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Seismic Response of Suction Caissons: effect of two-directional loading

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ABSTRACT

Dictated by the world's escalating energy demands, offshore infrastructure is moving beyond the immediate continental shelf into deeper waters with new types of facilities replacing the conventional fixed-bottom shallow water towers. This new deep-water world comes with some major scientific challenges. Owing to the 3D geometry of the superstructure, a non-negligible stressing in the out-of-plane dimension may be produced resulting in a complex loading pattern. Apart from some scant literature on the subject our understanding on foundation performance under such complex stressing is still at its infancy; this is further perplexed when the transient nature of loading is taken into account. This study presents 3-dimensional numerical analyses of the response of suction caissons subjected to several scenarios of 2-directional loading taking account of the appropriate environmental conditions. It is shown that, depending on the loading path, consideration of two-directional loading could greatly modify the capacity and stiffness of the foundation compared to their 1-directional counterparts.

Introduction

The challenge for the design of Offshore Wind Turbine (OWT) foundations is to safely assume large overturning moments under comparatively low vertical loading. Among the several foundation types currently implemented in medium depth waters, the alternative examined here is the "suction caisson" which was originally proposed for the foundation of off-shore oil platforms. It comprises a shallow footing whose capacity is enhanced by means of peripheral embedded skirts which confine the internal soil thereby creating a soil plug. Offshore Wind Turbines are required to operate in harsh environmental conditions, thereby being subjected to quite complex loading patterns. In fact, owing to the 3D geometry of the superstructure, a non-negligible out-of-plane stressing may be produced resulting in a fully 6-degree-of-freedom loading [Byrne & Houlsby, (2005); Bienen et al, (2007)]. As such, it may not always (if not only seldom) be conservative to design foundations on the basis of conventional analysis techniques referring to unidirectional loading in each plane; this becomes obvious when considering environmental loads such as the wind or waves which are not expected to act in a sole direction throughout the OWT's lifetime.

Understanding the potential importance and perplexity of the problem, this paper attempts a preliminary investigation on the potential impact of 2-directional loading or of the reversal of environmental loads (e.g. the wind) direction on the foundation stiffness, rate of deformation accumulation, and seismic response. Depending on the parameter under consideration, several caisson dimensions have been studied. The caissons are characterized by their diameter D (taken equal to 20, 25 or 30m) and the length of the caissons L expressed as a function of D through L/D ratio (taken equal to 0.2 or 0.5).

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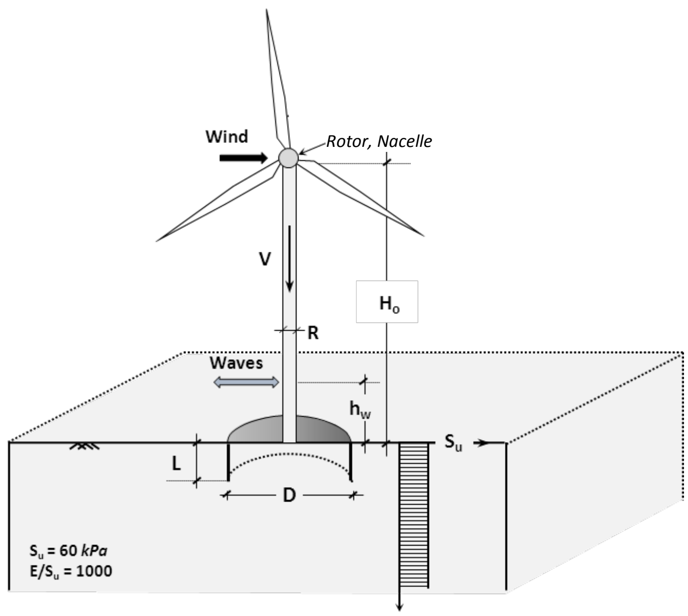


Figure 1. The problem under consideration and adopted nomenclature: a wind turbine founded on suction caisson in homogeneous soil.

Numerical Modeling Methodology and Validation

The analyses for the investigation of the problem were conducted in three-dimensional space using the finite element code ABAQUS. The mesh used for the analyses is shown in **Figure 2**.

The soil body is modeled using 8-node hexahedral continuum elements (C3D8), obeying to a kinematic hardening constitutive model with Von Mises failure criterion [Anastasopoulos et al, (2012)]. The ratio of E_o/S_u where E_o the elastic modulus for zero plastic strain was assumed equal to 1000. When considering earthquake shaking, proper free-field boundaries are assumed. The latter are implemented by kinematically connecting all peripheral nodes at each level with a central node at the same level. Moreover dashpots elements (C) are introduced at the model base. The damping coefficient C is calculated as follows

$$C=\rho\ V_s\ A \qquad (1)$$

where ρ the material density, Vs the shear wave velocity and A the effective area of the dashpot.

A homogeneous soil deposit has been assumed with an undrained shear strength equal to s_u = 60 kPa. (**Figure 2b**). The wind turbine is modeled as a tower with distributed mass and a concentrated mass on the top that represents the rotor-nacelle assembly. Its tower is modeled using linear elastic beam elements while the foundation is modeled using linear elastic shell elements.

It is widely accepted that due to several factors, usually relative to suction caisson installation process, the soil-caisson foundation interface conditions may not always be approximated as fully bonded [Randolph & House, (2002); Luke et al, (2005); Gourvenec et al., (2009)]. In order to simulate as realistically as possible the contact conditions between the foundation and the surrounding soil, contact elements are introduced. The latter are implemented with an advanced tensionless contact algorithm. As it is impossible to estimate the proportion of the residual interface strength a priori, its effect is herein investigated parametrically by means of the following two assumptions:

- In the first case fully bonded interface conditions are adopted
- In the second case, the strength along the interface is assumed to be a fraction (a) of the undrained shear strength of the soil. Factor a has been taken equal to 0.6.

The model has been used to calculate the failure envelopes of the foundation in the M-H (moment-horizontal force) space (Fig. 3a) carrying out both constant–ratio displacement probe tests and displacement controlled swipe tests (Tan, 1990).

The adopted numerical procedure has been able to successfully reproduce the plane strain results of Bransby & Yun, (2009) (Fig. 3b), confirming the soundness of the adopted methodology.

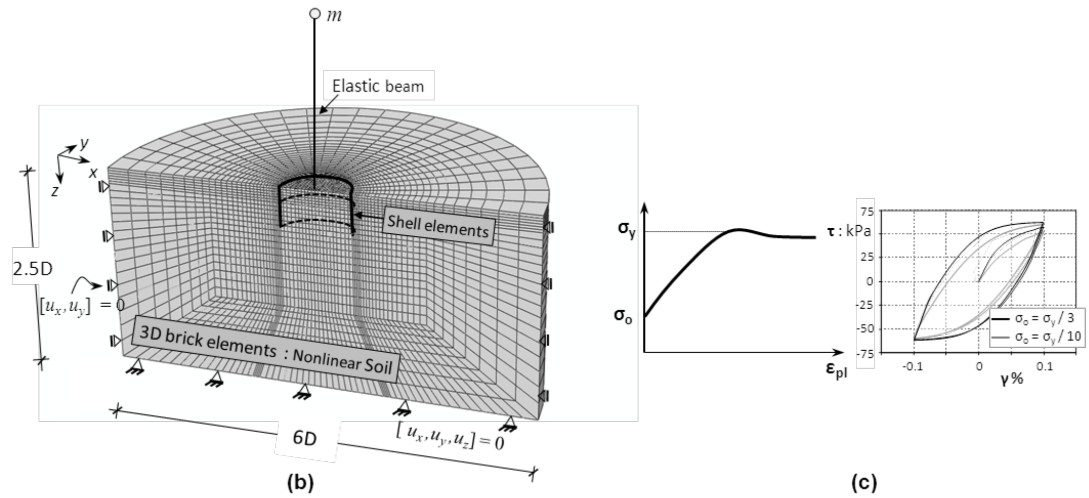


Figure 2. (a) Finite element mesh (a half-model section is presented); (b) One-dimensional representation of the nonlinear soil model.

Effect of 2-directional loading: Stiffness Degradation

The present section attempts a preliminary investigation of the effect of two-directional horizontal loading on the horizontal stiffness of the foundation. Horizontal displacement is applied at the nacelle level and the horizontal stiffness of the system is calculated as a function of the imposed horizontal displacement for two cases as explained below:

1. Calculation of the "unidirectional" stiffness in the horizontal x direction, assuming that no load acts on the horizontal y direction ($K_{X,Hy=0}$) as a function of the imposed displacement in the x direction.
2. Calculation of the "unidirectional" stiffness in the horizontal x direction, assuming that a certain amount of load (corresponding to a fraction of the foundation pure horizontal loading H_o) is maintained on the horizontal y direction ($K_{X,Hy\neq0}$) as a function of the imposed displacement in the x direction. This is accomplished by first applying displacement in the horizontal y direction, followed by calculation of the stiffness in the horizontal x direction in the same manner as previously as a function of the imposed displacement. Note that, as the foundation is perfectly symmetric, the ultimate capacity in pure horizontal loading is equal to H_o irrespectively of the load application direction (x or y).

This loading sequence could physically correspond to the wind load being preceded by a severe storm or seismic shaking event that caused a permanent deformation towards one direction; it could also be attributable to the environmental loads changing their main direction after having caused an irrecoverable displacement or rotation.

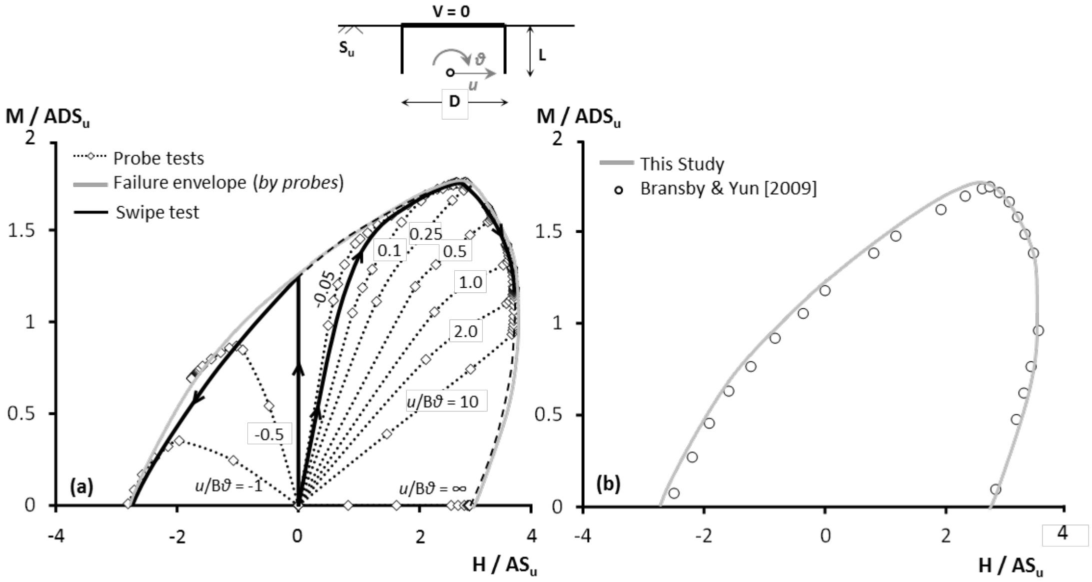


Figure 3. (a) comparison of the failure envelope produced by means of swipe test (bold black line) or displacement probe tests (grey line) for the case of zero vertical loading (V=0); (b) validation of the analysis procedure by comparing data with the Bransby and Yun 2009 solution. Note that A stands for the area of the caisson.

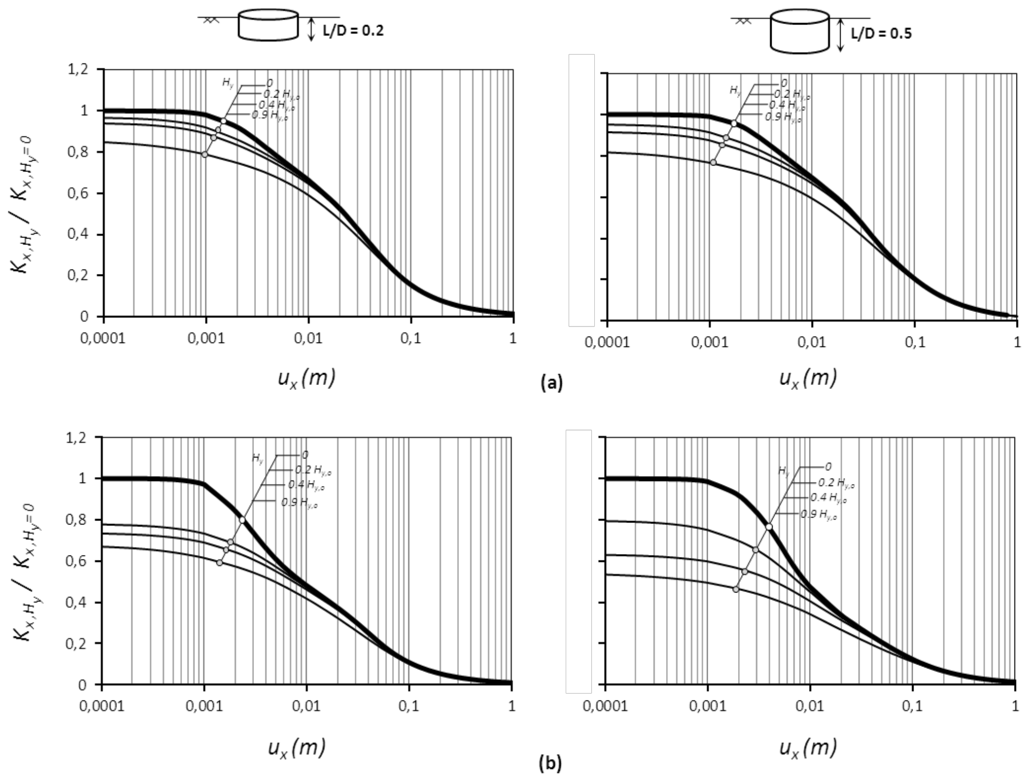


Figure 4. Dimensionless chart of the reduction in the horizontal stiffness of the shallow (L/D=0.2-left) and the deeply (L/D=0.5-right) embedded caisson for the two interface scenarios: (a) full contact (b) low adhesion.

The procedure described above has been repeated for both the shallowly and the deeply embedded caisson (D=20, L/D = 0.2 or 0.5) under either perfect or imperfect interface adhesion regime. Results of the $K_{x,Hy} \;/\; K_{x,Hy=0}$ ratio are plotted in **Figure 4** against the imposed displacement in the x direction for all cases analyzed.

Observe that the stiffness –especially at small deformations- is significantly reduced by the load in the y direction even when its amplitude is as low as $0.2H_o$, while the reduction is apparently more prominent at higher amplitudes. Indeed, soil yielding during the 1st loading step (application of Hy load) results in a decrease of stiffness in the second step as more displacement is now required for the foundation to mobilize the same amount of strength. This decrease is more emphatic in case of the deeply embedded caisson whose overall strength is to a greater extent attributable to the participation of the skirts (and which are now unable to offer the same reaction capacity due to soil pre-shearing).

Understandably, these phenomena become more intense when considering imperfect interfaces (**Fig. 4b**): partial detachment of the skirts from the soil during the 1st loading step annuls their participation in the total stiffness calculated in the 2nd step. This effect is clearly illustrated in the shape of the produced curves which demonstrate a complete absence of the initial elastic part of the curve resulting in stiffness degradation at even very low amplitudes of imposed displacements.

Effect of 2-directional loading: Accumulation of Deformation

The effect of change in loading direction is investigated by comparison of the foundation rotation accumulation in several cases. The general concept of this set of analyses is illustrated in **Fig. 5a** for the case of a suction caisson foundation subjected to the typical environmental loads (wind and waves). Although both are considered to be cyclic forces, the dominant period of the wind is significantly larger than that of the waves; hence our analyses have assumed that the wind is a constant horizontal force acting at the nacelle level, while waves have been modeled as a quasi-statically applied cyclic load as shown on **Fig. 5b**.

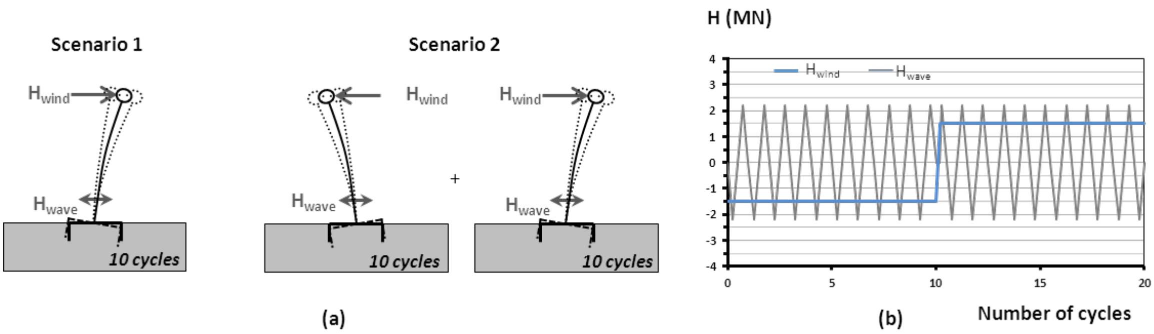
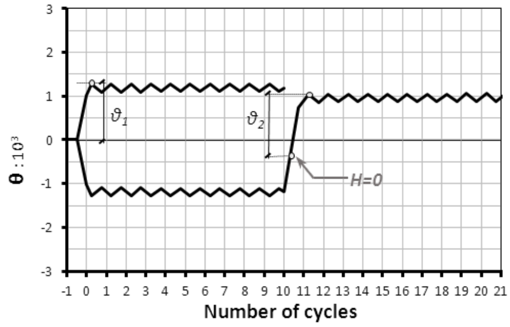


Figure 5. (a) Schematic definition of the two loading scenarios (b) Applied wind and wave forces

The main scope of this analysis is to preliminarily compare the accumulation of rotation with cycles of loading for the same loading pattern (Scenario 1, as defined immediately below) when it is assumed to be applied to virgin conditions with that when it is considered to be a product of wind direction reversal. As such, two scenarios are investigated:

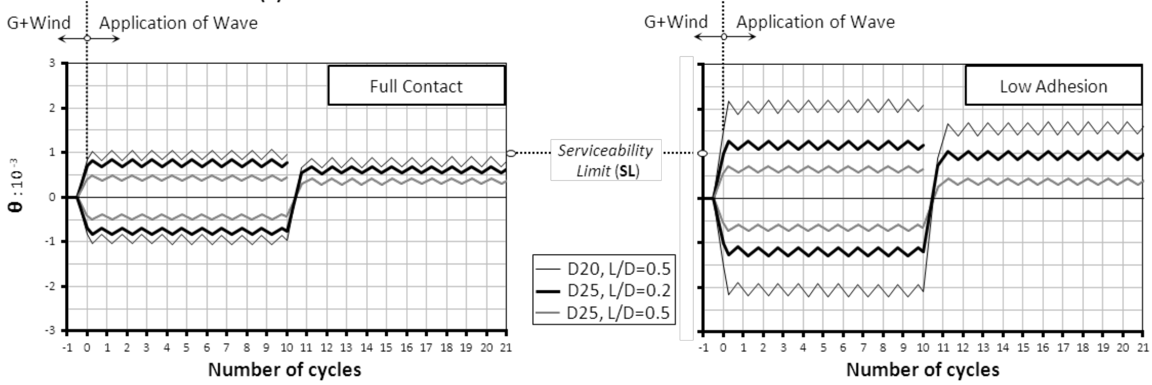
Scenario 1: Application of the wind load in the positive horizontal direction, followed by 10 cycles of wave loading.

Scenario 2: The same loading as Scenario 1 but this time having been preceded by an initial application of the wind loading in the negative horizontal direction followed by 10 cycles of wave loading.



(a)

Full contact	ϑ_1 : 10^{-3} rad	ϑ_2 : 10^{-3} rad	Increase of ϑ (%)
D20, L/D=0.5	1.04	1.17	12.5
D25, L/D=0.2	0.83	0.92	10.5
D25, L/D=0.5	0.49	0.53	7.1
Low Adhesion	ϑ_1 : 10^{-3} rad	ϑ_2 : 10^{-3} rad	Increase of ϑ (%)
D20, L/D=0.5	2.17	2.86	31.8
D25, L/D=0.2	1.28	1.61	26.3
D25, L/D=0.5	0.72	0.75	3.5



(c) (d)

Figure 6. (a) Definition of θ_1, θ_2 (b) Tabulated results for all cases examined. Foundation Rotation as a function of loading cycles for Scenario 1 and Scenario 2 loading assuming (c) Full Contact or (d) Low Adhesion Interface Conditions

Again, this investigation has been repeated for both embedment ratios and for either fully bonded or low adhesion interface conditions. **Figure 6** portrays the results for all cases analyzed. The maximum rotation attained during scenario 1 loading is defined as ϑ_1 (**Fig. 6a**), while that produced after the reversal of wind direction as ϑ_2. Observe that both values refer to the rotation accumulated under application of the same amount of loading. Yet, in the former case (Scenario 1 under virgin conditions) rotation accumulation initiates at the foundation's un-deformed state (vertical position), while, under Scenario 2 initiation of deformation takes place at an already rotated state but towards the opposite direction (**Fig. 6a**). Consequently, the residual rotation after the end of loading is lower; however the amount of rotation acquired (ϑ_2) is obviously increased compared to ϑ_1. In fact, as the initial rotation increases, so does the initial soil yielding. As a result the available shear resistance upon reversal of loading is reduced which, in turn leads to the development of higher rotation. Although this is the trend in all configurations examined, it is noteworthy that the amount of increase varies among them from 3.5% up to 31.8% (**Fig. 6b**).

The increase is higher in case of the D=20m, L/D=0.5 caisson under either full contact or low adhesion interface conditions: this low-diameter alternative mainly relies on the contribution of its deep skirts; hence soil pre-shearing during the 1st loading step considerably reduces the available resistance upon reversal of loading. This reduction is greater in case of low adhesion interface due to partial detachment of the foundation in the 1st step.

When examining the large diameter (D = 25m) caisson however, the available overall strength of the L/D = 0.5 foundation is large enough to be marginally affected by the applied load. Indeed, it only develops a minimal amount of rotation (θ_1 or θ_2) in either interface case while its increase due to pre-shearing is quite insignificant. On the contrary, the available strength of the shallowly embedded (L/D = 0.2) large-diameter (D = 25m) system is not as high (as a consequence of the smaller length of its skirts) rendering it more vulnerable to yielding due to the cyclic loading, especially when low adhesion interface is accounted for.

Effect of 2-directional loading: Seismic Response of Suction Caisson

Although OWT's are slender high-frequency structures, it has been shown (e.g Kourkoulis et.al., 2012) that with the environmental forces acting simultaneously with the earthquake loading the rotation developed at the foundation, is not only irrecoverable, but rather keeps being accumulated during each cycle. This section investigates the effect of two-directional horizontal seismic shaking on the response of an OWT founded on either a D=20m, L/D = 0.5 suction caisson or a very conservative D = 30m, L/D = 0.5 alternative. For the sake of simplicity, seismic loading is represented by an idealized Ricker pulse shown in **Fig. 7a**. In the first analysis step, the wind load is applied modeled as a constant horizontal force. In the next step, the acceleration time history is applied on the base nodes of the model either in the x horizontal direction only (representing the "uni-directional" loading case) or in the x and y horizontal directions. In the latter case, two scenarios are investigated: (a) in-phase and (b) out-of-phase motion in the x and y direction (**Fig. 7a**).

Results are plotted in **Fig. 7b** in terms of rotation time histories at the foundation. It is shown that, in accord with previous findings, the two-directional loading tends to increase the rotation accumulated in each loading cycle. This tendency is obvious in the low-diameter alternative where the skirts' capacity is severely reduced (as explained in the previous section). In the conservative D = 30m alternative, the 2nd horizontal component has only minimal effect unless the out-of-phase scenario is considered. In this latter case, the maximum value of rotation (apparently attained at the instant of the pulse peak) does remain unaffected (and rather marginally reduced), but its residual value increases by a non-negligible 40%. Indeed, at around t = 4.8s (Fig. 7b, right) the foundation has originally (one-directional or in-phase scenarios) the tendency to return to its equilibrium position; at that instant however, the y-direction pulse (in the out-of-phase case) has a positive direction which hinders the foundation's return and in fact causes it to reverse its motion direction towards the positive rotation (blue line). Consequently, and due to the lack of subsequent pulses that would perhaps alter the situation, the foundation is forced to retain that rotation which remains as irrecoverable residual deformation after the end of shaking.

Conclusions

This paper has utilized 3D non-linear numerical analyses to preliminarily investigate the effect of two-directional loading on the response of suction caisson OWT foundations subjected to environmental loads of non-constant direction of action such as wind or waves and seismic loading. It is shown that:

1. Foundation stiffness may be even substantially reduced due to soil yielding provoked by initial soil yielding attributable to the existence of loading in the 2nd direction
2. Rotation accumulation with cycles of wave loading may increase as a result of wind loading reversal, depending on the foundation dimensions and soil-caisson interface

conditions

3. Seismic shaking in two directions severely augments the rotation developed by the low-diameter caisson and, when the 2nd component is out-of-phase, could substantially increase the residual deformation of even a conservatively designed foundation.

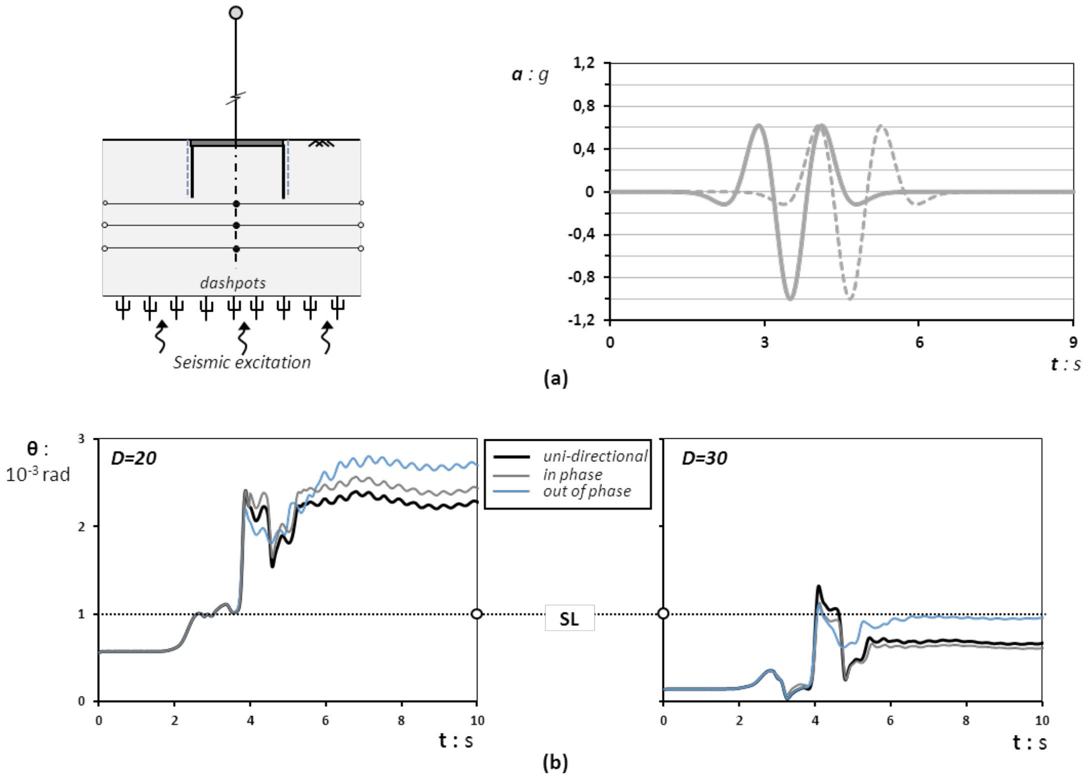


Figure 7. Response of the turbine on the two foundation alternatives subjected to Ricker excitation [f=0.5, amax=1g] assuming imperfect interface conditions: (a) Boundary conditions for earthquake loading; acceleration time history used as input for the dynamic analyses (out of phase scenario represented by the dashed curve). (b) rotation time history for the two foundations

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