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Shaker design and experiments

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Frequency-amplitude decoupling in the Gentle Driving of Piles (GDP) method: shaker design and experiments

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Abstract. This paper presents a new shaker design for the Gentle Driving of Piles method. Specifically, a lab-scale vibratory device has been developed that can simultaneously apply axial and torsional vibrations, both possessing frequency-amplitude decoupling. This design was implemented and tested in a lab-scale experimental campaign, where both pile and soil were extensively instrumented. The monitoring of the dynamic pile and soil behaviours during driving with various installation settings is of utmost importance to comprehend the governing mechanisms of the process. In that manner, the optimization of pile installation may be realized both for axial vibratory driving and GDP. In this work, the frequency-amplitude decoupling is pivotal, as it is showcased that both enhanced installation performance and reduced power consumption can be attained with proper selection of the installation settings and exploitation of high-frequency torsion.

1. Introduction

Offshore wind is a primary source of renewable energy [1]. The international sustainability targets - set in view of the energy transition - require a significant increase of offshore wind capacity. This leads to ever increasing size of offshore wind turbines (OWTs), water depth of installation and distance to shore [2]. As a consequence, engineering challenges continuously arise in the design and installation of OWTs and innovative solutions are required to accommodate the growing offshore wind demand. At present, OWTs are primarily supported by bottom-fixed foundations and in particular, monopiles correspond to the large majority of OWTs foundations up to date [3]. Monopile installation is mostly performed by means of impact hammering. However, this method raises major environmental concerns related to underwater noise emissions, which can be only partially mitigated by employing costly sound-proofing measures [4]. As a result, alternative installation techniques that are environmentally friendly and high-performing are vital for the offshore wind industry.

Vibratory pile driving is an efficient alternative to impact piling and has been widely employed in onshore applications. However, its deployment in the offshore environment remains limited, due to the incompleteness of the research works in the topic. To further boost the potential of vibratory technology, the Gentle Driving of Piles (GDP) was developed and successfully tested throughout an extensive experimental campaign that was executed during 2019 at Maasvlakte

II site in the Port of Rotterdam [5, 6]. This technology is based on the combination of high-frequency torsional and low-frequency vertical vibrations, aiming to improve the pile installation process. The preceding field campaign showcased the installation performance of the GDP method and pointed towards potential technical improvements [7].

In this paper, the focus lies in the introduction of new and unique features in the context of axial vibratory and GDP methods. Specifically, a lab-scale shaker that accomplishes frequency-amplitude decoupling of the input excitation has been designed, engineered and manufactured. Frequency-amplitude coupling is a common constraint in standard vibratory devices, operating based on the counter-rotation of eccentric masses. The present shaker consists of a main optimized aluminium block that is connected with three linear hydraulic actuators, two positioned horizontally and one positioned vertically, in order to generate torsional and vertical vibrations. The actuators are position-controlled during installation, and their amplitude and frequency are variable and independent to each other. Furthermore, an experimental campaign was designed and executed, in which the new lab-scale GDP shaker was employed to install piles into a conditioned soil; the respective results are discussed herein. Particular emphasis is placed on the effect of the different shaker settings on the installation performance, which is studied by means of direct shaker (input) and pile measurements.

2. Development of a new GDP shaker design

The primary concept of GDP is the enhancement of the installation performance compared to standard pile driving techniques. This method utilizes the simultaneous application of low-frequency/axial and high-frequency/torsional vibrations to drive the pile into the soil up to the target penetration depth. By virtue of the torsional component, the axial driving loads can be reduced, thus leading to lower noise emissions, as the torsion-induced shear waves (SH) do not propagate in seawater [8]. The first step towards testing the GDP hypothesis was the design and manufacture of a new vibratory device that could generate the envisaged axial-torsional excitation, namely the first GDP shaker.

Similarly to standard vibratory devices, the dynamic excitation in the first GDP shaker was generated by the counter-rotation of masses with constant eccentricity. The shaker operated by means of hydraulic motors and three exciter blocks were necessary to induce axial and torsional vibrations of dissimilar amplitude and frequency. In particular, one exciter block generated the vertical load, whereas two blocks were required for the torsional moment. The GDP shaker is shown in Fig. 1, being connected to a pile during the GDP campaign [5].

A point of improvement was identified in the previous medium-scale experiments, namely the decoupling of frequency and amplitude. In that manner, the benefits of high-frequency torsion can be realized without implying increase of torsion amplitude, and thus high power consumption. To that end, a new shaker design was pursued that can accomplish this goal. The recently designed lab-scale GDP shaker consists of three double-acting linear pistons connected to an aluminium block (of approximately 10 kg), that transfers the loads to the pile by means of a mechanical clamp. The main new feature of this shaker - compared to the previous design - is the capability to decouple the driving frequency and amplitude in a controlled manner. The pistons are hydraulically driven and their specifications are described in Table 1, whereas the new lab-scale GDP shaker is shown in Fig. 2.

Two of the pistons are mounted in the block at diametrically opposite locations and act towards opposite directions, in order to generate a torsional dynamic load. The third piston is mounted in the center of the shaker perpendicular to the other two pistons and generates the vertical (dynamic) excitation. The oil flow of the three pistons is individually controlled by a fast opening valve, that is capable of generating high-frequencies. For controlling the valves, an in-house control hardware and software system has been built. This controlling system enables us to set the driving amplitude and frequency of each of the pistons independently. The

Figure 1: The GDP shaker connected to a pile via a bolted flange connection.

Table 1: Technical specifications of the hydraulic pistons of the scaled GDP shaker.

Design Pressure [bar]	Weight [kg]	Stroke [mm]	Shaft diameter [mm]
150	1	10	16

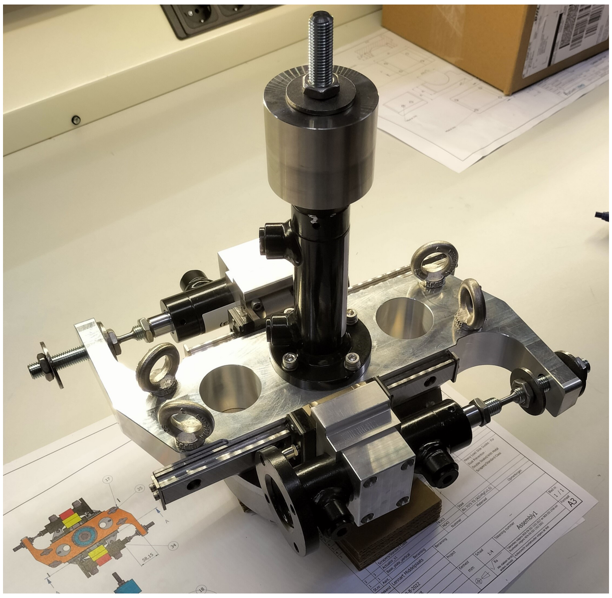


Figure 2: The new lab-scale GDP shaker.

amplitude of each piston is controlled by means of three potentiometers measuring the stroke of the piston and sending a fast signal to the control hardware, that controls the valve speed via a purpose-designed software (see, Fig. 3).

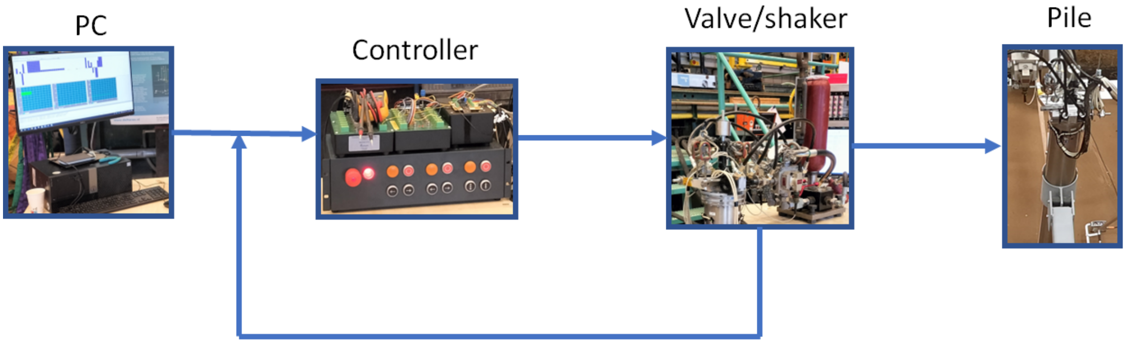


Figure 3: Feedback control system of the lab-scale GDP shaker.

The magnitude of the load generated by the pistons can also be modified by attaching extra masses to the pistons. The shaker is further instrumented with two full-bridge strain gauge circuits to directly measure the forces exerted by the pistons that generate the torsional load.

3. Lab tests campaign

3.1. Test set-up

The laboratory scale experimental campaign is carried out in the GeoModel container at the Deltares facilities, in the Netherlands, shown in Fig. 4. To this end, several pile driving tests were conducted in different soil preparations by means of the newly designed GDP shaker. In each soil preparation, the pile was driven, extracted and re-driven in three test locations per soil preparation.

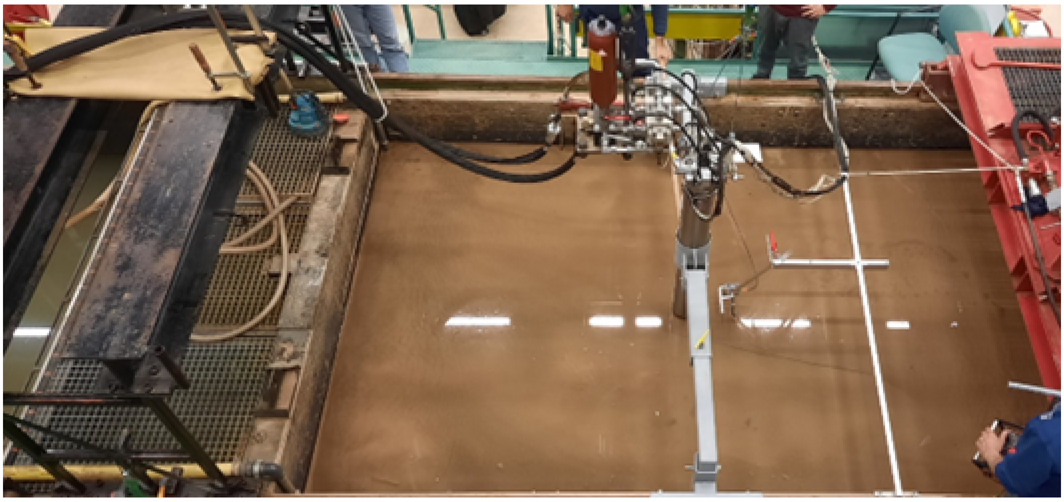
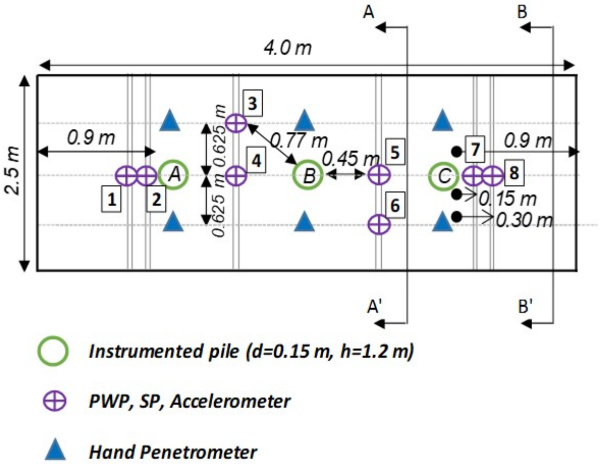
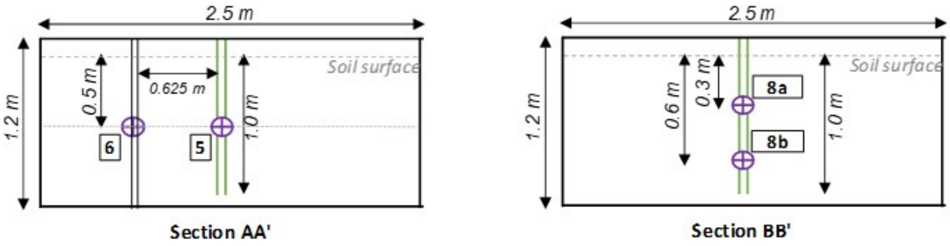


Figure 4: The GeoModel container of dimensions 4x2.5x1.2 m at the GeoLab of the Deltares facilities in The Netherlands.

To conduct the pile driving tests, the first step lies in conditioning the soil of the container to obtain the desired characteristics. To this end, the container was filled in with baskarp sand and water, until the sandy soil was fully saturated. The densification process of the sand sample took place in two phases. First, shock waves were generated via hammer impacting to the side



(a) Overview of the soil instrumentation in the GeoModel container.



(b) Soil instrumentation at cross-section AA' and BB'.

Figure 5: Detail description of the soil instrumentation in the GeoModel container consisting of Pore Water Pressure (PWP) and Soil pressure (SP) sensors and accelerometers.

walls of the container. Secondly, a more refined approach was employed, where vibrating needles at low amplitudes were inserted for approximately 2 h to 3 h, depending on the desired final relative density of the soil at hand. The needles were placed in multiple locations in the soil container, with a view to achieve (as far as possible) a homogeneously densified soil preparation.

The test pile consists of stainless steel material and is scaled down such that the L/D and D/t ratios are retained comparable to the conventional offshore monopile ratios. The geometrical and material characteristics of the test pile are described in Table 2

Table 2: Geometrical and material specifications of the test pile.

Material	Length [mm]	Outer diameter [mm]	Wall thickness [mm]
AISI 304	1200	154	2.0

3.2. Soil instrumentation

The GeoModel container is instrumented at eight locations, by means of Pore Water Pressure (PWP) and Soil Pressure (SP) sensors and accelerometers, as shown in Fig. 5. For each soil preparation, driving tests were conducted at three locations A, B, C as depicted in Fig. 5a. The soil instrumentation is aimed to provide high-frequency sampled measurements of the dynamic soil behaviour during driving, at various depths and distances from the pile. Cone penetration tests were conducted at six different locations of the soil container, both prior to and after the installation tests, by means of a hand penetrometer as shown in Fig. 5a. The measured quantities are relevant indicators of soil reaction during driving, the homogeneity of the soil package and the disturbance of the soil due to the installation process. Upon the installation tests, a few soil samples were also extracted and subjected to laboratory testing, in order to further analyse the respective soil characteristics.

3.3. Pile instrumentation

The test pile is instrumented with four tri-axial accelerometers and eight rosette-type strain gauges, attached around the pile circumference at 15 cm below the pile top as shown in Fig. 6. Specifically, the four tri-axial accelerometers are located at the outer pile wall and at equidistant locations, i.e. 90 degrees apart from each other. As regards the rosette strain gauges, the same arrangement with the accelerometers is followed (i.e. four along circumference), yet both outer and inner pile walls are instrumented (eight in total) (see Figs. 6a to 6e.). This configuration serves to measure the pile vibrations as accurately as possible, while avoiding any effect introduced by the clamping mechanism. This instrumentation set-up aims to provide - apart from direct measurement of the respective quantities - the required input to perform an energy flux analysis of the driving process, to assess the installation efficiency for different installation settings.

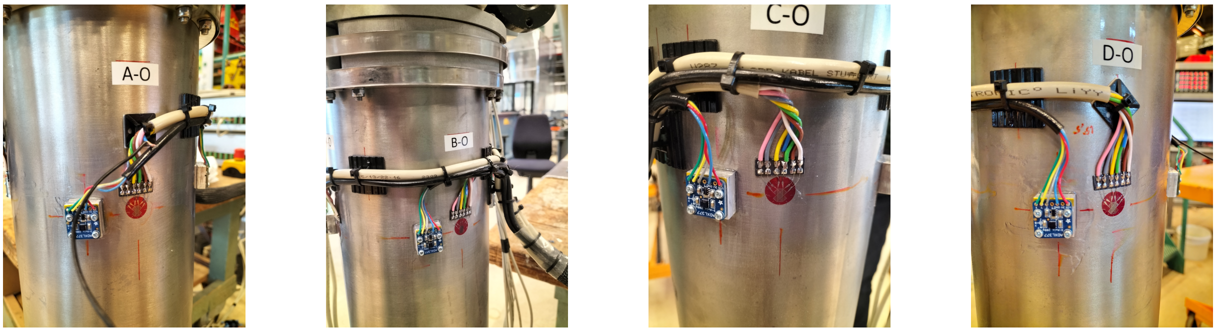
4. Results

The laboratory experimental campaign is carried out in the GeoModel container, facilitating the investigation of different soil conditions, i.e. ranging amongst loose, medium-dense and dense soil. In this paper, the results obtained from the tests conducted in medium-dense soil conditions and for various GDP shaker settings are presented.

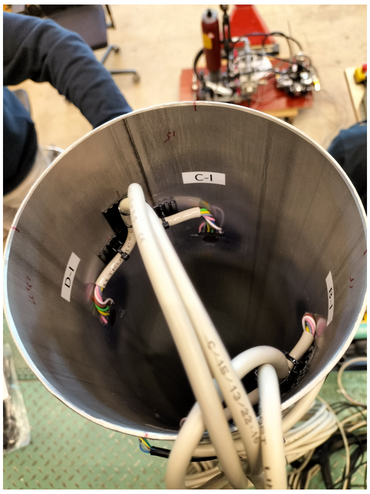
Table 3: GDP shaker settings for the studied driving test.

Parameters	Torsional freq. [Hz]	Torsional ampl. [mm]	Vertical freq. [Hz]	Vertical ampl. [mm]
1	69	2.5	23	1.5
2	92	1.5	23	1.5
3	92	2.0	23	1.5
4	69	3.0	23	1.5
5	69	4.0	23	1.5
6	-	-	23	4.0
7	69	3.0	-	-

Figure 7 shows one pile installation process, in which different time windows with different GDP shaker settings were considered. The initial and final pile embedments are approximately 25 cm and 40 cm, respectively. As it can be observed from Fig. 7, making use of the first



(a) Position A (b) Position B (c) Position C (d) Position D



(e) Inner pile wall instrumentation

Figure 6: Pile instrumentation consisting of tri-axial accelerometers and strain gauges in rosette configurations.

set of the GDP shaker parameters, the pile penetrates into the soil at high penetration speed. This is related with the fact that the GDP technique uses the torsional vibrations as the main mechanism for driving the pile into the soil. Given that, the stresses near the surface of the soil are small, the resistance towards the pile penetration is relatively small facilitating the pile penetration at relatively high speed. After a few second (≈ 50 s) the penetration rate drops and pile refusal is met, i.e. further penetration is not feasible. Subsequently, the settings of the shaker were switched to the second parameter set; the vertical excitation remains invariant, whereas the torsional frequency and amplitude were increased and decreased, respectively. As a result, the penetration rate started to increase as can be observed by the change of slope for the new set of parameters (red line) compared to the first installation part (blue line). In the next installation windows, various parameter combinations were tested with the aim to achieve a similar penetration profile.

Figure 8 shows the time-frequency analysis of vertical pile acceleration during the driving process. As can be observed, the majority of the energy is present in the driving frequency, whereas appreciable energy content is present also in the super-harmonic components of the fundamental frequency. This occurrence is anticipated, due to the non-linear character of the process and the potential periodic input arising from coupling of the system components (i.e. pile-shaker-soil), thus rendering the application of single-harmonic input infeasible in practice.

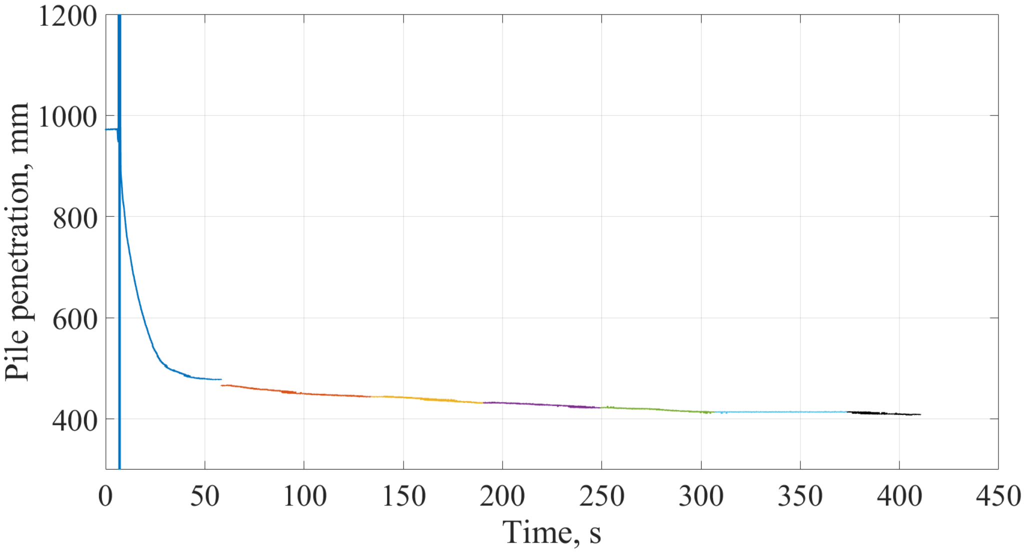


Figure 7: Pile penetration in medium-dense soil conditions by means of the GDP shaker.

An interesting case can be seen for the sixth parameter set, where only the vertical component of the shaker is active thus resembling the standard axial vibratory driving.

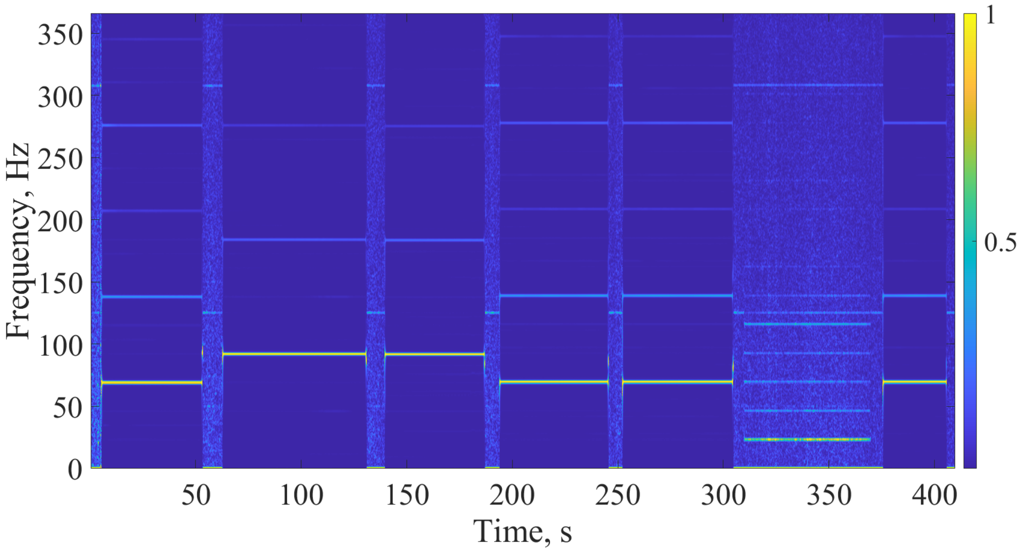


Figure 8: Time-frequency analysis of the longitudinal accelerations in the pile.

In Fig. 9, the measured mechanical power generated by the GDP shaker is depicted. An interesting feature of the GDP method is testified by this graph. In particular, the comparison of the first and second sets of parameters (blue and red lines of the graph, respectively) showcases that the power is reduced substantially and yet the pile penetration increases (see Fig. 7). This result constitutes a major finding, as it implies that a favourable penetration profile can be achieved without necessarily increasing amplitude, and thus the power consumption; on the contrary, a frequency increase that is accompanied with amplitude can reduction can provide both enhanced installation performance and reduced power consumption. In that manner, an advantageous approach to deal with refusal can also be considered.

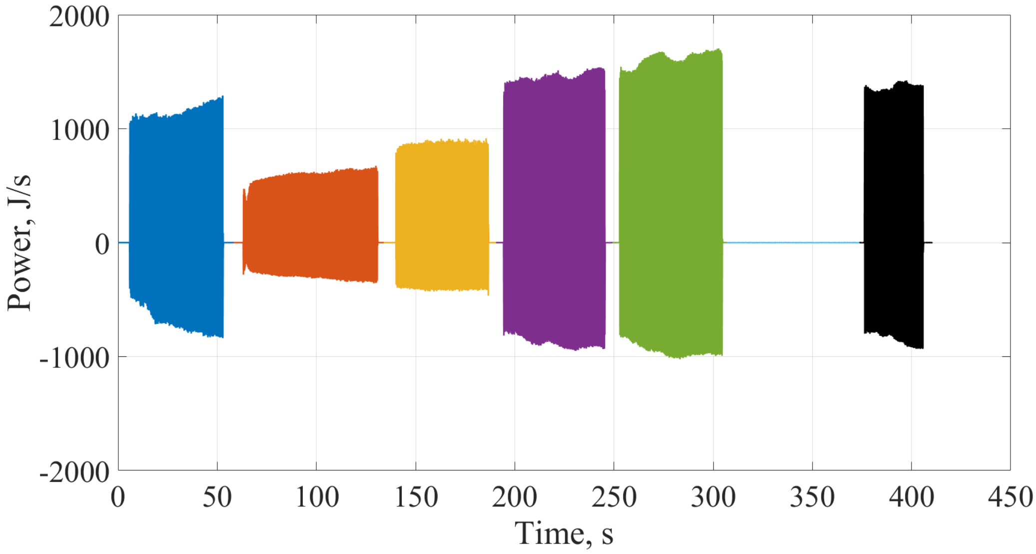


Figure 9: Input mechanical power measured at the GDP shaker.

5. Conclusions

In this paper, a new laboratory-scale GDP shaker design has been presented that enables frequency-amplitude decoupling, accompanied with a series laboratory tests in sand conditions. The major contribution of this work consists in showcasing the capabilities of this improved GDP shaker design and demonstrating experimentally that the power consumption of the GDP shaker can be not only stabilized, but also decreased by selecting an appropriate set of installation settings without compromising the installation performance. The experimental tests presented in this paper constitute part of a campaign that is still ongoing. Therefore, it is the intention of the authors to publish further results and more detailed findings in the near future.

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