Seabed response to wave-induced loading around a monopile foundation: insights from physical modelling

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ABSTRACT: Wave-seabed interaction around offshore monopile foundations significantly influences seabed dynamics and foundation behaviour. In particular, the development of wave-induced pore pressures under irregular wave loading requires further investigation to assess seabed behaviour under more realistic wave conditions. This paper presents experimental results on wave-induced pore pressures in the seabed surrounding an embedded, scaled monopile subjected to both regular and irregular waves. Tests were conducted under a range of wave heights, wave periods and water depths. Pore pressures were measured at several locations and depths around the monopile. Comparisons between regular and irregular wave tests show that regular waves provide a reasonable approximation of the seabed response when significant pore pressure values are considered. In contrast, the maximum pore pressures induced by irregular waves are substantially larger and can be up to nearly twice those obtained under regular wave loading. Comparisons with field pore pressure data confirm that the experiments reliably capture the wave-induced component of the seabed response, highlighting the relevance of the findings for offshore design applications.

1 INTRODUCTION

The growing reliance on offshore wind energy has highlighted the need for reliable foundation designs, particularly monopiles, which are widely favoured for their construction simplicity and industrial scalability. However, these foundations are subjected to complex wave-structure-seabed interactions, where the stability is influenced not only by wave loads but also by the surrounding seabed's response (Stuyts et al., 2023).

Several experimental studies have investigated wave-induced pore pressure responses in the seabed around monopile foundations. Wave flume experiments by Wang et al. (2019) showed that pore pressures under regular waves are largest near the seabed surface and decrease with soil depth, with both wave height and wave period strongly influencing their magnitude and spatial distribution. Diffraction effects were observed to cause pressure concentration in front of the monopile near the seabed surface. Building on this work, Zhang et al. (2020) examined pore pressure responses under irregular long-crested wave loading using different wave spectra and reported increasing pore pressures with increasing wave height and wave period. Their results indicated that irregular waves can induce larger pore pressure responses than equivalent regular waves when maximum values are considered. Further experimental work by Chen et al. (2022) showed that irregular wave loading, particularly when combined with currents, leads to higher pore pressure responses concentrated in the upper seabed. More recently, Gkougkoudi-Papaioannou et al. (2025b) conducted wave basin experiments under regular wave loading and examined the influence of wave parameters and water depth on pore pressure development around a monopile.

Despite these advances, most experimental investigations have been conducted in two-dimensional wave flumes, where boundary effects can influence the wave field and the resulting pore pressure response around the monopile. Previous studies have generally focused only on maximum pore pressures obtained over relatively short test durations and have not considered significant pore pressure measures. Moreover, direct comparisons between regular and irregular wave loading have been limited. To address these aspects, physical model tests were performed in a wave basin to study how varying wave conditions influence pore pressures in the seabed surrounding a monopile foundation. The experiments focused on the impact of regular and irregular waves, which better represent realistic offshore conditions. This study presents a comparison of the pore pressures under regular and irregular wave loading, as well as a comparison of experimental results with field pore pressure data.

2 EXPERIMENTAL SETUP

The experiments were conducted at the Coastal & Ocean Basin (COB) in Ostend, Belgium, a hydrodynamic testing facility with dimensions 30.0 x 30.0 x 2.3 m (L x W x H) and a circular central pit with an adjustable depth of 3.1 m. A stainless-steel cylinder was used to represent the monopile foundation and was installed in the central pit, which was filled with poorly graded medium sand dredged from the North Sea (Figure 1). The sand was compacted in six layers using the undercompaction methodology suggested by Ladd (1978). Ladd (1978) presented undercompaction guidelines for small scale geotechnical tests and, therefore, the steps of their methodology were modified to align with the scale of the COB experiments. The preparation of the sand in this study, aimed at replicating in-situ seabed conditions, as presented in Stuyts et al. (2023). Cone penetration test (CPT) data from the prototype site showed cone resistance values of approximately 15 MPa in the upper 3 m and increasing to 30-40 MPa, indicating a transition from medium-dense to very dense sand. Therefore, a high degree of compaction was targeted in the physical model tests to reflect in-situ conditions and achieve a representative relative density.

The experimental setup included four arrays of wave gauges to monitor both the incident wave conditions and the water surface elevation around the monopile (Figure 2). Pore pressure sensors were placed at three depths below the mudline and positioned around the monopile (front, sides and back) to capture high-resolution data on wave-induced pore pressure variations (Figure 3). Three different water depths over an horizontal foreshore were examined, each subjected to varying wave heights and wave periods, under both regular and irregular wave conditions using the JONSWAP spectrum. The tested wave conditions are shown in Table 1. Further details on the scaling considerations, experimental setup and the testing conditions can be found in Gkougkoudi- Papaioannou et al. (2025a, 2025b).

Figure 1. Overview of the experimental setup including the monopile, wave gauges, anchored ropes and filled central pit.

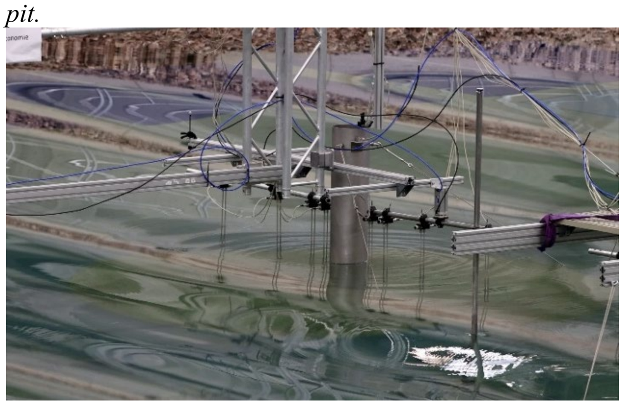

Figure 2. Overview of the experimental setup in the filled wave basin including the monopile and wave gauges.

Table 1. Target wave conditions.

Test No.	d (m)	H (m)	T (s)	L (m)
TS01	1.388	0.114	1.226	2.35
TS02	1.388	0.176	1.452	3.26
TS03	1.388	0.189	1.442	3.22
TS04	1.388	0.203	1.503	3.48
T01	1.20	0.10	1.40	3.02
T02	1.20	0.12	1.40	3.02
T03	1.20	0.16	1.40	3.02
T04	1.20	0.16	1.80	4.67
T05	1.20	0.16	2.20	6.30
T06	1.00	0.10	1.40	2.97
T07	1.00	0.12	1.40	2.97
T08	1.00	0.16	1.40	2.97
T09	1.00	0.16	1.80	4.48
T10	1.00	0.16	2.20	5.93
T11	0.80	0.10	1.40	2.88
T12	0.80	0.12	1.40	2.88
T13	0.80	0.16	1.40	2.88
T14	0.80	0.16	1.80	4.21
T15	0.80	0.16	2.20	5.48

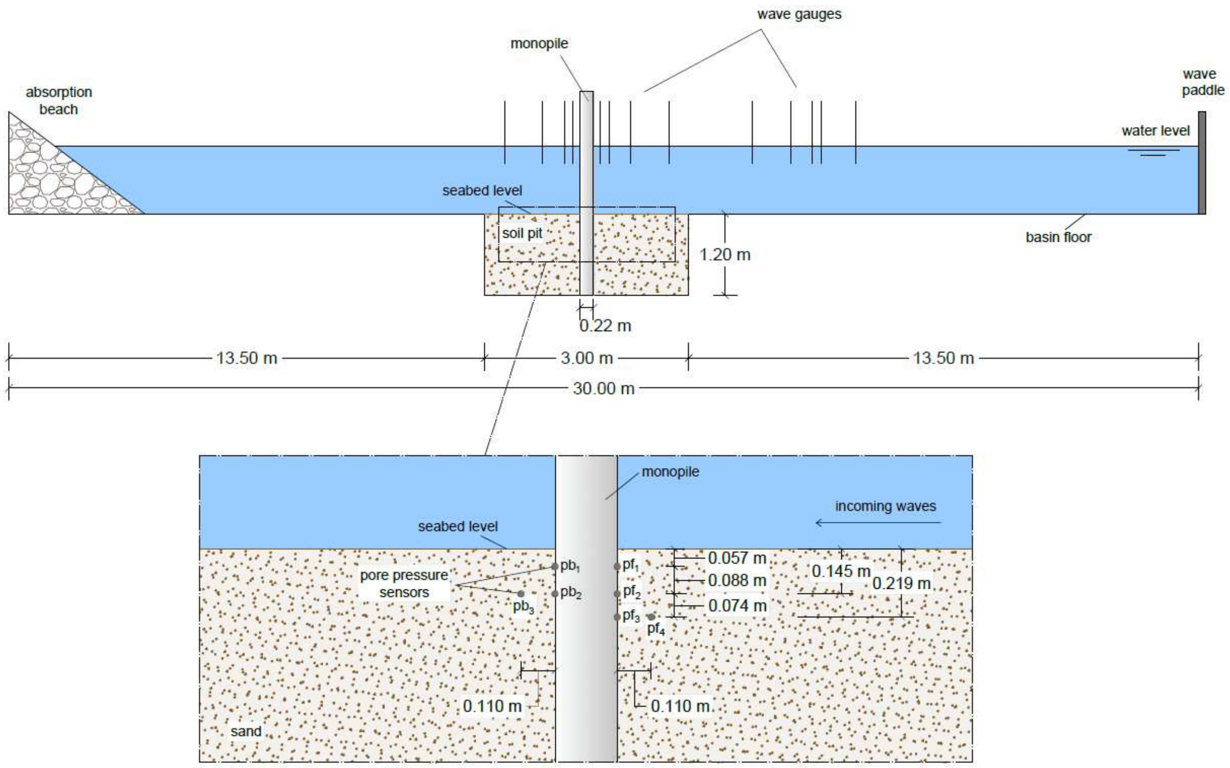

Figure 3. Cross-section of the experimental setup including the pore pressure sensors and wave gauges positions.

3 RESULTS AND DISCUSSION

3.1 Experimental results

To evaluate the seabed response, the analysis of pore pressures was carried out using two complementary metrics. First, the spectral significant pore pressure height P was calculated from the zero-th spectral moment, analogous to the definition of spectral significant wave height H_{m0}. Second, the maximum pore pressure height P_{max} was obtained from direct time series analysis. For regular waves, only the time series approach was applied, given the monochromatic nature of the loading. In this case, the pore pressure height is defined solely as P, with no distinction made between significant and maximum values.

Figure 4 compares the pore pressure time series under regular and irregular wave loading measured at the cross section in front of the monopile, for a test with wave height H=0.16 m, wave period T=1.40 s and water depth d=0.80 m (test T13). The figure also indicates the pore pressure amplitude under regular waves and the spectral significant pore pressure amplitude under irregular waves, $p=P/2$, as well as the maximum pore pressure amplitude, $p_{max}=P_{max}/2$. Distinct differences are observed between the two cases. Unlike regular sinusoidal waves, which maintain nearly constant wave heights and constant cyclic pore pressure fluctuations, irregular waves exhibit variable wave heights, including intermittent high-energy events. These high-impact waves cause abrupt peaks in pore pressure within the seabed, generating localised and transient responses that cannot be reproduced by regular wave loading. As shown in Figure 4, the maximum pore pressure amplitude p_{max} under irregular waves is about 1.65 times larger than the pore pressure amplitude p under regular waves for this test. On the other hand, the spectral significant pore pressure amplitude p under irregular waves is comparable to the pore pressure amplitude p under regular waves. This suggests that, when the spectral significant pore pressure amplitude p is considered, regular waves can serve as a simplified approximation for the wave-induced seabed response.

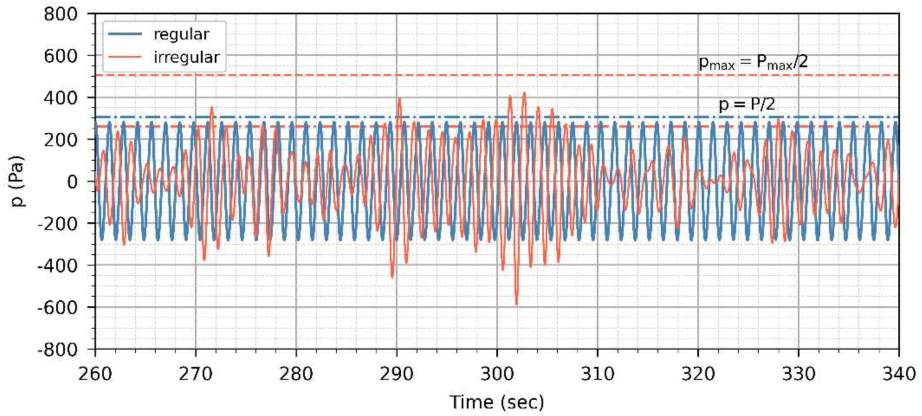

Figure 4. Comparison of pore pressure time series under regular and irregular wave loading at the front cross-section for tests with H=0.16 m, T=1.40 s and d=0.80 m (T13).

This observation is further examined by comparing the results obtained under regular and irregular wave loading for tests with a target wave height of H=0.16 m. Figure 5 presents a comparison of the non-dimensional pore pressure height under regular waves and the non-dimensional significant pore pressure height under irregular waves, $P/(\gamma \cdot H)$, as a function of wave period at the front cross-section. It can be seen that, for most of the tested wave conditions, regular and irregular waves induce comparable pore pressure responses. For a wave period of T=1.80 s, however, regular waves result in higher non-dimensional pore pressure heights at this cross-section. In both cases, the non-dimensional pore pressure heights increase with increasing wave period and decreasing water depth, indicating a consistent dependence of the seabed response on both wave period and water depth under regular and irregular wave loading.

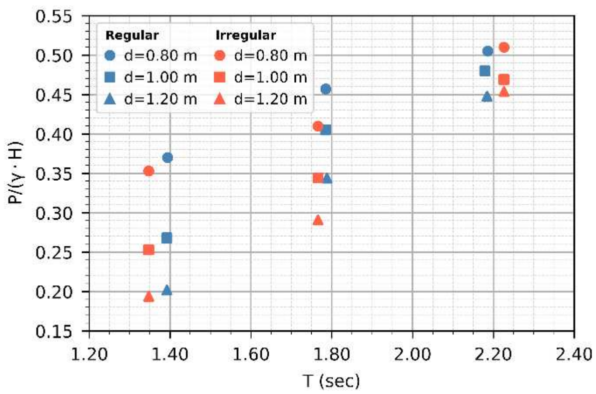

Figure 5. Non-dimensional pore pressure height as a function of wave period for tests with H=0.16 m at the front cross-section under regular and irregular waves.

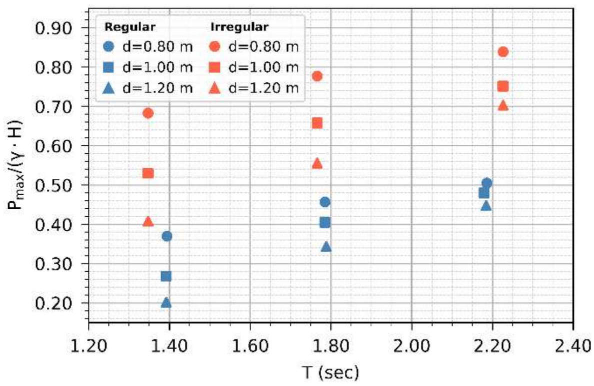

Figure 6. Non-dimensional maximum pore pressure height as a function of wave period for tests with H=0.16 m at the front cross-section under regular and irregular waves.

A similar comparison for the maximum pore pressure heights is shown in Figure 6. In contrast to the significant values, the maximum pore pressures induced by irregular waves are substantially larger than those obtained under regular waves. In several cases, the maximum pore pressure under irregular wave loading is nearly twice as high as that under regular wave conditions, with the largest differences observed for longer wave periods. This highlights the importance of extreme wave components in irregular seas, which are not captured when considering only regular wave loading. P_{max} captures the largest individual pore pressure peak within a record of roughly 1000 waves, whereas P reflects the characteristic pore pressure response associated with the highest one-third of waves in a given sea state. As such, P_{max} is more directly related to short-term extreme loading that may contribute to localised instability or liquefaction, while P provides a representative measure of the overall seabed response under the considered wave conditions. Both parameters therefore provide useful but different perspectives on seabed response.

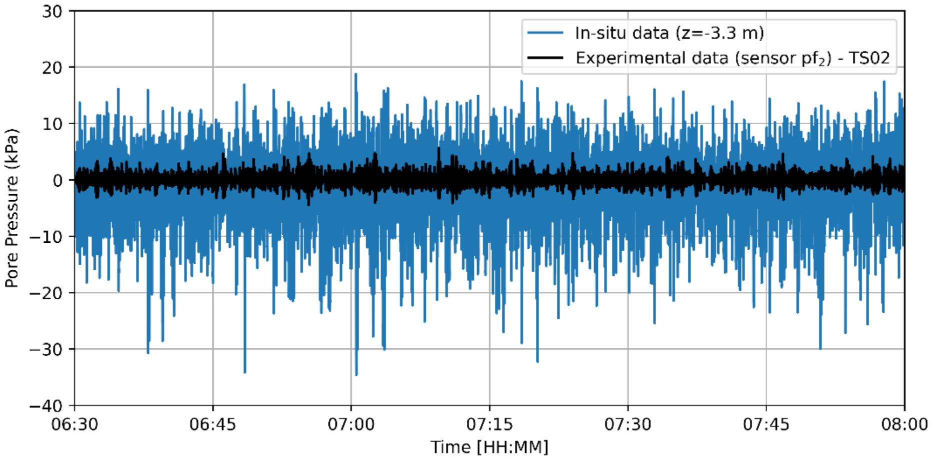

Figure 7. Comparison of in-situ pore pressure data from Stuyts et al. (2023) (Episode 3) with scaled experimental data from test TS02.

3.2 Comparison with field data

To assess how experimental findings translate to real world conditions, model-scale pore pressure measurements are compared with field pore pressure data reported by Stuyts et al. (2023), considering the same sandy sediment; further details on the sand properties and installation procedure are provided in Gkougkoudi-Papaioannou et al. (2025a). Field measurements represent fully operational conditions, incorporating the combined effects of wave and wind loading and structural dynamics, while the fixed-monopile laboratory configuration is particularly relevant to the installation phase of offshore wind turbine foundations, when structural movement is limited. Therefore, the pore pressure behaviour across different phases of a foundation's lifecycle can be assessed.

The recorded pore pressures from test TS02 with d=1.388 m, H=0.176 m and T=1.452 s are converted to prototype scale using a 1:23 scaling factor. This results in prototype conditions of d=31.70 m, H=4.00 m and T=6.94 s. Test TS02 was chosen as it corresponds to wave heights observed during a one-day storm episode (Episode 3) in the reference study, where significant wave heights ranged between 2 m and 5 m. Figure 7 compares the scaled pore pressure time series from test TS02 with the in-situ time series from the selected storm episode over a representative time interval. The comparison focuses on sensor pf_2, which corresponds to a prototype sensor located at z = -3.3 m. The field measurements show that negative excess pore pressures generally reach higher amplitudes than positive ones. Even so, both datasets display similar transient pore pressure patterns, and neither indicates a gradual buildup of pore pressure over time. This suggestes under the examined conditions the seabed remains in a drained and cyclically stable state. The field-recorded pore pressures are approximately 3 to 5 times larger than those measured in the laboratory. This is expected, as the in-situ data include additional effects from external loads and monopile motion, whereas the experimental setup, where the monopile is rigidly fixed, captures the wave-induced pore pressure component only.

4 CONCLUSIONS

This study investigated the effects of regular and irregular wave loading on pore pressures around a monopile foundation in a sandy seabed. The analysis focused on both the significant and maximum pore pressure heights, providing insight into how these responses vary with wave conditions. While significant pore pressures were comparable between regular and irregular wave conditions, irregular waves produced substantially higher maximum pore pressures. This indicates that regular wave conditions can serve as a simplified approach in certain modelling contexts, while irregular waves need to be considered when predicting extreme seabed responses.

Both measures increase with decreasing water depth, with tests at shallower water depths producing higher pore pressures. Additionally, the results show a dependence of the seabed response on the wave period: for both regular and irregular waves, significant and maximum pore pressures generally increase with increasing wave period.

Comparison with field data confirmed that the experimental measurements reliably capture the wave-induced pore pressure component. The field records exhibit higher pore pressure magnitudes, due to additional load-induced pore pressure response in the seabed by the dynamic loading imposed by the monopile. Cumulative pore pressure build-up was not observed under the examined conditions, suggesting that the seabed maintained a drained and cyclically stable condition under the tested wave loading scenarios in Belgian North Sea sands.

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