Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Optimised CPT-based Methods for the Prediction of Soil Resistance to Suction-Assisted Penetration

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ABSTRACT: Accurate prediction of soil resistance is essential for the successful installation of suction caissons in offshore environments. Cone Penetration Testing (CPT) is a widely used geotechnical investigation technique that provides insights into soil stratigraphy and mechanical properties. CPT-based methods are available in the recommended practices and in literature for the prediction of soil resistance to suction assisted penetration, however these methods do not explicitly address potentially complex soil conditions such as partially drained sands, silts or heavily interbedded sands and clays, which are common in areas like the North Sea, East Asia and East Coast USA.

This paper briefly discusses methods for the identification of 'transitional' soils, those which cannot be fully aligned with the common behaviour of fine-grained or coarse-grained soils, and focuses on the need for improved prediction accuracy in these challenging conditions by optimising existing CPT-based methodology for assessing soil resistance during suction assisted penetration to explicitly consider flow effects. The proposed prediction methodology integrates data from several offshore trial campaigns, individual caisson installations and large-scale projects ensuring that the proposed methods are robust and grounded in practical experience. The potential effectiveness of installation mitigations such as pressure pauses and two-way cycles are also discussed. Practical recommendations for implementing these methods in real-world scenarios and strategies for mitigating installation risks are also provided.

Keywords: suction caisson, suction installation, suction-induced flow, methodology, transitional soils.

1 INTRODUCTION

Suction caisson foundations are being increasingly considered for offshore wind developments due to potential advantages such as noise free installation, reduced number of offshore lifts (due to integrated sub-structure and foundations), potentially faster installation times (Carbon Trust, 2019) and removability at the end of service.

Suction caisson installation is relatively well understood in 'clean' clays and 'clean' sands; however, complex soil conditions, such as partially drained sands, silts or heavily interbedded sands and clays are considered to pose significant installation risk. Partially drained or 'transitional' soils are defined as those which cannot be fully aligned with the common behaviour of fine-grained or coarse-grained soils and at times also referred to as intermediate or partially drained, this is discussed in detail in Torre et al. (2023).

The aim of this paper is to:

- complement on the guidance for identification and characterization of 'transitional' soils,
- propose a framework for considering drainage in suction caisson installation assessments, and
- Provide some guidance on the application of potential installation mitigations for different soil conditions.

2 STATE OF ART METHODOLOGIES

One of the most popular methods used for suction caisson installation analysis is DNV-RP-C212 (2021) as detailed in Carbon Trust (2019) Suction Caisson Design Guidelines.

The penetration resistance from the DNV-RP-C212 approach correlates the CPT cone tip resistance (q_c) with the penetration resistance via empirical coefficients calibrated on the soil type (binary split either sand or clay).

The DNV resistance coefficients were not derived from suction installation operations; however, it is considered likely that there was some flow through the soil when the water entrained in the skirt chambers was ‘pushed out’ during foundation set down and skirt penetrations. Several authors have proposed methods which consider suction effects, Senders and Randolph (2009) expanded on the DNV approach to include a ‘pressure factor’ which reduces the soil resistance as the applied suction pressure approaches the critical hydraulic gradient for piping. ‘Piping’ is defined as hydraulic failure of the soil where the pressure differential starts to erode the soil forming a pipe shaped discharge tunnel. The critical suction pressure is a function of geometrical parameters, such as caisson diameter and penetration, but also of physical parameters, such as soil weight and degree of compaction (relative density arrangement).

Andersen et al. (2008) used field data from several suction caisson installations to derive empirical values for their proposed coefficients. The range is noted to be significant; and this is considered likely to be due to the differential flow effects in different soils.

Klinkvort et al (2019) expanded on the Andersen (2008) methodology to account for ‘constrained’ flow associated with impermeable layers. However, the Klinkvort method relies on calculation of ‘no flow’ resistance and does not consider partial drainage conditions as those potentially encountered in 'transitional’ soils.

The methods outlined above are considered appropriate for sands and clays. However, uncertainty regarding the flow response often leads to a wide range of coefficients.

3 AUTHOR EXPERIENCE & KEY ISSUES

Authors have extensive experience with installation of suction caissons worldwide including projects in the North Sea, Irish Sea, West Africa and China. The soils at these sites range from ‘clean’ sands through to high strength clays including ‘transitional’ soils. Some key issues that influenced suction installation predictions and operations are discussed in more detail below.

3.1 Soil Variability and Interpretation

Suction caisson installation is sensitive to soil variability. This is especially the case when suction caissons are used for jacket structures, where conditions at each leg need to be assessed and adequately understood. It is common practice for only one exploratory location, CPT or borehole, to be performed per structure. However, lateral soil variability, even at small distances well within the structure footprint, are not uncommon, particularly at sites with complex depositional environments, hence additional survey data may be required to characterise soils across the structure footprint.

When conducting geotechnical design or installation analyses, soil behaviour is generally interpreted either as drained or undrained, which does not always represent the actual in-situ behaviour of the soils and can create installation uncertainties especially for suction caissons that are particularly sensitive to changes in drainage.

Author experience and Bilici et al. (2023) indicate that Robertson (2016) and Schneider et al. (2008) soil behaviour type interpretation frameworks are considered most suitable at identifying ‘transitional’ / partially drained soils. As the CPT pore water pressure measurement is important for these soils, the Schneider et al. (2008) pore pressure chart is generally considered better to identify these, especially when soils exhibit high negative pore pressure. The aforementioned CPT soil behaviour classifications should, where possible, be used in conjunction with tests on physical samples in order to assess the grain size and permeability of the soils under consideration to better understand and or validate soil drainage.

3.2 Commentary on Existing Methodologies

3.2.1 Methodology Comparison

Due to the potential sensitivity of suction caissons to different soil conditions, it is generally advised to consider multiple methods and coefficients for the prediction of the installation requirements. However, such approach could lead to wide resulting prediction envelopes with consequent poor understanding of the potential risks (Figure 1).

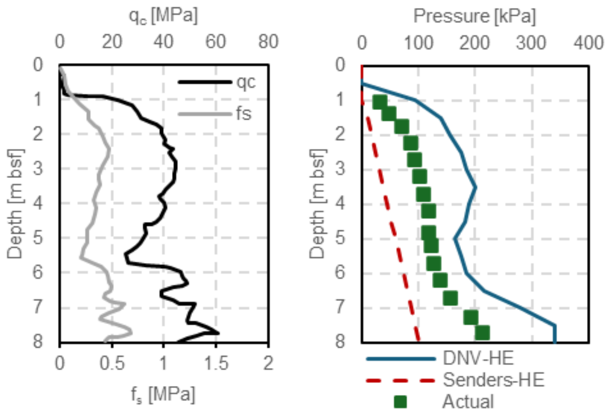

Figure 1. Comparison of predictions and actual pressures

Figure 1 shows a comparison of two methods for a suction caisson penetrating into sand and the actual installation pressure. The Senders methodology provides significantly lower pressure conditions whereas the DNV approach (with standard coefficients) tends to overpredict the recorded installation pressures.

The main difference between these two methods is deemed to be due to the Senders accounting for seepage reducing installation resistance. The Senders resistance reduction is a function of the predicted 'piping' limits which are often 'conservatively' low, therefore any significant pressure will tend to reduce the internal and end bearing resistance to zero. Experience would indicate that the DNV method tends to provide more conservative and accurate predictions especially where site-specific trials have been undertaken to refine the relevant coefficients.

3.2.2 Soil interpretation / sensitivity

Experience would indicate that in 'clean' sands with good flow there is a tendency of similar measured installation pressures irrespective of CPT q_c. This is illustrated by a comparison of data from four different locations with sand of varying relative densities as shown in Figure 2. Pressures and depths are recorded in similar manners for all plots.

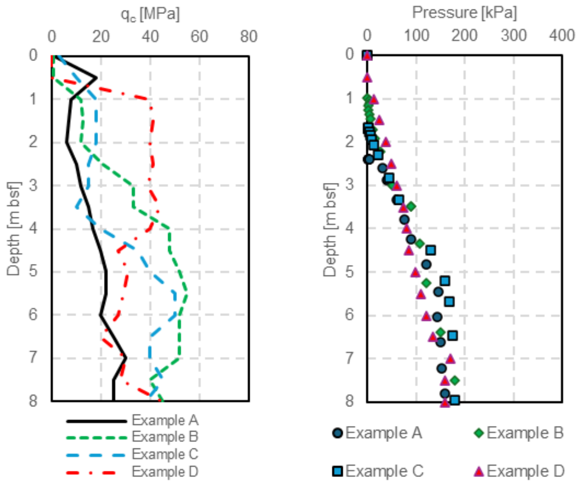

Figure 2. Actual pressures for clean sands with varying q_c

The comparison shown in Figure 2 above indicates a trend for similar pressures despite significant variation in sand relative density as indicated by the CPT q_c values. For example there was a factor between 2.5 and 3 on the increase in CPT q_c between example A and B at 6m but very similar required installation pressures. This would indicate that the flow effects are dominating in 'clean' sands. Conversely, there is significant experience with locations with apparently similar CPT q_c profiles but significantly different installation responses as shown in Figure 3 below.

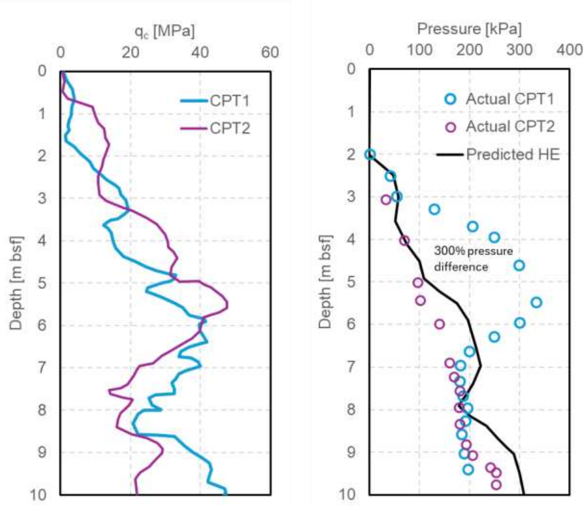

Figure 3. Example of suction pressure response for 'similar' CPT profiles

3.3 Pumping Volumes / Flow through soil

Experience from several offshore developments would indicate that significant volumes of water are 'pumped' through the caissons during installation operations, often in excess of 50% greater than the caisson volume. As an example, caissons with ~650m^3 internal volume often took ~4hours to install with flow rates of 200-300m^3/hr giving total flow volumes of more than 1000m^3; similar behaviour was noted for sandy and clayey locations. This would imply that more than 350m^3 of water is extracted from the soil plug and surrounding soils. These observations are from installations in sandy and clayey soils and would indicate there may be some flow even in predominately 'undrained' soils (clays).

Klinkvort et al (2019) suggested flow below 'impermeable' layers may be due to 'lifting' of the clay plug and / or cracks forming in the clay layers. However, recent experience with caissons equipped with pore pressure sensors has shown increased pore pressures at the internal skirt wall relative to original in-situ pore pressure, indicating potential seepage / flow in the remoulded zone adjacent to the caisson wall.

The water volume requirements highlight the importance of understanding flow rate through the surrounding soil which will depend upon the hydraulic (pressure) gradient and soil coefficient of permeability. For an indicative applied underpressure of 100kPa the flowrates as indicated in Table 1 may be anticipated for different soil conditions.

Table 1: Indicative flow rates through soil

Soil type	Penetration depth / pathlength	
	1m	5m
Clean sand	~400m^3/hr	~100m^3/hr
Well graded sand	~20m^3/hr	~3m^3/hr
Silty sand	~0.5m^3/hr	~ 0.05 m^3/hr

This would indicate that flow through soil is likely to significantly reduce as permeability decreases and/or pathlength (penetration depth) increases. The application of the underpressure may not result in significant change in pore pressures along the skirt length meaning limited reduction in effective stresses / penetration resistance.

4 REVISED METHOD

The revised method was developed based upon an internal database which includes suction installation records and associated CPT data for a variety of soil conditions worldwide. The subset of installation records considered for the calibration of the proposed method includes 84 installation positions across 5 sites located in different areas of the world (covering different soil conditions).

The soil interpretation was assessed in line with the discussion presented in Section 3.1 above.

Following the findings from offshore installation experience, as briefly outlined in Section 3, a new formulation is proposed for the estimation of the resistance to suction assisted penetration (R), taking into account for the potential effects for flow conditions during the actual installation by means of flow coefficients (ϵ). The proposed formulation was calibrated to represent a best estimate (BE) profile and an update of the methodology originally suggested in Torre et al. (2023).

$$R = k'_p \epsilon_p \, A_p \, \bar{q}_c(d) + \pi \, D_{int} \int_0^d k'_f \, \epsilon_{int} \; \bar{q}_c(z) \; dz + \pi \, D_{ext} \int_0^d k'_f \, \epsilon_{ext} \; \bar{q}_c(z) \; dz \quad (1)$$

where:

- R : soil resistance to suction pressure [kN]
- z : depth below seabed [m]
- d : depth of tip of suction caisson [m]
- k'_p: modified empirical coefficient as function of Q_{tn} and F_r, relating q_c to tip resistance [-]
- k'_f: modified empirical coefficient as function of F_r, relating q_c to shaft resistance [-]
- Q_{tn}: normalized cone tip resistance [-]
- F_r: friction ratio [%]
- $\overline{q_c}(d)$: average cone resistance at skirt tip, function of depth [MPa]
- A_p: tip area of suction caisson [m^2]
- D_{int}: Internal diameter suction caisson [m]
- D_{ext}: External diameter suction caisson [m]
- ϵ: generic notation for flow coefficient, based on flow criteria, empirical coefficients and ratio between actual penetration and caisson diameter [-]
- ϵ_p: end bearing flow coefficient [-]
- ϵ_{int}: internal friction flow coefficient [-]
- ϵ_{ext}: external friction flow coefficient (assumed to 1, implying no flow at the outer side of the caisson) [-]

The end bearing and internal flow coefficients can be assumed to be similar (i.e. $\epsilon_{int} \cong \epsilon_p$) where good flow is anticipated, however additional research would be required to confirm the assumptions made in this paper.

4.1 Flow coefficient (ϵ)

Several flow-induced mechanisms are to be taken into account during the suction assisted stage. The key aspects affecting the flow conditions through the soil are applied pumping (pressure and flowrate) and soil permeability. The suction pressure results in seepage/flow inside the skirt which generally increases the pore pressure and reduces the resultant effective stresses, consequently reducing the skirt friction.

Based on CPT derived parameters, indicative of the soil properties and drainage conditions, and following observations and interpretation of a wide database, the following criteria have been found as potential contributing factors for poor flow:

- Criterion 1 (CPT soil classification type, I_c criterion). Poor flow when the $I_c > 2.1$, where I_c is according to Robertson (2016),
- Criterion 2 (Normalised pore pressure, B_q criterion). Poor flow when $B_q > 0.04$.

Both criteria shall be satisfied to have a no-flow condition. The two criteria shall be evaluated with a concept top to bottom, starting from the seabed, implying a continuity of flow condition generated within the internal compartment of the caisson. The formulation of the flow coefficient below is based on the pressure factor concept proposed by Houlsby and Byrne (2005) but with a slight modification of the (a,b,c) coefficients based on back analysis of available data.

$$\epsilon = \begin{cases} \min\left(a_\varepsilon - b_\varepsilon \cdot \left[1 - e^{-\frac{d}{c_\varepsilon \cdot D_{out}}}\right], 1\right) & (no\,flow) \\ 1 & (flow) \end{cases} \quad (2)$$

where:

- a_ε, b_ε, c_ε: flow formula parameters [-] (0.9, 0.55, 0.1)
- D_{out}: outer caisson diameter [m]
- d: depth of tip of suction caisson [m]

4.2 End bearing and shaft (k_p, k_f) coefficients

The assessment of the dataset indicated initial trends with respect to the end bearing coefficient as function of a number of CPT derived parameters. The most interesting trends were identified based on the normalized cone tip resistance (Q_{tn}) and friction ratio (F_r) following Robertson (2016). The following main observations could be made:

- Loose or soft soils would require larger end resistance coefficients,
- The required end resistance coefficients tend to reduce with increase of normalized cone resistance (Q_{tn}) and to increase with increasing friction ratio (F_r),
- Shaft friction coefficients tend to increase with the increase of friction ratio (F_r), with a somewhat steep increase in the range of F_r indicative of transitional soils, following the nomenclature proposed by Robertson (2016).

The proposed formulation for the two coefficients is reported in the following:

$$k_p = [a_p + b_p \cdot e^{(c_p \cdot Q_{tn})}] \cdot [d_p \cdot F_r + e_p] \quad (3)$$

$$k_f = \frac{a_f}{1 + e^{b_f \cdot (F_r - c_f)}} \quad (4)$$

where:

a_p, b_p, c_p, d_p, e_p : bearing formula parameters [-] (0.2, 0.18, -0.18, 0.1, 1)

a_f, b_f, c_f : friction formula parameters [-] (0.04, -1, 4)

A representation of the k_p and k_f coefficients is provided in Figure 4 in conjunction with the Robertson (2016) soil types which indicates significant sensitivity with regards to shaft friction (k_f) and CPT friction ratio as well as end bearing and soil type (particularly transitional to clayey soils).

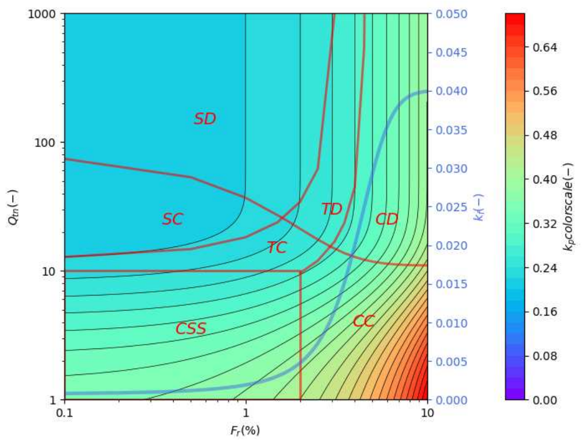

Figure 4. End bearing and shaft resistance coefficients
(SD = Dilative Sand, SC = Contractive Sand, TD = Dilative Transitional, TC = Contractive Transitional, CD = Dilative Clay, CC = Contractive Clay, CCS = Contractive Sensitive Clay)

An example of the performance of the proposed method is provided in Figure 5 for different soil profiles. The predictions generally provide much better matches than traditional methods (such as DNV and Andersen) with the measured pressures for the range of dilative soils and interlayered profiles.

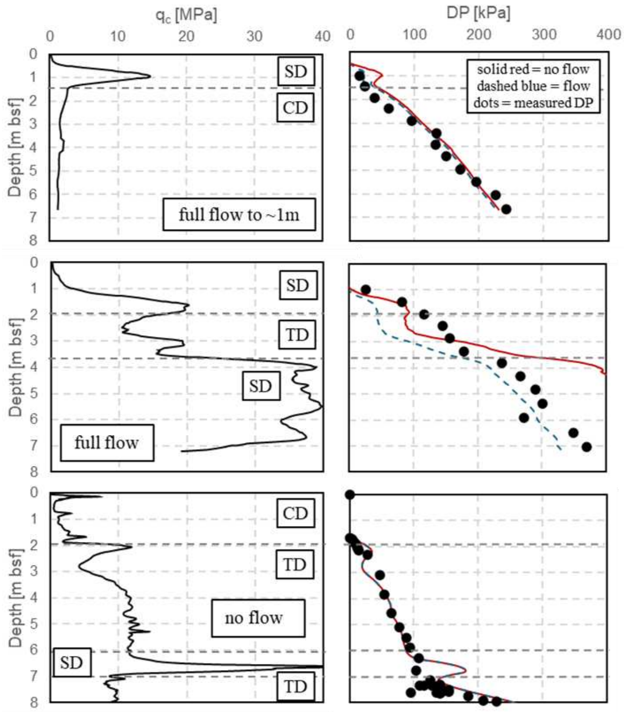

Figure 5. Proposed prediction method against installation records (example of different soil profiles)
(when the no flow condition is fulfilled, solid red and dashed blue lines overlap)

Estimated coefficients from the back analysis are comparable to other values from literature as included in Table 2 for reference.

Table 2: Values of k_p and k_f for sand and clay

Soil type		Most Probable (R_{prob})		Highest expected (R_{max})	
		k_p	k_f	k_p	k_f
Clay		0.4	0.03	0.6	0.05
Sand	DNV	0.3*	0.001	0.6	0.003
Sand	(Andersen et al, 2008)	0.01-0.55	0.001	0.03-0.6	0.0015
Sand	(Senders, 2009)	0.2	0.002-0.003	0.6	0.003-0.005

**Note: Based on author experience 0.2 may be more appropriate for suction caissons*

5 MITIGATION DISCUSSION

There are several potential mitigation strategies if installation is problematic, particularly with regards to high pressures approaching cavitation or buckling limits. The aim of this section is to outline the effectiveness of the mitigations under different soil conditions based upon author experience.

5.1 Pressure Pause / Pore Pressure Recharge

As already mentioned, low permeability in 'transitional' soils could result in temporarily 'draining' the water source in the vicinity of the caisson. The lack of resultant flow/seepage and reduced pore pressure at the caisson wall can result in increased stresses and penetration resistance. Stopping suction operations and waiting for a short period as illustrated in Figure 6a should allow the pore pressures to (partially) recover.

Experience indicates that pressure pauses of 10-30 minutes typically result in significant reductions (20-40%) in required pressures for 1-2m of additional penetration. However, suitable 'pause' times should be determined based upon the caisson size, soil conditions (layering and permeability) and penetration depth.

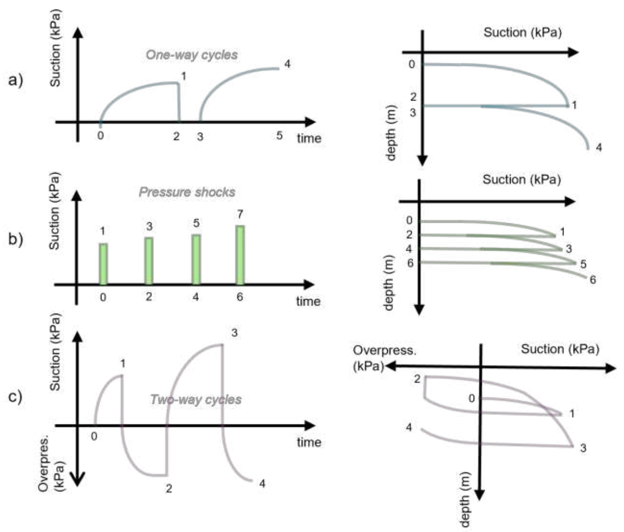

Figure 6. Mitigation illustrations

5.2 Pressure Pulses / Pressure Shocks

Piping can be a particular risk at shallow penetrations in loose granular soils, particularly with steady state 'seepage'.

Author experience indicates high pressure, short duration 'pulses' can be used to increase penetration at shallow depth, as illustrated in Figure 6b. Therefore, 'pulsing' could be considered as a potential installation mitigation when piping is considered a significant risk at shallow penetrations reverting to constant flow/pressure once sufficient penetration is achieved. However, where piping channels have already developed this tends to be less effective and should be combined with other techniques such as depression backfill and sandbags.

5.3 Two-Way Cycles

Two-way cycling involves applying an overpressure to push the caisson out a small distance before re-applying the underpressure to continue penetration as shown in Figure 6c. Two-way cycles are well recognised as a mitigation option in clays where full remoulding can significantly reduce soil strength at the caisson interface, whereas conventional theory suggests this should have limited benefit in 'clean' sands. This was validated by authors' experience. In clays repeated two-way cycles may continue to reduce resistance. An example for a location with a predominant clayey soil profile with an expected sensitivity of 1.5 is given as:

1st cycle – total reduction ~14%
2nd cycle – total reduction ~32% (extra ~18%)
3rd cycle – total reduction ~36% (extra ~4%)
4th cycle – total reduction ~45% (extra ~9%)

The initial penetration would be expected to result in partial remoulding and the 1st two-way cycle, full remoulding. However, experience indicates that additional cycles frequently do result in further degradation. This could be due to additional water being introduced to the remoulded soils at the caisson interface as discussed in section 3.3, this would further reduce the remoulded strength.

6 CONCLUSIONS

The potential for poor flow / seepage due to 'transitional' soils (or layering) has been identified as a significant risk to suction caisson installation. The aim of this paper is to provide a framework to assist with the identification of 'transitional' soils and allow for them in the suction installation analyses and predictions.

The proposed formulation can be adapted to site specific conditions when trial campaigns are planned to reduce the risk of installation or verify any potential for primary steel design optimization.

The method and proposed coefficients will be further refined in the future when additional data become available.

AUTHOR CONTRIBUTION STATEMENT

A Torre & J Irvine: Original draft. **E Tataki, G Peeters & I Torres:** Review and contribution to sections.

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