Interaction Mechanisms of Mooring Lines in Very Soft Clay

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Abstract: Previous researches on mooring lines have contributed to the development of analytical and numerical integration methods designed to predict tension distribution and inverse catenary configurations of an embedded chain in clay. These methods have not been comprehensively validated in laboratory and field studies for the calibration of their constitutive parameters, and thus provide only limited support to the design of offshore foundations. The present work describes a laboratory investigation program carried out in a scale model to investigate the interaction mechanism between saturated clay and the steel chain of mooring lines. Chains and metal tubes with different nominal diameters and lengths were embedded vertically and horizontally in soft clay and pulled-out at the constant rate of 5 mm/min to failure. The results showed that the load × displacement response of mooring lines depends on soil characteristics, displacement direction, chain geometry, slenderness ratio and stiffness. It is also dictated by soil behavior which is controlled by interparticle forces. The results and the discussions presented in this study, mainly the estimated parameters, the explanation of how the interaction mechanisms occur, and the influence of the soil in the strain softening behavior are important for the design of offshore foundations that involves mooring lines.

Keywords: Model Tests, Mooring Lines, Soft Soil, Offshore Foundation, Soil-Chain Interaction, Inverse Catenary.

1. Introduction

In deep water fields, drag anchors and piles have been used as foundation elements of offshore structures and are designed to withstand static, cyclic and transient loads (API RP 2A, 2006). Once the anchors are embedded into the seabed, a set of mooring lines is required to connect them to the floating units. Therefore, the load capacity required to stabilize platforms becomes the result not only of the soil–anchor interaction, but also of the mooring chain-soil interaction. Catenary mooring systems directly influence the installation process and the embedment capability of drag anchors, as well as the failure mode of the piles, the chain forces and angle at the anchor point (Degenkamp and Dutta, 1989; Neubecker and Randolph, 1995; Nie and Zimmerman, 2010).

Previous studies - Reese (1973), Gault and Cox (1974), Vivatrat et al. (1982), Degenkamp and Dutta (1989), and Neubecker and Randolph (1995) - have investigated the factors that influence the anchor performance and have proposed conceptual analytical and numerical integration methods to estimate both the inverse catenary and the load distribution of the embedded chain.

After these works, many experimental, analytical and numerical studies developed have contributed to improve the understanding about the foundation of the offshore platforms. Despite significant progress, many
challenges and issues (for example: interaction mechanisms of chain in soft soil) continue to deserve the attention of researchers.

Considering the importance of developing analytical and numerical tools capable of handling the soil-chain interaction for the design of offshore foundations, the present study entailed performing a set of laboratory tests in a reduced scale model (1:40) to investigate the chain–soil interaction and failure mechanism. The purpose of this paper, a part of Sampa’s thesis developed in 2019, is to continue the study previously developed by Rocha (2014), Sampa (2015) and Rocha et al. (2016) at the Federal University of Rio Grande do Sul on static and dynamic load attenuation on mooring lines embedded in marine clays. The analysis and discussion of test results are mainly focused on the behavior of embedded mooring chains in clay under the two idealized response of vertical and horizontal chain loading, and on the parameters required to estimate the pullout resistances. The main conclusions are summarized and compared with previous reported studies.

2. Experimental Investigation

2.1. Experimental Setup and Chain Installation

Laboratory model tests were conducted in two testing apparatus illustrated in Figures 1 and 2. Samples are prepared in an acrylic chamber with internal dimensions of (L)1.52 m × (W)0.24 m × (H)0.80 m, and the chains and metal tubes are connected to a pullout device to perform vertical and horizontal pull-out tests.

Three steel configurations corresponding to (i) free chains (non-welded), (ii) welded chains, and (iii) metal tubes were embedded in saturated clay and tested under tension to investigate the respective interaction mechanisms. The nominal diameters of both chains’ configuration are 3 mm, 4 mm and 5 mm. The length of welded chains varies from 100 to 500 mm, while the length of free chains varies from 50 to 500 mm. In addition to chains, 100 mm, 300 mm and 500 mm long metal tubes, having an outside diameter of 25.55 mm, were used for comparison because their circular cross-sectional area simplifies interpretation and allows direct comparisons with pile foundations.

Figure 1 – General view of the experimental setup used in the vertical pull-out tests.
Testing preparation for vertical pullout tests follows three main steps: (i) positioning and tensioning 6 vertical chains inside an empty acrylic tank, with the chains spaced 22.5 cm apart along the height of the tank to avoid any influence during the subsequent load application on the steel chain; (ii) mixing the slurry and carefully filling the tank with soil up to 720 mm; and (iii) relieving the tension on the chains and assume the equilibrium condition inside the soil before testing. Preparation of horizontal pull out tests is similar except for the procedure adopted for positioning the chains inside the tank. The chamber is initially filled with slurry to a pre-established height, where two chains are laid horizontally and tensioned (through a steel wire welded to the first link), before re-start filling with slurry to the final height of the sample. Chains were embedded in four different depths, corresponding to 0.60 m, 0.45 m, 0.30 m and 0.15 m. Immediately after sample preparation, a water constant head of 50 mm was placed above soil surface to keep water content constant. The slurry was then set to rest for 24 hours before starting the test.

2.2. Sample Preparation and Characterization

The slurry used in all of the tests was reconstituted from a mix of 85% of kaolin, 15% of sodium bentonite and tap water. Initially, dry weights of kaolin and bentonite were measured in a precise weighing scale and mixed on a plastic receptacle until a uniform color of the mixture was obtained. The mixture was then hydrated using tap water in a heavy duty slurry mixer for 20 min to attain a homogeneous sample at a water content of 120% (1.12\(\cdot w_L\)). Finally, the slurry was poured in the acrylic chamber. This process was repeated seven times due to the small capability of the mixer and the large size of the acrylic tank.

The results of the physical, chemical and mechanical tests carried out to characterize clay slurry are presented and discussed in an article entitled “Physical-Chemical-Mechanical Behaviors of a Clay Manufactured in the Laboratory to Replace Brazilian Marine Clay”. This article was submitted to COBRAMSEG 2020 under the number 119757.

2.3. Pull-Out Test

Forces and displacements were measured by a load cell and two LVDTs, respectively. Pullout tests start by connecting a high strength steel wire to the end of the embedded chain while recording the pullout forces by a load cell. A displacement rate of 5 mm/min was applied until the residual pull-out resistance had been
achieved. On average, each test last for about 20 min, which was the time required to impose a 10 cm displacement to the chain. In a few cases, after testing, the chains were removed out of the soil at the same displacement rate for a visual examination of the chain-soil interface to determine the shape of the cross-sectional area.

A total of 88 tests were performed, being 32 on vertical direction (18 with free chains (VFC), 11 with welded chains (VWC) and 3 with metal tubes (VMT)) and 56 on the horizontal direction (42 with free chains (HFC), 12 with welded chains (HWC) and 2 with metal tubes (HMT)).

3. Results and Discussion

Figure 3 illustrates the typical load × displacement curves measured experimentally and their respective normalizations. This behavioral trend was observed in all tests carried out with free and welded chains and metal tube.

To explain this behavior, a representative model of these curves with four behavioral states (I, II, III and IV) was adopted based on the Ratz concept proposed by Randolph (2003). The first state – I corresponds to the linear section and occurs at the initial stage of the chain displacement. This linear behavior is due mainly to the clay minerals properties. According to Isopov et al. (1984), this response can be a result of the partial tilting of particles and microaggregates in the direction of the shear force without displacement relative to one another. Load removal at this stage of deformation leads to elastic restoration with time of the initial state of particle arrangement. It is expected that most of the shaft resistance is mobilized in this state.

The second state is a curvilinear (hyperbolic) line of approximately 1 to 3 mm in length that represents the transition between the end of the straight line and the peak of the curve. Isopov et al. (1984) described a similar behavior as the gradual change of the elastic deformation to viscoelastic in the narrow shear zone, leading to the rebuilding of the soil microstructure in this zone. Its occurrence may be related to the near-complete mobilization of shaft resistance while the base resistance is still being mobilized. This behavior was mainly observed in the results of the tests performed with higher undrained shear resistance and chain length. Neglecting this stretch, assuming a straight line before the peak, will not affect the behavior of the curves, since it is very short and was observed in a few curves.

The maximum load is fully mobilized at displacements less than 10 mm, and this range depends on the chain stiffness and the clay plasticity. Due to the flexibility of free chains, the ratio of chain displacement to diameter at failure (L/D) increases with chain length. For tests carried out with welded chains and metal tubes, this ratio is relatively constant for a wide range of chain length, and the values are 0.36 (VWC), 0.39 (HWC)
and 0.14 (VMT). The high plasticity of the clay, due mainly to the presence of bentonite, contributes significantly for the large displacement – 0.2D to 0.6D – before the peak.

Figure 4 presents the results of some tests performed with reversal of the displacement direction in order to investigate the soil influences on the linearity of measured curves. Regardless of the displacement magnitude, the curve responses tended to be linear after the change of displacement direction, reflecting thixotropic and viscous behaviors even for the short time.

![Viscous and thixotropic behaviors with reversal of the displacement direction.](image)

The analysis of the failure surface shows a gradual mobilization of displacement of the free chain links, from the first to the last, at the beginning of the tests. A small displacement is required to homogenize the displacement of all chain links so that the chain stiffness influences the shape of the failure surface at the beginning of the test. The flexibility of free chains allows them to better accommodate in soil reflecting in a failure surface, irregular in shape along the length of the chains. This irregularity tends to disappear with increasing displacement. As a consequence, at the beginning of the tests, the shaft resistance was mobilized gradually and a shear area slightly larger than the chain cross section was mobilized in order to align all links in the direction of the pull-out force. This behavior was not clearly observed in the tests performed with welded chains due to their stiffness.

Regarding the maximum load, it was assumed that its magnitude depends on the yield conditions of the clay, represented by the undrained shear strength, $s_u$. Therefore, the base ($Q'_b$) and shaft ($Q'_f$) resistances can be estimated from the maximum load measured ($Q$), taking into account the chain weight ($W$), as shown in Equation (1). The own weight of chain is not taken into account in analysis of tests carried out with chains embedded in a horizontal direction. Figure 5 illustrates the model proposed from the results of the experimental investigation to represent the interaction mechanism of chain in a clay slurry.

$$Q' = Q - W = Q'_f + Q'_b$$

(Due to the chain geometry, the results of the experimental investigation confirm that the shaft resistance is a result of both the shearing resistance of the clay and the chain – soil shear interface. This mechanism was best understood by the observations made after the exhumation of chains, which indicated that the lateral resistance developed along a non-circular cross – sectional shear area, as shown in Figure 5 (top view). This cross – sectional shear area closely resembles a four – pointed star. Considering that the shaft resistance is fully mobilized before the peak, the Equation (2) can be used to estimate its value.)
where $f_{sc}$ and $f_{ss}$ are unit shaft resistance chain-soil and soil–soil, respectively. $A_{sc}$ and $A_{ss}$ are frictional area per unit of length chain-soil and soil–soil, respectively.

The chain geometry and the embedment of the chain in a very soft clay make it difficult to separately determine the areas $A_{sc}$ and $A_{ss}$. One simplifying assumption is to assume a unique frictional area as ($A_{ts}$). The shaft resistances of both chains and metal tubes can now be estimated according to Equation (3), considering an average unit shaft resistance ($\bar{f}$) mobilized along the unit shear area ($A_{ts}$). The average unit shaft resistance, $\bar{f}$, is expressed based on the total stresses’ method, being $\bar{\alpha}$ the mean adhesion factor.

$$Q'_{f} = \int_{0}^{L} (f_{sc} A_{sc} + f_{ss} A_{ss}) dz$$

Equation (3) can be modified and rewritten as Equation (4), considering that the unit shear area depends on the effective chain diameter (D) and $\beta$ parameter which takes into account the shape of the failure surface (different from circular failure surface).

$$Q'_{f} = \int_{0}^{L} f_{ts} A_{ts} dz = \int_{0}^{L} \bar{\alpha} s_u A_{ts} dz$$

$$Q'_{f} = \int_{0}^{L} \alpha' s_u D dz : \bar{\alpha} \beta = \alpha'$$

As illustrated in Figure 5, the mobilization mechanism of the base resistance in clay slurry at larger depths is by punching shear. The soil mass, above (vertical chains) or front (horizontal) to the first link, is subjected to compression and deformation as soon as the chain displacement begins.

The mobilization of the base resistance also starts as soon as the first link is displaced because of the full embedment of the chain in soil. Near the surface, by reason of the small weight of the overburden, chain displacement tends to drag soil in a larger area. Equation (5), analogous to the bearing capacity expression, is used to estimate the base resistance as a function of the undrained shear strength and the projected base area ($A_{b}$). The effect of the overburden load was neglected, as suggested by Terzaghi (1943), Skempton (1951) and others for piles embedded in soft soils.
\[ Q'_b = q A_b = N_c s_u A_b \]  

(5)

where \( N_c \) is the bearing capacity factor.

Considering that the projected base area \( (A_b) \) depends on the effective chain diameter \( (D) \) and \( \zeta \) parameter which takes into account the shape of the base area (different of circular area), the Equation (5) can be modified and rewritten as Equation (6).

\[ Q'_b = N'_c s_u D^2 \quad \therefore \quad N_c \zeta \pi / 4 = N'_c \]  

(6)

From the Equations (4) and (6), the parameters \( \alpha' \) and \( N'_c \) required to estimate the shaft and base resistances, respectively, was calibrated using Multiple Linear Regression Method as shown in Figure 6.

![Figure 6 – Calibration of \( \alpha' \) and \( N'_c \) parameters from the measured net capacity load.](image)

With regard to the post-peak state, there is a significant decrease of measured load with chain displacement, characterizing the strain softening behavior. This behavior is essentially the result of the progressive degradation of the interface resistance from the maximum value to the residual value, not by the decrease of the cross-sectional shear area. This conclusion is valid since the strain softening behavior was also observed in the tests performed with metal tubes that have constant cross-sectional area. The degradation of the clay structure and subsequent reorientation of particles in the displacement direction is the main reason for the strain softening behavior.

With respect to the fourth state at large displacements the curves reach a residual state where there is a tendency of load stabilization with the increase of displacement. The particle orientation and complete formation of the sliding surface are the main factors for the residual state. The same behavior was also observed in the results of miniature vane shear test. In most cases, the load measured tends to stabilize from displacements greater than 45 mm. Thus, the parameters necessary to calculate the base and lateral resistances in residual state can be adjusted from the same equations proposed to estimate the resistances in peak state. This investigation on residual resistances and the quantification of their parameters afterwards are very important for the design of offshore foundations, since the mooring lines are subject to large displacements during the installation of anchors.
4. Conclusions

This paper presents results of laboratory model tests carried out to investigate the interaction mechanism of mooring lines in clay slurry. The loads measured in pullout tests consist of base resistance, soil-soil interaction and soil-chain interaction due to the chain geometry. The load × displacement response of mooring lines depends on soil characteristics, displacement direction, chain geometry, slenderness ratio and stiffness. It is also dictated by soil behavior which is controlled by interparticle forces. The results of this study, mainly the estimated parameters, the explanation of how the interaction mechanisms occur, and the influence of the soil in the strain softening behavior are important for the design of offshore foundation that involve mooring lines. A complete discussion on interaction mechanism of chain in soft clay can be found in Sampa (2019).

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