Numerical model for analysis of the load attenuation on mooring lines in catenary system

Eduardo. G. Rosa[1], Marcelo. M Rocha[1]

[1]*Dept. of Civil Engineering, Federal University of Rio Grande do Sul - UFRGS*
99 Osvaldo Aranha Ave, 90035-190, Porto Alegre - Rio Grande do Sul, Brazil
eduardo.gibbon@ufrgs.br, mmrocha@ufrgs.br

Abstract. With the advancement of oil exploration at greater depths, the solution to maintain offshore platforms in place has changed from a traditional rigid system to a flexible system formed by mooring lines. Usually, a mooring line consists of an anchor chain attached to the floating unit in the upper end and the anchor or foundation element at the lower end, which implies that, along its length, the chain is not only submerged in water but also embedded in soil. Experimental investigations conducted on reduced scale have shown that the load applied at the embedment point located on the seabed surface does not reach the same magnitude at the anchoring point. The so-called "load attenuation" is related to the inverse catenary shape developed by the mooring line embedded in the soil, providing a transversal reaction force and longitudinal friction force in the soil-chain interface. In order to evaluate the problem from a numerical point of view, an initial 3D finite element model of the anchor chain embedded in marine soil was built in the ANSYS software. As a starting point, the anchor chain behavior is adopted as elastic, the soil is considered perfect elastoplastic with Drucker-Prager yield criterion and the contact interface is simulated by Coulomb's law of friction. The load attenuation levels obtained for several cases are compared to reference results, both experimental and numerical, and the stress disturbance in soil is presented in terms of von Mises equivalent stress.

Keywords: anchor-chain interaction, mooring line, load attenuation, inverse catenary.

1 Introduction

As oil exploration activities began to migrate to greater depths, permanent mooring systems have been developed to maintain the position of floating units, once the rigid and fixed systems normally adopted in shallow waters would require way too large structures to withstand the environmental loads of ocean and wind. Basically, the mooring systems are composed by the mooring lines, most commonly made of steel chains, and the anchoring device itself, which can be a torpedo pile, for example, which is a solution developed by Petrobras in Brazil (ARAUJO et al. [1]).

From a mechanical point of view, the operation of the mooring system is relatively simple: the upper end of the chain connects to the floating platform, where the environmental loads act, and the lower end connects to the foundation element, the main responsible for transferring the loads to the soil. However, the existence of interaction between soil and chain in the mooring line segment found embedded in the soil introduces some complexity in the analysis, since it causes force reactions along its length, which motivate investigations in several studies, as Vivatrat el al. [2], Degenkamp and Dutta [3], Neubecker and Randolph [4,5], Neubecker and O'Neill [6], Liu et al. [7], Rocha et al. [8], to cite a few.

According to Neubecker and Randolph [4], after the system is installed and the application of loads takes place, the anchor chain induces cutting and sliding at the interface of contact with the soil, which, in turn, opposes the movement and induces the formation of the traditional inverse catenary configuration normally associated with this kind of problem (see Fig. 1). In this scenario, the components of soil strength, both in transversal and longitudinal direction to each infinitesimal segment of the anchor line, promote what is known as "load attenuation": the force acting directly on the foundation element is lower than the force observed at the point of embedment in the soil. In addition to the attenuation in the load magnitude, the formation of the inverse catenary also influences the load capacity related to the foundation, depending on the angle formed in the connection between chain and anchor device (ROCHA et al. [8]).

The determination of load attenuation range related to a specific situation is of great interest to companies in the industry, as it would certainly lead to a less expensive system design. In this context, it is still necessary to consolidate methods that assess the diversity of parameters (soil's strength and behavior, geometric characteristics of the inverse catenary, equivalent diameter of the chain to be considered, stiffness of the contact interface, among others) which influences the analysis. Due to the huge dimensions of these mooring systems, experimental investigations on full scale become practically unfeasible; therefore, should be highlighted the importance of reduced scale investigations and numerical models, as recently done by Sampa et al. [9] and Braun et al. [10].

Based on the above, the current paper presents a 3D finite element model, built with the aid of ANSYS software. In the analysis, the soil is taken as a perfect elastoplastic material, with Drucker-Prager yield criterion, simulated by solid elements, the chain is considered as a purely elastic material and modeled by linear elements, while the soil-chain interface is described by Coulomb's law of friction and represented by pairs of target and contact elements. Through the results obtained, it was possible to evaluate the level of load attenuation obtained for several proposed scenarios and to visualize the stress disturbance developed in the region of interest.

2 Model description

The problem of load attenuation in a mooring line system can be understood as consisted of three main elements: soil, chain and anchoring device. For simplification, this last component is represented as a fixed support, being responsible for providing the horizontal and vertical reactions which represent the resulting attenuated load (F_a) reaching and acting on the foundation element.

The simulated soil mass consists of saturated clay, as usual in this type of situation. In this initial approach, a perfect elastoplastic behavior is admitted by the Extended Drucker-Prager model, available in ANSYS, which describes materials with non-linear behavior dependent on hydrostatic pressure. Its main difference in relation to the classic Drucker-Prager model lies in the possibility of defining yield and flow potential functions in a linear (actually assumed herein), hyperbolic or exponential form. Thus, the following input data must be supplied to the software: undrained shear strength (S_u), Young modulus (E_s), Poisson's ratio (ν_s), specific weight (γ), friction angle (φ), dilatancy angle (ψ) and cohesion (C). From these, the lateral earth pressure coefficient (K_0), the pressure sensitivity parameters (α_{ps} and $\bar{\alpha}_{ps}$) and the equivalent uniaxial yield stress (σ_Y) are determined. The element type chosen for analysis is SOLID185, with hexahedral format, used for modeling 3D solids in general; this element is defined by eight nodes with three degrees of freedom each: translations in the X, Y and Z directions.

For the anchor chain simulation, the element type chosen is LINK180. This element has a linear geometry, defined from two end nodes that present the translations in the X, Y and Z directions as degrees of freedom. It is capable of representing structural components with uniaxial behavior, such as truss bars and cables, for example. In one of the key options provided, it is possible to set its stiffness contribution in tension only, a condition that was adopted in the current model. Due to the level of loading and the dimensions related to the chain, the behavior of the material is considered purely elastic; thus, the respective values of Young modulus (E_c) and the Poisson's ratio (ν_c) are supplied to ANSYS. The definition of the element is complemented by associating an area corresponding to the material cross-section.

One of the most important factors to be incorporated into the model is the configuration of the anchor chain that is embedded within the soil mass, since, as previously discussed, in the process of mooring line implementation, it is expected the formation of an inverse catenary shape. The scheme considered is shown graphically in Fig. 1, which identifies some of the necessary parameters for the construction of the curve.

Wherever experimental data are available, it is possible to estimate the format of the inverse catenary through interpolations, as done by Braun et al. [10], or through previously deduced equations, as done by Li et al. [11] and adopted in the current paper. Since the submerged section of the anchoring line is designed in a "usual" catenary configuration, penetration into the seabed occurs practically horizontally, which leads to the use of the following formulations, eq. (1) and eq. (2), where x_a and y_a stand for the horizontal and vertical distances between the anchoring point and the embedment point, respectively, while β_a is the inclination angle between the anchor chain and the horizontal plane, where it connects to the foundation element.

$$x = x_a - B\left[\sqrt{\frac{y}{B}}\left(1-\frac{y}{B}\right) + \arcsin\left(\sqrt{\frac{y}{B}}\right)\right] \tag{1}$$

$$B = \frac{y_a}{\sin^2 \beta_a} \tag{2}$$

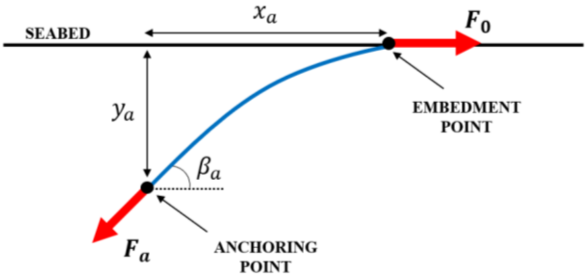
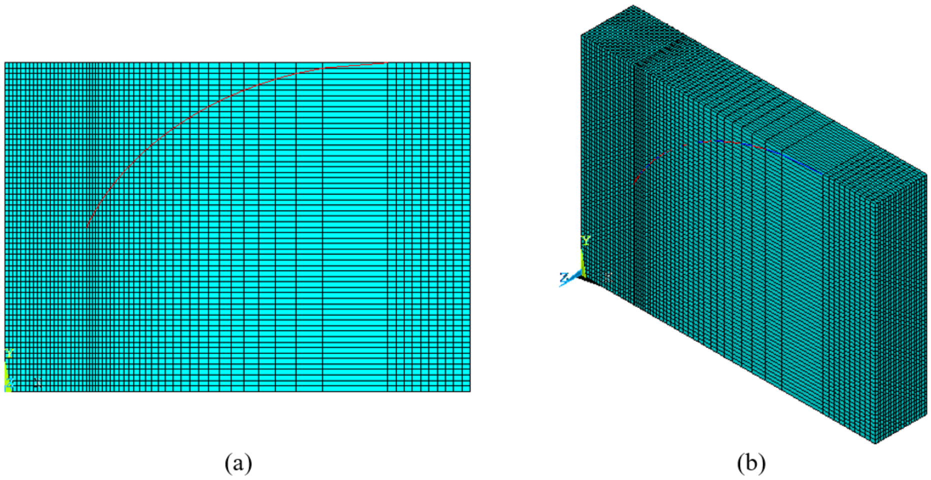


Figure 1 – Scheme of the embedded mooring line segment.

For incorporation in the model, the inverse catenary that represents the embedded mooring line segment was divided into equally spaced points in vertical direction, somehow simplifying the mesh generation in ANSYS. A small code was developed in PYTHON, providing the horizontal and vertical coordinates of the nodes where the geometric union between soil and chain elements must occur. The frontal view and the isometric perspective of the mesh used for one of the investigated cases are shown in Fig. 2:


(a)

(b)

Figure 2 - Mesh visualization: (a) front view and (b) isometric perspective.

After ensuring the geometric continuity between the LINK180 and SOLID185 elements, it is created the contact interface between the soil and the chain, using contact and target elements, CONTA177 and TARGE170, which establish a line-to-surface contact-type pair. The CONTA177 element can be used to represent contact and sliding between a linear segment (anchor chain) and a 3D target surface, defined by the element TARGE170 and represented by the group of areas formed by each face of the soil elements. Among the key options of the contact element, there is the possibility of adjusting the normal (K_n) and tangential (K_s) stiffness of the contact interface, which, as pointed out by Braun et al. [10], are important parameters concerning the load attenuation level expected.

As in any problem related to the modeling of a physical space, the soil mass must present large enough dimensions to prevent the boundary conditions from influencing the results. In addition, a symmetry condition is assumed with respect to the XY plane, which allows better computational performance in analysis processing.

Finally, translation restrictions and stresses that aim to simulate the initial geostatic condition predicted in the soil were applied in Z direction.

3 Model validation

In order to verify the accuracy of the finite element model proposed, the experimental results provided by Degenkamp and Dutta [3] are used, which consist of a series of tests aimed the simulation of a reduced scale mooring line system. In these tests, a horizontal force is applied to the free end of the chain (F_0), and the resulting attenuated force (F_a) and the angle of inclination (β_a) developed at the anchoring point are evaluated. For each case studied, the authors also provide the values of x_a and y_a, both necessary to determine the inverse catenary configuration. Additionally, the load attenuation results obtained by Li et al. [11], who similarly proposed a numerical model in ANSYS, and the results obtained by Neubecker and Randolph [5], according to an analytical expression proposed by the authors themselves, are brought to comparison; this is possible because refer to the same data from Degenkamp and Dutta [3]. Although the current work has a similar approach to that developed by Li et al. [11], it should be emphasized that the premises regarding the conception of the numerical model present relevant differences, as the types of finite elements applied and mesh discretization in ANSYS, for example.

In the experimental investigations, a saturated clay with undrained shear strength (S_u) equal to 4.52 kPa and saturated specific weight (γ_w) of 18.8 kN/m³ was used. Complementing the input data for the present numerical model, a Poisson's ratio (ν_c) equal to 0.49, friction (φ) and dilatancy (ψ) angles equal to zero are assumed, aiming to simulate undrained loading conditions. The relationship between modulus of elasticity and soil resistance (E_c/S_u) is taken as 500.

Regarding the properties of the anchor chain, the experimental cases in which the nominal diameter is equal to 9.5 mm are chosen and checked. The chains are of studless type, with Young modulus (E_c) estimated at 5.44e7 kPa and Poisson's ratio (ν_c) equal to 0.3. In addition, the friction coefficient (μ) equal to 0.5 was assumed as representative for the soil-chain interface.

From the described values, six different scenarios were simulated, each one presenting different characteristics related to the configuration of the mooring line inside the soil and the magnitude of the force applied at the free end (F_0). For each case, the force at the anchor point (F_a) was taken from the ANSYS post-processing tools, as the Table 1 below summarizes the results obtained:

Table 1- Experimental and numerical resultant forces at anchoring point.

CASE	ANCHORING DEPTH [m]	HORIZONTAL FORCE AT EMBEDMENT POINT [N]	RESULTANT FORCE AT ANCHORING POINT FROM DEGENKAMP AND DUTTA (1989) [N]	RESULTANT FORCE AT ANCHORING POINT FROM LI ET AL. (2016) [N]	RESULTANT FORCE AT ANCHORING FROM CURRENT WORK [N]
CASE 6.1	.4065	708	404	414	380
CASE 6.4	.4065	6148	5447	5346	5443
CASE 7.1	.2040	672	364	361	493
CASE 7.4	.2040	7799	6900	6723	6899
CASE 8.1	.6120	1268	658	671	709
CASE 8.4	.6120	5831	4875	5070	4767

For load attenuation level evaluation, it is considered the relation $1 - F_a/F_0$, in terms of percentual values. The respective obtained results are shown in the following Table 2:

Table 2 - Load attenuation level comparative.

CASE	LOAD ATTENUATION FROM DEGENKAMP AND DUTTA (1989)	LOAD ATTENUATION FROM NEUBECKER AND RANDOLPH (1995b)	LOAD ATTENUATION FROM LI ET AL. (2016)	LOAD ATTENUATION FROM CURRENT WORK
CASE 6.1	43%	41%	42%	46%
CASE 6.4	11%	11%	13%	11%
CASE 7.1	46%	45%	46%	27%
CASE 7.4	12%	9%	14%	12%
CASE 8.1	48%	48%	47%	44%
CASE 8.4	16%	17%	13%	18%

To complement the set of results brought in Table 1 and Table 2, the behavior of the stresses developed in the soil due to the disturbance caused by the anchor chain, in terms of von Mises equivalent stress, is illustrated in the sequence of figures that follows (Fig. 3 to Fig. 8):

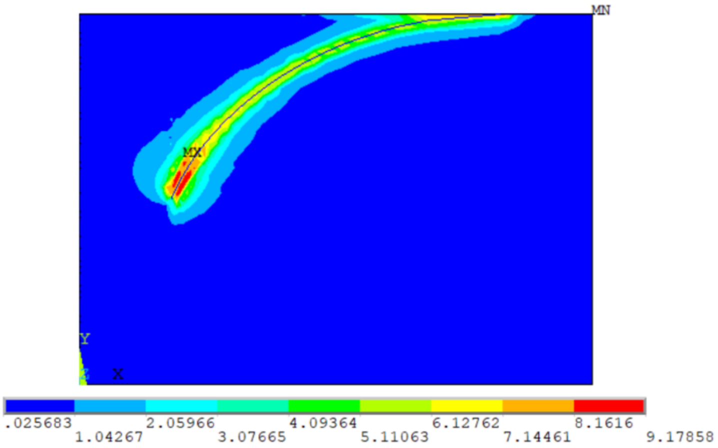


Figure 3 - Contours of von Mises equivalent stress for Case 6.1, in kPa.

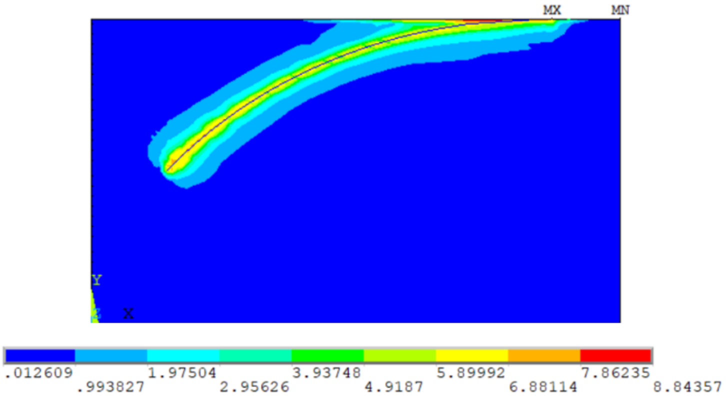


Figure 4 - Contours of von Mises equivalent stress for Case 7.1, in kPa.

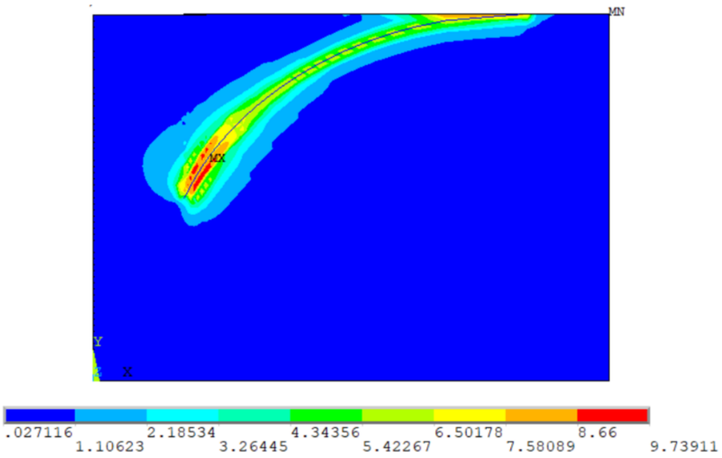


Figure 5 - Contours of von Mises equivalent stress for Case 8.1, in kPa.

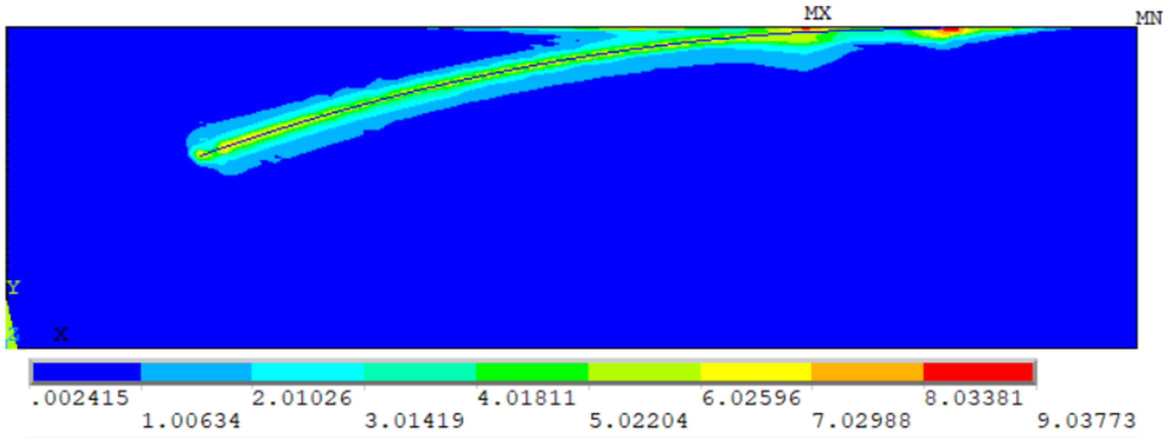


Figure 6 - Contours of von Mises equivalent stress for Case 6.4, in kPa.

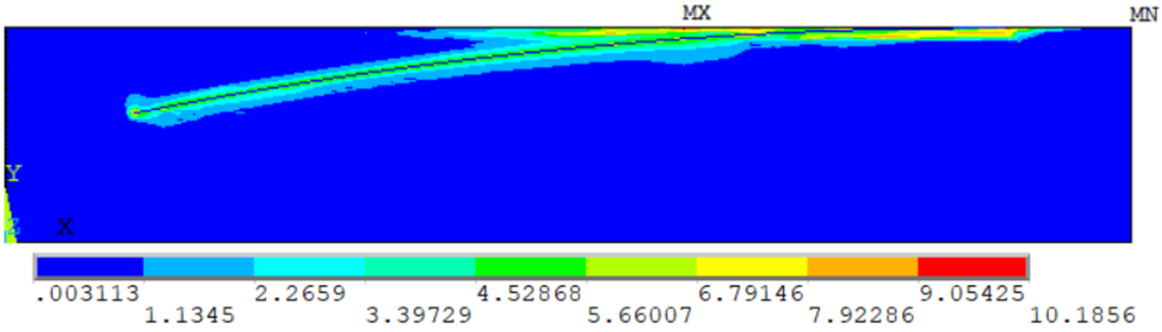


Figure 7 - Contours of von Mises equivalent stress for Case 7.4, in kPa.

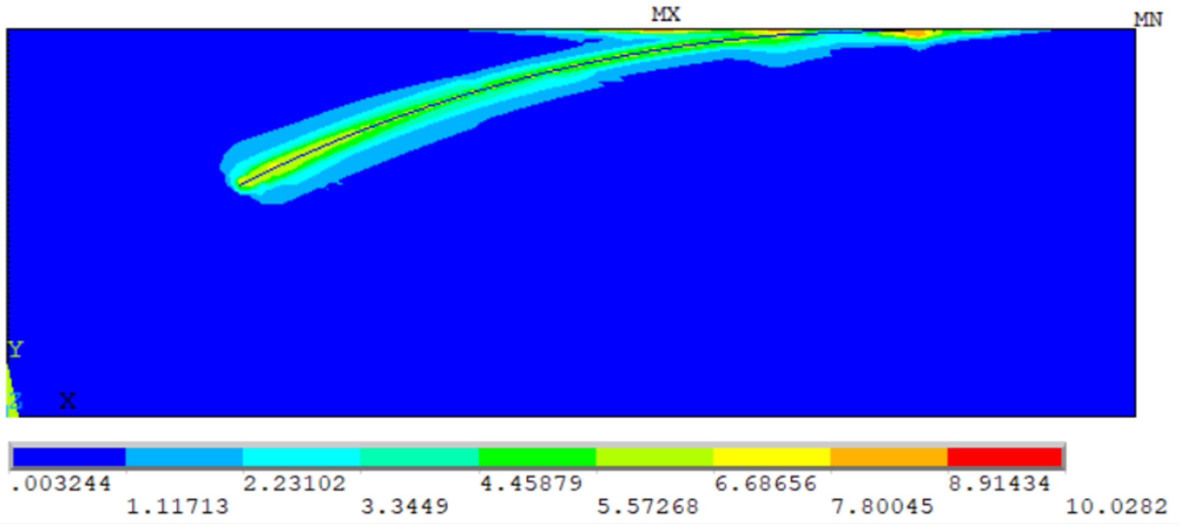


Figure 8 - Contours of von Mises equivalent stress for Case 8.4, in kPa.

4 Conclusions

The current paper describes the elaboration and validation of a finite element numerical model in the ANSYS software, which provides a reference for understanding the mechanisms involved in the soil-chain interaction, an inherent feature of mooring systems.

The construction of the model was guided by simplified, although realistic, assumptions, both in terms of mesh generation and in the choice of element types and material's behavior, which represent a starting point for this kind of analysis and a reduced computational cost. In future versions, not only should the arrangement of nodes that connect soil and chain elements be improved, but it is also intended to assess viscous time dependent effects that may influence the results.

With regard to load attenuation levels, all values were considered satisfactorily close to the experimental and numerical reference results, except for the case 7.1. In this case, as it has smaller depth and length of embedded anchor chain, it is likely that the standard division of elements adopted for the inverse catenary has not been able to correctly mobilize the reactions imposed by the soil. Besides, the shape of the embedded chain spreads more horizontally than in cases 6.1 and 8.1, which may be related to the construction equation used.

As for the stress disturbance caused in the soil, it is possible to visualize, especially in cases 6.1, 7.1 and 8.1, what the authors Li et al. [11] named as a "dumbbell" shape, with more pronounced mobilization regions at the ends of the anchor chain and smoother in the central region. This indicates that the load attenuation is not uniform along the depth. Such behavior is less pronounced in cases 6.4, 7.4 and 8.4, where the magnitude of loading is increased, leading to the belief that, once the soil strength on the seabed surface is exceeded, there is a great reduction on the load attenuation, as the inverse catenary itself become more aligned to the applied force, reducing the transversal component of reaction in the anchor-chain interface.

Acknowledgements. The authors recognize and would like to thank the support of the *Federal University of Rio Grande do Sul (UFRGS)* as well as the scholarship provided by *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)*, which encourages good researchers to keep the good knowledge and the technology improvement in Brazil.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] J. B. de Araujo, R. R. D. Machado and C. J. de Medeiros Junior. "High holding power torpedo pile: results for the first long term application". In: *International Conference on Offshore Mechanics and Arctic Engineering*,vol. 37432, pp. 417-421, 2014.

[2] V. Vivatrat, Philip J. Valent and Albert A. Ponterio. "The influence of chain friction on anchor pile design." In: *Offshore Technology Conference*. Offshore Technology Conference, 1982.

[3] G. Degenkamp and A. Dutta. "Soil resistances to embedded anchor chain in soft clay". *Journal of Geotechnical Engineering*, vol. 115, n. 10, pp. 1420-1438, 1989.

[4] S. R Neubecker and F. M. Randolph. "Performance of embedded anchor chains and consequences for anchor design". In: *Offshore Technology Conference*. Offshore Technology Conference, 1995a.

[5] S. R Neubecker and F. M. Randolph. "Profile and frictional capacity of embedded anchor chains". *Journal of geotechnical engineering*, vol. 121, n. 11, pp. 797-803, 1995b.

[6] S. R. Neubecker and M. P. O'Neill. "Study of chain slippage for embedded anchors." In: *Offshore Technology Conference*. Offshore Technology Conference, 2004.

[7] H. Liu, W. Zhang, X. Zhang and C. Liu. "Experimental investigation on the penetration mechanism and kinematic behavior of drag anchors.". *Applied Ocean Research* 32, no. 4, pp 434-442, 2010.

[8] M. M. Rocha, F. Schnaid, C. C. M. Rocha and C. S. Amaral. "Inverse catenary load attenuation along embedded ground chain of mooring lines". *Ocean Engineering*, vol. 122, pp. 215-226, 2016.

[9] N. C. Sampa, F. Schnaid and M. M. Rocha. "Atenuação de cargas dinâmicas em linhas de ancoragem de plataformas offshore". In: *XVIII Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica*. XVIII Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica, 2016.

[10] A. L. Braun, A. Brüch and S. Maghous. "A mixed 3D-1D finite element formulation for analysis of geomaterial structures with embedded curvilinear inclusions: application to load transfer in mooring anchor systems". *Latin American Journal of Solids and Structures*, vol. 15, n. 8, 2018.

[11] S. Li, B. Z. Xu, Y. Z. Wu and Z. G Li. "Study on interaction between soil and anchor chain with finite element method". *China Ocean Engineering*, vol. 30, n. 6, pp. 942-953, 2016.