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Numerical simulation of offshore foundations subjected to repetitive loads

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ABSTRACT

This paper analyzes the long-term offshore foundation that undergoes numerous mechanical cycles. The numerical approach follows the hybrid scheme that incorporates a mechanical constitutive model to extract stress into strains at the first cycle into polynomial-type strain accumulation functions to track the progressive plastic deformation. In particular, the strain function contains the fundamental features that require simulating the long-term response of geomaterials: volumetric strain (terminal void ratio) and shear strain (shakedown or ratcheting), the strain accumulation rate, and stress obliquity. A model is calibrated under zero-lateral strain boundary condition by relaxing model parameters. The semi-empirical numerical scheme is used to simulate two offshore foundations subjected to repetitive loads (i.e., monopile and shallow foundation). Numerical results show that the most pronounced displacements occur during early cycles ($N < 100$), yet their incremental rate approaches toward an asymptotic value. With stress redistribution around the foundations, vertical and horizontal displacements increase with the number of cycles and the asymptotic displacement increases with higher load amplitude.

1. Introduction

The massive consumption of fossil fuel creates a stringent demand for new energy sources while also raising serious environmental concerns. Many developed countries have agreed to legally bind to reductions in the emissions of greenhouse gases (Breidenich et al., 1998). As a result, the energy produced from renewable sources and the need for geo-storage is steadily increasing. In particular, there has been a rapid growth in the use of offshore wind farms. Among the offshore foundation that has to resist the combined loading induced by ocean waves and wind, the selection of foundation mainly depends on the water depth, sediment properties, loading types, and available construction method (Malhotra, 2010). A common characteristic of offshore foundations is that the surrounding geomaterials experience numerous mechanical cycles. The global response of granular materials beneath a wind turbine foundation subjected repetitive loads can be divided into elastic deformation and permanent deformation. Accurate prediction of geostructure performance is critically dependent on whether or not soils experience progressive accumulation of plastic deformation. The progressive displacement that occurs during long-term operation of wind turbine can inflict serious damage to the offshore foundation performance. For example, the gravity-based foundations subjected to eccentric load with 10^7 cycles can lead to settlement and rotation larger than the structure deformation tolerance and monopile response under cyclic load may produce unexpected rotation along the pile (Bouckovalas et al., 1984; Sawicki and Swidzinski, 1989; Yeo et al., 1994; Niemunis et al., 2005; Morgan and Ntambakwa, 2008; Achmus et al., 2009; Ben-Hassine and Griffiths, 2013). Thus, the reliable design of offshore foundation requires evaluating and predicting the surrounding soil response during large number of cycles.

Soil response subjected to cyclic load cannot be predicted with classical constitutive models that only can produce plastic strains induced by first cycle because they fail to accumulate strains during the number of load repetitions; the cumulative displacements remains mostly constant (Pasten et al., 2014). This study focuses on analyzing the long-term response of two offshore foundations (i.e., monopile and shallow foundation). The numerical approach follows the hybrid model that combines Modified Cam Clay model to extract the stress and strains at the end of the first cycle and empirical strain accumulation functions to track the progressive plastic deformation. In particular, the strain function includes the fundamental features that require simulating the long-term response of geomaterials: volumetric strain (terminal void ratio) and shear strain (shakedown and ratcheting), the strain accumulation rate, and stress obliquity. This manuscript starts with a review of long-term soil response under repetitive loading, followed by a numerical modeling and field examples.

2. Fundamental features of long-term soil behavior

2.1. Soil response during repetitive loading

The analysis of long-term soil response on geostructures requires characterizing the plastic strain accumulation that depends on soil type and density, initial effective stress (static stress), cyclic stress amplitude and obliquity, and the number of cycles (Niemunis et al., 2005; Wichtmann et al., 2010a, 2010b). Fig. 1 schematically shows the soil

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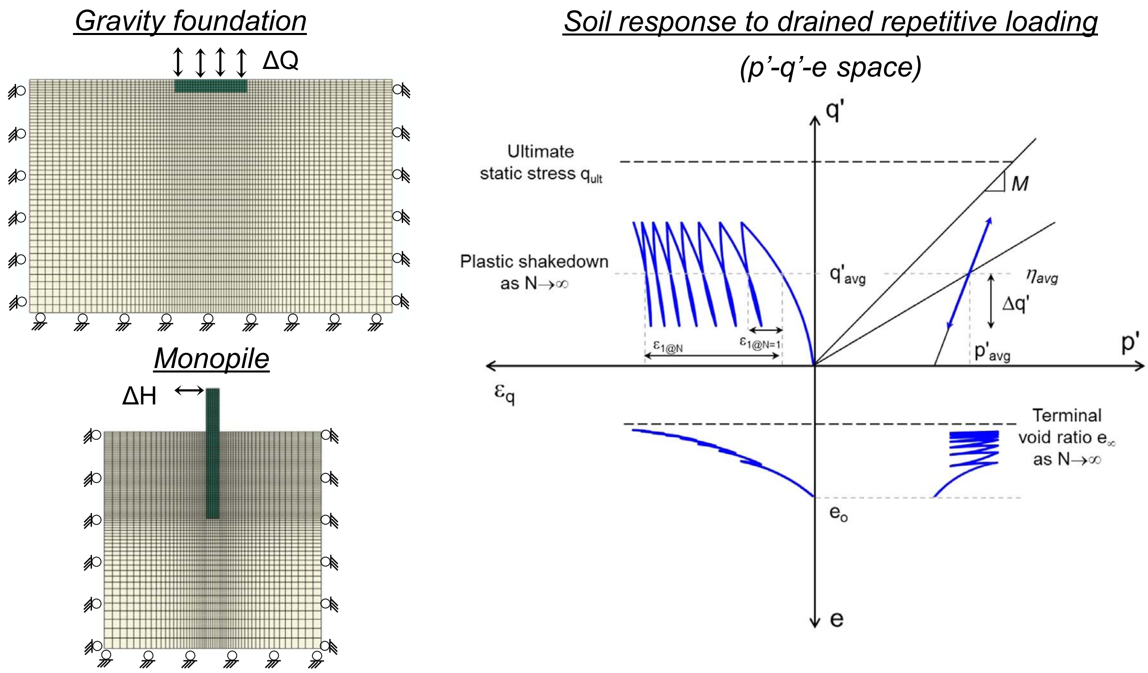

Fig. 1. Physical response of offshore foundations subjected to drained cyclic loading. ΔQ and ΔH are cyclic load amplitudes exerted on gravity foundation and monopile. M critical friction angle, η stress obliquity, and N cycle number. Finite element mesh used in this study is presented with boundary conditions; vertical displacement is allowed on side boundaries, the bottom boundary is vertically fixed, and the top surface is free.

Table 1
Strain accumulation functions for volumetric and deviatoric strains to construct the accumulated strain vector for plasticity. Parameters a, b, and c are function compositions in Eqs. (1) and (2) (General formulation refers to Chong and Santamarina, 2016).

Type	Volumetric strain		Shear strain	
	Accumulation function	**Accumulation rate**	**Accumulation function**	**Accumulation rate**
Exponential function	$\varepsilon_v^{acc}\|_N = \varepsilon_v\|_{N=1}\cdot\left[1+\frac{a}{\alpha}(e^{-\alpha}-e^{-\alpha\cdot N})\right]$	$\frac{d\varepsilon_v^{acc}}{di} = \varepsilon_v\|_{N=1}\cdot a\cdot e^{-\alpha\cdot i}$	$\varepsilon_q^{acc}\|_N = \varepsilon_q\|_{N=1}\cdot\left[1+\frac{a}{\alpha}(e^{-\alpha}-e^{-\alpha\cdot N})+c(N-1)\right]$	$\frac{d\varepsilon_q^{acc}}{di} = \varepsilon_q\|_{N=1}\cdot(b\cdot e^{-\alpha\cdot i}+c)$
Polynomial function	$\varepsilon_v^{acc}\|_N = \varepsilon_v\|_{N=1}\cdot\left[1+\frac{a}{1-\alpha}(N^{1-\alpha}-1)\right]$	$\frac{d\varepsilon_v^{acc}}{di} = \varepsilon_v\|_{N=1}\cdot\frac{a}{i^{\alpha}}$	$\varepsilon_q^{acc}\|_N = \varepsilon_q\|_{N=1}\cdot\left[1+\frac{b}{1-\alpha}(N^{1-\alpha}-1)+c(N-1)\right]$	$\frac{d\varepsilon_q^{acc}}{di} = \varepsilon_q\|_{N=1}\cdot\left(\frac{b}{i^{\alpha}}+c\right)$
Power function	$\varepsilon_v^{acc}\|_N = \varepsilon_v\|_{N=1}\cdot\left[1+\frac{a}{1+\alpha}(N^{1+\alpha}-1)\right]$	$\frac{d\varepsilon_v^{acc}}{di} = \varepsilon_v\|_{N=1}\cdot a\cdot i^{\alpha}$	$\varepsilon_q^{acc}\|_N = \varepsilon_q\|_{N=1}\cdot\left[1+\frac{b}{1+\alpha}(N^{1+\alpha}-1)+c(N-1)\right]$	$\frac{d\varepsilon_q^{acc}}{di} = \varepsilon_q\|_{N=1}\cdot(b\cdot i^{\alpha}+c)$
Log-linear function	$\varepsilon_v^{acc}\|_N = \varepsilon_v\|_{N=1}\cdot[1+a\cdot\ln(N)]$	$\frac{d\varepsilon_v^{acc}}{di} = \varepsilon_v\|_{N=1}\cdot\frac{a}{i}$	$\varepsilon_q^{acc}\|_N = \varepsilon_q\|_{N=1}\cdot[1+b\cdot\ln(N)+c(N-1)]$	$\frac{d\varepsilon_q^{acc}}{di} = \varepsilon_q\|_{N=1}\cdot\left(\frac{b}{i}+c\right)$

response beneath offshore foundations subjected to repetitive load. When soil specimen is characterized by the average mean stress p_{avg}, deviatoric stress q_{avg}, initial void ratio eo, and the cyclic stress amplitude Δq, it converge to plastic shakedown in q′-ε_q space and terminal void ratio in p′-e space. In addition, average stress obliquity η_{avg} related to initial state of stress in p′-q′ space defines the volumetric and shear strain accumulation by assuming associative flow rule in plastic theory (Niemunis et al., 2005). Those effects related to the stress obliquity and the stress states prior to cyclic loading (preloading) are observed in experimental studies (Chang and Whitman, 1988; Wichtmann et al., 2010a, 2010b). For example, initial stress condition up to the failure line produces more shear strain than volumetric strain. Even though the cyclic stress amplitude Δq is smaller than ultimate static stress q_{ult}, the soil can accumulate the plastic strain during number of load repetitions. Thus, the soil response of geotechnical systems subjected to mechanical repetitive loads gives rise to an emergent response that does not take place in monotonic loads usually considered in design.

2.2. Constitutive models

Classical constitutive models that produce irreversible plastic potentials during unloading fail to accumulate strains induced by the number of load repetitions. The geostructures subjected to cyclic load can be simulated by tracking each cyclic response; yet small accumulation rate hinders capturing physical deformation response due to larger accumulation of numerical errors. Consequently, numerical modeling based on implicit calculation is limited to predict the long-term response (Achmus et al., 2009). Even though the process of strain accumulation can be implemented with empirical approaches that fit experimental results with number of load cycles, their use is restricted to boundary value problems that need to satisfy with force equilibrium and strain compatibility. Thus, semi-empirical numerical schemes have been developed by incorporating classical constitutive mode into strain accumulations functions (Suiker and de Borst, 2003; Niemunis et al., 2005; François et al., 2010; Kuo et al., 2012). In particular, a hybrid scheme is proposed by combining a mechanical constitutive model to extract stress and strains induced by the first cycle and empirical strain accumulation function (log-linear type in Table 1) to track the progressive plastic deformation (Pasten et al., 2014). The strain function includes the fundamental features that require simulating the long-term response of geomaterials: volumetric strain (terminal void ratio; see the references to (Narsilio and Santamarina, 2008; Chong and Santamarina, 2016)) and shear strain (shakedown and ratcheting; see the references to (Koiter, 1960; García-Rojo and