Block Island Structural Monitoring Program

FINAL REPORT

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Abstract

This is the final report for BSEE Contract No. 140E0119C0003: *Block Island Structural Monitoring Project*. The objectives of this project were to: 1.) Design and install a continuous monitoring system to obtain a benchmark set of structural performance data that adequately represents the Block Island Wind Farm turbines, support structures and foundations; 2.) Develop an automated processing methodology for the data produced by this monitoring system; and 3.) Archive and report observed structural performance over a period of approximately 12 months in a manner that can serve as the basis for validating design assumptions relevant to regulatory plan review and oversight functions. These objectives were accomplished by instrumenting Tower B2 of the Block Island Wind Farm with accelerometers at four different heights and an inclinometer and strain gauges at the base of the tower. Measurements were made using a data acquisition system at a frequency of 50 Hz over a 12-month period in 2022-2023 and the system continues to collect data.

Specific tasks for this project included the following:

- Development of a finite element model for use as a digital twin;
- Determination of resonant frequencies and damping of the overall structure;
- An evaluation of the stress-strain time histories over a 12-month period at the base of the tower;
- Measurement of tilt of the structure over a 12-month period;
- An assessment of cyclic loading on the pile foundation; and
- An assessment of structural fatigue from the strain gauge measurements.

Specific technical results from the study can be found in the attached reports that served as deliverables for the project. In general, the results of this project will help to inform design through the monitoring of a relatively unique support structure in geological and environmental conditions that are different than those found in offshore wind farms in Europe. Monitoring the structures' response provides invaluable information regarding the fatigue of the support structure, which directly impacts decisions regarding service life extension. Finally, this study demonstrates that an active monitoring program coupled with modeling from a digital twin can be used for fault and damage detection throughout the service life of the wind farm.

Keywords

Offshore Wind Turbine (OWT), Optimal Sensor Placement (OSP), Bayesian Assimilation Framework (BAF), Structural Health Monitoring (SHM), Finite Element Analysis (FEA), Block Island Wind Farm (BIWF), Jacket-Supported Structure

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1 Project Objectives and Structural Monitoring Plan

1.1 Project Objectives

The primary objective of the *Block Island Structural Monitoring Project* (BSEE contract number 140E0119C0003) was to design and install a continuous monitoring system to obtain a benchmark set of structural performance data that adequately represents the Block Island Wind Farm turbines, support structures and foundations. Other objectives were to develop an automated processing methodology for the data produced by this monitoring system and archive and report the observed structural performance over a period of approximately 12 months in a manner that can serve as the basis for validating design assumptions relevant to regulatory plan review and oversight functions.

The Block Island Wind Farm (**Figure 1**) is distinguished by its status as the first U.S. offshore wind farm, its jacket support structure and foundation design adapted from the oil and gas industry, and its presence in Rhode Island State waters. Through the *Block Island Structural Monitoring Project*, the Bureau of Safety and Environmental Enforcement (BSEE), the Bureau of Ocean Energy Management (BOEM) and the Rhode Island Coastal Resources Management Council (CRMC) have established both a benchmark data set describing offshore wind structural performance in U.S. waters and norms that guide the planning and execution of future monitoring projects in the U.S.

Figure 1. Location and images of the Block Island Wind Farm (BIWF; photo credit: Eric Thayer/Bloomberg). Structural monitoring was performed on Tower B2.

1.2 Details of Structural Monitoring System

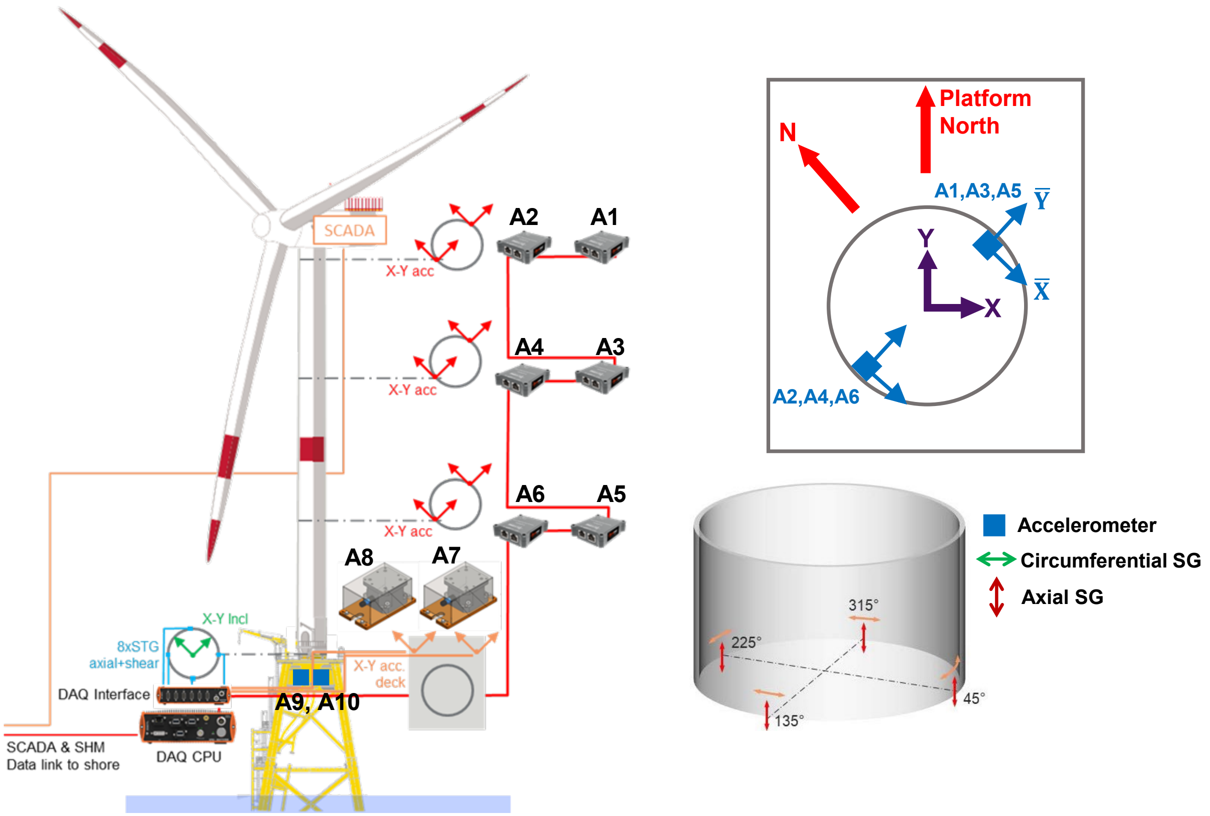
The continuous monitoring system was designed by the Norwegian Geotechnical Institute (NGI Inc.) as a post-construction system that can be installed to monitor long-term structural performance (i.e., several years). The system includes wired accelerometers, strain gauges, an inclinometer, and a self-contained data acquisition system. This section details the sensor layout, choice of sensors, details of the data acquisition system, and strategy for remote access of the system for data transfer and troubleshooting.

1.2.1 Sensor Layout and Locations

The sensor locations were designed based on the following considerations:

- Sensors must be installed without the need for a rope-team or divers, so suitable locations only include the deck platform and the tower;
- Sensor locations should be at existing platform levels. The existing platforms along the tower provides accessibility to both sides of the tower;
- Wired sensors should be close to exiting cable trays;
- Sensors should be able to measure the fore-aft, side-side, and torsional motions of the structure; and
- Strain measurements are required in addition to the acceleration data to be able to estimate stresses and the fatigue life of the structure.

The resulting continuous monitoring system consisted of 9 wired accelerometers, 8 strain gauges (SG), and 1 inclinometer. The accelerometers, inclinometer, and the data acquisition system (DAQ) were installed in April 2021, with final approval on April 18, 2021. The SGs were installed on October 24, 2021. The instrumentation plan of wired accelerometers and data acquisition system are shown in **Figure 2**.



(a) (b)

Figure 2. Elevation (a) and top view (b) of instrumentation plan.

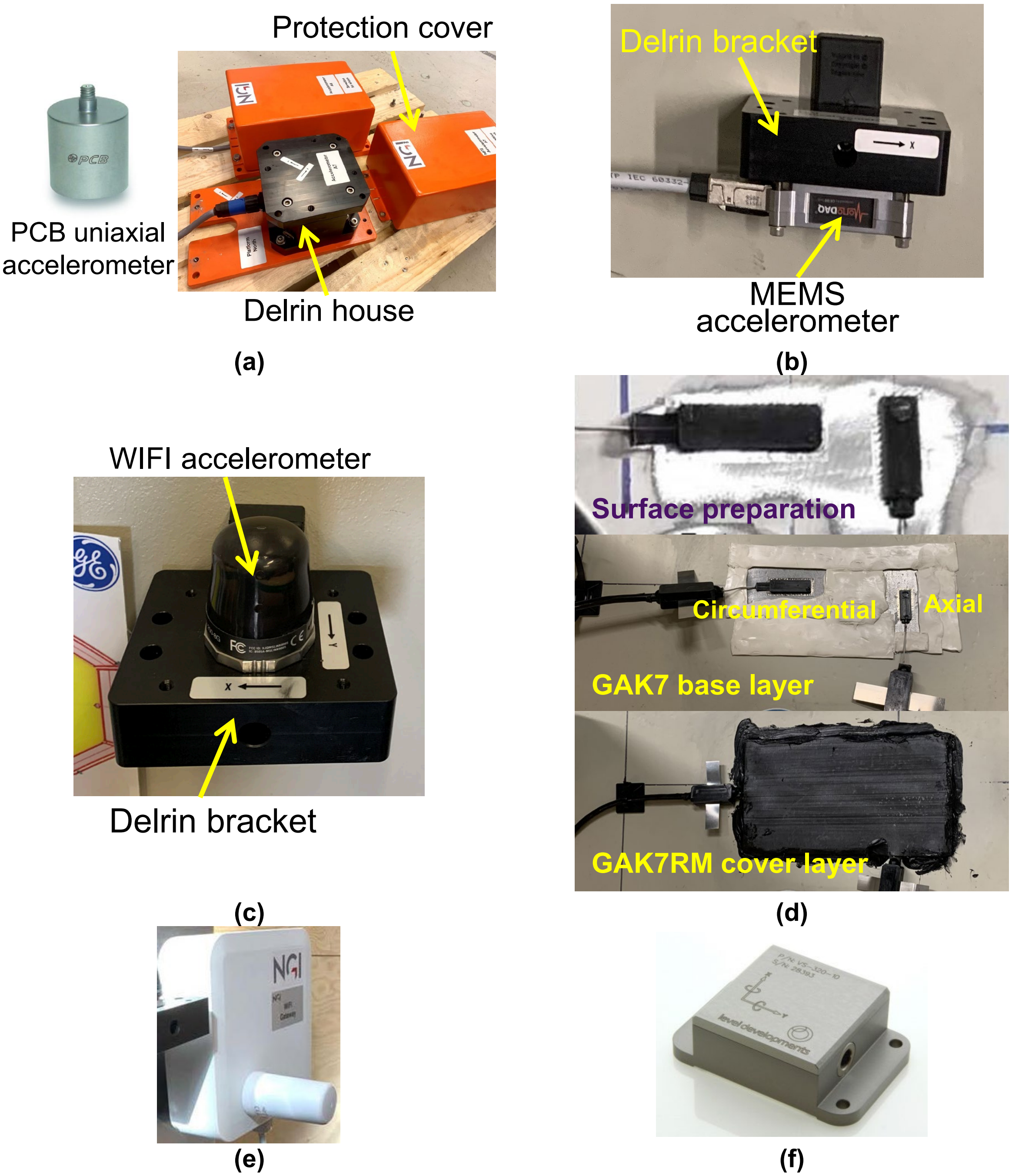
The wired accelerometers are named as ‘A1’ to ‘A10’. A7, A8 and A9 are retrofitted biaxial accelerometers, and the others are MEMS triaxial ones. A1 – A6 accelerometers were placed along the height of the tower at three different levels: A1 and A2 were mounted on the opposite inner surface of the tower at 76.9 m above the deck platform; similarly, A3 and A4 are located at 52.4 m, and A5 and A6 are located at 27.9 m. This layout was intended to measure the torsional motion of the turbine structure. A7 was mounted on the northeast corner of the platform (relative to platform north). A8 was not mounted due to cabling constraints encountered on site. A9 and A10 were placed inside the DAQ cabinet for comparative testing, which can also be used as spares to external sensors.

The measurement directions of the accelerometers ($\overline{X}$ and $\overline{Y}$) are rotated 45 degrees clockwise from the structural coordinate system (X and Y with respect to platform north). The 4 axial SGs and 4 circumferential SGs were paired one to one and mounted at 4 symmetric points 0.7 m above the deck platform on the inner surface of the tower, as shown in Figure 2(b). The 9 wired accelerometers and the inclinometer are working properly and providing high-quality measurements continuously since April 18, 2021, with additional strain data collected since October 24, 2021. The monitoring system has a sampling frequency of 50 Hz. The data are stored in a series of data sets with a period of 10 minutes.

1.2.2 Choice of Sensors

Located at the top of the tower and approximately the tower third points, accelerometers A1-A6 were procured as triaxial MonoDAQ-E-gMeter fully integrated low-noise 3D MEMS accelerometers with EtherCAT interface. The small and lightweight MEMS accelerometers were mounted underneath a Delrin bracket with magnet fixture for easy non-destructive attachment to the vertical steel walls inside the tower (**Figure 3(b)**). Four wireless triaxial accelerometers (Lord MicroStrain IP67; **Figure 3(c)**) with a gateway transceiver (**Figure 3(e)**) were also mounted inside the tower wall by a magnetic footing to evaluate the feasibility of using a wireless system. At the base of the tower and on the platform, very low accelerations were expected and therefore higher sensitivity accelerometers were deployed at A7-A10, consisting of 2 PCB 393B04 ICP accelerometers in perpendicular directions and mounted inside a waterproof Delrin enclosure to work as a biaxial accelerometer (shown in **Figure 3(a)**). Two of these biaxial accelerometers (A7, A8) were custom built for measurement on the deck. The biaxial accelerometer enclosure was mounted on the deck by means of a doubler plate and protected against impact by a painted steel cover (**Figure 3(a)**).

The SGs are full bridge and temperature compensated spot weldable axial (HBWF-35-125-6-99UP-SS) and circumferential SGs (HBWS-35-125-6-99UP-SS-FB) provided by HPI, as shown in **Figure 3(d)**. The 4 axial SGs and 4 circumferential SGs are paired one to one and mounted together on the inner surface of the tower. To mount the SG, grinding and polishing were required to remove the steel coating, and then the surface was cleaned with solvent. Then an axial SG was attached to the surface vertically, and the circumferential SG was placed horizontally (**Figure 3(d)**). After the completion of SG installation, GAK7 base layer was applied around the SG and cover the grinded surface. Finally, GAK7RM cover layer was used to cover the base layer, and GAK1100 was injected under the rubber flap around the edge of cover plate. These processes are shown in **Figure 3(d)**. The inclinometer is a temperature compensated biaxial MEMS inclinometer, which was mounted inside the DAQ cabinet, as shown in **Figure 3(f)**.



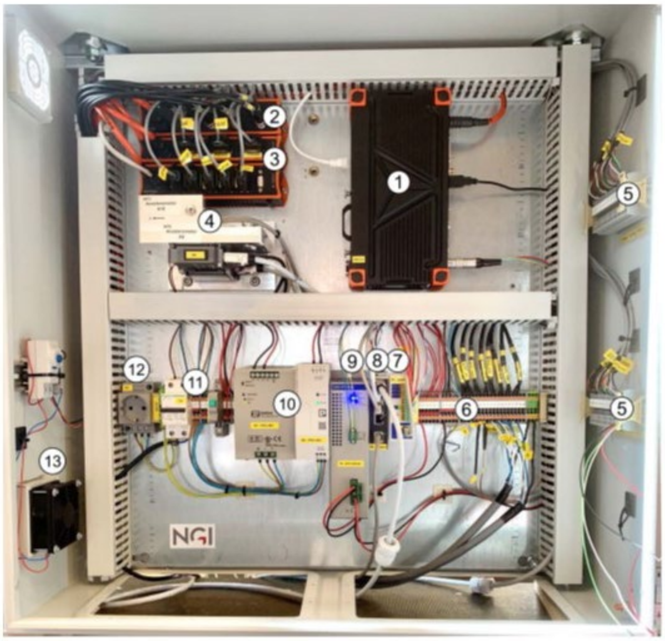
(a) (b) (c) (d) (e) (f)

Figure 3. (a) Retrofitted biaxial accelerometer using two PCB uniaxial accelerometers; (b) MEMS triaxial accelerometer mounted on Delrin bracket with magnet fixture; (c) Wireless accelerometer mounted on Delrin bracket; (d) Installation process of SGs; (e) Gateway transceiver for wireless accelerometers; (f) Biaxial inclinometer.

1.2.3 Data Acquisition System, Data Transfer, and Storage

The data acquisition system (DAQ) was located inside the transition piece. A fiber optic link was used to connect the DAQ to the substation in Block Island. The recorded and filtered data was streamed over this fiber optic link without any need of data reduction. The CPU in the DAQ was operated remotely using the software TeamViewer™ via the fiber optic link and internet access. The main frequency band of interest for dynamic measurements at Block Island is 0.1 to 10 Hz. To avoid aliasing effects, data was sampled at 50 Hz and low pass filtered by the DAQ CPU with a 10 Hz 6th order Butterworth filter. To achieve the required data synchronization for modal shape analyses, EtherCAT LAN based streaming was used and provided millisecond synchronization between the sensor channels. The EtherCAT streaming accelerometers (A1 - A6) and other type of sensors (retrofitted biaxial accelerometers, inclinometer and 8 SGs) were hooked up directly or via interface modules to the EtherCAT line for synchronized logging by the DAQ CPU. Each sensor or data acquisition unit can be distributed along the EtherCAT LAN, and the wired accelerometers are powered over Ethernet. The system architecture allows for flexible configuration and connectivity. Each sensor and interface unit are automatically recognized and configured by the small and ruggedized (IP67) DAQ CPU. The CPU sampling can be synchronized to external systems by GPS time and operated remotely via the fiber optic link and internet access.

The main components of the DAQ are shown in **Figure 4**. DEWESoft-X3 software was installed on the DAQ CPU for system configuration, real-time analysis/checks and data export/storage. The data was stored in proprietary binary file format (.d7d) that can be exported to other formats. The raw measurements were preprocessed by removing spikes, filtering noise and down-sampling to improve system identification accuracy, but these processes only happen in Matlab for system identification, and the original measurements remain untouched. A Box cloud storage was allocated enough space to save the huge amount of raw data. Every 10 minutes of data from all sensors is saved into a binary data file which is approximately 5.6MB. This means that all the data from one year of monitoring is less than 300GB.



1. SBOXe CPU
2. Krypton accelerometer module 3xSG interface module
3. Krypton 3xSG and 6xSG interface modules (one spare channel)
4. Bracket with PoE injector, biaxial inclinometer, 2xICP and one MEMs accelerometer
5. Terminals for hook-up of strain gauges
6. Terminal for hook-up of deck accelerometers and internal sensors
7. Web relay
8. Network switch
9. UPS (1500 mAh)
10. 24 and 48 Vdc power supplies
11. Terminal ond fuses 110 Vac mains and 48 Vdc
12. Socket (EU) for mains power
13. Fan with thermostat

Figure 4. DAQ box.

2 Project Team and Personnel

The Block Island Structural Monitoring Project Team was led by Dr. David Ciochetto of the Rhode Island Coastal Resources Management Council (CRMC). The technical leads of the project were Dr. Christopher D.P. Baxter of the University of Rhode Island (URI) and Dr. Eric Hines of Tufts University. Co-investigators included Drs. Aaron Bradshaw and James Hu from URI, Dr. Babak Moaveni from Tufts University and Per Sparrevik from the Norwegian Geotechnical Institute. **Table 1** lists key institutions and project personnel who collaborated to develop the work and author project reports.

Table 1. Project Personnel

Institution	Last Name	First Name	Title
RI Coastal Resources Management Council (CRMC)	Ciochetto	David	Principal Ocean Engineer
University of Rhode Island (URI)	Baxter	Christopher	Professor
	Bradshaw	Aaron	Professor
	Hu	Saulon (James)	Professor
	Story	Maeve	Graduate Research Assistant
	Scarborough	Isaac	Undergraduate Research Assistant
Tufts University	Hines	Eric	Professor of the Practice
	Moaveni	Babak	Professor
	Song	Mingming	Research Assistant Professor
	Mehrjoo	Azim	Graduate Research Assistant
	Partovi-Mehr	Nasim	Graduate Research Assistant
	Moynihan	Bridget	Graduate Research Assistant
Norwegian Geotechnical Institute (NGI)	Sparrevik	Per	Technical Expert and Discipline Manager Subsea Technology
	Meland	Henrik	Project Engineer

3 Project Tasks

The project began in September 2019 and ran through July 2023. The schedule of the project was extended twice due the COVID-19 pandemic and scheduling delays in sensor installation. **Table 2** summarizes the project Tasks and Subtasks, which are taken from the Milestone Summary Table of the proposals' Technical Volume.

Table 2. Project Tasks

Task/Subtask/ Deliverable No.	Description
Task 0	**Preparatory Works**
0.1	Post-award conference
0.2	Stakeholder meeting with Ørsted
0.3	Acquire BIWF design drawings
0.4	Preliminary measurements of dynamic response
0.5	Development of initial finite element model
0.6	Finalize number and types of sensors and installation plan
0.7	Develop optimal sensor placement methodology
Task 1	**Measure accelerations at different turbine locations to determine resonant frequencies and damping**
1.1	Deployment of accelerometers, strain gauges, a tilt meter, and a data acquisition system
1.2	Development and implementation of automatic data cleansing and modal identification system
Task 2	**Determination of stresses and bending moments at various locations on the structure, including at the tower and jacket connection**
2.1	Formulate a joint input-parameter estimation framework for determination of stresses
2.2	Finalize structural model for use during the 12-month data collection regime
2.3	Develop soil springs for the updated finite element model
Task 3	**Measurement of possible tilt of the jacket structures due to accumulated displacement of the foundation soils**
3.1	Initial evaluation of tilt meter functionality
Task 4	**Assessment of actual fatigue performance of the overall structure through analysis of cyclic stresses and strain in the structure versus design assumptions**
4.1	Evaluation of structural fatigue
4.2	Evaluation of cyclic axial loads on pile foundations (soil fatigue)

4 Project Milestone Reports

Project Deliverables for the Block Island Structural Monitoring Project include 10 technical reports, totaling 300 pages, and submitted according to the Milestones/Deliverable shown in **Table 3.** In addition to these deliverables, there are several publications from this work that are in review by Ørsted or in preparation and are included in the bibliography. Numerical designations for deliverables in **Table 3** follow project Tasks, Subtasks and Milestones described in the Milestone Summary Table from the proposal for the project.

Table 3. Project Deliverables

Milestone/ Deliverable	Title	Lead Author
D0.5	Initial Finite Element Model and Preliminary Planning Report for the Block Island Structural Monitoring Joint Project	Song
D0.7	Optimal Sensor Placement Study for Offshore Wind Turbine Applications	Mehrjoo
D1.1	Structural Instrumentation and Monitoring of the Block Island Offshore Wind Farm	Hines
D1.2	Development and Implementation of Automatic Modal Identification	Song
D2.1	Formulation and Implementation of a Bayesian Inference Framework for Estimation of Inputs and Strain/Stress Time Histories Using Final Finite Element Model	Song
D2.2	Evaluation of Foundation Stiffness of Tower B2 Block Island Wind Farm	Bradshaw
D2.4	Report Stress Time History for 12-Month Period Accounting for Soil Springs and Compare Expected Versus Measured Response	Partovi-Mehr
D3.1	Evaluation of Platform Tilt of Tower B2 Block Island Wind Farm	Bradshaw
D4.1	Structural Fatigue Evaluation of Turbine B2 Block Island Wind Farm	Partovi-Mehr
D4.2	Evaluation of Cyclic Pile Behavior of Tower B2 Block Island Wind Farm	Bradshaw

5 Significant Conclusions

The overall objective of the Block Island Structural Monitoring Program was to bring together industry, academia, government, and other stakeholders to advance offshore wind technologies in the United States. It is hoped that the data obtained and lessons learned from this work will reduce uncertainties, establish a benchmark for this type of structure in the offshore Atlantic, and enhance BSEE's efficiency and effectiveness overseeing offshore wind energy projects. Ultimately, the results of this study will provide both researchers and educators a unique data set to help foster growth and innovation in the United States offshore wind industry.

In addition to these broad conclusions, there were several specific findings from this work. These include the following:

- Modal parameters of the structure (i.e. first natural frequency and damping) vary considerably with operational conditions (e.g. parked vs. operating, wind speed, etc.) and direction (fore-aft vs. side-to-side). [Deliverable D1.2]
- Vertical foundation stiffness did not significantly affect the first natural frequency of the offshore wind tower. This is understandable in this case study as the foundation sediments at Block Island are very dense. [Deliverable D2.2]
- Foundation damping was estimated for several storm events using a combination of measured loads and modeling. During operation, foundation damping contributes little to overall damping in the fore-aft direction (as it is dominated by aerodynamic damping), but it does contribute to damping in the side-to-side direction and during idling.
- Inclinometer data suggests that platform B2 tilted toward the east approximately 0.25 degrees from May 2021 to September 2022. More work is needed to understand if these measurements accurately reflect behavior of the tower and, if so, what are the underlying mechanisms responsible for this movement. [Deliverable D3.1]
- Operational conditions (e.g. start-up/shut-down, changes in blade pitch, peak power production) contributed more to structural fatigue than observed storms during the study period. [Deliverable D4.1]

Finally, the results of this study suggest that service life extension of offshore wind support structures is possible through relatively inexpensive measurement campaigns.

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