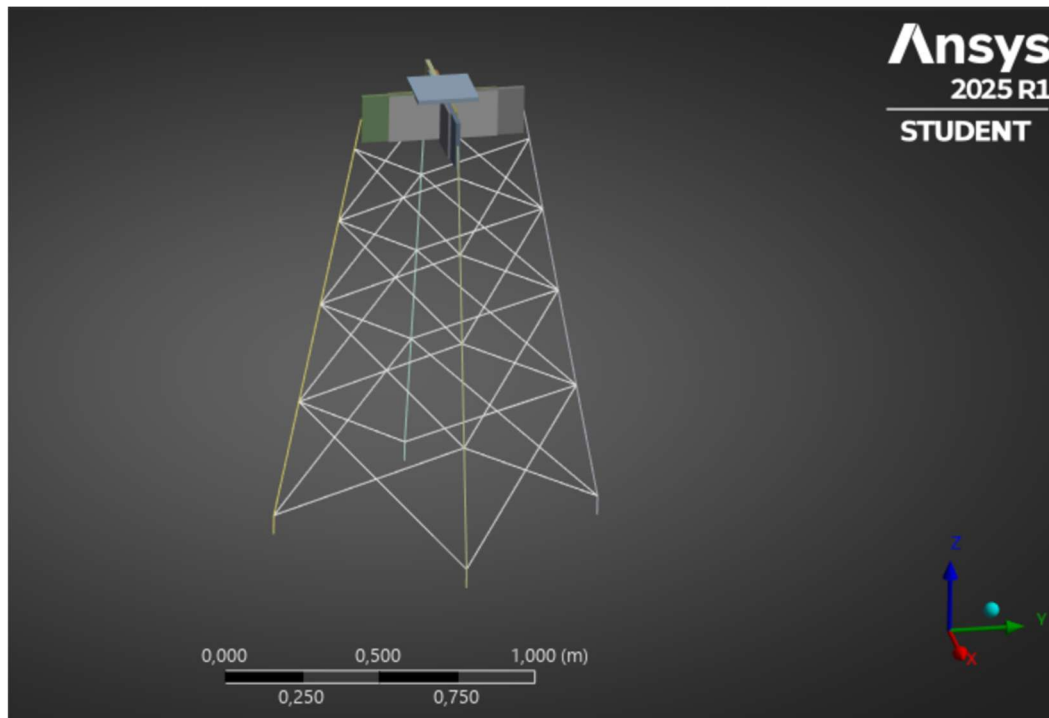


Experimental Modal Analysis of a Scaled Jacket Foundation for Offshore Wind Turbines

Eksperimentel modal analyse af et skaleret jacket fundament til havvindmøller



Course: Experimental Modal Analysis of a Scaled Jacket Foundation for Offshore Wind Turbines

Date: 22/08-2025

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Introduction

The development of this report was in fulfilment of the project course *Experimental Modal Analysis of a Scaled Jacket Foundation for Offshore Wind Turbines* during the period of 04/08/2025-22/08/2025. The project takes part in the research initiative ‘Hybrid Wind’ by performing modal analysis of a scaled jacket structure for offshore wind turbines.

Hybrid Wind

Hybrid Wind is a major European research project, the objective of which is for cold climate effects on wind turbines to be investigated. The project examines how jacket foundations for offshore wind turbines behave when exposed to large temperature changes and how this behaviour affects their performance. The Hybrid Wind project aims to improve early-on damage detection and create robustness to weather effects. Through the project, the goal is to develop digital twins for performance and health monitoring [1].

Project course

The primary objective of the project course, *Experimental Modal Analysis of a Scaled Jacket Foundation for Offshore Wind Turbines* is to perform modal analysis (EMA) on a scaled jacket structure to examine it in multiple configurations. The tests will be categorized as ‘undamaged’ and ‘damaged’. The ‘damaged structure’ will be simulated by adding mass to the structure in form of magnets. The goal is to establish empirical relations between the first global modes and added mass.

The structure's vibrational behaviour is tested by using hammer excitation and monitoring it with six accelerometers. The dynamic response of the ‘undamaged’ and ‘damaged’ jacket structures is determined using frequency response functions and modal parameters, which include natural frequencies, damping ratios, and mode shapes.

To support the Hybrid Wind objectives, the experimental results will be compared to a finite element model in ANSYS, and the modal shapes will be compared using the Modal Assurance Criterion (MAC).

Scaled jacket structure

As pictured in Figure 1, the scaled jacket structure is a 1:50 model of the proposed 20 MW wind turbine jacket structure by Rambøll. The four-legged jacket structure is supported by four X-braces and is constructed of hollow rods. To simplify production of the scaled jacket, one cross-section was chosen for the braces (1.27 x 12.7 mm) and one for the legs (1.5 x 50 mm). The same cross-section was used for the piles and elements connecting the legs to the transition piece. The transition piece is a symmetrical structure consisting of four steel plates and a top plate. The scaled jacket was produced during the master's thesis project *Design and Dynamic Monitoring of a Jacket Foundation Model by a Digital Twin* [2], from which technical drawings of the scaled jacket can be found on pages 73-75.

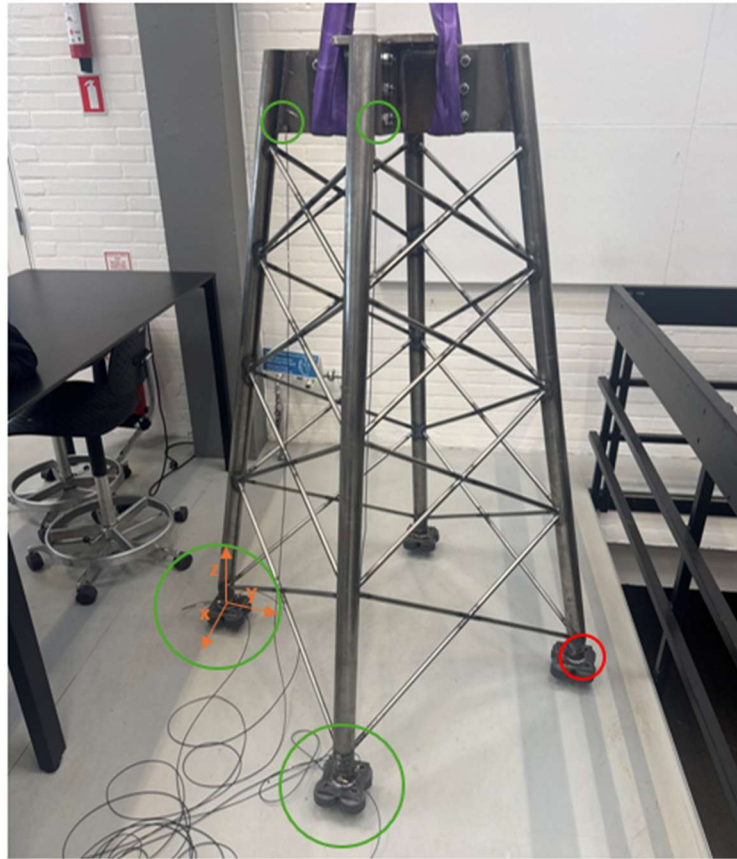


Figure 1: 1:50 scale model of the jacket structure equipped with six accelerometers and supplemented with additional mass at the base of the pile footings.

Experimental Setup

To minimize influences on the structure, it was chosen to investigate the natural frequencies of the scaled jacket structure with the boundary conditions as free-free. In order to isolate the system from external constraints, the structure was suspended, and the bottom steel plate was removed.

Placement of accelerometers

During the project *Design and Dynamic Monitoring of a Jacket Foundation Model by a Digital Twin* [2], an FE model in ANSYS was developed. This model was used to determine the expected mode shapes and decide where to place the six accelerometers.

The main objective of the experiments was to capture the first global modes. For the free jacket structure, the first mode is the expansion and subtraction of the legs. This mode will be referred to as the first breathing mode. The second global mode to be investigated is the first torsional mode.

Three accelerometers were placed on two of the legs, as shown in Figure 1. One in the transition piece and two on the piles. In the transition piece, the accelerometers were oriented in the direction of the expected torsion: the x-direction on the first leg and the y-direction on the second. For both legs, the two accelerometers at the base were oriented in the x- and y-directions, respectively.

Data collection

An impact hammer (type 8206) from Brüel & Kjær was used to excite the structure. Six Deltatron (4507 B 005) accelerometers from Brüel and Kjær, as well as a CompactDAQ USB chassis (cDAP-9171) from National Instruments, were used to measure force and acceleration. The measurements were monitored using NI FlexLogger (2024 Q3) software. To excite both the breathing and torsional modes simultaneously, the hammer was hit horizontally at a 45-degree angle in the xy-plane on the bottom of one of the two legs where the accelerometers were not placed.

Measurement procedure

The experiment was conducted a total of nine times for the collected experiment. The first experiment served as the model for the ‘undamaged’ structure, which had no additional mass. The subsequent eight experiments were categorized as ‘damaged’, and a magnet weighing 0.21 kg was added to the bottom of each pile for each experiment. This resulted in eight experiments with increasing additional masses from 0 to 1.68 kg at the bottom of each pile.

A total of ten hammer hits were used to excite the structure for each experiment. The suspension of the jacket resulted in minimal damping; therefore, the structure was left to vibrate for 10 seconds, after which the vibration was damped by holding onto the structure.

The sampling frequency was up to 400 Hz, because of Nyquist-Shannon sampling theorem. The frequency of the first torsional mode was initially expected around 190 Hz from the ANSYS model [2]. Each measurement lasting 10 seconds and averaged over 10 impacts.

Signal Processing

The main objective of the experiment is to determine the jacket structure’s dynamic properties using experimental modal analysis, in which the input force is measured and controlled. For a lab-controlled experiment, it is a practical approach as by controlling the input, the data quality significantly improves the estimation of dynamic properties.

Welch’s method

In signal processing, Welch’s method is used to estimate power spectral densities (PSDs). The method utilizes signal segmentation, which allows for overlap of the segments and application of window functions to each segment. Each segment is processed using Fast Fourier Transformation (FFT) and averaged to reduce variance and determine a more reliable PSD [4].

A weighting function, referred to as a window is applied to reduce leakage of data. For this experiment an exponential window is utilized to comply with the periodicity assumption of the Fourier Transformation. Additionally, no overlapping segments were used, with an average of ten segments employed.

Frequency Response Function estimation

From the power spectral densities determined by Welch's method, frequency response functions (FRFs) are estimated, which are mathematical representations of the ratio of output response and

applied force. The FRFs are estimated using the H_1 estimator, which assumes that there is no noise on the input. A complex-valued FRF is determined for each input-output set. This results in the estimation of six frequency response functions, as there are six measurement placements and one placement of applied force [3].

The pLSCF algorithm

During signal processing of the experiment, the poly-reference Least-Squares Complex Frequency-domain (pLSCF) algorithm is used to determine the structure's dynamic properties. Operating on time-discrete data, the algorithm utilises multiple output signals as referred to by the name 'poly-reference'.

The algorithm determines the modal parameters in two steps. First, the algorithm models the system FRFs using the Right Matrix Fraction Description (RMFD). A least squares approach is applied to fit this model across a range of user-defined model orders, yielding complex poles that represent the system's natural frequencies and damping. A stabilization diagram is then used to identify consistent poles and determine the appropriate model order for each mode.

In the second stage, the mode shapes are obtained from the least squares solution and are determined by the participation and residue vectors. Because the participation vectors are normalized and the residues are uniquely defined, the mode shapes are also uniquely defined [4].

FE model

An FE model from ANSYS was used during the course to estimate the mode shapes and natural frequencies of the scaled jacket [2]. As previously mentioned, the FE model was used to predict the global modes and determine the accelerometer placement. After executing the control case of the 'undamaged' structure, the FE model was modified to align more accurately with the experiment.

Table 1: Elastic properties for steel elements in altered FE model in ANSYS.

Young's modulus braces	Young's modulus legs	Young's modulus TP	Poisson's ration
195 GPa	215 GPa	205 GPa	0.29

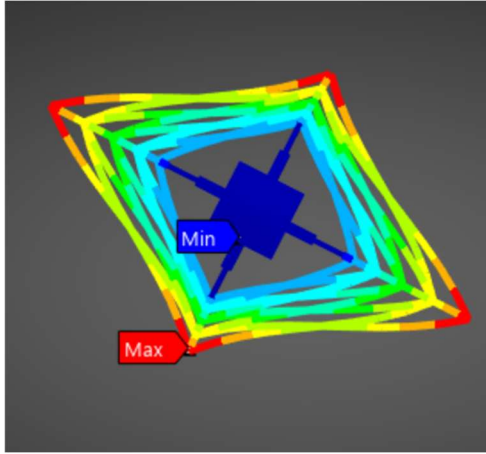


Figure 2: First breathing mode, mode 7 for 'undamaged' structure.

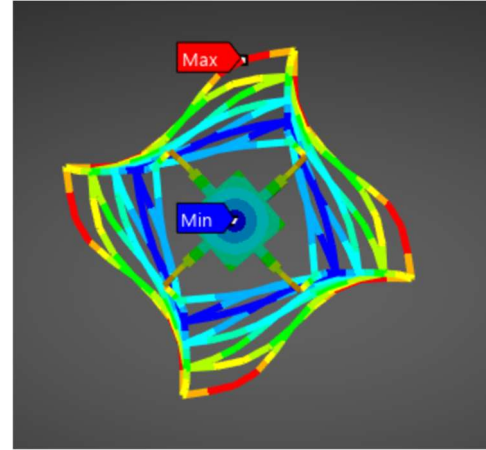


Figure 3: First torsional mode, mode 16 for 'undamaged' structure.

Structure of the FE model

The jacket structure, including the piles and the elements that connect the transition piece, is built using quadratic beam elements. No meshing is used for the piles and elements connecting the transition piece, while the jacket structure is meshed with three subdivisions per element. The transition piece is made of nine plate elements with a mesh resolution set to 2, a moderately fine mesh. The same cross sections used to build the scaled structure are used in the FE model.

Alteration to the FE model

As mentioned, the boundary conditions and the steel plate in the FE model have been removed to represent the free structure. In the scaled model, a 100x100x10 mm plate is placed on each pile as a footing for the jacket to stand on. These plates were not included in the original ANSYS model. Therefore, to better simulate the scaled structure, a 0.787 kg point mass was added to the bottom of the piles.

After performing the control case of the 'undamaged' structure, we set the Young's modulus of elasticity to 195 GPa for the braces and 215 GPa for the leg elements. This change best approximated the natural frequency of the torsional mode and required the least drastic alteration to the elements' properties. The elastic properties i.e. Young's modulus and Poisson's ratio, as given in Table 1, determine the shear modulus in ANSYS.

Results

The EMA results will focus on the first two global modes, breathing and torsional, as shown in Figure 2 and Figure 3. Table 2 shows the change in natural frequencies from the original to the altered FE model for both global modes and local brace modes. Note that since there are no boundary conditions, the first 6 modes will be rigid body modes.

For each experiment, the modal parameters are estimated in two frequency bands using the pLSCF method: 10-140 Hz and 130-260 Hz. The model order is fixed at 50.

Table 2: Influence of alterations to the FE model on natural frequencies to the ‘undamaged’ scaled jacket.

	1 st breathing	1 st braces	2 nd braces	3 rd braces	1 st torsional
Original FEM	54.84 Hz (mode 7)	76.28 Hz (mode 8)	108.2 Hz (mode 9)	116.5 Hz (mode 11)	189.7 Hz (mode 17)
Altered FEM	43.63 Hz (mode 7)	74.36 Hz (mode 8)	103.9 Hz (mode 9)	113.6 Hz (mode 11)	174.00 Hz (mode 16)

Table 3: Damping ratios for each element for the ‘undamaged’ structure in experiment 1 and ‘damaged’ structure in experiment 2-9 as determined for the first breathing mode and first torsional mode.

Experiment nr.	Added mass / per pile (kg)	Damping ratio (%) – First Breathing mode	Damping ratio (%) – First Torsional mode
1	0.00	0.0918	0.126
2	0.21	0.176	0.0896
3	0.42	0.118	0.0777
4	0.63	0.134	0.118
5	0.84	0.0822	0.0705
6	1.05	0.128	0.0821
7	1.26	0.0174	0.0852
8	1.47	0.189	0.103
9	1.68	0.466	0.0854

The experimentally determined damping ratios are processed after analysis according to [2] as described by Equation (3.1) - (3.2). The corrected damping ratios are determined and shown in Table 3. As evident by the values of Table 3, the determined damping ratios are inconsistent and show no clear trend. Generally, the damping ratios are low with a damping with less than 0.2%. There is however one outlier in experiment 9 for breathing, where the damping ratio is determined to be 0.466%.

The numerical modes are reduced to only include the nodes corresponding to the accelerometers in the experimental setup. The numerical and experimental modes are then compared using the Model Assurance Criterion (MAC). Each MAC matrix was illustrated, as shown by Figure 4 for Experiment 1 for the ‘undamaged’ structure. The natural frequency for both the numerical and experimental dataset as well as the MAC value is collected in Table 4 and Table 5 for the breathing and torsional mode, respectively.

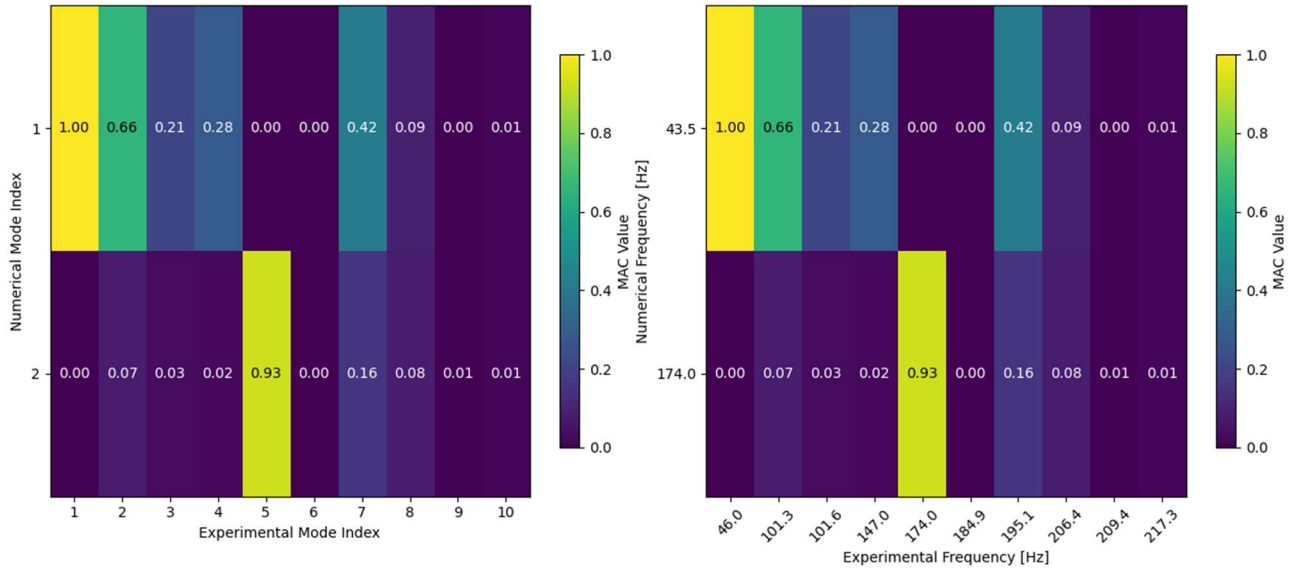


Figure 4: MAC matrix for experiment 1, the ‘undamaged’ structure with no additional mass added to the base of the piles.
Given by both the mode index and determined natural frequencies.

Table 4: Numerical and experimental results for natural frequencies of the first breathing mode, and the corresponding MAC value for mode shapes.

Exp. nr	Numerical Breathing (Hz) / mode nr.	Experimental Breathing (Hz) / mode nr.	MAC value
1	43.46 / mode 7	46.01 / mode 1	1.00
2	41.46 / mode 7	43.54 / mode 1	1.00
3	39.71 / mode 7	41.44 / mode 1	1.00
4	38.15 / mode 7	39.68 / mode 1	1.00
5	36.77 / mode 7	38.08 / mode 1	1.00
6	35.53 / mode 7	36.63 / mode 1	1.00
7	34.39 / mode 7	35.34 / mode 1	1.00
8	33.37 / mode 7	34.20 / mode 1	1.00
9	32.42 / mode 7	33.19 / mode 1	1.00

Table 5: Numerical and experimental results for natural frequencies of the first torsional mode, and the corresponding MAC value for mode shapes.

Experiment nr.	Numerical Torsional (Hz) / mode nr.	Experimental Torsional (Hz)	MAC Value
1	174.00 / mode 16	174.01 / mode 5	0.93
2	171.19 / mode 16	169.15 / mode 8	0.79
3	168.65 / mode 16	165.20 / mode 9	0.70
4	166.38 / mode 16	160.61 / mode 9	0.88
5	164.33 / mode 16	157.33 / mode 10	0.82
6	162.48 / mode 20	151.93 / mode 9	0.86
7	160.88 / mode 20	145.92 / mode 8	0.93
8	159.29 / mode 20	144.40 / mode 8	0.91
9	157.91 / mode 20	142.60 / mode 8	0.94

As apparent by Table 4, the MAC value for the breathing mode shows very strong similarity for the six nodes as measured in the experiment. The MAC value for the torsional mode, as shown in Table 5, displays varying similarity ranging from 0.70-0.93.

The results for the natural frequencies are plotted against the mass added to the piles in Figure 5-8. Additionally, the change in natural frequencies compared to the base case of the ‘undamaged’ structure is plotted against the mass. For each of the plots, curve fitting using an exponential model with offset is used. The uncertainty of the fitted curve is determined using the first-order delta method, and the 95% confidence interval is calculated based on the t-distribution.

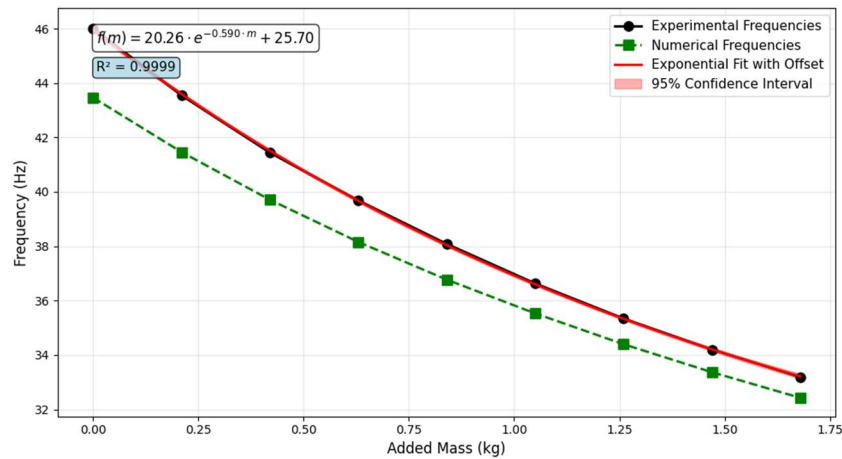


Figure 5: Natural frequency against increase of mass for the first breathing mode, for experiment 1-9 with exponential fit with offset and a 95% confidence interval.

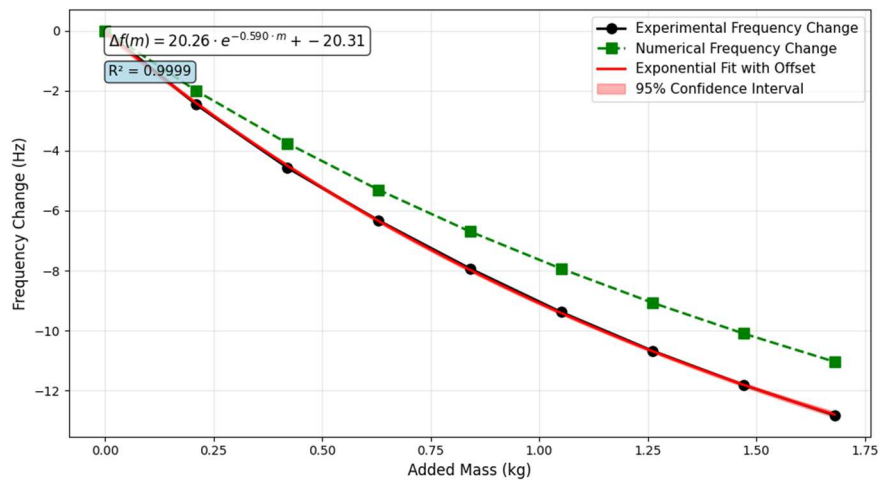


Figure 6: Change in natural frequency from the first determined value against increase of mass for the first breathing mode, for experiment 1-9 with exponential fit with offset and a 95% confidence interval.

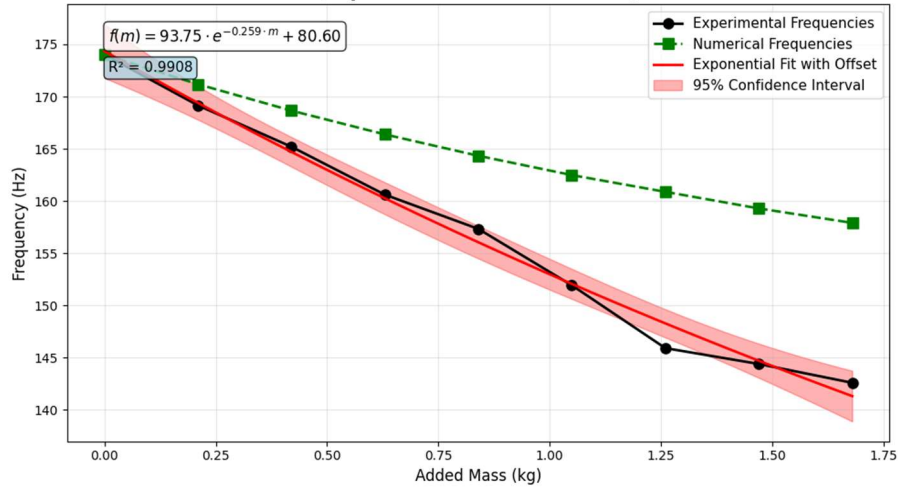


Figure 7: Natural frequency against increase of mass for the first torsional mode, for experiment 1-9 with exponential fit with offset and a 95% confidence interval.

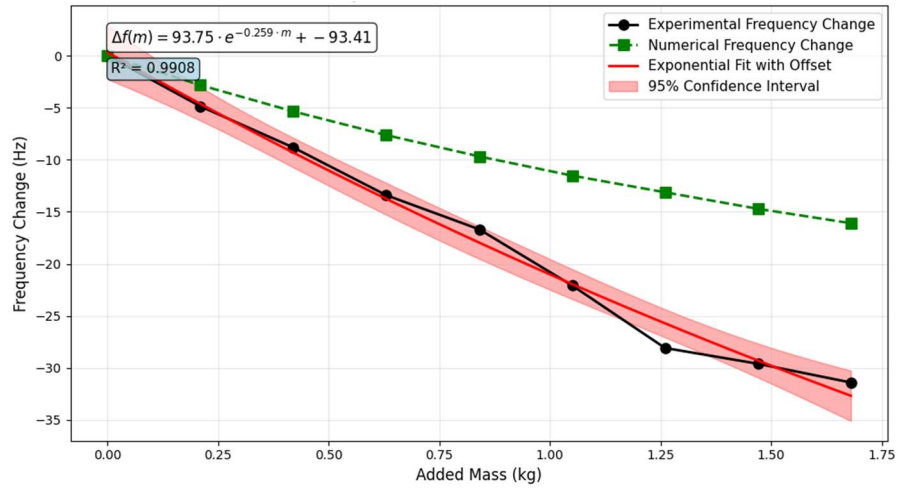


Figure 8: Change in natural frequency from the first determined value against increase of mass for the first torsional mode, for experiment 1-9 with exponential fit with offset and a 95% confidence interval.

Discussion/Conclusion

The determination of modal parameters for the first two global modes was achieved using both experimental modal analysis and numerical simulations, focusing on the relation between natural frequencies and mass increments for the ‘damaged structure’. For both observed global modes, the relationship between natural frequency and increasing mass is well described by an exponential curve fit with offset.

First breathing mode

Notably, the first breathing mode exhibits strong correlation between the data and the fitted curve, with R^2 close to 1.0 and no significant outliers. Additionally, the experimental data show a similar trend to the one observed in the FE model from ANSYS. The Modal Assurance Criterion (MAC) values support this correlation, showing high agreement between the experimentally determined

mode shapes and those predicted by ANSYS. In the FE model, the first breathing mode consistently appears as mode 7, which is the first non-rigid body mode. This is consistent with the experimental results, where the first breathing mode is also consistently identified as the first mode in the first frequency band considered (10-140 Hz).

First torsional mode

The first torsional mode also follows an exponential curve fit with off-set, though with less consistency in comparison to the breathing mode. However, it still shows great correspondence and only has one data point for Experiment 7, which is outside the 95% confidence interval. Significant differences are evident when comparing the numerical results of ANSYS and the experimental data. The natural frequencies decrease at a higher rate than the numerical, and there are significant differences for the mode shape with the MAC value ranging from 0.70-0.93.

In ANSYS the first torsional mode is identified at mode 16 for experiments 1-5 but shifts to mode 20 for experiments 6-9. For the determined experiments, the mode number ranges from 5 to 11 but does not generally increase with an increase in mass. This could be due to some symmetric brace modes exhibiting as one or two signals, or modes appearing in only some experiments.

Damping ratios

The damping ratios for the first breathing and torsional modes are inconsistent and show no clear correlation. For the first breathing mode, the damping ratios range from 0.0174%-0.466%, with 0.466% being a significant outliers determined in Experiment 9. For the torsional mode, the damping ratio ranges from 0.0705%-0.126%. These inconsistencies could be due to the damping ratios being small and largely influence by uncertainties associated with experimental testing.

Experimental challenges

Throughout the experiment, the signals showed inconsistencies when the hammer's impact was too large, resulting in disproportionately large individual response signals compared to the others. These inconsistencies became increasingly difficult to avoid as the added mass increased. These inconsistencies in the response signals could also explain the outliers observed in breathing mode for the damping ratio and natural frequencies for the torsional mode.

Conclusion

The experiments successfully employed Experimental Modal Analysis to determine key modal parameters, including natural frequencies, damping ratios, and mode shapes. By systematically adding mass to the base of the piles, empirical relationships were established using exponential curve fits with offsets, revealing strong correlations and minimal outliers.

The first breathing mode exhibited the highest consistency with the fitted function and showed the strongest agreement with numerically simulated results. Both the variation in natural frequencies and the corresponding mode shapes demonstrated high similarity, as confirmed by the Modal Assurance Criterion (MAC), indicating reliable mode shape matching across configurations

Despite one outlier from the established exponential fit, the first torsional mode still exhibited a strong overall correlation between added mass and natural frequency. However, compared to the breathing mode, the torsional mode showed greater inconsistencies when compared to the FE model. The change in natural frequency showed reduced similarity, as did the mode shapes, which was reflected in lower MAC values.

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