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Inverse catenary load attenuation along embedded ground chain of mooring lines

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ABSTRACT

The present paper presents an investigation of the static load attenuation emerging from the soil frictional forces acting on the embedded part of an anchor chain. Mooring line tension makes the embedded chain segment to develop an inverse catenary shape between the deep down point (DDP) and the padeye. Both the shape of the catenary and the mobilized frictional forces have significant influence on the total loading capacity of the anchoring system. The work is based on laboratory tests using a scale reduced model, designed to evaluate the catenary development and the load attenuation in respect to the installation depth, nominal chain angle and soil mechanical properties. As the experiments comprehend both loading and unloading cycles, the results provide a substantial database for confrontation of constitutive models for soil-chain interaction. In the literature, the usual assumption to relate frictional (F) and transversal (Q) forces in a catenary segment, ds, is a direct proportionality. However, present results indicate that such a simple relation is an oversimplification of a far more complex relation that cannot be accurately used for modeling the catenary development. Besides an hysteretic behavior, the mean relation F/Q presents a dependence on the undrained soil shear strength, s_u, also contradicting the usual assumption that F and Q are both linearly dependent on this parameter.

1. Introduction

The present work is motivated by the need of improving knowledge on the inverse catenary shape and the load attenuation along the embedded ground chain segments in mooring lines of offshore platforms. *In situ* measurements are difficult to be carry out in deep water conditions (over 2000 m), and presently only theoretical methods of analysis based on a static limit state approach are available. The quantification of expected load attenuation levels is of upmost importance for taut leg anchoring system design, for presently the nominal loads are taken as the peak of time series generated from given design sea wave height spectra, which is believed to be a conservative approach. It is expected that both mean load levels and dynamic loading fluctuations not fully reach the anchoring device, which in the present case is the *Torpedo* type anchors used by Petrobras in Brazil, described by Amaral and Costa [1] and illustrated in Fig. 1. Petrobras has developed the so-called torpedo piles (also known as dynamically installed piles) for deep water applications (e.g. Araujo et al., 2004; Fernandes et al., 2006; Amaral, 2008; Henriques Jr. et al., 2010 and Sousa et al., 2011).

In this context, the work focuses on the inverse catenary chain segment embedded below sea bottom, as depicted in Fig. 2 (Link to DDP). In most cases this segment length may exceed 30–40 m, and provides a significant reaction that contributes to the total resistance of the anchoring system. This reaction may be even increased due to inertial or viscosity forces arising from dynamic loading of the mooring line. The inverse catenary is hence expected to act as a type of low pass mechanical filter for the dynamic design loads.

Besides the attenuation of transmitted loads, the catenary shape itself has an important influence on the anchor capacity, for it defines the loading angle with respect to the torpedo axis. The more vertical the catenary reaches the torpedo, the lower is the expected anchor capacity. For this reason the catenary changes in shape, altering the magnitude of forces reaching the torpedo, which is the object of research in the present study. In order to quantify the differences between traction forces at the DDP and at the link point, herein called attenuation forces or simply attenuation, a 1:40 length scaled model has been designed, calibrated and extensively used along the research program. The scaling assumptions essentially rely on an rigid-plastic soil behavior, with the undrained shear strength, s_u, expressed as a function of soil density, ρ, embedment depth (from sea bottom), z, and gravity acceleration, g. These assumptions have shown to be a

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Fig. 1. Torpedo type offshore anchors and chains used by Petrobras (Petrobras archive).

simple and robust basis for future experimental improvements toward large-scale testing programs.

2. Theoretical background

There are presently some limit state formulations available in the literature (Vivatrat et al., 1982; Degenkamp and Dutta, 1989; Neubecker and Randolph, 1995; Kim, 2005; Wang et al., 2010; Randolph et al., 2011; Lee et al., 2014) for modeling the soil-chain interaction, which are recalled herein for the sake of establishing a common ground for further discussion. In conformity with these formulations, the present experimental program provides the chain traction force at the DDP and at the padeye, as well as an approximate catenary shape. The basic parameters enrolled in this type of formulation are listed below and shown in Fig. 3:

T_0	chain traction force at the DDP
T	chain traction force at an intermediate point
T_n	chain traction force at the padeye
θ_0	chain axis angle to horizontal at the DDP
θ	chain axis angle to horizontal at an intermediate point
θ_n	chain axis angle to the horizontal at the padeye
F	longitudinal friction force per unit length
Q	transversal reaction force per unit length
w	chain weight per unit length
s	along chain line coordinate, starting at padeye
L	total embedded chain length

The indices 0 and n have been chosen to easy compatibility with an eventual finite differences approach. Fig. 3 also shows the forces acting on a differential element of the chain with length ds, which must be considered in order to derive the following equilibrium equations:

$$F = \frac{dT}{ds} - w\sin\theta \tag{1}$$

$$Q = T\frac{d\theta}{ds} + w\cos\theta \tag{2}$$

It may be observed that the frictional force is defined as positive when directed against the line coordinate, s, which starts at the padeye for compatibility with previous works. By briefly neglecting the self weigh influence, which is relatively very small, it can be seen that while the frictional forces change the tension magnitude along the chain, the transversal forces change its direction. These equilibrium equations are the departure point for any model proposition. They must be followed by some hypothesis on the distribution of frictional and transversal forces along the embedded chain, which may depend on some kinematic parameter to yield a constitutive model for the soil-chain interaction. This model could be then verified against the experimental results for total attenuation and direction change:

$$T_0 - T_n = \int_L (F + w\sin\theta)ds \tag{3}$$

$$\theta_0 - \theta_n = \int_L \frac{1}{T}(Q - w\cos\theta)ds \tag{4}$$

In the references previously cited, the relationship between F and Q is always expressed as:

$$F = \mu Q \tag{5}$$

where μ is a dimensionless friction coefficient. It is also usually assumed that F and Q, but not μ, are directly proportional to the

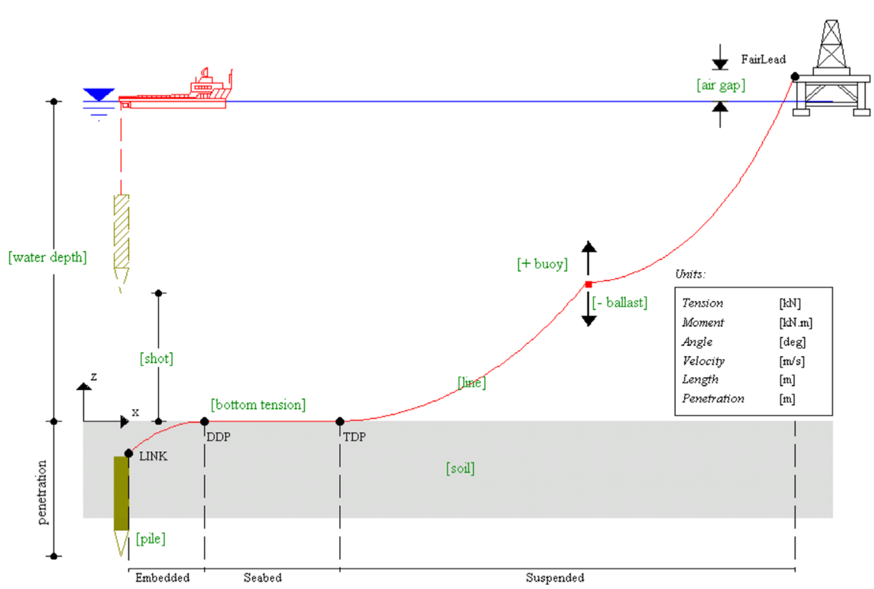

Fig. 2. Context of analysis, where the segment LINK-DDP (the inverse catenary) is the main subject of investigation (DIGIN Software User´s Manual).