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Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
- Short Call 2020, Final Report -

Lead Applicant Name	Dr. David Igoe
Host Organisation name	Trinity College Dublin
Project Title	Pile Ageing Study for Offshore Wind Applications
Contract Number	2020-sc

This report covers the period 1st December 2020 to project end date 3oth June 2022

2. **(a) Project information**:

Final project report (*max 2500 words, excluding figures and headings*):

Executive summary (lay abstract, approx. 250 words):

In order to achieve the greenhouse gas emissions targets set out in the Paris agreement, Ireland will need to significantly decarbonise its energy supply. Due to reducing costs, offshore wind now offers the most viable means for large scale decarbonisation of Irelands electricity supply by 2030. The new program for government 2020 has targeted 5GW of offshore wind capacity to be installed by 2030 at an estimated cost of more than €10 billion. At the end of 2019 there was 22 GW of offshore wind installed in Europe, mainly in areas near shore with favourable shallow water conditions. The foundations of an offshore wind turbine can represent up to 25% of the overall cost of development and more than 90% of offshore wind turbines installed to date are fixed to the seabed using steel piled foundations. This project investigated pile ageing effects, one of the key challenges facing offshore foundation designers. The investigation was undertaken through a combination of novel field and laboratory testing and the results indicate that the rate at which pile capacity increases appears to be independent of pile diameter, which is an important step in enabling the use of ageing factors for large scale offshore piles. The finding of this project significantly advance the scientific knowledge of pile ageing and will result in improvements in the design efficiency of Offshore Renewable Energy.

- Results, scientific/engineering targets reached beyond the state of the art and conclusions

The author previously identified the potential key mechanism controlling pile ageing to be related to enhanced interface dilation due to (i) chemical processes initiated from particle breakage during driven pile installation and (ii) a slow recovery of the stress regime in the ground from pile installation through soil creep. The main objectives of this project was to undertake a new suite of pile field tests to better quantify the mechanisms of pile ageing and potential scale affects which may influence the ageing process.

The field tests were undertaken at the Geotechnical research test bed located in Redbog near Blessington, Co. Wicklow. A satellite image of the location is shown in Figure 1. The site is

situated on an active Roadstone quarry, approximately 2km outside of the town.

Figure 1: Redbog quarry location

Previous areas used for research in Redbog (known as sites 1 and 2 [1]) were no longer available and therefore a new site within the quarry needed to be selected and characterised. Following a site walkover of various potential locations, a new site approximately 100m from the site 1 was selected (referred to as Site 3, shown in Figure 2).

Figure 2: Location of new site 3 relative to previous locations

A ground investigation (GI) was carried out at Blessington test site 3, between the 18th - 20th November 2021. The breakdown of the investigations are detailed as follows:

- 1 no. Trial Pit Investigation (18/11/21)
- 22 no. Cone Penetration Tests (CPTu) tests (18/11/21 - 20/11/21)
- 3 no. Seismic CPTu (SCPTu) tests (20/11/21)

The trial pit, shown in Figure 3, shows that the ground consists of a thin strata of topsoil (<1m) overlaying dry dense sand material to >7m below ground level.

Figure 3: Trial pit a Blessington Site 3 (from Gallagher 2022)

In total 22 CPTu tests were undertaken by site investigation contractor In-site SI. A description of the equipment, methodology and results are detailed in the following subsections. GPS locations of the CPT points were recorded following the GI. A map was generated in QGIS using these GPS points by Gallagher 2022, as shown in Figure 4.

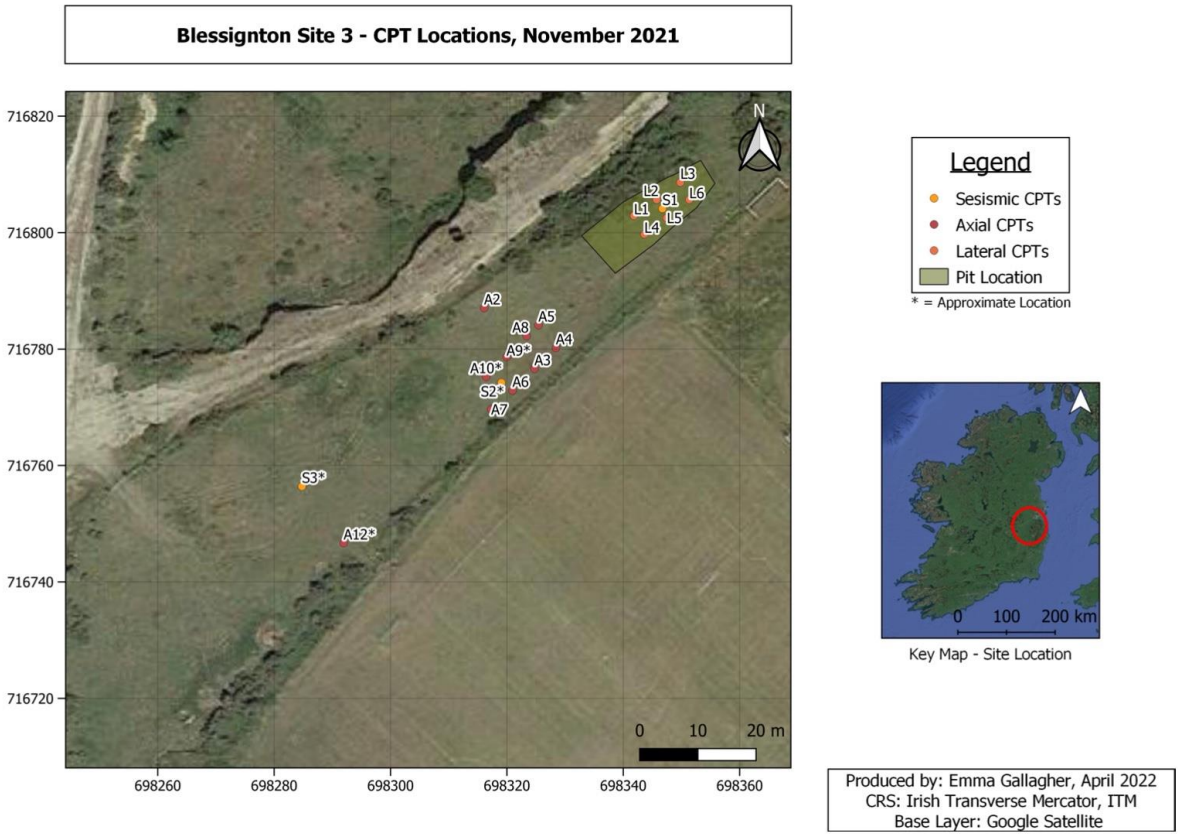

Figure 4: CPT Testing Locations Site 3 (from Gallagher 2022)

A 20 tonne track-mounted CPT rig was used for the tests at the Blessington site. The rig and CPT cone used is shown in Figure 5.

Figure 5: (a) CPT rig and (b) CPT cone used for site 3 ground investigation (from Gallagher 2022)

The pile tests were undertaken in the locations of CPTs A3 – A10 as shown in Figure 4.

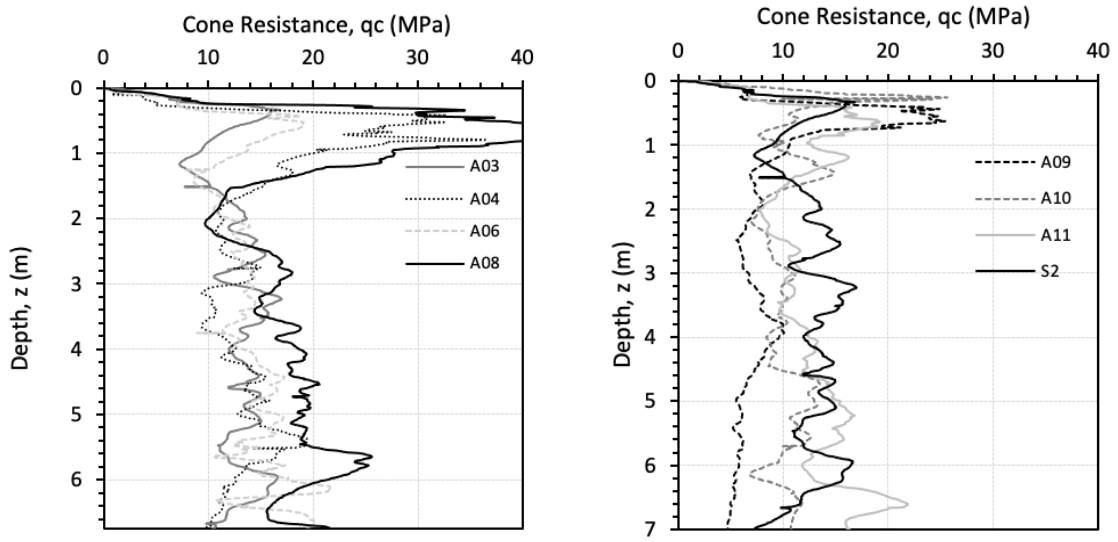

Figure 6: CPT profiles for (a) large diameter pile tests and (b) small diameter pile tests from Blessington site 3

In addition to the CPTu profiling, 3 Seismic CPTs (SCPTu) were undertaken in order to measure shear wave velocity profiles across the site. The shear wave velocity (v_s) and maximum shear modulus (G0) measured from site 3 are shown in Figure 7.

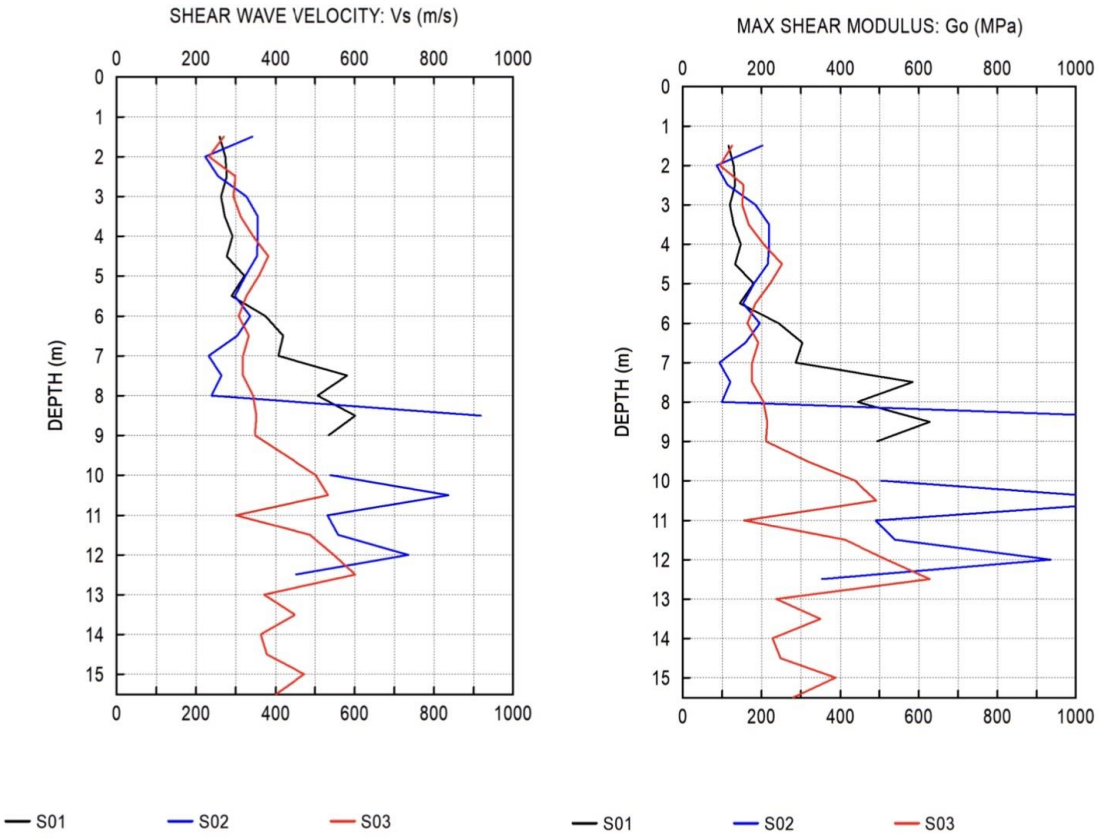

Figure 7: (a) Shear wave velocity (v_s) and (b) maximum shear modulus (G_0)

Following the ground investigation, four 457mm diameter open-ended steel pipes and four 219mm diameter open-ended steel pipes were driven to investigate the effect of ageing on pile axial capacity (piles shown in Figure 8). All piles were 7.2m in length and intended to be driven to a final embedment depth of 6.75m below ground level. All piles had a constant wall thickness of 6.35mm.

Figure 8: Open-ended steel piles used in testing

The piles were installed by impact driving on 27/04/2022 using a 4 tonne Junttan (HHK4) piling hammer. During installation, dynamic Pile Driving Monitoring (PDM) was undertaken by Lloyds acoustics (see Figure 9). For this, each pile was instrumented with a pair of strain gauges and a pair of accelerometers near the pile head. These sensors are mounted on the two opposite faces of the pile shaft near the pile head. The data analysis for PDM is based on field measured dynamic records, sophisticated modelling and numerical techniques, and one-dimensional elastic wave propagation principles. Field testing was done according to the case method procedures as applied with a Pile Driving Analyzer (PDA). Pile Driving Monitoring results include evaluation of hammer/ system performance, dynamic pile stresses, pile structural integrity, and pile resistance and static bearing capacity. Figure 10 shows the installation blow counts vs depth.

Figure 9: Installation of (a) 457mm diameter and (b) 212mm diameter steel piles in Blessington including pile driving monitoring instrumentation

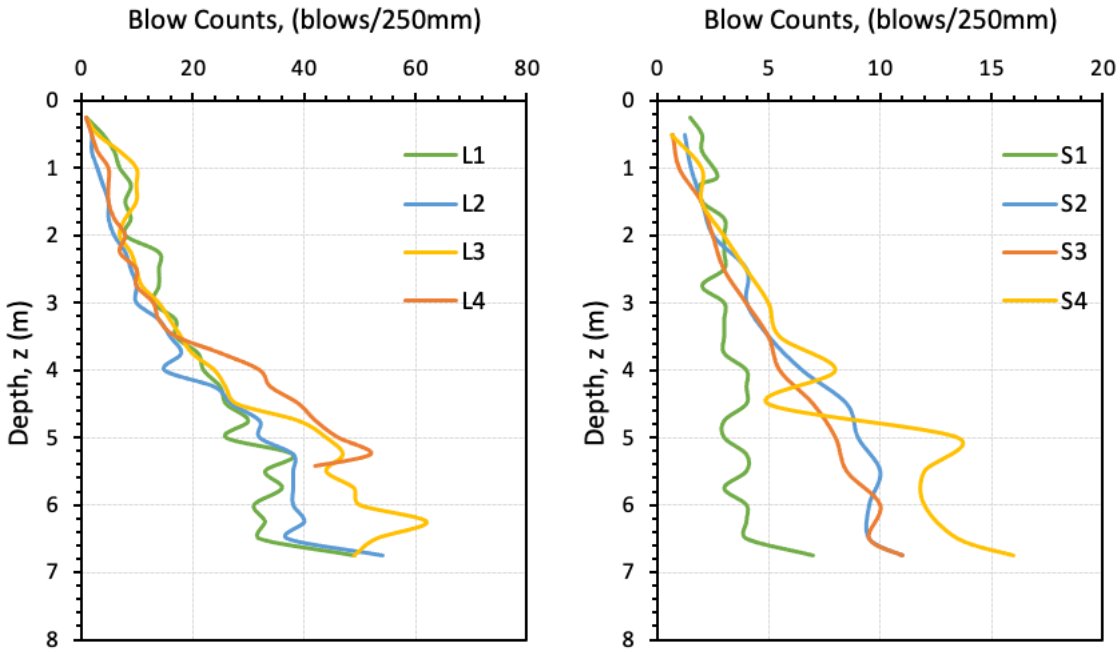

Figure 10: Pile driving blow counts for (a) 457mm diameter and (b) 219mm diameter steel piles in Blessington

All the small diameter (219mm) piles were driven successfully to 6.75m depth with no issues. For the large diameter (457mm) piles, piles L1 and L2 were driven successfully. During

driving on pile L3, below 4.5m depth there was visible distortion of the steel near the pile head (see Figure 11), resulting in off-centre hammer blows and uneven transfer of energy into the pile. Despite this damage to the head of pile L3, the pile was able to be installed to the target depth of 6.75m, albeit requiring a larger number of blows than piles L1 and L2. Pile L4 experienced similar issues, with more severe distortion noted once 5m of penetration had been achieved. For pile L4, it was decided to stop the pile driving at 5.4m below ground level in order to prevent damage to the piling hammer.

Figure 11: Damage to pile head for (a) Pile L3 and (b) Pile L4 in Blessington

Following pile installation, the piles were load tested in tension to measure the pile shaft capacity at different time intervals after driving. One of each pile diameter was load tested at 1 day, 15 days and 85 days after installation. Further testing (1 year age) is scheduled for summer 2023 but could not be completed in time for this report. In order to load test the piles, a 300 tonne reaction frame was provided by Lloyds acoustics. The frame was placed on 4 concrete blocks and the pile was loaded using a hollow cylinder hydraulic jack. The load was transferred through a high strength steel threaded Dywidag bar which was screwed into a loading nut welded under the pile cap. The loads were measured using a 100 tonne load cell and the displacement were measured using Linear Variable Differential Transformers (LVDTs) attached to an independent reference frame (as shown in Figure 12).

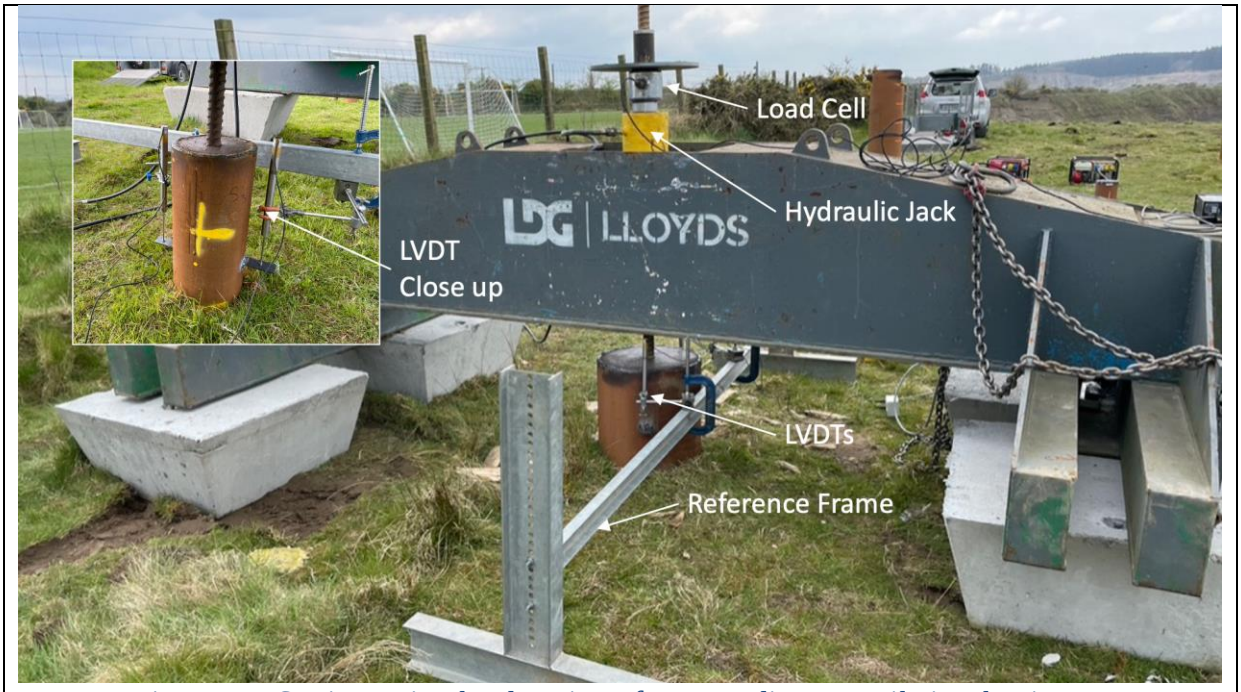

Figure 12: Static tension load testing of 457mm diameter pile in Blessington

Three 219mm diameter and three 457mm piles were load tested on 1, 15 and 85 days after installation. In order to account for variability in the soil CPT profiles for each location, the pile capacities are normalised by the predicted capacity using the Unified Sand CPT method (Lehane et al 2020). These are compared with historic data (from Gavin and Igoe 2021) from Blessington Site 1 as shown in Figure 13. The y-axis data has been removed while awaiting publication. With the exception of two piles, there is a strong ageing trend, with pile capacity increasing 100% from end of driving capacity approximately 1 month after driving. There tests indicate that there is no clear evidence of a diameter dependence of pile ageing, which is encouraging if these ageing trends are to be extrapolated to very large diameter offshore piles.

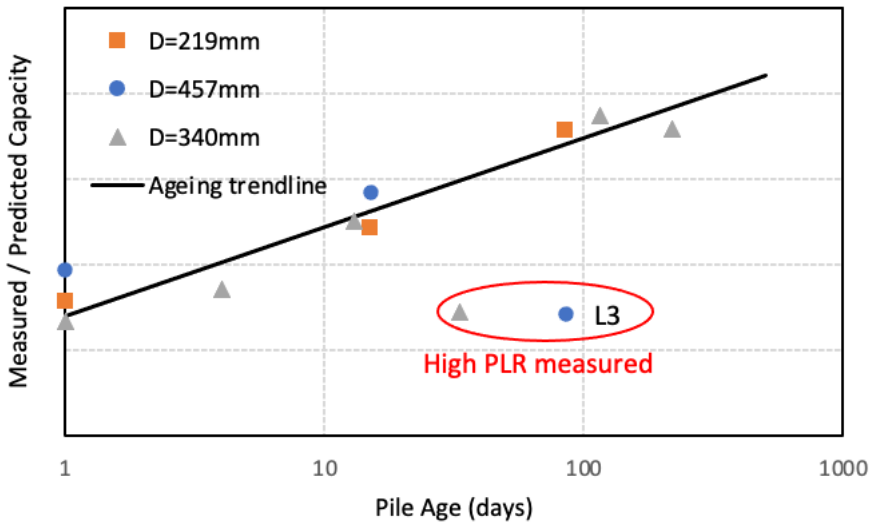

Figure 13: Ageing Trend for piles in Blessington

- Implementation (milestones, deliverables, project management)

The ground investigation for Blessington site 3 was undertaken in November 2021 to ensure the soil material was consistent with other areas of the quarry. After some delays pile Driving was undertaken in April 2022 with pile testing immediately following this until the end of the project.

- Outputs to date

This project will contribute greatly to Geotechnical Engineering and renewable energy R&D in Ireland. The outputs from the project include:

- The characterisation of a new test site (Blessington site 3) which was used for the pile tests described in the report and will be used for future soils and foundation testing.
- A publication for the Journal Géotechnique (world's premier journal in the field of Geotechnical Engineering) is being prepared based on the pile ageing work undertaken during this project.
- The pile installation data from this study is also being used to contribute to a journal paper on pile driveability predictions.
- Publicly available dataset of pile test field data will be hosted on the TCD open access repository (TARA) once the journal paper is published.
- This project was used as the basis for an MAI dissertation – Gallagher (2022).

- Impact

This research project has resulted in improved scientific understanding of pile ageing which is particularly useful for marine renewable energy. It is envisaged that the long term impact of this and subsequent research on pile ageing will lead to adoption of pile ageing factors in design standards used for offshore wind. In the short term, it is accepted that ageing capacity gains will generally not be considered as part of the baseline pile length calculations due to the uncertainty surrounding the mechanism and lack of large scale demonstrators. However, in the short term some limited allowances for pile ageing effects can be used as part of a mitigation strategy in case of pile driving refusal, where the pile capacity can be reassessed with ageing factors in such cases. A similar strategy was adopted for the design of jacket piles for the Beatrice offshore wind farm in the UK (Manceau et al. 2019).

This project further enhances the PI's status as a world leading researcher. This project has also enhanced the PI's potential to participate in international consortia with world leading experts. This project adds to R&D in Ireland and builds on our national capacity and capability to carry out internationally leading research in the offshore geotechnical and wind energy fields.

<u>Refernces</u>

- Gallagher, E. (2022), "Investigation into Pile Axial Capacity and Ageing Effects in Sand", Trinity College Dublin, MAI Dissertation, April 2022.
- Gavin, K., and Igoe, D. (2021). "A field investigation into the mechanisms of pile ageing in sand." Géotechnique, 71(2):120-131 https://doi.org/10.1680/jgeot.18.P.235
- Lehane, B.M., Liu, Z., Bittar, E., Nadim, F., Lacasse, S., Jardine, R., Carotenuto, P., Rattley, M., Jeanjean, P., Gavin, K., Gilbert, R., Bergan-haavik, J. and Morgan, N. (2020). A new CPT-based axial pile capacity design method for driven piles in sand. Proc. 5th Int. Symp. Frontiers Offshore Geotechnics, ISFOG-21, Paper No. 3457. DFI publications, New Jersey.
- Manceau, S., Thurmann, V., Sia, A., and McLean, R. (2019). "Mitigating pile driving refusal risk for a North Sea offshore wind farm through design and installation planning." Proceedings of the XVII ECSMGE-2019, Reykjavik, Iceland, 1–8.

Publications:

- Igoe, D. (2022). "Field experiments on pile ageing in sand", In preparation for Géotechnique
- Igoe, D., Lehane, B.M., Gavin, K.G., (2022) "The evaluation of the Unified Sand method in pile driveability predictions", In preparation for Ocean Engineering