Steel piles driven with Follower in Glacial Till and Chalk

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ABSTRACT

Offshore, pile driving monitoring (PDM) is a well recognised practice which can be employed to control driving behaviour and determine pile bearing capacity. The use of an instrumented follower to perform pile driving monitoring and pile testing activities is less common due to the higher complexity of signal interpretation. However, PDM presents advantages in terms of cost optimisation during construction and testing activity, particularly in cases where the piles are driven below water and validation is needed for a large amount of piles.
This paper aims to present the testing procedure, the main field observations during pile driving activities and some examples of the interpretation of signals recorded during driving, of a vast pile driving campaign carried out on hollow cylindric piles of 0.61m OD and length variable between 14m and 22m. These piles were mainly driven in glacial till deposits overcoming chalk.
A follower was used to drive the piles to target penetration with the aim of avoiding the use of an under-water hammer and sensors. This mobile add-on pile section was designed to allow operations in a water depth of approximately 20m. On a pre-defined number of piles, strain gauges and accelerometers were installed on the external shaft of the "test piles", and placed at two different levels respectively, at the top of the follower and the pile. This allowed the strains and accelerations to be measured at different levels, assessing energy losses between the pile and follower system.
Signal matching analysis procedure at both instrumentation levels was used to define the follower and pile behaviour while driving. This allowed the use of the instrumentation at only the follower top for the majority of the other tested piles.
Most of the piles were driven in glacial till deposits, and signal matching analyses performed at the end of continuous driving evidenced a high variability in space of the estimated static soil resistance to driving. Short and long-term restrikes were performed to estimate the long-term pile capacity, evidencing a relevant gain in terms of back-analysed static resistance only after a significant waiting period.
In some locations, the pile tip was entering by 1/3 of the pile shaft within chalk deposit. On these piles, the long-term capacity was also estimated. Recorded signals after a short term restrike or driving interruption evidenced a fast evolution of the interface behaviour. An increase of pile bearing capacity is proven with long-term restrikes as well.
This paper discusses the main findings of this pile driving testing campaign, with focus on the functionality of an instrumented follower to drive piles in shallow water.
Understanding the hammer/follower/pile/soil system in detail enables to instrument the follower rather than the pile top and allows the validation of a large number of piles in both a cost and time effective way.
Soil plug measurement was performed on all tested piles to check the global behaviour of the pile and soil while driving, and supporting hypotheses used for the signal matching analyses.

Keywords: follower, driven pile, chalk, glacial gill, set-up, pile, driving, monitoring.

1 INTRODUCTION

Installation and validation of underwater foundations in shallow waters require a complex management, especially when piles are not designed to have sufficient stick-up length above seabed level at the end of the installation. To drive piles to their target penetration, underwater hammers are required, which are not always a cost-effective solution. More than for the installation itself, the technical issues are increasing when pile capacity validation is required as this entails the installation of dedicated sensors on piles. Pile driving monitoring (PDM) has been proven for years to be a beneficial solution to estimate the pile axial capacity compared to the more expensive and time demanding solution of performing static pile testing. However, the underwater equipment for PDM in such configuration is impacting the overall cost of the pile testing campaign, being the sensors lost at the end of driving.

A pile driving monitoring programme was commissioned in Danish waters to validate piles design and capacities for three piers and one pylon foundation of a new bridge. Piles behaviour assessment during continuous driving, with a particular focus on the long-term pile capacity estimation, was required during this testing campaign to validate the foundation design.

The foundation, made of hollow steel cylindrical piles with 0.61m outer diameter, were driven with a hydraulic hammer until their target penetration (of about 14 to 20m below seabed level). At the top of the piles a gravelly layer was placed after the installation to allocate then the piers foundation on their tops.

These piles were driven with no stick-up length at the end of drive and a technical solution was required to extensively monitor and investigate the pile capacity.

They were driven in glacial till and chalk, with a significant variability in thickness and strength of these soils over the site.

A site solution was adopted to find a compromise between technical requirements and cost, by using a long follower specifically made for the project which allowed to drive the piles to their target penetration, without the extensive use of underwater equipment. As well, the system turned out to be a flexible solution to allow PDM and long-term restrikes to estimate the gain in capacity of the driven piles with time.

A pile driving analyser (PDA®) was used to record strains and accelerations from the sensors installed at the top of the follower and of the piles. A commercial software based on 1D stress wave theory was used to process the recorded signals and estimate the axial pile capacity both at the end of driving (EOD) and after a set-up time.

In this paper, the pile-follower solution is discussed, and main findings of the pile load testing campaign are presented.

2 BEHAVIOUR AND MODELING

Different follower types do exist, the most used being mainly cylindrical steel pipes. This "add-on" section is installed on top of the pile and acts as an extension of the driven pile. The same add-on is designed long enough to ensure that the hammer remains above water. The geometry of the follower and its connection to the pile top is a key aspect for the efficiency of the system, and its knowledge is required for a correct use of PDM to estimate axial pile capacity; this because the added section alters stresses distribution and energies transmitted at the pile head. The connection between follower and pile is traditionally made by gravity.

To assess the pile driving behaviour and the pile capacity by applying the 1D stress wave theory it is fundamental to study and model the follower behaviour and its interaction with the pile correctly.

3 PILE TESTING CAMPAIGN

Pile driving monitoring and restrike tests were performed for selected piles at dedicated piers and one pylon of a new bridge project. For each tested location, a minimum of 5 to 8 piles were driven to their target penetration and monitored during continuous driving and after a set-up time. This paper presents the results of two selected locations.

Installation was performed from a barge operating in water depth ranging from 15m to 20m.

At each pier location the first phase of the PDM campaign consisted in the installation of the so called "test pile" which was instrumented both at the pile top and at the follower top with four strain gauges and two accelerometers.

Sensors were all connected through cables to reach safely the pile driving analysers places on the barge deck (PDA® acquisition units). In this case, underwater sacrificial sensors and cables were used to record signals at the pile top, while above water and reusable sensors and cables were used to record signals at the follower top.

The main aim of the "test pile" was to study the overall system behaviour and validate the calculation process to be applied afterwards to the remaining piles, which were instrumented only at the follower top.

The other piles of the tested piers were subsequently driven and monitored easily by using the removable add-on, equipped with the instrumentation placed at the top.

Numerous restrike tests were also planned, for each monitored pile. A minimum set-up time, from 1 day to several weeks/months were considered. The restrike tests were efficiently performed by re-positioning the instrumented follower and the impact hammer at the pile top and connecting the sensors and cables to the PDA® acquisition units.

3.1 Soil type

An extensive in-situ soil investigation campaign was performed along the bridge axis, comprising mainly of cone penetration tests and core-sampling boreholes with associated laboratory tests. At the selected site location two main soil type were identified.

The firsts 10m to 20m were usually characterized by till deposit. This type of soil was mainly a glacial till, clayey like with high content of sand and silt; presence of gravel and cobbles was also documented over the investigated depths. The undrained soil strength (S_u) was tested throughout undrained unconfined triaxial tests and resulted to be in average equal to 100kPa with depth.

Below the glacial till layer, structureless chalk was detected. A cone penetration resistance (q_c) of about 20MPa was measured, with alternated layers and peaks reaching 40MPa.

3.2 Pile test and follower geometries

A total of 23 piles were planned to be monitored. With the proposed solution, only 4 of them were required monitoring by installing sensors both at the top of the follower and of the pile. Their outer diameters were 0.61m, with uniform wall thicknesses ranging between 13mm to 20mm.

To drive the piles, the removable add on (follower) was used with a length of about 22m and an overall weight of about 1.6tons.

A picture of the follower is reported in Fig. 1.

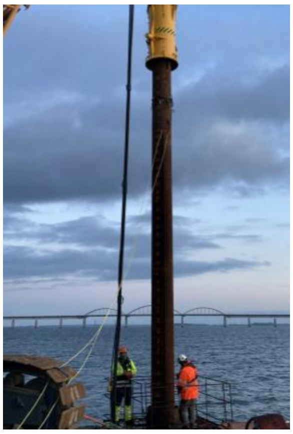

Fig. 1. Follower used for piling activities with above-water instrumentation

4 PILE DRIVING MONITORING

At each pier location the first pile installed was named "test pile" because instrumented at its pile top and at the follower top simultaneously.

A representative 1D numerical model of the pile and follower system was set up and used for signal matching analyses. Comparisons between results obtained from the analyses carried out from signals recorded at pile and at follower top were performed to validate the numerical model.

The model was built to ensure the correct representation of stress and energy distribution along follower and pile. These quantities, and blow counts, were recorded during pile driving and used to perform comparisons. Different driving configurations, both at EOD and restrike (RE), have been studied to ensure the applicability of the process to most of tested piles. Different soil types have been considered, for piles installed in glacial till only or for piles installed in glacial till overlaying structureless chalk. Dependent-less of driving configuration, soil type and pile dynamic behaviour variability, consistency of the results from analyses performed using signals of the sensors installed at pile top and sensors installed at follower top was observed.

By adopting the pile/follower model in the signal matching, pile capacity calculated with signals from pile and follower top sensors resulted in comparable values, with generally less than 2% lower value of pile capacity assessed at follower top. Although this difference could not be directly associated to the driving energy itself, it has been noticed that the greater difference was observed for high hammer energy level and high loss at the follower and pile interface.

The computed energies from the model were captured with an accuracy of 4% when compared to the measured ones. Furthermore, also stresses level at pile top were captured by the numerical model with an accuracy of about 2% over the tests performed.

Energy losses due to follower presence were investigated. Overall, the 1D model reproduced the phenomena well and energies computed from the signal matching process and the measured energies at pile top level displayed similar values (error of +/-1%).

Energy losses at follower/pile interface was observed to range from 2 to 10% with a peak value at 20%. Despite this variability, mainly related to different dynamic response of the soil/pile/follower system, numerical model built was found to reproduced well the phenomena. The instrumented follower methodology and the numerical model have proven their applicability for the analyses where piles were not instrumented. The model returned pile capacities, energies, and stresses in comparable range between signals measured from top of the follower and pile.

This pile/follower model was systematically applied to estimate the pile capacity at end of driving and at time of restrike, by the signal matching technique using the software CAPWAP®.

The following Fig.2 and Fig.3 display respectively examples of the signal matching analyses adopting the pile/follower model built.

The black curve represents the measured reflected signal (so called Wave Up) while the blue dotted line represents the computed reflected signal. A good match is observed, sign of a good representation of the pile/follower/soil system behaviour.

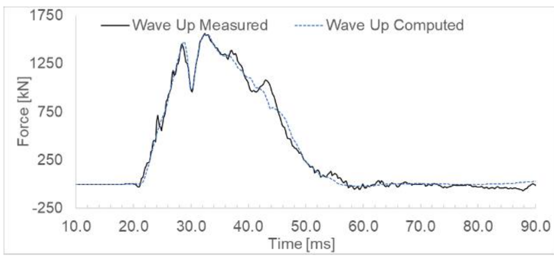

Fig. 2. Example of signal matched at from pile top – Restrike condition.

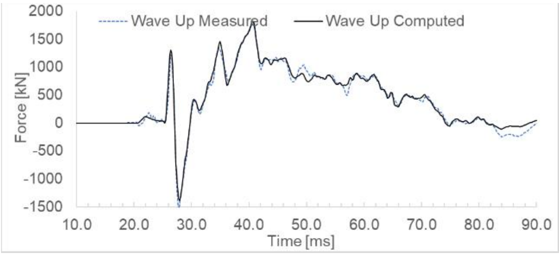

Fig. 3. Example of signal matched at follower top – Restrike condition.

5 EVOLUTION OF PILE CAPACITY WITH TIME

Throughout the testing campaign, the piles have been tested in different driving conditions, allowing investigation into the evolution of the pile capacity with time. It is well recognized that the pile capacity at the end of driving is usually smaller than the long-term one, that can be assessed with static pile testing or by a so called "restrike" test (RE). This is mainly due to soil shaft friction degradation and pore pressure built up which affect the soil mechanical properties during driving.

The estimation of the long-term pile capacity from dynamic pile testing is a key element when validation of foundation capacity is requested. It is important to wisely study a restrike testing plan, allowing to minimize the impact on the overall site construction schedule, and to return as much information as possible.

A restrike test consist in re-striking the pile after a resting period, providing the possibility to the soil to recover its long-term properties.

Depending on the soil type, the required amount of time for the soil to recover its long-term mechanical properties can be highly variable.

This testing campaign allowed to investigate the evolution with time of the pile capacities in piles driven in two main soil profiles: glacial till material only (called hereafter (i)) glacial till overlaying structureless chalk (called hereafter (ii)).

The restrike tests were carried out at different time intervals, from 24 hours to 83 days in glacial till (i), and from 1 minute (driving interruption) to 7 days in layered glacial till overlying chalk (ii). A restrike plan was discussed with the Site Managers to allow coordination between marine means and site constraints, to guarantee a rapid and seamless validation process.

Fig.4 and Fig.5 illustrate the variability of pile capacities at EOD and RE, obtained by the signal matching analyses using the measurements from pile and follower tops (for a total of 16 locations), in soils context (i) and (ii), respectively.

As can be noticed in Fig. 4, an important variability in terms of pile capacity at EOD and RE is observed, for piles driven in glacial till (i), from the results of the 11 locations reported in the figure. Excursion between maximum and minimum estimated pile capacity is around +/-32% at EOD, evidencing how the till soil profile provides a different soil response from location to location.

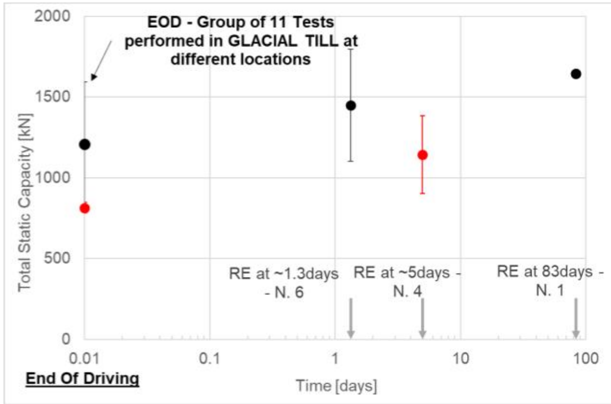

Fig. 4. Pile capacities at EOD and RE conditions in i) glacial till soils.

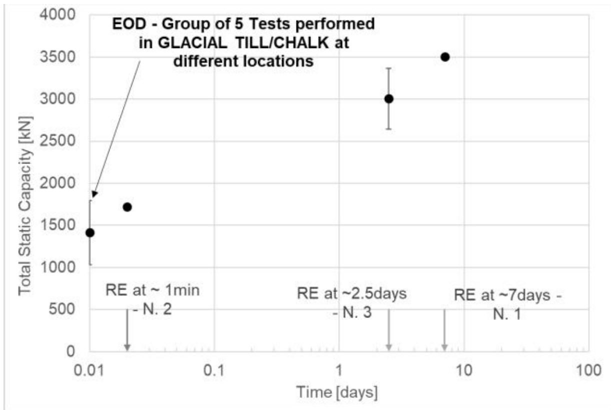

Fig. 5. Pile capacities at EOD and RE conditions in ii) glacial till soils overlaying chalk.

This variability is less marked when results from analyses performed in glacial till overlaying chalk (ii) are considered, however the lower number of tests performed in this soil configuration could impact the trend. Fig.5 highlights an excursion between maximum and minimum pile capacity around +/-27% at the EOD.

Despite the separation of total pile capacity in base capacity and shaft friction is difficult and not fully reliable in the signal matching process, it can be observed that the trend is such that the variation of the end bearing appears limited at the EOD and as well as with time, for both type of soil (i) and (ii). Excursion between maximum and minimum end bearing values is about 10 to 15%.

The skin friction contribute is the main actor in the variability of pile capacity observed at end of drive and over time.

This is highlighted in Table 1 where examples from results obtained for piles embedded in glacial till overlaying chalk are displayed, comparing values interpreted after driving interruption or restrikes to the initial EOD.

Table 1. Estimated skin friction (SF) and end bearing (EB) contributes at the end of continuous driving and at restrike. Glacial till and chalk.

Pile N0.	Waiting time	Cap. gain	Contribute to Total capacity gain		
			SF Till	SF Chk	EB
	[day]	[%]	[%]	[%]	[%]
P1'	0.001	45	-1	102	-1
P1'	1.97	185	45	52	3
F-P1'	0.001	45	-2	101	1
F-P1'	1.97	180	32	62	5
F-P1'(*) (+2m)	*N/A*	*23*	*-2*	*98*	*4*
F-P3'	2.16	155	17	82	1
F-P4'	6.93	147	30	69	2
F-P5'(**)	*2.92*	*80*	*47*	*53*	*0*

(*) Driving restart after interruption. Overdrive of +2m led to full loss of set-up in upper till layer at time of the test.
(**) Low hammer energy and set per blow at RE - Full pile capacity not mobilized.

Globally, restrike tests indicate a shaft capacity increase on piles with time, occurring faster in chalk than in glacial till and this can be attributed to different pore pressure dissipation ability of the two materials.

The comparison of the shaft resistance interpreted from the analysis of a RE with the corresponding EOD analysis on the same pile allows to estimate the gain in pile capacity over time. This gain over time is expressed by the set-up factor.

Set-up factors computed from the tests performed in both soil configurations (i) and (ii) are plotted over time respectively in Fig. 6 and Fig. 7.

Regarding glacial till materials, it is evident that marked variability is observed in the set-up evaluation, as noticed already in the discussion of pile capacity tests. This is observed clearly around 1 and 7 days restrike time. On the contrary, with increasing set-up time, the trend could become steady and overall, the variability less. Indeed, more tests would be required to confirm this trend for long resting time.

In Fig. 6 the tests performed have been interpolated using a logarithmic correlation proposed by Skov & Denver (1988), who defined an equation applicable for various soil types.

Buckley et al. (2020) study was also used, as based on an intensive pile load testing campaign performed in similar soil conditions. Buckley et al. evidenced also an important variability in terms of set-up values and long-term pile behaviour in glacial till. The proposed A and t_0 values to be used in Eq.1 resulting from these studies are used in the Fig.6 and reported in Table 2.

The Eq.1 with A and t_0 values calibrated by Skov & Denver using restrike tests performed in sands, is reported and considered as a lower bound curve.

The equation Eq.1 with A and t_0 values proposed by Buckley et al. (2020) in glacial till fit with the upper bound values.

The logarithmic equation proposed by Skov & Denver (1988) is reported hereafter:

$$Q/Q_0 - 1 = A + Log_{10} t/t_0 \quad \text{(Eq.1)}$$

where Q is the pile capacity at time t (t= time since the initial driving) and Q_0 the capacity calculated at $t=t_0$, t_0 is the time elapsed after initial driving from which the increase in capacity is linear in logarithmic time scale, A an empirical coefficient function of soil type.

Table 2 gathers the A and t_0 values used in Fig.6:

Table 2. A and t0 values used for the curves in Figure 6

	A	t_0 (day)
Skov & Denver (1988) – sand	0.2	0.5
Buckley et al. (2020)	0.4	0.01

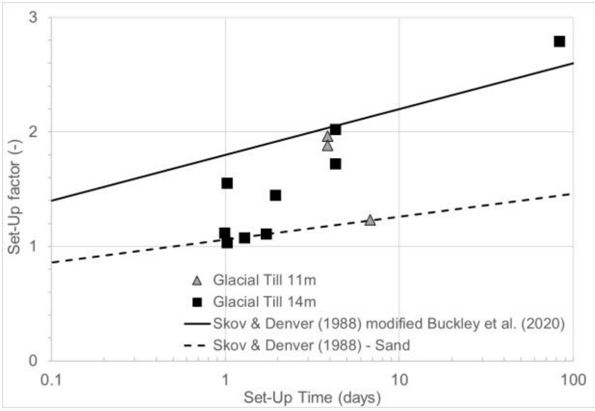

Fig. 6. Shaft friction - set-up from dynamic tests in glacial till

Regarding chalk, the rapid degradation of the shaft friction during pile driving is a well-known phenomenon as well as the trend to under-estimate the long-term pile capacity when using test data from the end of drive. This have been confirmed by the re strike tests performed on piles driven partially in chalk. In the present testing campaign, the piles were embedded in chalk for about 30% of their total embedment, which lead to an h/R* ratio of about 60, h being the relative distance from the pile toe and R* the equivalent solid radius as expressed by Eq.2 below:

$$R* = (R^2 - R_i^{\,2})^{0.5} \quad \text{(Eq.2)}$$

where R and R_i are respectively the outer and the inner radius of the pile.

From the analyses of driving interruptions or short term restrikes, it was noticed that the increase of the pile capacity was occurring faster in chalk than in till. This is supported also from the signal matching performed during an interruption event, where the fast increase in capacity was noticed already after a couple of minutes.

However, it was also noticed that re-driving process after a set-up time, was leading to degradation of the soil resistance, both in till and chalk.

The set-up calculated for the tests performed in layered soils (ii) is presented in Fig.7. The interpolation of these values has been done using the correlation proposed by Tan et al. (2004) for non-cohesive soils that follows the Eq.3:

$$Q(t) = Q_u[\alpha + (1-\alpha)(\frac{\frac{t}{T_{50}}}{1+\frac{t}{T_{50}}}) \quad \text{(Eq.3)}$$

where Q(t) is the pile capacity at time t (t= time since the initial driving), Q_u the ultimate capacity with 100% of set-up realized, T_{50} the time required to realize 50% of the pile set-up and α empirical factor (improving early stage). Adding Q_0 (capacity at time of the initial driving) in the equation, the equation provides the relation of the set-up with time. In this paper, only the shaft component of the pile capacities was used to compute the set-up.

The coefficients proposed by Buckley et al. (2020) for the Eq.3 for piles driven in chalk deposits, have been used and the resulting trendlines are plotted in Fig.7. The Table 3 gathers the variable values used in Eq.3 to plot the trends displayed in Fig.7:

Table 3. Coefficients used in Eq.3 to establish the curves of Fig.7.

	Qu/Q0	α	T_{50} (days)
Buckley et al. (2020) – high h/R*	5.6	0.18	0.02
Buckley et al. (2020) – low h/R*	2.95	0.26	0.07

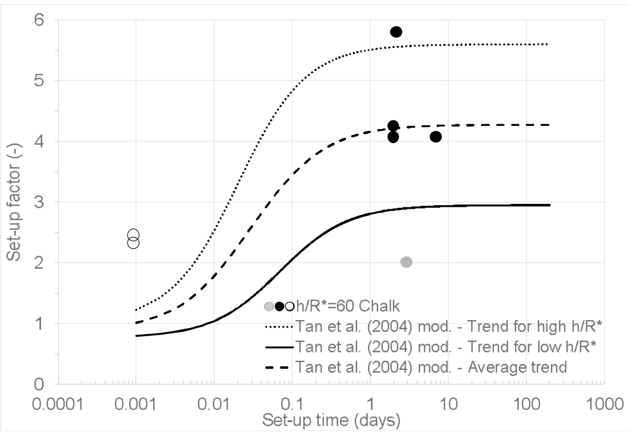

Fig. 7. Shaft friction set-up from dynamic tests in chalk

The trend observed in chalk globally fits with the correlation proposed by Tan et al. (2004) by adopting coefficients suggested by Buckley et al. (2020). The gray dot in the Fig.7 display the data from a restrike on pile P'5 where the hammer energy did not allow to mobilize the full pile capacity, and therefore the set-up factor is under-evaluated. The points located above the correlation in the early set-up stage are issued from the analyses of a driving interruption of 1 minute and 20 second (empty dots). These points highlighted a faster pile capacity evolution in chalk than what expected from the current publications.

6 CONCLUSIONS

The use of an instrumented follower was effective to optimize a pile testing campaign, allowed to perform offshore tests for a large number of piles driven under-water and numerous restrike tests, with reduced amount of underwater sensors. The instrumentation of the follower enabled the reduction of cost of equipment required for the monitoring of about 6 times and avoided extensive use of underwater sensors, keeping a high reliability of the estimate of the axial pile capacity. As well the follower system turned out to be an effective solution, allowing to test additional piles initially not planned without impact on the instrumentation cost.

The quality of the analyses and of the estimate of pile capacity were obtained by an accurate study of the pile and follower system, modelled to obtain a correct energy transfer to the pile and a correct reproduction of measured stresses at follower and pile top for the tuning of the system. This allowed to correctly process the signals and therefore refine the estimate of the pile capacities, by a reverse signal matching process also in case measurements at the pile top were not available.

In this study, the instrumentation of the pile and follower made possible to perform a significant number of tests in the medium term (1 to 7 days), which allowed to establish correlations that were adopted very profitably to estimate the long-term pile capacities for two types of soils. This demonstrated that the instrumentation of the follower is a valuable and reliable technique to carry out long-term restrike tests on under-water piles which otherwise is technically very complex and expensive.

No sensors and cables losses were experienced over the campaign, with 100% of data recorded. Long-term restrikes, planned for the near future on the same piles, can validate the proposed formulations.

Site cooperation in marine environment, resulted in a key element to perform a successful extensive pile load testing campaign, in terms of data quality and results.

7 AKNOWLEDGEMENTS

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