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Modeling underwater cable structures subject to breaking waves

Alexander Niewiarowski[a,*], Sigrid Adriaenssens[a], Ruy Marcelo Pauletti[b], Khalid Addi[c], Luc Deike[d]

[a] *Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, 08540, USA*
[b] *Polytechnic School at the University of São Paulo, Avenue Prof. Almeida Prado, Trav. 2, 83, 05508-900, São Paulo, SP, Brazil*
[c] *University of La Réunion, Saint-Denis | Laboratory of Physics and Mathematical Engineering for Energy and the Environment, 117 rue du Général Ailleret, 97430, Le Tampon, La Réunion, France*
[d] *Princeton Environmental Institute, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, 08540, USA*

A R T I C L E I N F O

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A B S T R A C T

Motivated by the design of a protective anti-shark cable net enclosure located in heavy surf on La Réunion, France, this paper presents a modeling technique for underwater cable structures subject to breaking wave action. Such modeling capability is not offered in leading commercial software. Forces on underwater cable structures are frequently modeled using the well-established Morison equation. These forces are functions of the fluid velocity and acceleration, which are normally calculated using an appropriate wave theory. Such an approach works well in many applications, but it does not permit the modeling the effects of breaking waves. However, considering the absence of wave impact loads on submerged structures, the Morison equation is still valid provided that a suitable hydrodynamic time history is available. In the presented work, the Morison equation is coupled with a high-resolution breaking wave simulation obtained by solving the full air-water Navier-Stokes equations, creating a time-domain analysis approach suitable for studying underwater cable structures subject to breaking waves. The hydrodynamic model is validated using the software package ProteusDS, and the presented model is used to characterize the mechanical response of a moored cable net. This research is of relevance to the analysis and design of submerged cable structures.

1. Introduction

Recently installed cable net shark barriers in strong surf (La Réunion, France) have suffered from persistent damage and high maintenance costs,[1,2] The barriers consist of cable or rope netting anchored to the sea floor and tensioned by buoys. Seeking to improve the barrier's design has exposed a gap of knowledge in modeling and designing such structures. Although the modeling of submerged cable nets has been extensively studied in the context of fishing and aquaculture applications (e.g., Cui et al., 2014; Huang et al., 2006; Kristiansen and Faltinsen, 2012; Moe et al., 2010; Xu et al., 2013; Yao et al., 2016), these existing models do not account for the impact of breaking waves as such nets are not typically subjected to breaking wave action. This paper presents a novel approach to incorporate breaking wave action into a hydrodynamic time-domain analysis model for the analysis of underwater cable structures.

Generally, the modeling of underwater cable structures subject to hydrodynamic loads (but not wave break loads) is a well-studied problem. The Morison equation (1950), first developed to describe wave forces on slender piles, is typically used for this purpose (see §2.1).

Commercial software such as Orcaflex[3] and ProteusDS[4] can model a wide variety of moored structures subject to the effects of wind and non-breaking waves. Such software generates sea states using wave functions, from which the necessary velocity and acceleration data are calculated and applied to the Morison equation. However, such a modeling approach cannot handle breaking waves. When a wave breaks, a strong turbulent flow is generated and the fluid velocities and accelerations no longer vary in time with the wave period; no analytical theories provide a useful description of fluid motions in such cases (e.g., Drazen et al., 2008; Perlin et al., 2013; Rapp and Melville, 1990).

However, if the cable structure remains submerged, then there are no impact forces imparted and the Morison equation remains valid, allowing the possibility of using numerical simulations to describe the fluid motion instead of analytical theories. Using such a numerical

* Corresponding author.
E-mail address: aan2@princeton.edu (A. Niewiarowski).

[1] http://reunion.orange.fr/actu/reunion/la-degradation-du-filet-anti-requins-de-boucan-canot-en-images.html.
[2] https://vimeo.com/258646602.
[3] https://www.orcina.com/SoftwareProducts/OrcaFlex/.
[4] https://dsa-ltd.ca/proteusds/overview/.

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approach, this paper describes a time-domain analysis model suitable for underwater cable structures subject to breaking wave action. With the proper adjustments to the wave simulation, this approach can be easily implemented to model moored cable structures in a wide variety of environments.

The paper is structured as follows. Following this introduction, the requisite background knowledge on lumped-mass cable modeling and recent contributions to the area are presented, and the numerical methods used to simulate breaking waves and obtain the post-breaking velocity field are described in §2. In §3, the structural model, the wave simulation, and their coupling are presented. The structural model is validated with the commercial software ProteusDS using three simple benchmarks that ensure the proper functionality of the model and the hydrodynamic forcing function. Finally, sample results are presented in §4 for a section of an underwater cable net under a breaking wave. The paper concludes with a summary of the presented approach in §5. In this work, vectors and matrices are denoted by lowercase and uppercase bolded italics, respectively, while scalar quantities are denoted by plain italics.

2. Background

Given the centrality of fluid mechanics to the design of any underwater structure, this section begins with a brief review of the physical phenomena relevant to moored cable structures, namely, the forces described by the Morison equation, as well as a description of the numerical breaking wave simulation. Numerical modeling techniques suitable for characterizing the behavior of underwater cable structures are also reviewed.

2.1. Hydrodynamic forces on cables

Throughout the literature, cable elements are commonly regarded as cylinders to simplify the computation of hydrodynamic forces. A complete treatment of flow around cylinders is offered by Sumer and Fredsøe (2006). When a structure, like a cable net, is composed of slender elements whose diameters are much smaller than the wavelengths of the waves affecting them, scattering and diffraction effects can be ignored. A special theory has been developed for this situation, originally proposed by Morison et al. (1950) for the case of fixed vertical piles, and later generalized to include moving cylindrical bodies. A complete treatment of flow around cylindrical bodies is offered by Sumer and Fredsøe (2006).

To summarize, the Morison equation (Eq. (2.1)) expresses the hydrodynamic wave force $\boldsymbol{f}_{ext}$ on a unit length of a cylinder as the sum of three terms: drag force, hydrodynamic mass force, and the Froude-Krylov force.

$$\boldsymbol{f}_{ext} = \underbrace{\tfrac{1}{2}\rho_f D C_d (\boldsymbol{v} - \dot{\boldsymbol{x}})|\boldsymbol{v} - \dot{\boldsymbol{x}}|}_{drag\ (\boldsymbol{f}_D)} + \underbrace{\rho_f C_m A(\dot{\boldsymbol{v}} - \ddot{\boldsymbol{x}})}_{hydrodynamic\ mass} + \underbrace{\rho_f A\dot{\boldsymbol{v}}}_{Froude-Krylov\ (\boldsymbol{f}_{FK})} \tag{2.1}$$

ρ_f is the mass density of fluid, D is the diameter of the cylinder, A is the cross-sectional area of the cylinder, $\boldsymbol{v}$ is the fluid velocity (calculated using a suitable wave theory or from a numerical simulation), and $\boldsymbol{x}$ is the element position. C_d and C_m are semi-empirical drag and hydrodynamic mass coefficients. The drag force is encountered in many engineering applications and cylinder drag is a well-studied problem. The other two terms in Eq. (2.1) also merit a brief explanation:

The hydrodynamic mass force describes the inertial effect due to the distortion of the fluid flow by the presence of the body. In general, the force $\boldsymbol{f}$ required to sustain the acceleration of a body with mass m through a stationary fluid is proportional to the body acceleration $\ddot{\boldsymbol{x}}$ and can be written as:

$$f = (m + m')\ddot{\boldsymbol{x}} \tag{2.2}$$

Here, $m' = \rho_f C_m A$ is the hydrodynamic mass (also referred to as added mass) of the unit cylinder, which is the mass of the fluid in the immediate vicinity of the body that is accelerated along with the body due to pressure effects. The hydrodynamic mass force is the additional force needed to accelerate this mass and can be obtained by integrating the pressure gradient that develops around the body as it accelerates. For the case of the cylinder, the added mass for flow perpendicular to the body is equal to $\rho_f A$, which gives rise to an added mass coefficient $C_m = 1$ as shown in Sumer and Fredsøe (2006). It is common to neglect the hydrodynamic mass force in the case of tangential flow around cylinders ($C_m = 0$).

The Froude-Krylov force is the surface integral of pressure generated by accelerating flow in far-field. A control volume of water having a mass m and undergoing acceleration $\dot{\boldsymbol{v}}$, must experience a force $m\dot{\boldsymbol{v}}$. If this control volume is replaced with another body, then that body must experience the same force $m\dot{\boldsymbol{v}}$. To summarize, the hydrodynamic mass force arises from near-field effects and depends on the relative acceleration of the body, while the Froude-Krylov force depends only on the acceleration of the fluid in far-field. The drag force, the hydrodynamic mass force, and the Froude-Krylov force represent the external loadings that are accounted for in the presented modeling approach (see §3) for submerged moored cables subject to breaking wave action.

2.2. Modeling of moored cable net structures

The moored cable nets that motivate the present work consist of cables and buoys. In this paper, however, only the cable elements are treated in detail, while the buoyant force from the buoys is considered as an additional external forcing on the system.

Both the finite element (FEM) (e.g., Huang, 1994; Ran et al., 1999; Williams and Trivailo, 2007) and the finite difference (FDM) (e.g., Ablow and Schechter, 1983; Mehrabi and Tabatabai, 1998; Milinazzo et al., 1987) methods have been used in the dynamic modeling and simulation of cable systems. The established FEM approach uses a consistent mass matrix, as in Wang et al. (1998). However, by far the most widely used model is the lumped mass (LM) cable model, which instead features a diagonal mass matrix $\boldsymbol{M}$ (providing computational advantages in situations involving $\boldsymbol{M}^{-1}$). Due to its ubiquity, the LM model is well-described (e.g., Buckham, 2003; Buckham and Nicoll, 2015; Masciola et al., 2014). To summarize the LM method, a cable is discretized into n segments and their masses are concentrated at $n + 1$ nodes. The nodes are assumed to be connected by viscoelastic springs, or in more complex formulations such as Buckham's (2003), bending and torsional springs as well.

After discretization, the entire cable is located in a chosen inertial frame, while cable segments are described individually with local element frames. Unlike traditional, stiffer civil engineering structures on land, hydrodynamic loads on compliant cable structures vary not only with time, but also with the structure's changing configuration and orientation. For example, the drag force and the hydrodynamic mass effect are each functions of anisotropic empirical and geometric coefficients, which may differ for each degree of freedom in the model. For cylindrical cable elements, these coefficients are defined with respect to an element's normal and tangential directions. For optimal computational efficiency, the treatment of such loads necessitates the construction of an appropriate local element frame.

The most common approach uses Euler angles and the Frenet-Serret frame, while an alternative has been proposed recently by Zhu and Yoo (2017), which accounts for not only geometry, but also environmental loading. In this approach, an orthonormal reference frame for element e (Fig. 1) is constructed using the element's normalized tangent vector $\boldsymbol{z}^e$ (defined using the element orientation vector l and length L) and the average relative nodal velocity vector $\boldsymbol{v}_R$ (defined in Eq. (3.8)):