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Proof of concept laboratory scale tests

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Gentle Driving of Piles: Proof of concept laboratory scale tests

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ABSTRACT: The global market for offshore wind energy is currently experiencing tremendous growth, which is expected to continue in the coming decades. Monopiles are one of the most frequently used foundations for Offshore Wind Turbines (OWTs) and are commonly driven into the seabed using impact hammering. The demand for higher capacity OWTs requires the installation of larger monopiles. As monopiles, however, become bigger their installation with hammering and mitigation of generated noise becomes challenging and costly. To optimize installation and to limit noise emissions, an innovative installation technique known as the Gentle Driving of Piles, GDP, has been developed. This technique combines vertical and torsional vibrations under different frequencies with the main driving assistance coming from the torsional force. This paper presents and discusses the results from a series of lab-scale pile driving tests performed in dense sand using the GDP method. For these tests, a lab-scale GDP shaker has been mobilized. During installation of the scaled piles, the frequencies and amplitudes of the vertical and torsional excitation were varied independently with the objective to increase the penetration speed. The results show improved pile driveability with high-frequency, low-amplitude torsional vibrations and showcase the potential of the GDP method in improving installation performance.

Keywords: offshore monopiles, monopile installation technique, vibratory driving; lab-scale testing; Gentle Driving of Piles

1 INTRODUCTION

Improving driving efficiency while reducing the noise emissions during the installation of XXL monopiles is a challenge for the offshore wind industry. Large monopiles require large forces to drive them into the soil. Most of the installation techniques which are in use today basically push the pile down by applying vertical forcing. For impact driving, his causes radial expansion which increases soil resistance and radiates noise in water. To address this, a novel pile-driving technique, named Gentle Driving of Piles (GDP) has been developed (Metrikine et al., 2020). With GDP, the monopiles are installed by exiting low-frequency and high-frequency vibrations in both the vertical direction and in the horizontal plane by rotation around the vertical axis. The GDP concept has the advantage that the major driving assistance comes from the torsional excitation which does not induce radial expansion. In addition, this technique introduces high frequency vibrations that reduce disturbance of the soil around the monopile. The proof-of-concept of the GDP technique was established by building the first GDP shaker and testing piles in terms of both installation and post-installation loading performances (Tsetas et al., 2023). The effectiveness of the GDP technique has also already been proven onshore using scaled piles with a diameter and length of approximately 1 and 15 m respectively. The scaled piles were installed in non-saturated medium dense to very dense sands at the Tweede Maasvlakte (Maasvlakte II) in The Netherlands as part of the GDP project (Kementzetzidis et al., 2023).

For the tests in this paper, a new lab-scale GDP shaker is designed and manufactured which allows for frequency-amplitude decoupling (Gómez et al., 2024). In this study, the performance of the GDP shaker and the GDP technique is demonstrated by performing a set of laboratory scale pile driving tests in which the pile penetration into the compacted sand bed is controlled by varying the amplitude and frequency of the applied axial and torsional vibration.

The development of the GDP technique goes through a series of research stages in a series of JIP development programmes, comprising the ongoing GDP 1.2, which is the basis for this paper (https://grow-offshorewind.nl/project/gdp1-2). The planning and setup of these projects was facilitated by GROW, which is a Dutch consortium established to initiate research and accelerate innovation in offshore wind (https://grow-offshorewind.nl/).

2 SCALE MODEL GDP SHAKER

The lab-scale GDP shaker that was mobilized for the tests in this study has been designed, constructed, and tested in the Stevinlab at the faculty of civil engineering at TU Delft. The shaker excites both the torsional and the vertical vibrations and allows for: (i) full decoupling of the higher-frequency torsional vibrations from the lower-frequency axial vibrations and (ii) independent control of the frequencies and amplitudes of vibration in both vertical and torsional directions. The lab-scale shaker consists of a main block made of aluminium that accommodates 3 hydraulic double-acting linear motion pistons, with a stroke of ±5 mm, that generate the vertical and torsional vibrations. Two of the pistons are mounted on the block at diametrically opposite locations and act in opposite directions to generate a dynamic torsional moment. The third piston is mounted in the center of the shaker perpendicular to the other two pistons and generates vertical excitation. The weight of the shaker is approximately 15 kg and the dynamic mass is about 2 kg per piston. The shaker is connected to the pile via a friction-based steel clamping component. A picture of the lab-scale GDP shaker is shown in Figure 1.

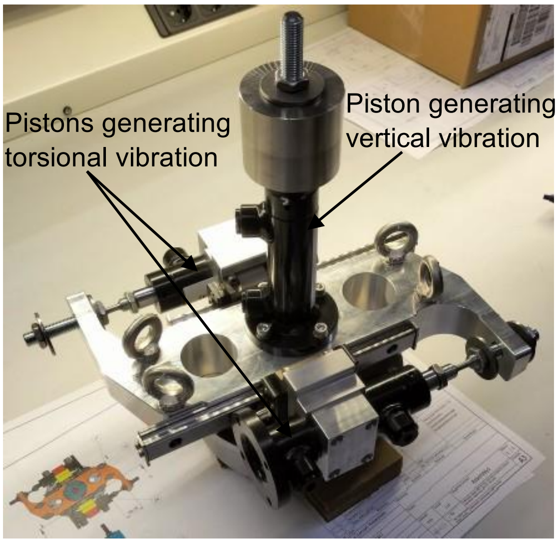

Figure 1. The developed lab-scale GDP shaker used in the tests presented in this paper.

3 LABORATORY SCALE TESTS

3.1 Test set-up and soil preparation

The pile driving tests were executed at Deltares in the Netherlands using the GeoModel testing facility (https://project-geolab.eu/geo-model-container-deltares/). This facility compromises of a rigid model container with loading and measurement systems. The dimensions of the container are 4 by 2.5 by 1.2 m^3 (l x w x h; where l, w and h is the length, width and height, respectively). For the pile driving tests, the container was filled with Baskarp B20 sand the particle size distribution and basic index properties of which are given in Figure 2 and Table 1 respectively.

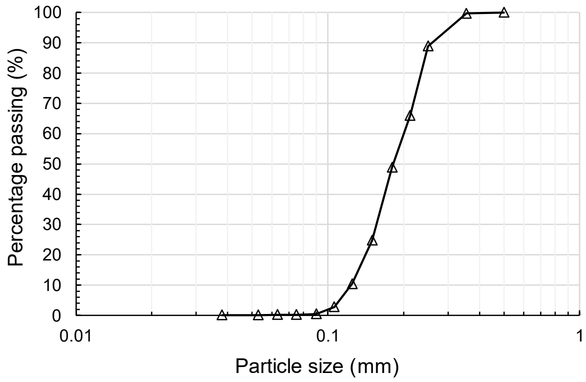

Figure 2. Particle size distribution curve of Baskarp B20 sand.

Table 1. Index properties of Baskarp B20 sand.

Parameter	Baskarp B20
Particle density, G_s [g/cm^3]	2.641
Minimum void ratio, e_{min} [-]	0.510
Maximum void ratio, e_{max} [-]	0.880
Mean particle size, D_{50} [mm]	0.182
Coefficient of curvature, C_c [-]	0.98

At first, a loose and homogeneous sand bed was created by making use of the fluidization system of the facility. This system includes a group of pipes located at the bottom of the GeoModel container. The pipes have small orifices through which pressurized water is pumped into the sand bed and the soil fluidizes from bottom to top. After fluidization, the sand was densified by means of dynamic compaction using a vibratory needle. The needle, vibrating with a frequency of approximately 192 Hz, was manually lowered into the soil and slowly pulled out. The vibration was considered effective up to about 30-35 cm in radius of the needle. To achieve a uniform densification, the vibrating needle was therefore inserted in the sand bed at multiple locations spaced every 25 cm. The relative density at the end of the densification cannot be determined because the total sand mass in the container is unknown. To this end, the bulk density (and relative density) is measured by using a metal ring sampler which collected soil samples from various locations and depths in the container. The metal ring had a diameter of 6.66 cm and a height of 5 cm.

In total, 7 different sand bed preparations were performed following the procedure described above. The distribution of relative density with depth as measured using the metal ring sampler at various locations in the container is illustrated in Figure 3. As can be seen in this figure, the distribution is rather uniform, and the achieved relative density is on average in the order of 70%. It should be noted that the water table in the container was kept a few centimeters above surface level to ascertain a fully saturated sand bed.

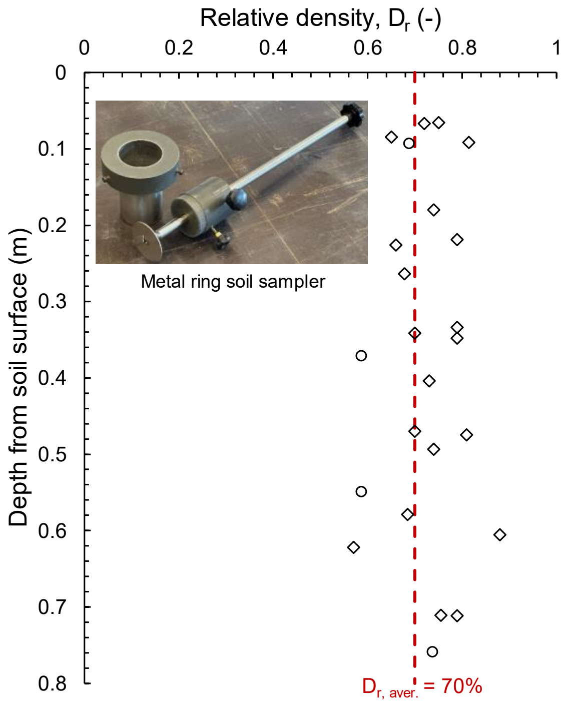

Figure 3. Distribution of relative density, D_r, with depth from soil surface.

3.2 Model pile

A stainless-steel model pile with an outer diameter, D, of 154 mm, length, L, of 1200 mm and a wall thickness, t, of 2 mm was used. For the pile driving tests, the L/D and D/t ratios are 8 and 77 respectively.. Figure 4 shows a picture of the model pile together with the GDP shaker as assembled for the lab-scale pile driving tests.

3.3 Testing programme

For the tests presented in this paper three rounds of identical sand bed preparations were performed (S1, S2 & S3). For each sand bed the soil was fluidized and compacted to a relative density of D_r = 70% as shown in Figure 3. The dimensions of the GeoModel container allow for installation of the model pile at three different locations (location A, B and C) in Figure 5. At each location, several pile driving tests with different driving parameters were carried out. Table 2 lists the test specifications for the executed pile installation runs. For checking the uniformity of the prepared sand beds, hand penetrometer tests were performed before pile installation and at different locations in the GeoModel container. The measured cone resistance profiles for the S1, S2 and S3 sand preparations are plotted in Figure 6. In this figure, the cone resistance profiles that are closest to the location of the pile installations presented herein are indicated with an arrow.

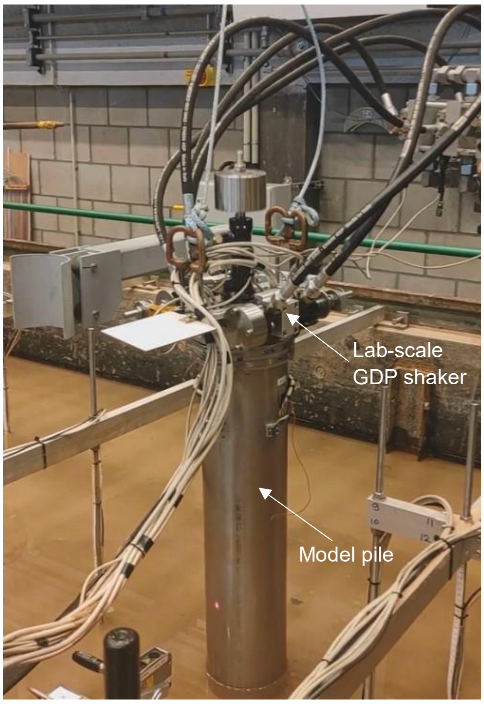

Figure 4. Model pile and lab-scale GDP shaker assembly.

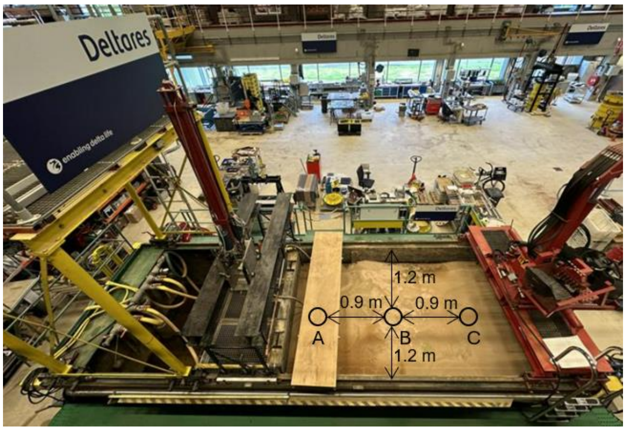

Figure 5. The Deltares GeoModel container. The locations of pile installations (location A, B and C) are marked in the picture.

4 TEST RESULTS

In this section, the influence on pile driving of the frequency and amplitude of vibration for both the vertical and torsional excitation is discussed.

Table 2. Overview of test specifications for the pile driving tests presented in this paper.

SB/L	P_IDX	Torsional vibration		Vertical vibration		Penetration depth		v_{max}
		f_T [Hz]	A_T [mm]	f_V [Hz]	A_V [mm]	Start [cm]	End [cm]	[mm/s]
S1/A	P1	0	0	23	≈ 0.8	0	0.36	0.07
	P2	0	0	23	≈ 1.6	0.36	0.78	0.10
	P3	0	0	23	≈ 2.4	0.78	2.59	0.18
	P4	0	0	23	≈ 3.3	2.59	5.81	0.20
	P5	30	≈ 0.8	0	0	7.10	14.56	0.37
	P6	40	≈ 0.8	0	0	14.56	18.52	0.40
	P7	50	≈ 1.0	0	0	18.52	19.34	0.36
	P8	60	≈ 1.0	0	0	19.34	27.50	0.43
	P9	70	≈ 2.0	0	0	27.50	47.14	0.57
	P10	80	≈ 1.5	0	0	47.14	52.66	0.57
S2/A	P1	0	0	32	≈ 1.4	0	2.63	1.71
	P2	0	0	32	≈ 2.3	2.63	12.57	1.69
	P3	69	≈ 2.4	0	0	12.57	59.82	4.38
S3/A	P1	23	≈ 1.4	69	≈ 1.4	0	34.57	22.14
	P2	23	≈ 2.0	69	≈ 1.4	34.57	45.52	4.46
	P3	92	≈ 1.2	23	≈ 1.2	45.52	48.16	1.45
	P4	92	≈ 1.3	23	≈ 1.2	48.16	61.47	1.17

Note: SB, Sand Bed preparation; L, Location in the GeoModel container as shown in Figure 4; P_IDX, Pile installation InDeX; f_T & A_T, frequency and amplitude of torsional vibration, respectively; f_V & A_V, frequency and amplitude of vertical vibration, respectively v_{max}, maximum penetration speed.

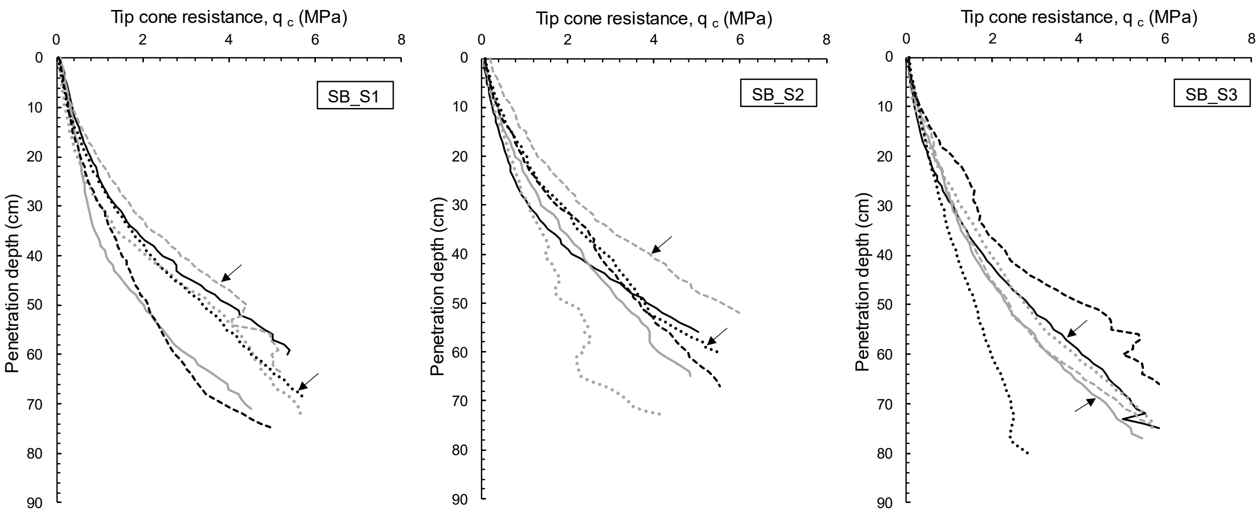

Figure 6. Hand penetrometer tests executed at different locations for sand bed preparations S1, S2 & S3; tip cone resistance against penetration depth.

The results are presented in terms of pile penetration as a function of time in Figure 7, Figure 8 and Figure 9 for the three different sand bed preparations, S1, S2 and S3, respectively. In these figures, the penetration speed against penetration depth is also plotted. For installation run, the changes during pile driving in the maximum single amplitude of the axial and torsional vibration and the corresponding changes in the applied frequencies are shown in Table 2. It should be noted that a set of driving parameters was changing when pile penetration has largely ceased. The pile penetration was measured by means of laser displacement measurements. The amplitude and frequency of both motions of vibration were measured at shaker level with potentiometers.

Figure 7 showcases the effectiveness of the vibratory torsional motion in pile driving in comparison to vibratory motion in the vertical direction only. As can be seen in this figure, the first four pile installation runs (P1, P2, P3 & P4) were performed at low-frequency vertical vibrations (f_V = 23 Hz), accompanied by a progressive increase of the amplitude. This increase had a minor effect in improving driveability with the penetration depth reaching only 58 mm from soil surface. Thereafter, the vertical vibration is deactivated and torsional vibration started with increasing frequency (f_T = 30 Hz up to 60 Hz) while the torsional amplitude, A_T, remained constant (P6, P7, P8, P9). For pile installation P10, both the amplitude and frequency were increased leading to a significant rise in penetration speed. Lastly, the amplitude is reduced again, and the frequency is increased to 80 Hz. It can be concluded that the low-frequency vibrations in torsional direction are beneficial in increasing penetration speed in occasions where low-frequency vibrations in the vertical direction led to refusal. Additionally, the results demonstrate that increasing torsional frequency improves driveability. It should be noted that in the series of pile installation runs shown in Figure 7, optimal performance in terms of maximum penetration speed, was achieved around f_T = 70 - 80 Hz with the relatively low amplitude of A_T = 1.5 - 2.0 mm.

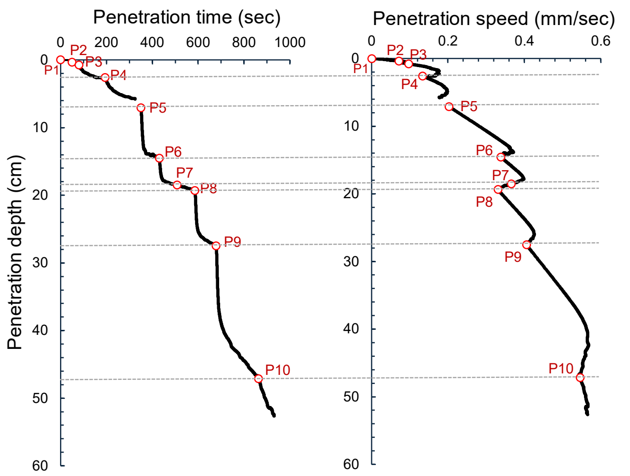

Figure 7. Penetration time and speed against penetration depth; pile installation runs for S1 sand preparation.

For the tests shown in Figure 8, pile driving started once again by considering only vertical vibrations (P1, P2). As was the case with the pile driving runs in Figure 7, with vertical vibrations alone the pile cannot penetrate more than approximately 126 mm. The penetration rate increased significantly, only when the torsional component was activated with driving parameters close to those of the optimal conditions in Figure 7 (f_T = 69 Hz, A_T = 2.4 mm).

Figure 9 presents the results from the last series of tests. Pile driving begun with low-frequency torsional (f_T = 23 Hz) and high-frequency axial vibrations (f_V = 69 Hz) with the same relatively low amplitude for both motions. This set of parameters led to refusal after approximately 35 cm of penetration (P1). As a next step, the amplitude of the torsional vibration was slightly increased (P2). This initiated penetration with a constant, yet lower penetration rate than in the case of the previous parameter set. In the next test (P3), the shaker parameters were changed to align with the founding principle of the GDP technology. That is integration of a low-frequency vertical (f_V = 23 Hz) and high-frequency torsional vibrations (f_T = 92 Hz) with the same low torsional and vertical amplitudes as in the initial pile penetration runs, P1 & P2.

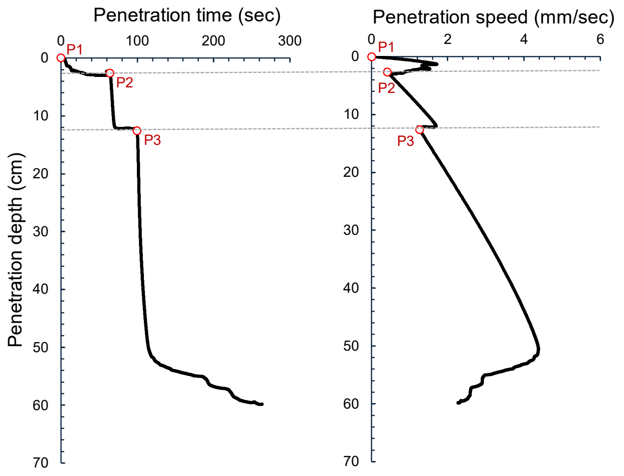

Figure 8. Penetration time and speed against penetration depth; pile installation runs for S2 sand preparation.

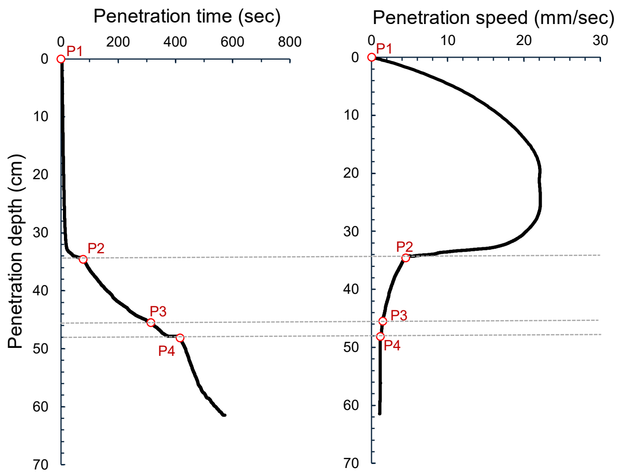

Figure 9. Penetration time and speed against penetration depth; pile installation runs for S3 sand preparation.

This set of parameters resulted to a restart of the penetration process, but refusal is again met almost immediately. Finally, the torsional amplitude is slightly increased, generating an input force that increases the penetration speed significantly. As expected, increasing amplitude is one of the actions that improves driveability. Nevertheless, the selection of amplitude should be done in accordance with the selection of the overall dynamic inputs as to improve driveability and reduce power consumption (Gómez et al., 2024). It should also be noted that for testing, as shown in Table 2, frequencies of torsional vibration in the range of 0 – 100 Hz were used, mimicking what can be applied in practice for full-scale monopiles.

5 CONCLUSIONS

A newly developed GDP lab-scale shaker has been mobilized that allows for independent control of the amplitude and frequency of two modes of vibration: torsional and vertical. The performance of the shaker was tested by means of lab-scale pile driving tests on dense sand. The main experimental evidence presented in this paper is summarized as follows:

- Use of low-amplitude vibrations at higher frequencies can improve efficiency in pile driveability, particularly when torsional vibration is used as the main driving mechanism.
- The above conclusion highlights the importance of frequency-amplitude decoupling in vibratory driving.
- The independent control of dynamic frequencies and amplitudes is a stepping stone towards automatization of the pile driving process. In automatization, the dynamic inputs shall be optimized as to enhance installation performance and reduce environmental impact.
- Lab-scaled testing on conditioned soil provided a successful platform for testing and validating the GDP 1.2 technique, enabling innovation and proof of concept for larger-scale applications.

AUTHOR CONTRIBUTION STATEMENT

M. Konstantinou: Writing- Original draft, Investigation, Visualization. **S.S. Gómez**: Writing- Original draft, Conceptualization, Project administration, Investigation, Visualization, Methodology. **A.V. Metrikine**: Supervision, Conceptualization, Writing- Reviewing and Editing. **R. van den Berg:** Investigation, Writing- Reviewing and Editing. **A.S. Elkadi**: Writing- Reviewing and Editing.

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