Development and preliminary testing of a new robotic tool for direct determination of 'p-y' soil reaction curves for offshore geotechnical applications

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ABSTRACT

Monopiles are the most widespread foundation option for offshore wind turbine foundations and their design is largely governed by lateral stability and serviceability. The determination of lateral soil reaction 'p-y' curves is a crucial element for their design. At present, 'p-y' curves are typically determined through indirect methods, such as correlation from fundamental constitutive parameters, CPT data or extracted through numerical procedures. This paper presents the specification requirements, initial mechanical design, sensor calibration and preliminary testing in a small calibration chamber of a new robotic site investigation tool, the ROBOCONE 'p-y' module. This new device can be fitted behind a standard CPT cone. It features a cylindrical module that, after insertion in the ground, can move sideways to closely mimic the kinematic mechanism experienced by a laterally loaded pile element and provide direct "in-situ" characterisation of the 'p-y' soil reaction curves. The imposed horizontal translation is substantially different from those of the typical pressuremeter and dilatometer, and analogous to that of a small laterally loaded pile. Movements of the module can be programmed to apply simple monotonic lateral loading conditions and complex stress-controlled or deformation-controlled histories (i.e. cyclic loading, consolidation stages, maintained load). These provide data that can be scaled directly to support advanced cyclic and whole-life design procedures for the lateral 'p-y' response of piles.

Keywords: ROBOCONE; Site; Investigation; Offshore.

1. Introduction

Offshore wind turbines are pivotal in the pursuit of future net zero carbon emissions targets. These structures harness the power of wind over open waters, providing a consistent and abundant source of renewable energy. The offshore environment offers higher and more reliable wind speeds, enhancing the efficiency of electricity generation. According to the policies proposed by the International Energy Agency (Li et al. 2022), offshore wind energy capacity will become the world's leading source of electricity, growing 25-fold between 2020 and 2040, reaching 560 GW by 2040. This growth implies the installation of offshore wind power capacity at a faster pace over the next few years.

Technological advancements in offshore wind turbine design, including those related to optimising the design and construction of its foundation, can greatly contribute to increased capacity and cost-effectiveness, as well as a more rapid development timeline. Enhancing and accelerating in-situ geotechnical investigation testing practices, to decrease the reliance on laboratory testing on collected soil samples, can lead to important time and cost savings for the project development. Real-time data from in-situ testing provides immediate insights into the geotechnical conditions at the construction site, allowing for prompt adjustments to foundation designs and ensuring the efficient and reliable deployment of offshore wind turbines (Bhattacharya 2019). For the purpose of geotechnical investigation and design, a wide range of devices have been deployed to directly test ground conditions in situ and determine soil characteristics.

Offshore foundations are often exposed to discontinuous cycles of loading, remoulding and reconsolidation during installation and long-term service. Cyclic loading and reconsolidation operations result in alterations in foundation capacity (Lai et al. 2020; Zhou et al. 2020). Evaluating these alterations requires characterisation data for the variations in the stiffness and strength of the surrounding soil as a result of the imposed loading and deformation.

These time-dependent effects have become understood through tests carried out on soil elements and models in the laboratory, analysing realistic stress histories. Cyclic triaxial tests are commonly employed to determine key soil response parameters under cyclic loading (Andersen et al., 1988; Andersen, 2015). However, the axisymmetric nature of cyclic axial loading and controlled confinement pressure in these tests may not fully align with the generalized stress conditions observed in-situ. The hollow cylinder apparatus provides an improvement in cyclic triaxial testing (Mandolini et al. 2021; Cheng et al. 2023), allowing precise control over the magnitudes and orientations of principal stresses, as well as replicating the stress history of soil elements within foundations under in-service loading conditions at specific locations. Sampling soil for hollow cylinder testing presents difficulties due to their large size, and is difficult for low strength soils leading to deformation and damage. Additionally, even brief periods of unsupported conditions can result in significant deformation. In-situ tests provide an alternative to characterize soils for offshore wind turbines foundations. Zhou et al. (2020) used the penetrometer to conduct cyclic loading with reconsolidation periods, and Hodder et al. (2010) studied soil strength degradation and recovery through the episodic T-bar cyclic testing.

However, recent advancement in robotic technologies have benefitted the offshore industry through, for example, remote operated vehicles and advanced sensing. Integrating robotics for ground exploration enables precise data collection by applying realistic loading condition to the ground, minimising human intervention, and promoting more streamlined and economical offshore operations (Zhao et al. 2022). This paper outlines some early advancement of the ROBOCONE project, aiming at introducing a novel device designed for intelligent in-situ ground testing, harnessing robotics. The project is targeting the development of a new in-situ device capable of applying realistic stress histories to simulate infrastructure loading over the entire lifespan. In this particular paper, the focus is directed towards the early development of a module dedicated to the determination of ‘p-y’ soil reaction curves.

2. The ROBOCONE project

2.1. Overview

The ROBOCONE is an innovative robotic tool specifically designed for intelligent and controlled soil probing in multiple active sensing directions, including vertical, horizontal, and torsional movements, as shown in Figure 1a (Creasey et al. 2023). Its primary objective is to assess the mechanical characteristics of the soil across the entire range of strains relevant to engineering design while accommodating complex load histories. Among other applications, the movements generated by this device in multiple directions can mimic the stress and strain conditions applied below the seabed by offshore wind turbine foundations (Figure 1b and c). The focus of this paper is towards the ROBOCONE 'p-y' module, which aims to facilitate direct extraction of the p-y soil response curve, both monotonic or over complex loading and deformation paths supporting whole-life design practices (Gourvenec 2022). In addition, the ROBOCONE module aims to identify fundamental mechanical soil properties.

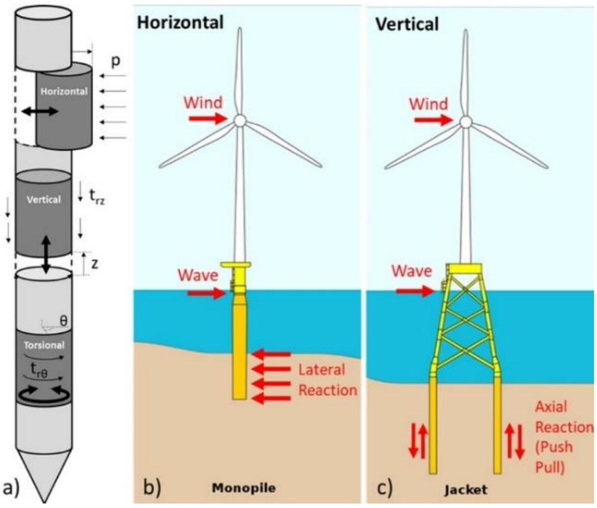

Figure 1. a) The ROBOCONE device. Schematic drawings of b) horizontal; c) vertical forces applied on offshore wind turbine foundations.

2.2. The p-y module

The ROBOCONE p-y module is conceived as an additional feature to a classic cone penetrometer, designed to be cylindrical and able to move horizontally, as illustrated in Figure 2a. This in-situ module is designed to simulate the load and displacement history imposed by a laterally-loaded pile element (Bateman et al. 2023). The ROBOCONE p-y module is different from other devices that probe the soil horizontally, such as the pressuremeter and the dilatometer, in that it creates an asymmetric bulb of pressure that causes the soil to flow around its cylinder.

Figure 2. The ROBOCONE p-y module: (a) schematic drawing; (b) initial aluminium prototype.

A prototype of the ROBOCONE p-y module is currently under development at the University of Bristol, in collaboration with the University of Southampton and the Trinity College of Dublin. Figure 2b shows a photo of the actual aluminium version of this prototype. The module has a built-in wedge mechanism that transforms vertical (axial) linear motion from a motor-driven lead screw actuator into straight-line horizontal (lateral) motion. The motion is translated from axial to lateral by a set of wedges with inclined surfaces. The system comprises a series of load cells to measure the soil resistance to lateral displacement (*p*) and a displacement transducer to measure the lateral displacement (*y*). The initial concept design specifications for the ROBOCONE p-y module are outlined in Table 1. The module is designed to fit in a 54mm diameter tube behind a conventional 15cm^2 cone penetrometer. This enlarged section is appropriate for housing parts of the internal mechanism as well as the sensors and wiring. If the rods above the module are a smaller diameter (e.g. consistent with a 10cm^2 cone) the module will also operate as a friction reducer, making it easier to push the remaining length of the cone to deeper depths.

Table 1. Initial ROBOCONE p-y module specification

Module diameter	54 mm
Module height	200 mm
Horizontal displacement range	0-13 mm
Displacement resolution	< 0.1 µm
Force capacity	~ 5-6 kN

3. Preliminary testing

3.1. Investigation of the sealing system

One important technical aspect of the ROBOCONE p-y module is the selection and implementation of an adequate sealing system for the relative movement between the p-y module (laterally sliding component) and the rest of the vertical pushing rods. As shown in Figure 3, two options have been considered: the first option consists of a deformable membrane tightly fixed to the outer diameter of the cone (Figure 3a), while the second represents three discs sliding against each other, one of which is fixed to the p-y module and the other to the solid cone penetrometer (Figure 3b). The advantage of the membrane option is the better sealing against water and fine particles, although it presents a major challenge involving the risk of membrane wear and puncturing due to both vertical penetration and lateral pushing against the soil grains. Note that the membrane thickness is also restricted due to the cone diameter, which cannot exceed 54mm. Consequently, the second option, seemingly more practical, has been selected. However, challenges related to the frictional resistance between the disks, which can in turn affect the determination of the lateral pushing force, and effectiveness against soil and water ingress are still present and will be analysed in the following sections.

3.1.1. Frictional resistance

A set of three sealing disks made of hard resin of 5 mm thickness each have been used. A close contact between the disks must be imposed to ensure the sealing function, but a compromise had to be found to avoid interference in the pushing force (*p*) determination. This contact is ensured by the bolt connection in Fig. 3. Since it is difficult to control and maintain the tightness of the bolt connection, a series of tests, without applying any external load, were carried out by applying different spacers size between the bolts and the ROBOCONE inner core (Fig. 3b).

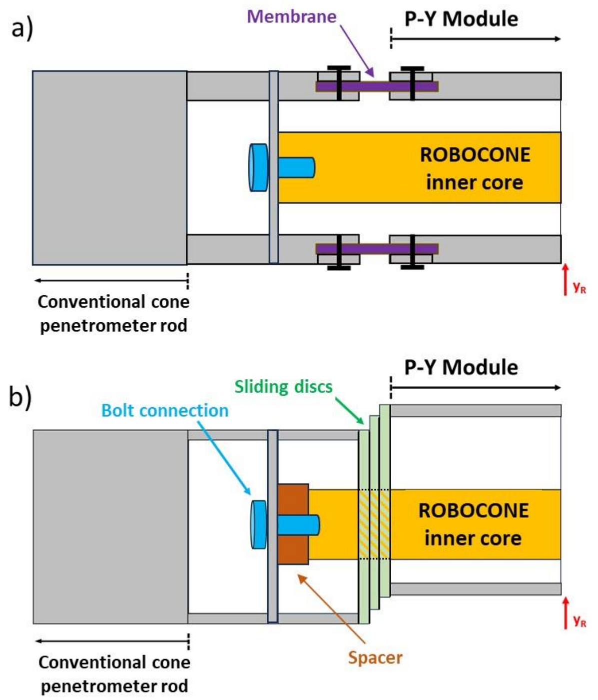

Figure 3. Sealing at the interface between the p-y module and the solid cone penetrometer: (a) membrane option; (b) sliding discs option.

In each test, the force measured by the load cells and the module displacement were recorded. A visual check on the ingress of soil particles was also undertaken. For a large spacer (i.e., larger than 5mm), no force was detected by the load cells while moving the module, confirming a smooth sliding wedge mechanism of the p-y module. However, this configuration cannot guarantee complete sealing of the device, as the finer particles and water can flow between the discs. In the absence of spacers, the bolts highly compress the disks and, although no particle ingress could occur, the high friction between the discs generated a force of around 300N when the module was pushed against air. Hence, an intermediate solution was sought. An intermediate spacer was implemented (approximately 4.5 mm) allowing close contact between the sliding discs to ensure sealing, while avoiding generating a high friction force. A test without applying an external load revealed a tolerable friction force of about 30 N under this testing conditions.

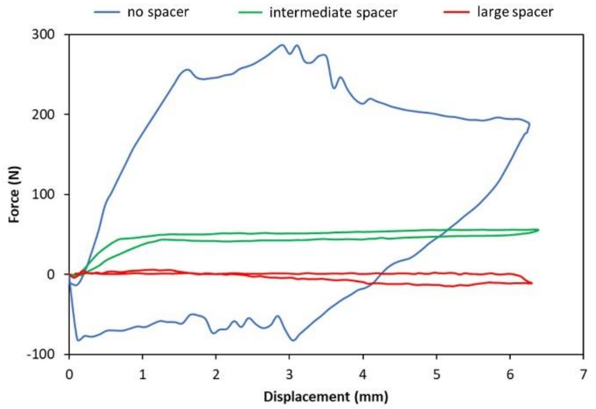

Figure 4. Tests of p-y module without loading, by applying different spacers size between the bolts and the ROBOCONE inner core

The measurements were repeated under complex cyclic loading in air, replicating the patterns that may be imposed by the ROBOCONE p-y module to determine cyclic p-y curves. (Figure 5). Four sets of four cycles, each with a displacement of 2mm, were executed without any external load on the module. Good repeatability of the frictional results can be observed, since the loading/unloading paths follow the same pattern each cycle. In addition, the fourth set of cycles overlapped the first set with an error of less than 3%. A total force of about 30N was also measured, confirming the frictional force obtained in the selected spacer configuration. This force corresponds to a stress of only 2.8 kPa on the projected area of the module (200 mm × 54 mm). This small extraneous force, even if not corrected for, has minimal influence on the measured soil characteristics. For example, in undrained conditions, assuming a bearing factor of $N_c = 10$, this stress would represent an error in the calculated soil strength of 0.28 kPa, which is negligible.

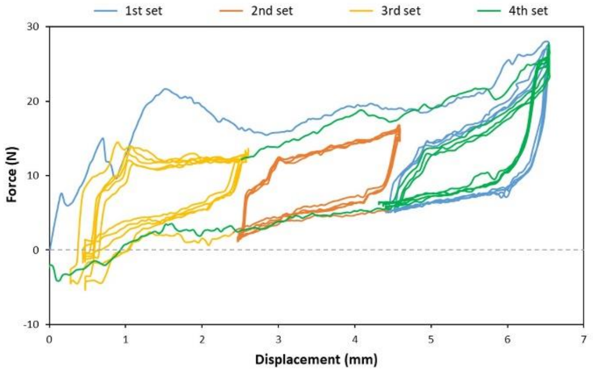

Figure 5. Complex solicitation test without any external load on the module

3.1.2. Effectiveness against soil ingress

Further preliminary tests were performed to investigate the sealing efficiency under selected spacer configuration. A handful of dry kaolin clay powder was applied (Figure 6a), by hand pressure, to the sliding discs at the interface between the p-y module and the solid cone penetrometer, during a full cycle of up/down movement of the module. The module was then dismantled. No powder ingress was observed inside the device, or even at the interface between the sliding discs. The same procedure was repeated with a wet clay slurry, without observing any ingress of slurry between the discs (Figure 6b). These observations suggest the sealing is effective under the selected configuration, for fine clay soils. Nevertheless, more realistic and demanding tests under large confining pressure and application of prolonged cycles will be carried to check these preliminary findings. Further tests may also consider different materials (such as Teflon-coated steel) for the sealing disks.

Figure 6. Sealing investigation against fine soil ingress: (a) kaolin clay powder; (b) marine clay slurry.

3.2. ROBOCONE bench testing

3.2.1. Force calibration

Before conducting tests of the p-y module in soil, the functionality of the device underwent checks to verify the precise and reliable measurements of both force and displacement.

The development of the p-y module presented a major challenge in accurately measuring the ground resistance against lateral movement. Initial tests were carried out in a bench setting, by moving the centre part of the module against a calibrated external load cell. This allows the influence of the sealing system on the measured load to be checked. The sum of the internal load cells forces is compared against the reaction force of the external load cell in Figure 7a. Figure 7b show some examples of the comparison between the value recorded by the pushing and reaction load cell. The light grey line in Figure 7b shows the initial tests carried out using a preliminary configuration for which not all the pushing load was detected by the load cell. This led to a revision of the mechanical loading and measurement system to obtain the coloured points (orange for loading and blue for unloading) in Figure 7b. For both testing configurations, the percentage difference between pushing and reaction force was calculate as shown in Eq. (1) and reported in Figure 7c. A systematic difference around 4% (repeatable across several tests) can be observed, suggesting the need to implement this slight correction into the calibration factor for the load cells.

$$\text{Percentage difference} = \frac{\text{External force} - \text{Internal force}}{\text{External force}} \times 100 \quad (1)$$

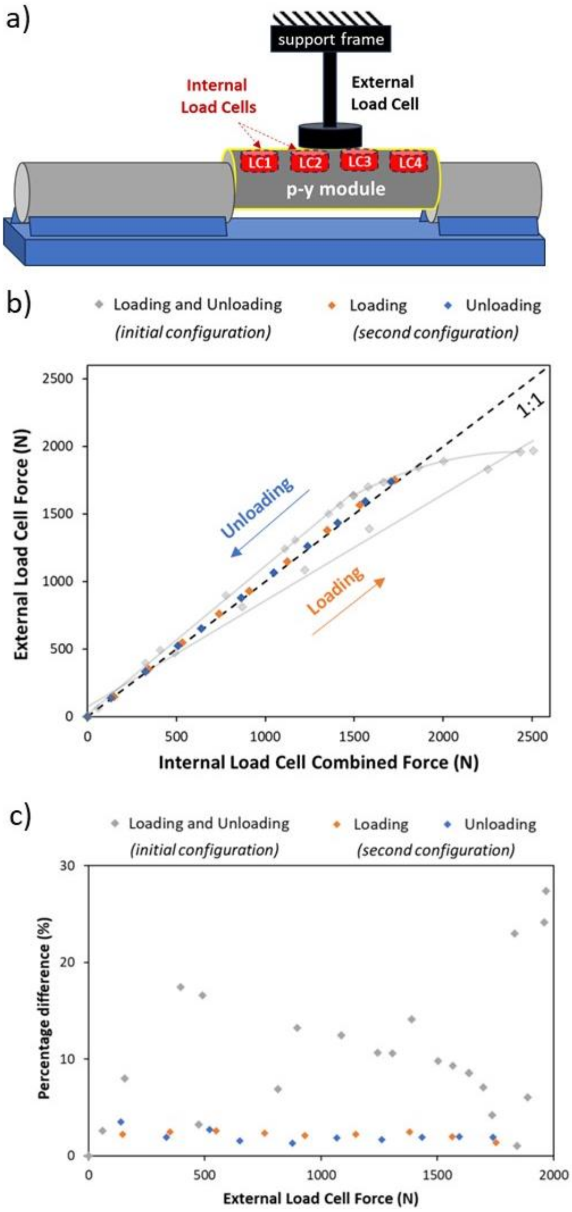

Figure 7. Comparison between the external load applied to the module and the force measured by the internal module' transducers: (a) Test configuration; (b) global overview; (c) percentage difference

3.2.2. Displacement calibration

In the development of the 'p-y module', space constraints involved the incorporation of an LVDT to measure the axial displacement of the internal core rather than directly measuring the lateral displacement of the module. Thus, a calibration process was done using a temporary external LVDT installed on the outer shell of the module to measure directly the lateral displacement (Figure 8a). Figure 8b compares the axial displacement of the internal core (i.e. the sliding bar) measured by the internal LVDT and the lateral displacement of p-y module measured by an external LVDT. A conversion factor of 0.4 is observed between the axial and the lateral displacements, which is consistent with the wedge geometry. Then, the percentage difference between the measured and the estimated module displacements was computed according to Eq. 2. A maximum error of about ±5% was observed (Figure 8c). This tolerable error may be due to a slight play in the wedge movement leading to a minor backlash in the module displacement.

$$\text{Percentage difference} = \frac{\text{Measured displacement} - \text{Estimated displacement}}{\text{Measured displacement}} \times 100 \quad (2)$$

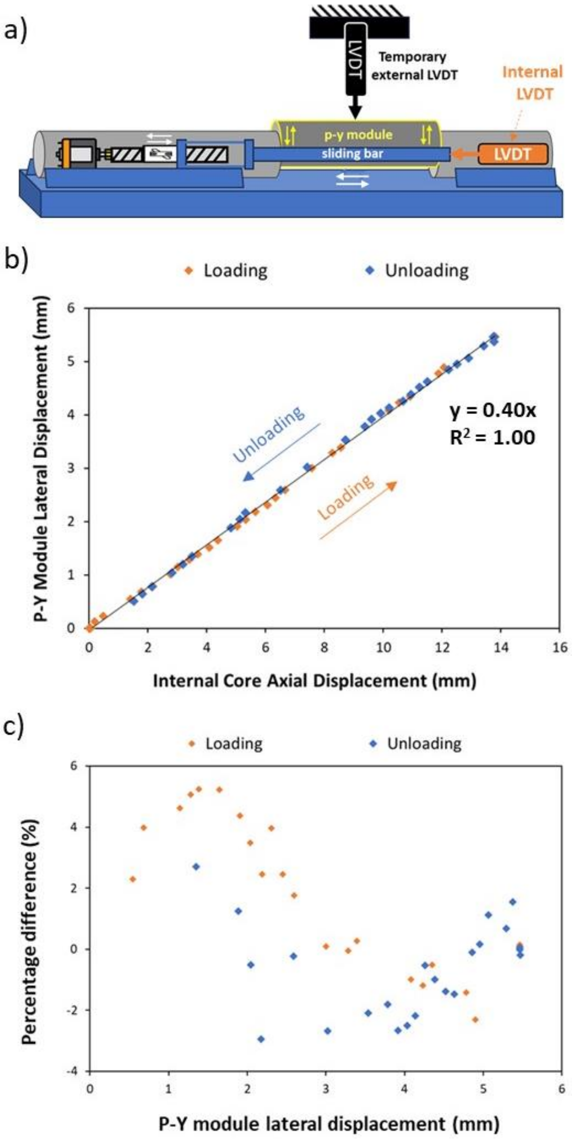

Figure 8. Comparison between the lateral and the axial module' displacements: (a) Test configuration; (b) global overview; (c) percentage difference

3.3. Testing in a calibration chamber

A small-scale calibration chamber was developed at the University of Bristol to explore the performance of the ROBOCONE p-y module (Figure 9). The cone was fixed at the centre of both top and bottom bases of the chamber, which has an inner diameter of 160mm. Two air pistons were connected to a hollow disc inside the chamber to apply the desired vertical stress on the soil surface before testing. The module, marked by a yellow rectangle at rest, moves laterally during testing to reach the red rectangle in Fig. 9.

To assess the operational efficiency of the p-y module, three initial tests were conducted using polystyrene and foam as test materials. These tests yielded a typical force-displacement p-y curve, providing valuable insights into the tool's behaviour under different loading conditions (Figure 10). Polystyrene pellets, having a cylindrical shape (1x3cm), were distributed all around the module without any vertical force being applied. Two sheets of foam (40x40x3cm) were also wrapped around the module. Notably, the two identical tests using polystyrene as the surrounding media revealed very similar reaction curves proving some initial confirmation of measurement repeatability. Furthermore, the tool's versatility was explored through the implementation of several loading cycles, involving both displacement-controlled and load-controlled loops. The collected data exhibited typical force-displacement curves, showing the system's capacity to manage and replicate complex load histories. This comprehensive evaluation demonstrates the robust functionality of the p-y module and the capability to handle diverse loading conditions effectively.

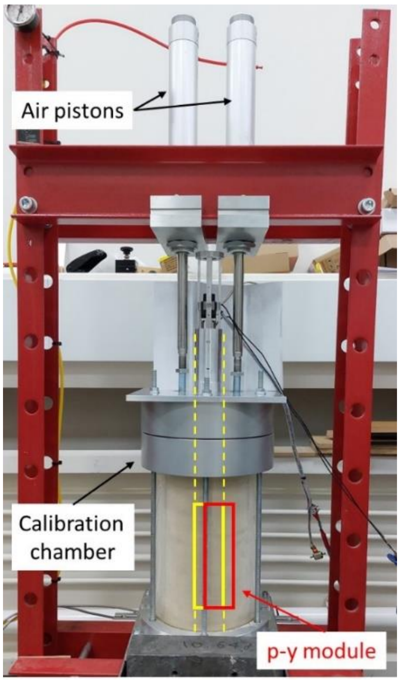

Figure 9. Preliminary testing of the p-y module in a small-scale calibration chamber.

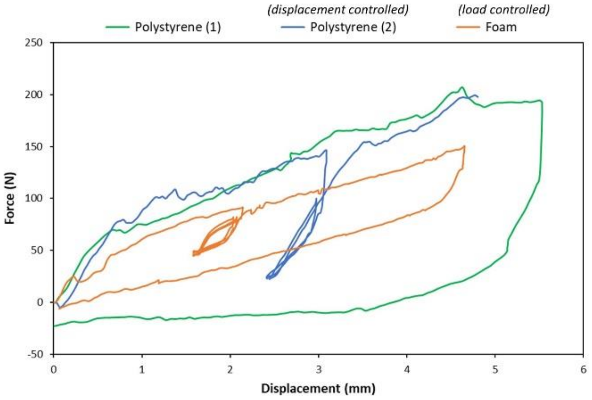

Figure 10. A typical force-displacement curve obtained using polystyrene and foam as test materials.

4. Conclusion

This paper has described some aspects of the development and testing phases of the new ROBOCONE 'p-y' module, a robotic site investigation tool designed to meet the specific requirements of offshore applications and contemporary whole-life design. Through discussions on specification requirements, sensor calibration, and preliminary testing in a small calibration chamber using analogous materials, this work has confirmed the tool's capability to closely replicate the kinematic mechanism experienced by laterally loaded pile elements. Future developments in this research project will include testing over a wide range of soil conditions in this small chamber, as well as testing in a larger calibration chamber to minimize the effect of boundary conditions. In parallel, numerical analysis is underway to support the interpretation of ROBOCONE measurements.

Acknowledgements

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