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A numerical model for the transient analysis of offshore foundations under cyclic loading

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A B S T R A C T

A comprehensive numerical model for the analysis of offshore foundations under a general transient loading is presented here. The theoretical basis of the model lies on the Swansea formulation of Biot's equations of dynamic poroelasticity combined with a constitutive model that reproduces key aspects of cyclic soil behaviour in the frame of the theory of generalised plasticity. On the practical side, the adoption of appropriate finite element formulations may prevent the appearance of spurious numerical instabilities of the pore pressure field. In this respect, the use of a coupled enhanced-strain element is here proposed. On the other hand, the practicality of the presented model depends ultimately on its computational efficiency. Some practical recommendations concerning the solution strategies, the matrix storage/handling procedures and the parallel multi-processor computation are here provided. Finally, the performance of the model with a benchmark study case and its practical application to analyse the soil–structure interaction of an offshore monopile under a realistic transient storm loading are discussed.
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1. Introduction

The offshore foundations are back in the spotlight of engineering research. In the context of a progressive depletion of the finite hydrocarbon reserves and the pressing need for clean and sustainable sources of energy, several countries worldwide are adopting ambitious policies for the branch of renewable energies. In order to achieve such goals, the harvest of wind energy through the use of large offshore wind turbines is likely to play a key role.

However, the challenges and questions faced by the geotechnical specialists for the foundation of such turbines in the seabed are far from closed. This is partly due to the growing interest in exploiting deeper waters and the fact that each site may require different engineering strategies depending on the soil conditions and water depth. Moreover, there are several phenomena inherent to the offshore environment, such as the effects on the foundation of a permanent exposure to cyclic loading from wind and waves, which are still not well understood and do require considerable efforts in research (see for instance [1]).

Currently, the most common solutions for the foundation of offshore wind turbines are either the gravity-based shallow foundations or some kind of support structure incorporating one or more driven piles, while other concepts such as the suction caissons or the tension-leg floating substructures are also being proposed and developed nowadays. The challenges raised by such foundations are aggravated by their large dimensions and especially by their high ratios of lateral to vertical loads, which make them unprecedented in the offshore engineering field.

Large monopile foundations of around 5 m in diameter are currently state of the art and plans for future wind farms in the North Sea already contemplate the possibility of monopiles with up to 8 m in diameter [2,3]. The behaviour of such foundations under the effects of a long-term cyclic loading is currently a subject of intense research.

In practice, the actual design of these foundations is often carried out in the frame of the guidelines and standards for offshore operations developed by the oil industry in the past decades, which

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focus the design analysis on the bearing capacity, the serviceability and the dynamic behaviour of the foundation.

However, most design considerations for cyclic effects are based on pseudo-static approaches where the foundation's response is calculated from a static analysis using modified (degraded) soil properties. This is usually performed by means of a reduced subgrade reaction coefficient, which provides in a rather unspecific way a lower bound (or "worst case") for the foundation's behaviour after cycling. It can be noted that such "cyclic degradation" is often just an arbitrary technique to merely estimate the magnitude of accumulated displacements and does not necessarily reflect the actual physical state of the foundation/soil after cycling.

Besides, the possible effects of the hydromechanical coupling in the saturated seabed are also regularly disregarded for practical design. There are only few studies that investigate the possible development of excess pore pressures around/underneath the offshore foundation on a cycle-by-cycle basis, especially for the case of large-diameter piles. In this respect, most studies perform a simplified analysis of the foundation including semi-empirical relations of pore pressure generation and dissipation obtained from undrained elementary tests (e.g. in [4–7]). Furthermore, they usually discretise the irregular storm loading as consecutive packages of load cycles with constant amplitude, disregarding thereby the actual sequence of loads and the so-called "order effects".

On the other hand, it must also be pointed out that apart from the excess pore pressure generated by the wave-induced displacements of the foundation, the change in water-level itself as the waves propagate over the seafloor may also result in a net pore pressure accumulation within the soil (see for instance [8–11]).

As pointed out by Taiebat [7], the relevance of the proper assessment of the hydromechanical coupling phenomena can be highlighted by the fact that the distribution of total stresses within the soil may be changing continuously due to transient reductions of soil stiffness when the pore pressure increases and the stress redistributes inside the "multi-element" soil body. Therefore, the stress states for the onset of failure cannot be determined from the initial conditions at the beginning of a phase of cyclic loading, since the effective stress paths will not necessarily move "horizontally" towards the failure envelope in a triaxial stress plane.

This all highlights the general need for the consideration of the fully coupled nature of the three-dimensional "boundary value problem" at hand. This paper aims to present a general framework for such task and to provide a compilation of useful techniques to overcome some key issues for its practical use.

The first part of the paper introduces briefly a mathematical model describing the equilibrium within a water-saturated seabed. The general dynamic formulation for a bi-phasic solid–fluid mixture and the particular case of saturated consolidation are there presented. Additionally, a constitutive model for the soil that reproduces the main aspects of sand behaviour and is able to generate a residual excess of pore pressure upon cyclic loading is introduced in the frame of the theory of generalised plasticity.

The second part addresses some practical aspects indispensable for the simulations, namely the particular conditions to ensure the stability of the pressure field, the provision of a suitable soil–structure interface, and crucially, the optimisation of the computational cost, for which some practicable techniques are discussed.

The third part illustrates the performance of the numerical model through the three-dimensional analysis of a benchmark study case, a flexible footing resting on an isotropic layer of water-saturated soil. Finally, the practical example of an offshore monopile under the transient cyclic loading imposed by a storm provides an insight into the relevance that a pore pressure accumulation may bear on the behaviour of the offshore foundations.

2. Model description

2.1. Theoretical model

2.1.1. Field equations

Here, the equilibrium of the seabed is described mathematically by means of the u–p_w model proposed by Zienkiewicz and coworkers in Swansea (see e.g. [12–15]), accounting for the mechanical interaction between the soil grains and the pore water based on the theory of dynamic poroelasticity originally due to Biot [16,17].

This model, in which the governing variables of the system are the absolute displacement $\boldsymbol{u}$ of the solid phase and the pressure p_w of the pore water, is formulated for fully saturated conditions and includes the following set of equations:

(i) the overall equilibrium or equation of motion for the whole system, expressed by the conservation of linear momentum for the bi-phasic mixture of pore fluid and solid grains,
(ii) the combined equation for the balance of masses and linear momentum of the fluid, and
(iii) constitutive and kinematic compatibility equations.

This set of equations can be expressed as follows

$$\boldsymbol{S}^T(\boldsymbol{\sigma}' - \boldsymbol{m}p_w) + \rho_m \boldsymbol{b} = \rho_m \ddot{\boldsymbol{u}} \tag{1}$$

$$\boldsymbol{m}^T\boldsymbol{S}\dot{\boldsymbol{u}} - \nabla^T(\boldsymbol{k_w}\nabla p_w) + \frac{\dot{p}_w}{Q^*} + \nabla^T\boldsymbol{k_w}\rho_w\boldsymbol{b} = 0 \tag{2}$$

$$d\boldsymbol{\sigma}' = \boldsymbol{D_{ep}} \cdot d\varepsilon \tag{3}$$

$$d\varepsilon = \boldsymbol{S} \cdot d\boldsymbol{u} \tag{4}$$

where $\boldsymbol{\sigma}'$ is the effective stress of the soil skeleton, $\boldsymbol{m}$ stands for the identity tensor (Kronecker's delta), ρ_m is the mass density of the solid–fluid mixture, $\boldsymbol{b}$ is the vector of body forces per unit mass, $\boldsymbol{u}$ is the acceleration of the solid skeleton (the acceleration of the fluid phase relative to the solid is disregarded here) and $\boldsymbol{S}$ the strain (or divergence) operator

$$\boldsymbol{S}^T = \begin{bmatrix} \partial/\partial x_1 & 0 & 0 & \partial/\partial x_2 & 0 & \partial/\partial x_3 \\ 0 & \partial/\partial x_2 & 0 & \partial/\partial x_1 & \partial/\partial x_3 & 0 \\ 0 & 0 & \partial/\partial x_3 & 0 & \partial/\partial x_2 & \partial/\partial x_1 \end{bmatrix} \tag{5}$$

Eq. (2) combining the balances of masses and the linear momentum of the fluid is obtained by isolating and equating Darcy's velocity of the fluid in both equations, where k_w is the permeability matrix, ρ_w is the specific weight of the pore fluid, and Q^* is the coupled volumetric stiffness of solid grains and fluid, given by

$$\frac{1}{Q^*} = \frac{n}{K_w} + \frac{1-n}{K_s} \tag{6}$$

whereas n is the porosity of the soil, K_w is the bulk modulus of the pore water and K_s is that of the solid grains.

This system of equations, along with the appropriate set of boundary and initial conditions, describes the behaviour of the coupled problem.

It must be noted that apart from disregarding the relative fluid acceleration, this formulation also assumes that the convective terms of the linear momentum equation and the gradient of fluid density in the mass balance equation are also negligible, while the term of dynamic filtration $\partial(\boldsymbol{k_w}\rho_w\ddot{\boldsymbol{u}})/\partial x_i$ is omitted for simplicity, since it only has some relevance in the range of high frequencies, where the u–p_w formulation is no longer valid [18].

There are a number of studies on the validity of these assumptions, for instance in [13,19], where a comparison of the various

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