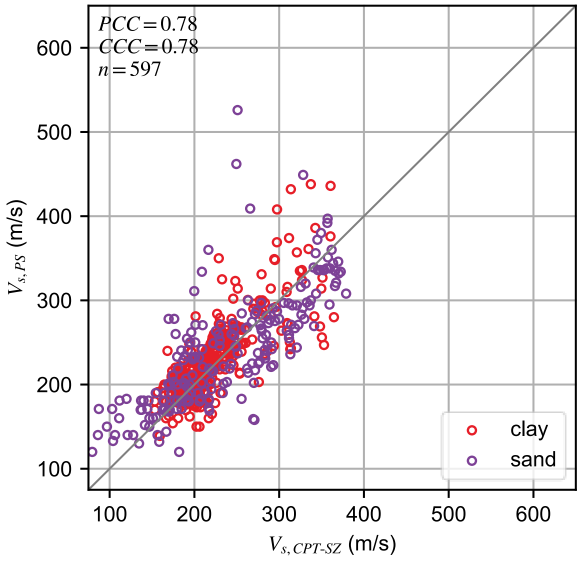

Figure 4. Correlation between PS logging data and CPT-SZ.

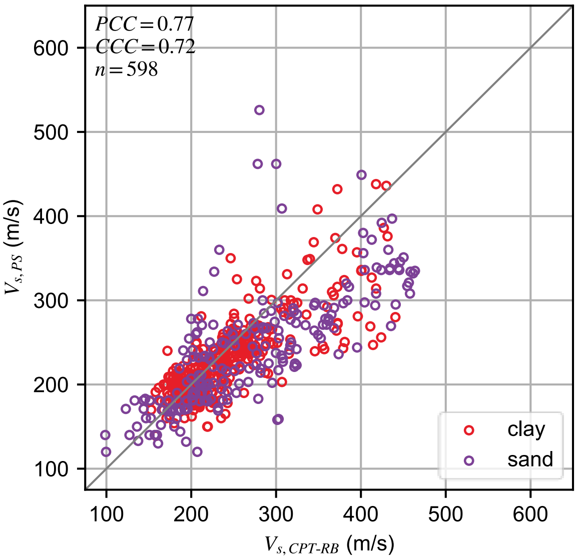

Figure 5. Correlation between PS logging data and CPT-RB.

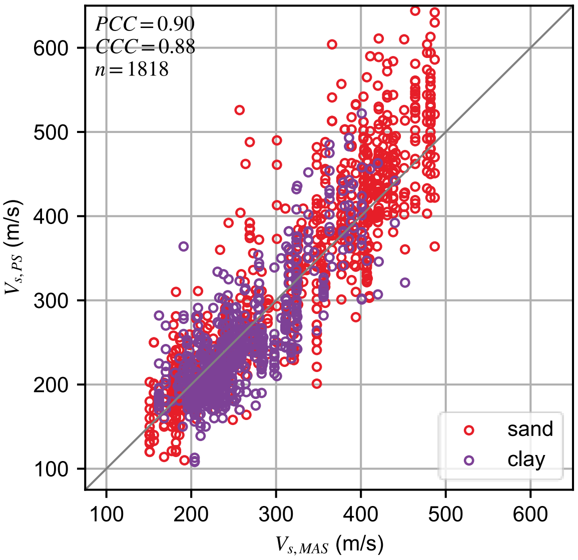

Figure 6. Correlation between PS logging data and MAS.

Table 1. Summary of correlation coefficients (method showing best correlation with respect to each correlation coefficient indicated in bold).

	n	PCC	CCC
MAS	1818	**0.90**	**0.88**
SPT-OG	1185	0.87	0.75
SPT-IT	1185	0.82	0.77
CPT-SZ	597	0.78	0.78
CPT-RB	598	0.77	0.72

4 FOUNDATION ANALYSIS MODEL

To evaluate the impact of V_s variability on foundation behavior, a structural analysis of the coupled wind turbine–foundation system was conducted. The analysis framework is illustrated in Figure 7, which provides a schematic representation of the modeled system. Each of the 21 turbine locations was analyzed using soil parameters derived from the respective in-situ survey methods, while other design parameters—including monopile and tower geometry, met-ocean conditions, and tidal variations—were kept constant to ensure a meaningful comparison.

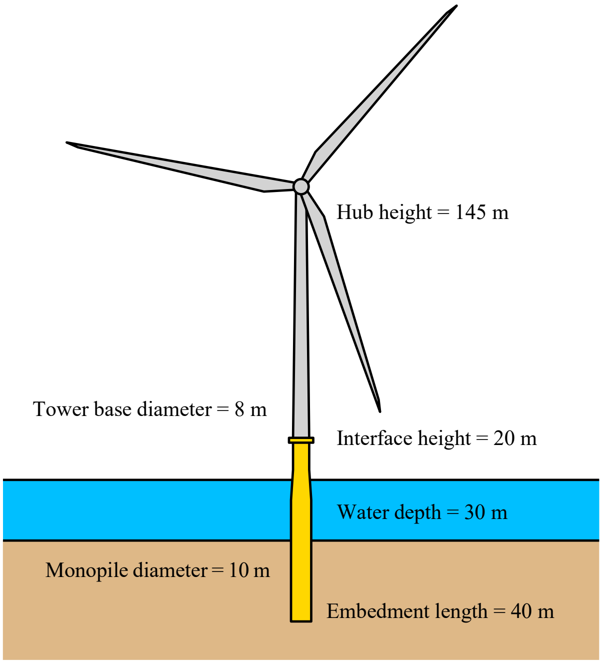

Figure 7. Details of the foundation and turbine geometry analyzed.

Soil-structure interaction was represented using nonlinear soil springs formulated according to the rule-based PISA approach (Burd et al., 2020). Shear modulus (G_0) was computed for each survey method based on the corresponding V_s values, while soil strength parameters, including relative density for sand and undrained shear strength for clay, were maintained constant.

Wind loads were applied as static equivalent forces at the tower interface, while wave loads were computed using Morison's equation, incorporating McCamy-Fuchs corrections for large-diameter monopiles. Three analytical assessments were performed: eigenvalue analysis to determine the fundamental natural frequency (f_1) and mode shape ratio (α_1), ULS analysis to estimate the maximum bending moment (M_{max}), and SLS analysis to evaluate accumulated permanent rotation (θ_P).

5 ANALYSIS RESULTS

The comparative analysis of foundation behavior revealed that variations in V_s have a pronounced impact on key structural response parameters. Figure 8 to Figure 11 present a comparison of f_1, α_1, M_{max}, and θ_P obtained for each survey method relative to PS logging. Each plot illustrates the response for the PS case on the y-axis and the corresponding response for method being compared on the x-axis. Each data point on this plot corresponds to the an analyzed turbine location.

The results indicate that while M_{max} is relatively insensitive to variations in V_s, the dynamic characteristics (f_1 and α_1) and long-term foundation performance (θ_P) exhibit notable deviations depending on the survey method. Both SPT-based correlations tend to overestimate f_1, leading to an underestimation of α_1 and θ_P. This behavior is consistent with the systematic overestimation of V_s observed in the previous section. In contrast, the CPT-Suzuki correlation underestimates f_1 while overestimating α_1, a direct consequence of its tendency to underestimate V_s in lower-velocity soil layers.

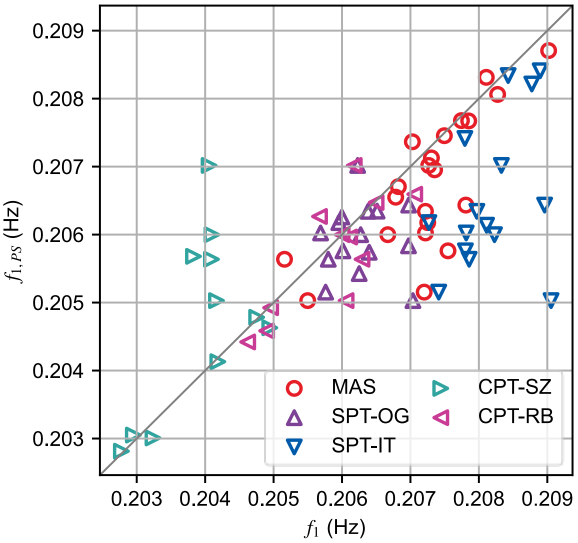

Figure 8. Comparison between PS case and estimated V_s case – f_1

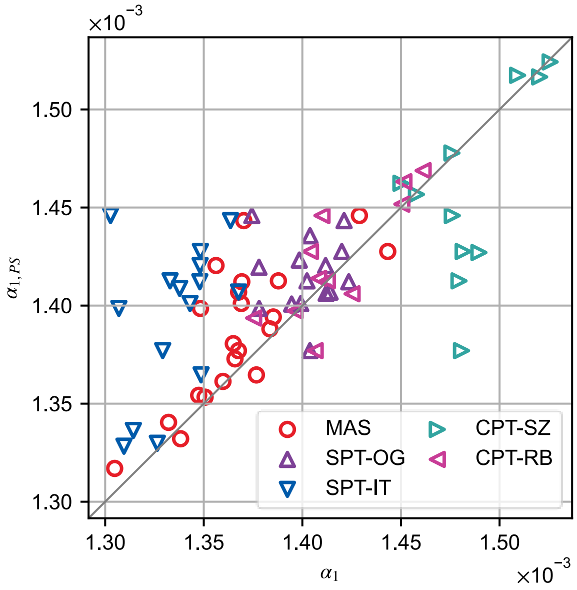

Figure 9. Comparison between PS case and estimated V_s case – α_1

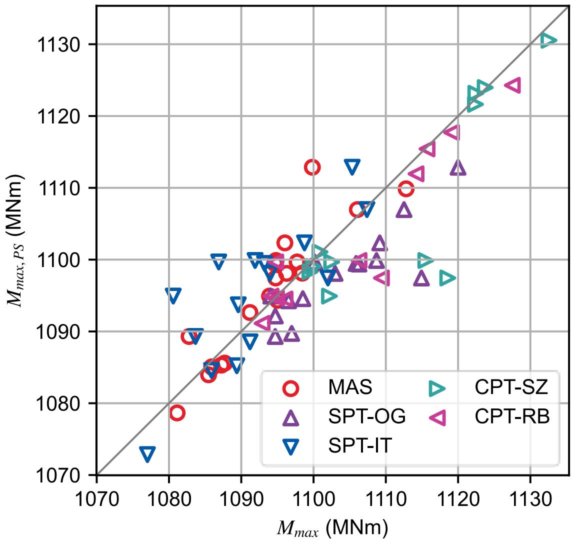

Figure 10. Comparison between PS case and estimated V_s case – M_{max}

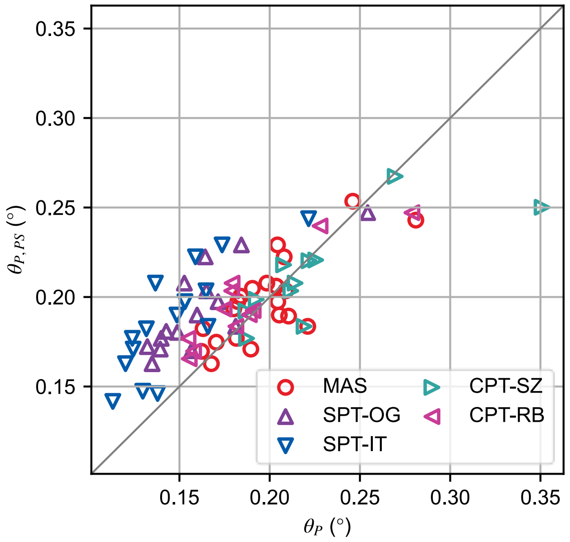

Figure 11. Comparison between PS case and estimated V_s case – θ_P

Among the alternative methods, MAS and CPT-Robertson provide the closest agreement with PS-based foundation response parameters. Relative accuracy of these methods is examined by evaluating percentage error for each case. Box plot of percentage error for each method is expressed in Figure 12 to Figure 15 for f_1, α_1, M_{max}, and θ_P respectively. Respective data points are indicated in purple while the box showing median and quartile ranges is indicated in red. Median error is consistently close to zero for MAS and CPT methods and the spread of errors is also smaller compared to SPT methods. Summary of the errors for each method is expressed in Table 2 in the form of mean absolute percentage errors. While errors in f_1 and M_{max} remain relatively small across all methods, deviations in α_1 and θ_P are more pronounced. The largest errors are observed for the SPT-based correlations, which exhibit mean errors exceeding 20% in θ_P. Conversely, MAS demonstrates consistently smaller overall errors, particularly in estimating θ_P, indicating its suitability for predicting long-term foundation performance.

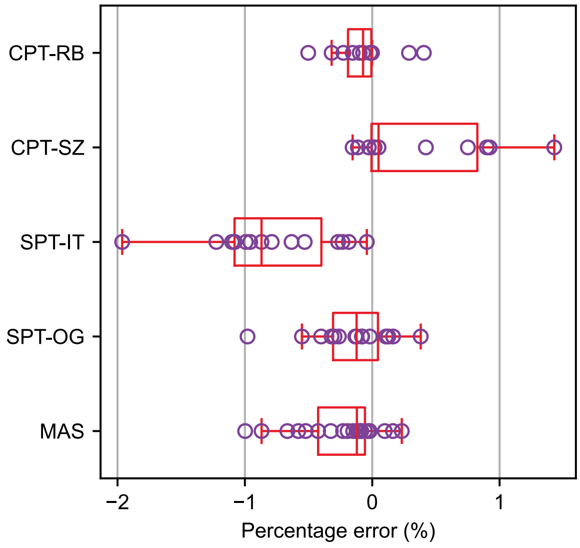

Figure 12. Box plot of percentage error – f_1

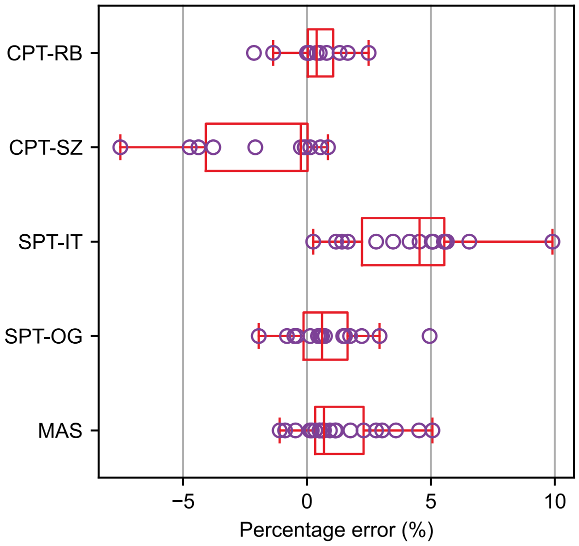

Figure 13. Box plot of percentage error – α_1

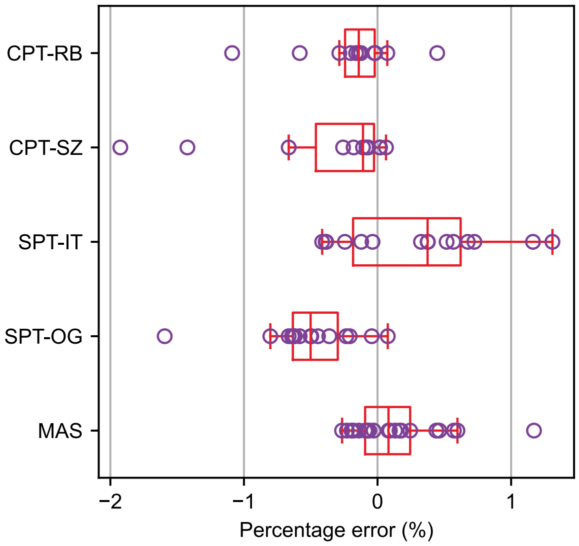

Figure 14. Box plot of percentage error – M_{max}

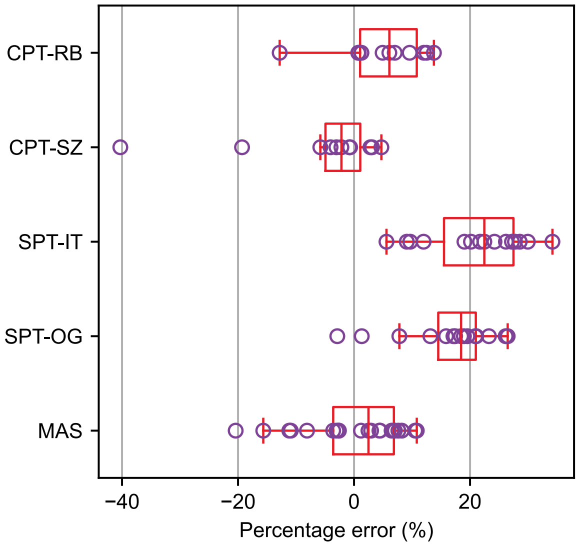

Figure 15. Box plot of percentage error – θ_P

Table 2. Mean absolute percentage errors for each response quantity and V_s estimation method (all locations).

	n	f_1	α_1	M_{max}	θ_P
MAS	21	0.29%	1.54%	**0.26%**	**7.20%**
SPT-OG	15	0.27%	1.40%	0.53%	16.70%
SPT-IT	15	0.80%	4.18%	0.51%	21.19%
CPT-SZ	11	0.44%	2.22%	0.44%	7.89%
CPT-RB	11	**0.19%**	**0.98%**	0.29%	7.42%

One contributing factor to the relative accuracy of CPT-based methods is the limited availability of PS data at shallow depths in CPT locations. Since missing PS data was supplemented with the respective method's V_s values for consistency in the analysis, the comparison results may inherently favor CPT-based estimates. This is further illustrated in Table 3, which presents the error summary considering only the locations where CPT data was available. Across these locations, MAS exhibits the smallest errors for all response quantities, reinforcing its potential as a reliable alternative to PS logging in offshore wind foundation design.

Table 3. Mean absolute percentage errors for each response quantity and V_s estimation method (locations with CPT data only)

	n	f_1	α_1	M_{max}	θ_P
MAS	11	**0.13%**	**0.72%**	**0.16%**	**6.82%**
SPT-OG	5	0.34%	1.71%	0.58%	14.11%
SPT-IT	5	0.99%	5.15%	0.77%	20.40%
CPT-SZ	11	0.44%	2.22%	0.44%	7.89%
CPT-RB	11	0.19%	0.98%	0.29%	7.42%

6 CONCLUSIONS

The findings of this study indicate that MAS offers a cost-effective and reliable alternative to PS logging for offshore wind foundation design. The accuracy of MAS-derived V_s profiles, particularly in shallow seabed layers, suggests its viability as a practical tool for offshore geotechnical investigations. Given its non-invasive nature and reduced logistical constraints, MAS has the potential to improve the efficiency of site characterization while minimizing environmental impact.

7 ACKNOWLEDGEMENTS

The authors gratefully acknowledge Oga Katagami Akita Offshore Green Energy LLC for providing valuable site investigation data essential to this study. We thank Takashi Murakami, Shota Hoshi, and Hiroyuki Kato from JERA Co., Inc.; Shusaku Nakashima and Madoka Harada from Electric Power Development Co., Ltd.; and Yuta Oishi from Arup for their valuable feedback and review of the manuscript. Our thanks also extend to Kawasaki Geological Engineering Co., Ltd. for their support in interpreting the microtremor array survey data.

8 REFERENCES

Burd, H. J., Abadie, C. N., Byrne, B. W., Houlsby, G. T., Martin, C. M., McAdam, R. A., Jardine, R. J., Pedro, A. M. G., Potts, D. M., Taborda, D. M. G., Zdravkovic, L., and Andrade, M. P. 2020. Application of the PISA design model to monopiles embedded in layered soils. *Géotechnique*, 70(11), 1067–1082.

Imai, T., and Tonouchi, K. 1982. Correlation of N-Value with S-Wave Velocity and Shear Modulus. *Proceedings of the 2nd European Symposium on Penetration Testing*, Amsterdam, pp. 67–72.

Inoue, Y., Imai, M., Matsubara, Y., and Hiraide, A. 2022. A new geotechnical investigation method – Development and application of the seafloor microtremor array exploration system. *Butsuri-Tansa*, Vol. 75, pp. sp50–sp59 (in Japanese).

Ohta, Y., and Goto, N. 1978. Empirical Shear Wave Velocity Equations in Terms of Characteristic Soil Indexes. *Earthquake Engineering & Structural Dynamics*, 6, 167–187.

Robertson, P.K. 2009. Interpretation of cone penetration tests — a unified approach. *Canadian Geotechnical Journal*, 46(11), 1337–1355.

Suzuki, Y., Tokimatsu, K., and Sanematsu, T. 2003. Correlations Between CPT Data and Soil Characteristics Obtained from SPT. *Journal of Structural and Construction Engineering*, 68(566), 73–80 (in Japanese).