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A simple macroelement for predicting cyclic rotations of suction caissons in sand

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ABSTRACT: Suction caissons are widely adopted as foundations for offshore wind turbines, due to their capability to resist high lateral forces and overturning moments. A critical aspect for their design is the accumulation of irreversible rotations under cyclic loads, which can compromise the functionality of the turbine over its service life. Advanced Finite Element (FE) models provide detailed insights on the cyclic foundation response, but require unfeasible computational costs for practical applications due to the large number of lifespan load cycles. To address this challenge, this work presents a novel macroelement model developed to predict the cyclic accumulation of irreversible rotations of suction caisson foundations in sand. Its constitutive features are inspired by the memory and bounding surface plasticity framework and by the results of 3D FE analyses carried out with SANISAND-MS model. By describing the soil-foundation interaction with a small set of generalized load-displacement/rotation variables, the proposed macroelement significantly reduces computational time compared to FE analyses, while maintaining the capability of predicting cyclic ratcheting and rotation accumulation. The model captures the effects of caisson geometry, load eccentricity and sand relative density. Validation against FE results establish the macroelement as a practical and efficient alternative for integrating soil-structure interaction effects into the design of offshore wind turbines.

KEYWORDS: Suction caisson, Cyclic loading, Macroelement model, Soil ratcheting, Offshore wind turbines

1 INTRODUCTION

Wind energy production is steadily rising in response to the global shift toward renewable resources, with offshore wind turbines (OWTs) offering a highly efficient solution for harnessing wind power. These systems not only contribute significantly to carbon emission reduction but also present geotechnical challenges, as their tall towers must transfer substantial loads and moments generated by both wind and waves.

Among the possible foundation solutions in marine environments, caissons offer significant advantages in terms of construction simplicity, load-bearing capacity, and the potential for decommissioning or reuse. These structures are widely used for anchoring and supporting pipelines, cables, and floating or semi-submerged energy systems (e.g., offshore wind, wave energy, temporary platforms). The behaviour of foundation caissons under cyclic loading has received increasing attention in the scientific community. Numerous experimental and numerical studies have investigated the effects of cyclic loading on the rotational behaviour, stiffness, and load-bearing capacity of caissons in various soil types. These studies highlight the importance of parameters such as relative density, soil-structure contact mode, and foundation geometry (Zhu et al., 2018; Luo et al., 2024; Cheng et al., 2022). Recent studies have explored alternative configurations (e.g., tripod or hybrid caissons), different loading conditions (unidirectional, bidirectional, irregular), and critical scenarios such as seismic liquefaction (Gao et al., 2021; Shakeran & Soroush, 2024), emphasizing the complexity of the problem and the need for integrated and validated models (Wang et al., 2017; Villalobos, 2006; Ueda et al., 2020).

From a practical perspective, assessing caisson rotation under monotonic and cyclic loading conditions is essential to ensure compliance with ultimate and serviceability limit states. The calculation of this rotation can be effectively addressed through 3D finite element (FE) simulations, which allow for detailed modelling of geometric configurations, load sequences, soil behaviour, and stratigraphic heterogeneity. However, these simulations are often computationally very demanding, making long-term analyses (up to 10^7–10^8 loading cycles, as mentioned in Houlsby, 2016) impractical when applied to multiple foundation sites.

As an alternative design strategy, in the last 30 years the use of macroelement (ME) approach is becoming popular to tackle soil structure interaction problems. This approach, used in the past for shallow foundations (Nova and Montrasio, 1991; Montrasio & Nova, 1997; Cremer et al., 2002; Grange et al., 2009; Salciarini & Tamagnini, 2009, Pisanò et al, 2016; Flessati et al., 2021, Gorini & Callisto, 2023), offshore foundations (Martin & Houslby, 2001; Byrne & Houlsby, 2003; Cassidy et al., 2006) piles (Li et al., 2016, Iodice et al. 2024), boulders impacting on granular soils (di Prisco & Vecchiotti, 2006), tunnels (di Prisco et al., 2018; di Prisco et al., 2020b; Flessati & di Prisco, 2020, di Prisco & Flessati, 2021; Flessati & di Prisco, 2025), earth embankments on piles (di Prisco et al., 2020a; Flessati et al., 2022; Mangraviti et al., 2023, 2025), anchored wire meshes (Boschi et al. 2022), pipelines interacting with active landslides (Cocchetti et al., 2009), stems from the idea of reproducing a complex system mechanical response via a low number of degrees of freedom and by defining a suitable incremental generalized constitutive relationship between the static and kinematic variables associated with the chosen degrees of freedom. The advantage of this approach is to abruptly reduce the degrees of freedom of the problem and thus the computational costs. However, the definition of the upscaled constitutive laws and the calibration of its parameters are particularly critical since they will be affected not only by the soil mechanical behaviour, but also by the foundation geometry and mechanical properties. In this work, the authors intend to propose a new one-dimensional macroelement to reproduce the moment-rotation response of caisson foundations for OWTs. This generalized constitutive law, based on the one proposed in Flessati & Marveggio (2023) for shallow foundations under cyclic loads, is conceived in the framework of the bounding surface plasticity theory. The main ingredients of this model are a bounding surface and a mixed isotropic-kinematic generalized strain hardening controlling the ratcheting.

The model is capable of reproducing the numerical results of Cesaro et al. (2026) and seems to be a very promising approach for design purposes. In addition, the model can also simply be introduced in structural finite element codes allowing to solve soil-structure interaction problems also accounting the turbine tower. This can be used to adequately reproduce the whole system response and to also optimize the tower design under dynamic loads.

2 MODEL FORMULATION

Most ME formulations available in the literature (Nova and Montrasio, 1991; Montrasio & Nova, 1997; Martin & Houslby, 2001; Cremer et al., 2002; Byrne & Houlsby, 2003; Cassidy et al., 2006; Grange et al., 2009; Salciarini & Tamagnini, 2009 Li et al., 2016; Iodice et al. 2024) are conceived considering multiple load/displacement components (vertical and horizontal loads/displacements and overturning moments/rotations). On the one hand, this approach provides a general framework for analysing foundation behaviour under independently varying load components; on the other hand, it results in greater mathematical complexity in the model formulation and makes parameter calibration more challenging. For example, MEs developed within the framework of elasto-plasticity theory require the definition of multiple loci in the generalized stress space (the yield surface, failure domain, and plastic potential). The shape and dimension of these loci depend not only on the mechanical properties of the soil, but also on the type and geometry of the foundation.

Also caisson foundations for OWTs are generally subjected to three main load components: (i) a vertical load arising from the self-weight of the superstructure, (ii) a horizontal load induced by environmental actions such as wind and waves, and (iii) an overturning moment resulting from the eccentricity of these horizontal actions. However, in case of the caissons used for OWT foundations, the vertical load is usually much lower than the vertical bearing capacity and is practically constant over time and the horizontal load and overturning moment are geometrically linked (e.g., by turbine height and sea level).

For this reason, it can be assumed that only one static variable is truly independent. Accordingly, the macroelement will be formulated by considering a single static variable. Moreover, from a practical perspective, in the case of isolated caissons, vertical and horizontal displacements are not primary design concerns. Therefore, from a kinematic standpoint, only one generalised strain variable (the rotation, θ) is of practical relevance. Given the engineering focus on θ, its work-conjugate variable, the overturning moment (M), is selected as the representative static variable.

The generalized constitutive relationship model is conceived in the framework of elasto-plasticity. Therefore, rotations are assumed to be given by the sum of a reversible/elastic contribution (θ^{el}) and an irreversible/plastic one (θ^{pl}):

$$\theta = \theta^{el} + \theta^{pl} \tag{1}$$

The elastic law is defined as:

$$M = K^{el}\theta^{el} \tag{2}$$

where K^{el} is an elastic parameter that depends on the elastic stiffness K_{MM} (rotational elastic stiffness under pure moment), K_{HH} (horizontal elastic stiffness under pure horizontal load), K_{HM} (cross coupled horizontal load/moment stiffness) and on eccentricity of the horizontal load (e)

$$K^{el} = \frac{K_{HH}K_{MM} - K_{HM}^2}{-K_{HM}/e + K_{HH}} \tag{3}$$

Since the model is one-dimensional, the yield function (f) and the plastic potential (g) are coincident and are expressed as:

$$f = g = |M - M_\alpha| - M_y = 0 \tag{4}$$

where M_α and M_y are two hardening variables, the former one describing a kinematic hardening, whereas the second one an isotropic hardening. Kinematic hardening allows irreversible strain accumulation during cycles, while isotropic hardening limits this accumulation over time, capturing the ratcheting response.

The plastic rotation increment ($d\theta^{pl}$) is related to the increment in moment (dM) as it follows:

$$dM = Hd\theta^{pl} \tag{5}$$

where the expression of the plastic compliance is inspired to that of Kementzetzidis et al. (2022):

$$H = \alpha m(|M_u\, sgn(dM) - M|)\left|\frac{1}{\alpha}ln\left(1 - \frac{M}{M_u}sgn(dM)\right)\right|^{\frac{m-1}{m}} \tag{6}$$

where α and m are parameters governing the shape of the moment-rotation curve and M_u is the limit moment ("bounding surface").

Following an approach analogous to that presented by Flessati & Marveggio (2023), the evolution of the hardening variables is governed by the following rules:

$$dM_\alpha = H\left[1 - \mu\frac{M - M_{min}}{M_{max} - M_{min}}\right]d\theta^{pl} \tag{7}$$

$$dM_y = H\left[\mu\frac{M - M_{min}}{M_{max} - M_{min}}\right]d\theta^{pl} \tag{8}$$

where μ is a model parameter (between 0 and 1) that control the amount of kinematic and isotropic hardening, whereas M_{max} and M_{min} are two "memory" variables representing the maximum and the minimum value of moment ever imposed.

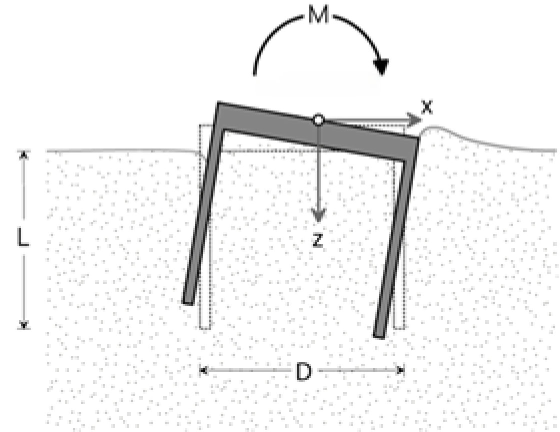

Figure 1. Geometry of the considered caisson foundation

3 MODEL PERFORMANCE

In this section the results of the macroelement are compared with the results of a series of FE simulations. The FE simulations (Cesaro et al., 2026) were performed by reproducing the soil response by means of the Sanisand-MS constitutive law (Liu et al., 2019), whose parameters were calibrated on the experimental tests results on Karlsruhe sand reported in Wichtmann (2005).

The caisson considered for the analysis has a diameter D=20m and the length of the skirt L=10m (Fig. 1). The sand is assumed to be dry and its initial void ratio is imposed to be equal to 0.7255 (relative density 50%). The caisson is modelled as a rigid body and the caisson-soil interface is assumed to be frictional (friction angle equal to 20°). The caisson is loaded by a moment.

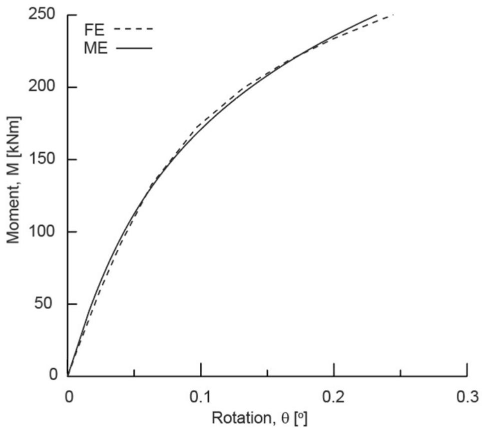

Figure 2. Monotonic load: comparison between finite element and macroelement results

To calibrate the model, the values of five constitutive parameters (K^{el}, α, m, M_u and μ) and the initial values of four internal variables ($M_{\alpha,0}$, $M_{y,0}$, $M_{max,0}$ and $M_{min,0}$) have to be defined. $M_{max,0}$ and $M_{min,0}$ are nil by definition. $M_{\alpha,0}$=0, since it is assumed that the response during the first load is independent on the loading direction (sign of the moment). K^{el} and $M_{y,0}$ can be calibrated on the initial (elastic) branch of the moment rotation curve. α, m and M_u were calibrated to reproduce the shape of the monotonic response, mainly focusing on accurately reproducing the response for small rotation values (Fig. 2). μ is calibrated to reproduce the cyclic accumulation of rotation as a function of the cycle number (results of Fig. 3 corresponding to one-way cyclic load for different $\zeta_b = M_{max,cy}/M_u$, being $M_{max,cy}$ the maximum moment imposed in the cyclic load history).

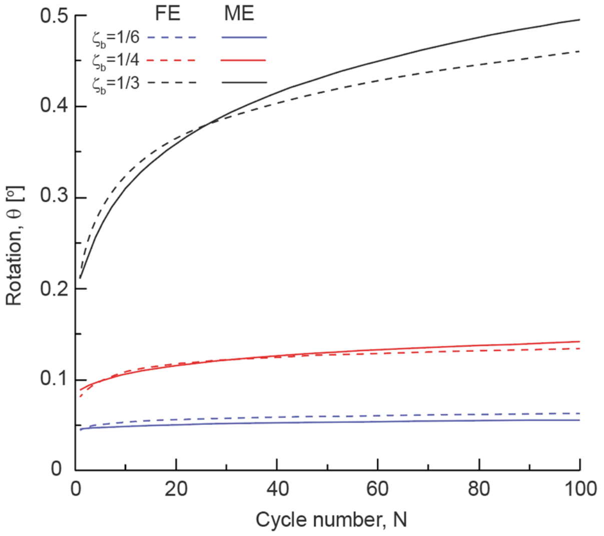

Figure 3. Cyclic load: comparison between finite element and macroelement results

4 CONCLUSIONS

In this paper the authors present a macroelement that can be used to reproduce the response of caisson foundation under cyclic loads. This model one dimensional and relates the overturning moment applied on the foundation with the rotation. This assumption not only simplify the formulation of the model and increase the computational efficiency, but also limit the number of parameters to be calibrated. The generalized constitutive law has five constitutive parameters that not only depend on the soil properties (friction angle and relative density) and on the caisson geometry (diameter and skirt length) but also on the characteristic of the superstructure that defines the eccentricity of the horizontal load.

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