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Development of a facility to perform 1-g lateral load tests on scaled monopiles in saturated sands

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ABSTRACT: This paper outlines the development of specialized facilities for extracting the soil reaction curves, focusing on soil scour conditions under saturated conditions. It describes the scale modelling of piles according to specific similitude rules and the selection of sand for experiments. Experimental setup considered for analysing the lateral load response of monopile foundation is explained. The construction of a custom tank to simulate the monopile boundary conditions is shown in detail along with brief overview for the saturation of soil bed. The development of in-house sand raining device for achieving the targeted relative densities at the model scale is shown. Calibration of the sand raining apparatus was conducted considering various configurations of mesh filters. This process resulted in attaining a wide range of relative densities, facilitating the preparation of the required sand bed at different density level.

1 INTRODUCTION

Monopile foundations are one of the most widely used foundation structures for OWTs (Offshore Wind Turbines). Deformation response of monopile foundation is generally carried out by the p-y method which provides insights about the soil-structure interaction which is independent of the load rate and generally used as an alternate to the comprehensive experimental or numerical simulations. Due to the observed shortcomings of conventional soil reaction curves, new approaches have been proposed for the reliable design of monopile foundation such as PISA. PISA p-y curves are calibrated using wide range of finite element modelling and field tests. Adoption of PISA p-y curves led to reduction in design conservatism and substantial savings for wind farm development. It has been observed that an enhanced research and development can have significant variation in LCOE for offshore wind farms (Bhattachrya, 2021). The new p-y curves can better capture the associated soil foundation interaction but still there are various uncertainties which are not incorporated into the models while calibrating the derived soil reaction curves. Additionally, examination of these uncertainites should be supported by the physical modelling of the monopile foundations. In the current research, efforts are concentrated on exploring the influence of these uncertainities on the the lateral response of monopile foundation. The research uncertainty which will be studied is the scouring effect around the monopile foundation on soil surface. Due to scour formation around a monopile foundation, there can be substantial decrease in strength and stiffness of the local available soil beneath the monopile foundation (Qi et al.(2016)). Therefore, current research focuses on the development of a 1-g experimental test facility designed to extract soil reaction curves through proper examination of lateral response of monopile foundations, particularly in scenarios where scouring around the foundation occurs. While several studies (Zhang et al., 2017; Qi et al., 2016; Li et al., 2021; Dai et al., 2021) have analyzed the lateral load response of monopile foundations considering scour effects, investigations incorporating soil saturation during soil ground modeling remain scarce. Notably, soil saturation has been identified to significantly influence soil resistance (Okamura and Inoue, 2012). This research showcases the development of experimental test facilities equipped to facilitate soil saturation within the model ground. Paper highlights the details for the full experimental test setup, soil under consideration and model tank setup. Additionally, the paper explains the in-house sand raining device aimed at preparing the model ground to a specific relative density, including a discussion on the device's calibration and its significance.

2 MODELLING OF MONOPILE

The Gulf of Khambhat site is a proposed site for offshore wind farm construction in India (FOWIND,2018). There will be the establishment of 3 rating of wind turbines i.e, 4 MW, 6 MW and 10 MW wind turbines. In the current study, the physical modelling of a monopile foundation has been considered in case of a 10 MW wind turbine henceforth, it will also allow the provision for modelling of smaller rating wind turbines as well. At model scale the monopile features an outer diameter of 150 mm and is embedded into the soil to a depth of 1 meter. The load is applied at an eccentricity of 400 mm above the soil surface, and the pile has a wall thickness of 3 mm. The scaling laws considered are based on the physics of the problem. The selection of the thickness of model monopile is such that the relative flexibility factor (E_sL^4/E_pI_p) (Poulos, 1982) remains constant for both model and prototype monopile. For the current model of the monopile, the relative flexibility factor obtained is 2.54, which corresponds to the rigid pile. The other dimensional relations used for analysing the response of the monopile foundations has been taken as per Rathod et al. (2021) which are shown in equation (1-6).

$$F_p = k_1^{0.5} \times k_2^2 \times k_3^{0.5} \times F_m \tag{1}$$

$$e_p = k_1^4 \times k_2^{-3} \times e_m \tag{2}$$

$$(EI)_p = k_1^{4.5} \times k_3^{0.5} \times (EI)_m \tag{3}$$

$$t_p = k_1^{4.5} \times k_2^{-3} \times k_3^{0.5} \times \left(\frac{E_m}{E_p}\right) \times t_m \tag{4}$$

$$(E_s)_p = k_1^{0.5} \times k_3^{0.5} \times (E_s)_m \tag{5}$$

$$y_p = k_2 \times y_m \tag{6}$$

Here, F is the applied lateral load, e is the loading eccentricity, EI is the pile flexural rigidity, t is the pile thickness, E_s is the soil stiffness, which is considered constant along the depth of the model ground, y is the pile deflection and k_1, k_2, k_3 are the scaling factors used for the embedded length, pile diameter and unit weight of the soil respectively. Further illustrating the scaling factors in detail, these factors can be characterized as $k_1 = (L_p/L_m)$, $k_2 = (D_p/D_m)$, $k_3 = (\gamma_p/\gamma_m)$ where subscripts p and m corresponds to prototype and model conditions respectively. Strain gauges are placed on the surface of the monopile to extract the deformation response of the monopile foundation under lateral loading.

3 SAND PROPERTIES

The sand under investigation in this study is sourced from the Solani river and is referred to as Solani river sand. The grain size distribution of the sand, acquired through sieve analysis, is illustrated in Figure 1. Subsequent to the grain size distribution analysis, the corresponding index properties have been determined and are documented in a Table 1.

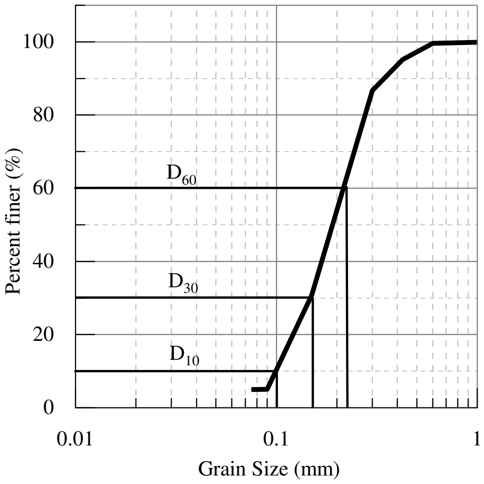

Figure 1. Gradation assessment of Solani River Sand through Sieve Analysis

Table 1. Index properties of the Solani sand

Properties	Value
D_{10}	0.1 mm
D_{30}	0.15 mm
D_{60}	0.21 mm
Uniformity coefficient, C_u	2.1
Coefficient of curvature, C_c	1.07
$\Upsilon_{d\text{-min}}$ (kN/m^3)	14.01
$\Upsilon_{d\text{-max}}$ (kN/m^3)	16.38

4 MODEL EXPERIMENTAL SETUP

Figure 2 (a) presents the initial experimental setup to analyse the lateral load response of a monopile foundation in which the pile can be loaded for both monotonic and cyclic loading with a two-way actuator placed on rigid reaction column. Based on the model for a 10 MW wind turbine's monopile foundation, the dimensions of the tank have been determined such that distance between the inner boundary of the tank wall and outer surface of the pile should have a distance larger than the 7D, where D is the diameter of the pile. The tank's dimensions ensure it is large enough to prevent boundary effects and is not subjected to the interference from the tank wall boundary when the model test setup is subjected to 1-g lateral load test or dynamic loading. A circular tank has been constructed for the model scale tests, as depicted in the Figure 2 (b-d). This figure showcases the detailed arrangements of the model tank through different views: perspective, elevation, and plan.

The choice of a circular design over a rectangular one addresses the issue of stress concentrations at the corners. Furthermore, the tank's depth considers the monopile's embedment length and includes an additional clearance of three times the pile diameter beneath the monopile's tip. To ensure ample lateral strength against potential lateral loading from the soil mass, the vertical circular sheet is strengthened with vertical angle sections measuring 75x40x6 mm. To enhance the reliability of predicting the reponse of the monopile foundation at model level, the tank is equipped to simulate saturated soil conditions through the inclusion of a porous stone assembly. This assembly is strategically placed at the base plates of tank which will allow for the drainage of water. Additionally, to withstand the gravitational load exerted by the sand mass and the self weight of the tank, the base of the tank assembly incorporates a channel section measuring 75x40x6 mm.

5 SAND RAINING DEVICE

Offshore grounds are commonly characterized as medium to highly dense grounds (He et al. (2021)). To achieve an accurate density, it is crucial to effectively model these conditions in laboratory experiments.

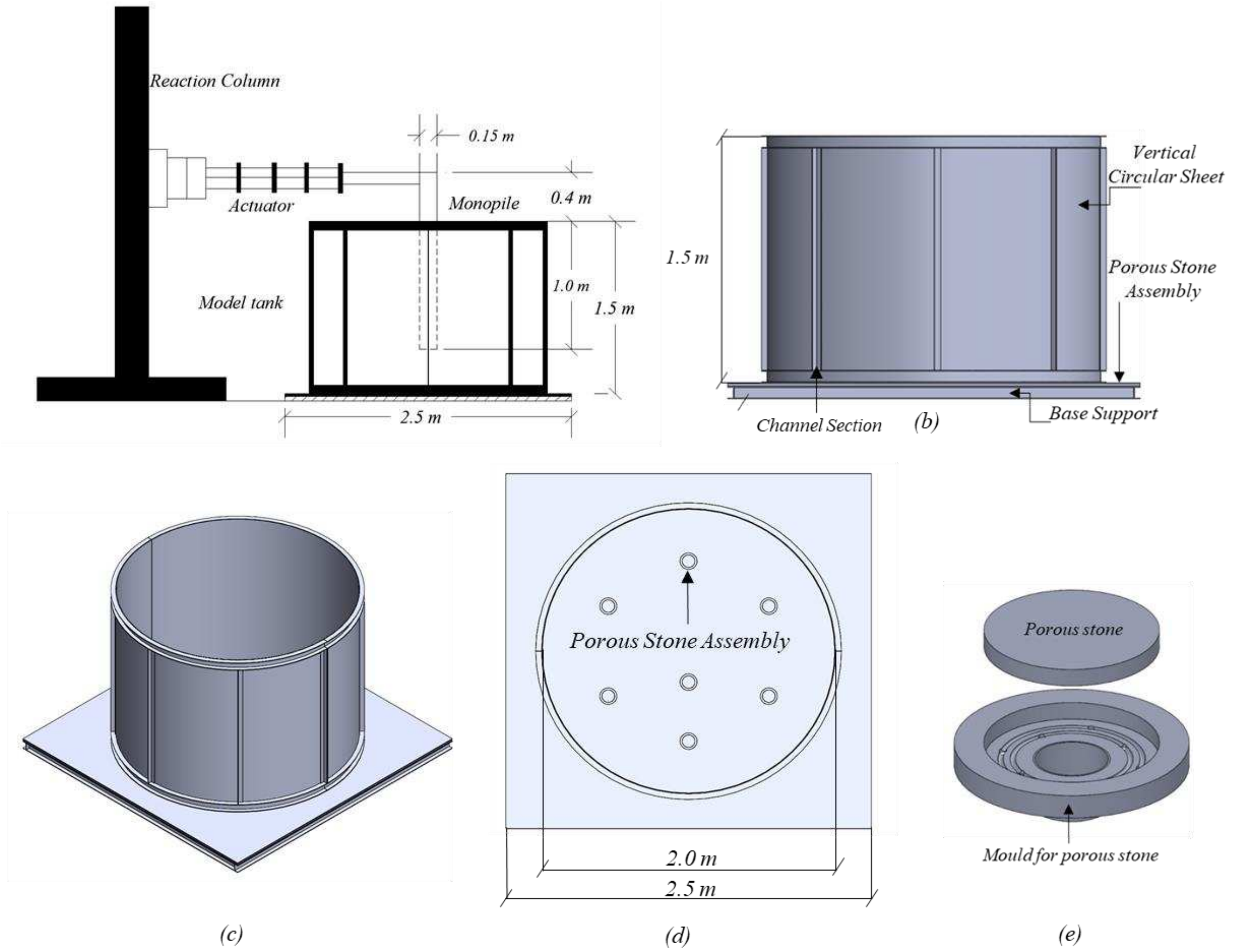

Figure 2. Experimental setup description: (a) Full test setup (b)Elevation view of model tank (c) Perspective view of model tank (d) Plan view of model tank (e) Porous stone assembly

The sand raining device is considered as one of the predominant techniques for modelling these grounds with precise relative density in experimental setups. A movable sand raining device setup as shown in Figure 3 is fabricated to facilitate the achievement of the desired relative density for the given experimental conditions. The dimensions of overall setup are planned which can better accommodate around the developed tank facilities. The hopper is mounted on a movable steel frame which has an adjustable height upto 3.5 metres, with a width of 3 metres. The frame includes a chain block mechanism to easily move the sand hopper in the vertical direction with little effort. It also has rolling wheels attached at it's top, allowing the hopper to move back and forth along the frame. Thus, by moving the hopper across and vertically along the frame, the sand raining device can cover a large area, making it possible to cover a substantial area, thereby facilitating the creation of model ground within the experimental setup. The design of sand hopper is to enable a seamless and efficient flow of sand particles. The schematic of the designed hopper is illustrated in Figure 4 (a). The upper part of the hopper takes the form of a cylinder with a 600 mm diameter. Below this cylinder, the hopper transitions into a truncated cone shape – a frustum – designed to facilitate the downward movement of sand. The upper circular base of the frustum has a diameter of 600 mm, while the lower circular base measure 50 mm in diameter. The slant height of the frustum is set at a particular angle relative to the vertical, which aids in the gravity-fed flow of the sand. Attached to the base of the conical section is another cylindrical tube, 50 mm in diameter and 200 mm in height. This tube helps to control and regulate the release of the sand from the hopper. The total height of the hopper is 630 mm in which 230 mm is height of upper cylinder, 200 mm is height of the conical section and another 200 mm height is contributed by the cylindrical tube. At both the ends of the cylindrical tube, there are flanges that allow for the use of two mesh filters at different positions enables the adjustment of sand flow, which can be important for achieving the different relative densities in the tank attachment of mesh filters. The ability to use two mesh filters at different positions enables the adjustment of sand flow. These filters can have various opening sizes and are used to control the size of the sand particles being dispensed.

6 SAND HOPPER CALIBRATION

The primary use of the sand hopper is to achieve specific sand densities by dropping sand from different heights into a container. To do this, the hopper is loaded with a set volume of sand. The sand is then released to fall from a predetermined height into tank below. A stopper plate is used to control the start and stop of the sand flow (Figure 4(a)). The fall height is adjusted using a threaded bob system, where the bob is tied at the end of the thread and length of the wire is set such that the tip of the bob is always touching the surface of the sand pile, ensuring consistent height of fall as the sand accumulates.

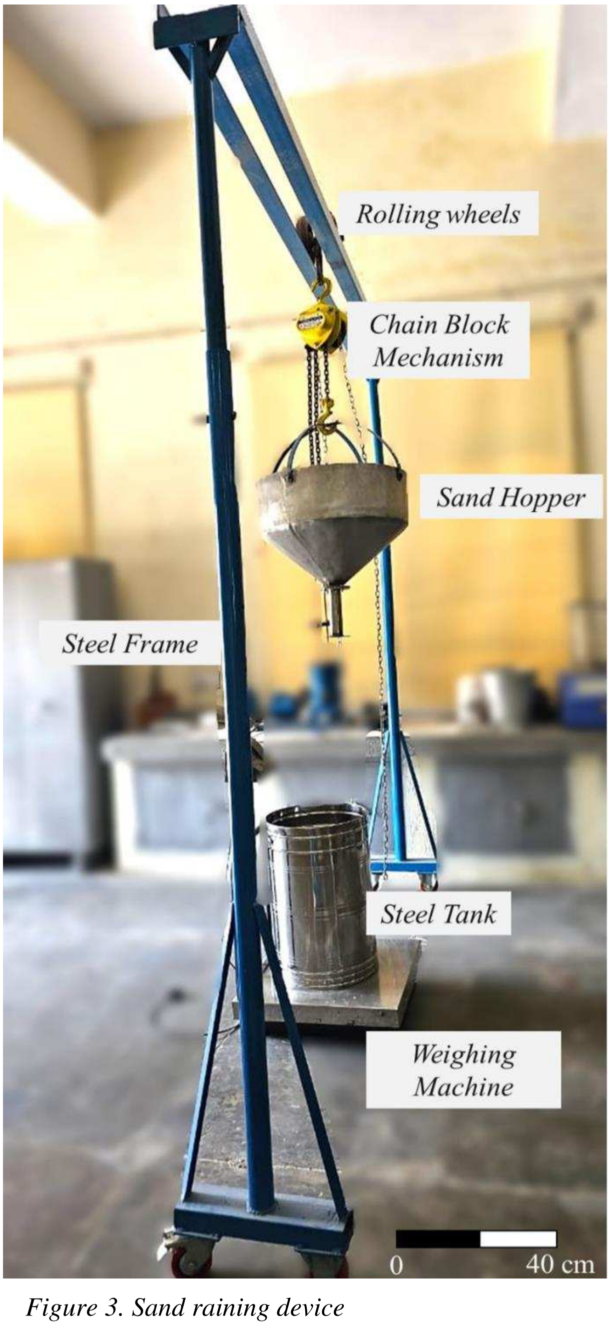

Figure 3. Sand raining device

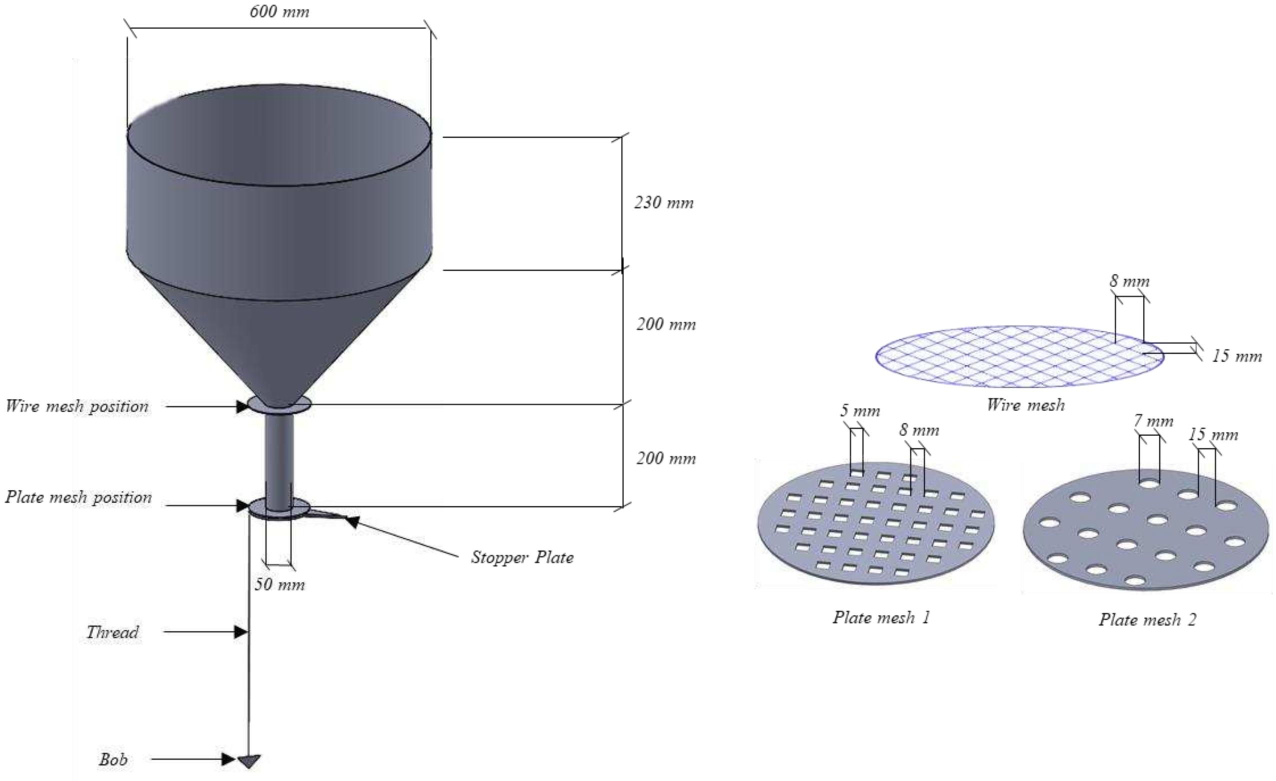

Figure 4. Three-dimensional drawing for components of sand raining device: (a) Sand hopper (b) Mesh filter details

The selection of the tank for calibrating the sand hopper ensures that the calibration results are applicable for preparing the sand beds with specific relative densities in the model tank. Additionally, the calibration tank is selected such that both horizontal and vertical movements of the sand hopper are utilized to accurately simulate the conditions during the sand bed preparation for the model tank. A series of tests are conducted to achieve the various relative densities of the sand. These tests are varied by using different mesh screens in the hopper. The current study uses steel wire meshes and steel plate meshes with different openings as shown in Figure 3 (b).

The steel plate with the square holes is referred as “Plate mesh 1” and that with the round holes is referred as “Plate mesh 2”. The percentage of opening area relative to the total surface area is 10.37% for Plate mesh 1 and that for Plate mesh 2 is 13.72%. In the current experiments, these meshes have been combined such that upper flange is fixed with the wire mesh while lower flange is varied with the plate mesh. The variations in mesh configurations allows to systematically change the sand’s relative density. The specific configurations allow to systematically change the sand’s relative density. The specific configurations and resulting geometrical variations of the meshes can be seen in the Figure 4. The test results of the calibration considering the different mesh configurations have been shown in the Figure 5. It can be seen that the relative density of the sand deposited in the tank increases with the increase in height of fall. A wide range of relative densities have been obtained ranging from 9.5% to 90.1%. It has been observed that the Plate mesh 2 shows higher relative densities as compared to the Plate mesh 1. This can be explained as the higher hole dimensions in Plate mesh 2 allows for more sand flux to pass therefore leading to the development of dense sand bed in the tank. To account for the relative density other than the scattered points, a cubic fit has been applied to both mesh configurations as shown in Figure 5, which will provide the approximate required height of fall to obtain at any intermediate relative density within calibration range.

7 CONCLUSIONS

The study outlines the establishment of experimental facilites aimed at investigating the extraction of soil reaction curves from the lateral load response of monopile foundation in saturated soil condtions, while also accounding for scour conditions around the foundation. It elaborates on the design process for

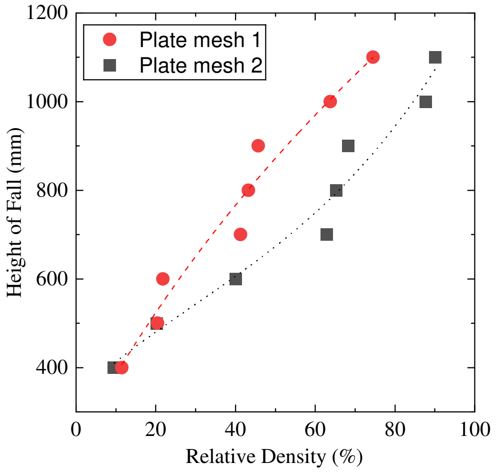

Figure 5. Variation of relative density with height of fall

developing model tank facilities, which are designed considering the site conditions of a selected site for an upcoming offshore wind farm in India. The design involves the considering a monopile for a 10 MW wind turbine as the pile model. The paper illustrates the similitude rules used for the scaling down the monopile foundation to correspond with the 10 MW wind turbine. Locally available soil, designated as the Solani river sand has been utilized for the preparation of the model ground. The detailing for the provision of drainage facilites has been explained which will facilitate the saturation of model ground. Additionally, the detailing of an inhouse constructed sand raining device is shown which will be employed for the preparation of model ground of particular specific relative density. Calibration of the sand raining device is shown in the study and it has been observed that the device is capable of achieving the relative density ranging from 9.5% to 90.1%. Overall, the study presents a brief overview on the detailing of the experimental arrangements created for addressing some of the uncertainites concering with the analysis of the lateral response of the monopile foundation.

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