Comparison of analytical and numerical design of suction anchors in deepwater clays

Dimensionnement analytique et numérique d'ancrages à succion en eaux profondes

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ABSTRACT: The paper presents the result of an extensive study on the undrained holding capacity of suction anchors with different length-to-diameter ratios. The clays used in this study have a linearly increasing undrained shear strength with depth. The paper proposes a 'ready-to-use' equation for the preliminary design of suction anchors in soft clays. To highlight the benefit of the design equation, three example projects where detailed design of suction anchors had already been carried out numerically are compared with the equation-based design. The comparisons show that the proposed equation can be used with confidence for the preliminary design of suction anchors in similar soil conditions. The paper also addresses the key assumptions and restrictions associated with the use of the design equation.

RÉSUMÉ : L'article compare l'analyse numérique et analytique de la résistance d'ancrages à succion de différentes dimensions et installées dans de l'argile molle à grande profondeur d'eau. Les argiles ont une résistance au cisaillement augmentant avec la profondeur. L'article propose une équation pour le dimensionnement d'ancrages à succion dans l'argile molle. Afin de vérifier la fiabilité de l'équation proposée, elle a été appliquée sur trois projets où le dimensionnement avait aussi été fait avec des analyses numériques détaillées. La vérification démontre que l'équation proposée peut être utilisée pour le dimensionnement préliminaire d'ancrages à succion installée dans des argiles similaires. L'article mentionne aussi les hypothèses et limitations de l'équation proposée.

KEYWORDS: suction anchor, analytical design, numerical design, clay, holding capacity

1 INTRODUCTION

Suction anchors are cylindrical steel structures, open-ended at the bottom and closed at the top. The length-to-diameter (aspect) ratio generally ranges from 3 to 6. Mooring tension line loads are applied through anchor chains at different angles and connected at a padeye. A suction anchor is installed by self-weight followed by pumping water out of the caisson to reach target penetration depth. This creates under-pressures (or suction) inside the anchor.

In an optimized design, the anchor top must be sealed during the lifetime of the structure if one relies on the suction in the holding capacity calculation (unless the sum of inside skirt wall friction at the time of design loading exceeds the reverse end bearing). A typical anchor design consists of both a preliminary and a detailed design phase. In a preliminary phase, the design is often based on limited soil data and environmental loads. The preliminary design is later refined or revisited in a detailed stage with updated mooring line loads and more complete soil data including advanced laboratory test results. These separate designs often affect project schedule and costs, especially when a quick sizing of suction anchors is necessary for a bidding process.

This paper presents the results of an analytical study of the undrained holding capacity of suction anchors with different length-to-diameter ratios in soft clays. From the study, a 'ready-to-use' equation is proposed to estimate the undrained holding capacity of a suction anchor for a given aspect ratio and to calculate the safety factor against failure under critical mooring line loads.

The proposed 'design' equation can provide useful information for suction anchor design projects from bidding stage to detailed design. To highlight the benefit of the proposed 'design' equation, the undrained holding capacity of suction anchors predicted by the equations is compared with the capacity computed by advanced numerical analysis (i.e. the finite element method) for three detailed design projects with suction anchors.

2 UNDRAINED HOLDING CAPACITY CALCULATION

2.1 *Key design parameters*

The undrained holding capacity of suction anchors depends on:

- Anchor geometry;
- Undrained shear strength of soil;
- Location of the load attachment point below mudline (i.e., depth of padeye);
- Mooring line load angle at seabed and at padeye;
- Set-up factor (α) outside/inside the suction caisson;
- Anisotropy factors representing the strength difference in simple shear (s_u^{DSS}), compression (s_u^C) and extension (s_u^E);
- Soil degradation due to cyclic loading and long-term constant loading; and
- Installation tolerances (i.e., misorientation and tilt).

In anchor design, the final anchor geometry is selected by iteration. The shear strength need to be carefully selected based on field and laboratory test results and engineering judgment. Statistical analyses can be very useful when selecting the strength profiles. The holding capacity is governed by the low or best estimate of the strength while the penetration resistance is governed by the high estimate of the strength.

The optimum padeye depth, leading to the maximum holding capacity for a given geometry, is known to be approximately two thirds of the penetration depth in a clay with linearly increasing shear strength. To prevent the formation of a gap on the backside of the upper part of the anchor (active side of the anchor) under loading, the load attachment point is lowered slightly below the optimum depth.

Depending on the loading angle at the padeye, the governing failure mechanism would be one of three: a vertical pull-out mode, a horizontal failure mode or in most cases an interaction mode between the two. In general, the axial capacity tends to govern the suction anchor design as the load angle approaches 30° from the horizontal (e.g., El-Sherbiny et al. 2005).

The remolded shear strength at the interface between the skirt and the clay will increase with time after installation, resulting in an increase in capacity. It is therefore important to choose an appropriate value of α corresponding to a set-up period required by the client. Details on how to determine the α factor can be found in Andersen and Jostad (2002).

The stress conditions along a potential failure surface varies resulting in anisotropy in strength represented by direct simple shear, triaxial compression and triaxial extension. The design shear strengths are affected by loading types (e.g., cyclic wave loading, and/or constant loop current loading) due to rate effects and soil degradation. Installation tolerances can also affect holding capacity. A positive tilt results in a larger vertical load component relative to the pile axis while misorientation (or misalignment) will introduce torsion loading which may be considered by reducing the outside axial skirt wall friction.

2 .2 *Calculation methods*

The industry standard (e.g., DNV, 2005) requires the undrained holding capacity of suction caissons to be calculated by one of two methods: limit equilibrium or plastic limit analysis method or finite element method (Andersen et al. 2005). In this paper, the upper bound plasticity method was used for the analytical study. The 2D finite element procedure with side shear to account for 3D effect is used for most of suction anchor design projects at NGI.

2.2.1 *Plastic limit analysis method*

For calculation of the combined load capacity of suction anchors, Aubeny et al. (2003) updated the Murff and Hamilton (1993) plasticity model by reducing the four original optimization parameters characterizing the kinematics of the failure mechanism to only two parameters: the depth to the center of rotation of the rotating caisson and the velocity ratio between vertical and horizontal velocities.

Furthermore, the updated model takes into account the general loading condition at the padeye. Aubeny et al. (2003) used the upper bound analysis method that equates the external work performed by applied axial and lateral loads to the energy dissipation in plastically deforming the soil due to an assumed virtual displacement of the mechanism. The minimum force (unknown) leading to failure can then be solved by optimizing the two parameters from the equations. Details on the governing equations that relate the external and internal work can be found in Aubeny et al. (2003).

The updated plasticity model was implemented in an Excel spreadsheet program SAIL (Aubeny et al. 2003). The analytical study was carried out on the undrained combined load capacity for suction anchors with different aspect ratios and with undrained shear strength profiles with different set-up factors. The maximum capacity estimated by the SAIL program is the upper bound estimate of the true capacity for the failure mechanism. A more updated version of this model will become available shortly. However, the 2003 version is believed to provide a reasonably accurate solution for this paper.

2.2.2 *Finite element method*

The finite element method (FEM) is the most detailed calculation method that can accomodate complex geometries, full or partial drainage, undrained conditions and non-linear soil behaviour. The method provides the critical failure mechanism, safety factor and displacements. However, this method requires more detailed knowledge of the soil and is more time-consumimg if one is to correctly model and interpret the results (Andersen et al. 2005).

To eliminate many of the disadvantages while keeping the benefits of this method, NGI developed a tailor-made finite element program BIFURC (NGI 1997) to determine the undrained capacity of suction anchors in clay. BIFURC uses a strain-hardening elasto-plastic soil model together with interface elements. The interface elements model the reduced interface anisotropic strengths with adhesion and anisotropy factors.

The 3D effects are taken into account in BIFURC by introducing a non-linear relationship between the mobilized side shear τ and the length of the displacement vector δ (Equation 1).

$$\tau/\tau_{max} = 2 \cdot \left(\delta/\delta_f\right)^{0.5}/(1 + \delta/\delta_f) \tag{1}$$

where τ_{max} = the maximum side shear (=s_u^{DSS} * a side shear factor of 0.5 (roughness soil-steel) or 0.6 (roughness soil-soil)).

The roughness factors have been calibrated against full 3D finite element analyses and gave good agreement with the FE analyses (Jostad and Andersen 2015). The maximum shear stress τ_{max} is assumed to occur at a given value of δ_f (displacement at failure), which is typically set to 0.1 m in most cases.

In the program, the load is increased in steps and the holding capacity is obtained when a steady-state condition is reached. A failure limit is defined when the top displacement increases significantly for an infinitesimally small increase in the load (flat load-displacement curve). The holding capacity is estimated with the factored padeye loads and angles as input to the program. Therefore, the output in terms of safety factor indicates an extra safety margin beyond the required factors of safety.

3 PROPOSED 'DESIGN' EQUATION

Based on the upper bound plasticity method, an extensive study of the undrained holding capacity of suction anchors was carried out with different combinations of aspect ratios and shear strength profiles. As a base case, the calculation was made for a 4-m diameter anchor with an aspect ratio of 6. The base case shear strength was assumed to be 3.8 kN/m^2 (80 lb/ft^2) at the mudline and then linearly increasing with depth by 1.3 kN/m^2/m (=8 lb/ft^2/ft). The ultimate load at 11 different angles (0 to 40° in 5° increment, and 50° and 90°) at the padeye was estimated together with three set-up factors of α=0.25, 0.6 and 1.

The ultimate horizontal and vertical loads were normalized by the tip area of a suction anchor times the corresponding undrained shear strength at anchor tip for varying loading angles and for three different set-up factors of 0.25, 0.6 and 1.0. Figure 1 shows the estimated ultimate loads corresponding to the different angles for the three different α-factors.

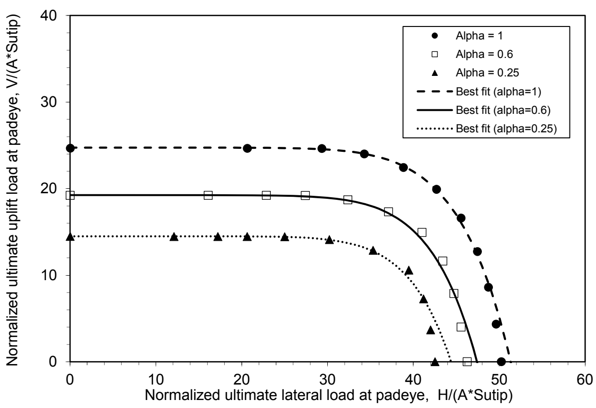

Figure 1. Interaction diagram of ultimate lateral and vertical loads normalized by tip area times undrained shear strength at anchor tip level.

The following equation was fitted to the values in Figure 1:

$$\left(\frac{V}{A \cdot s_{u_{tip}}}\right) = a\left(\frac{H}{A \cdot s_{u_{tip}}}\right)^b + c \tag{2}$$

where V and H = vertical and horizontal components of ultimate load capacity (kN), A = tip area of suction anchor (m^2),

s_{utip} = undrained shear strength at anchor tip level (kN/m^2) and *a, b, c* = coefficients from curve fitting analyses.

The coefficients for three set-up factors of 0.25, 0.6 and 1 were derived by nonlinear regression analysis using the toolbox of MATLAB®. The best fit coefficients of Equation (2) are summarized in Table 1 for the three set-up factors.

Table 1.Coefficients for three different set-up factors of 0.25, 0.6 and 1.

Set-up factor, α	*a*	*b*	*c*
0.25	-7.219E-15	9.289	14.49
0.6	-1.211E-14	9.07	19.24
1	-2.325E-14	8.785	24.74

For any value of α between 0.25 and 1, coefficients *a, b* and *c* can be calculated using Equations (3) to (5), respectively.

$$a = -2 \cdot 10^{-14} \cdot \alpha - 9 \cdot 10^{-16} \quad (3)$$
$$b = -0.673 \cdot \alpha + 9.463 \quad (4)$$
$$c = 13.669 \cdot \alpha + 11.061 \quad (5)$$

4 EXAMPLE PROJECTS FOR VERIFICATION

The first author carried out three detailed suction anchor designs using numerical analysis. These cases will verify the goodness of the proposed design equation. The analyses were performed with the program BIFURC. Table 2 describes the key parameters for each, including the final anchor geometry and the soil parameters including the set-up factor, as well as water depth, mooring line angle at the padeye for the governing load conditions and installation requirements.

Table 2. Key parameters for three verification projects in this study.

Parameter	Project A	Project B	Project C
Water depth (m)	1200	1000	2100
Anchor diameter, D (m)	4.9	4.0	5.8
Target penetration depth L_f (m)	28.3	14.5	35.0
Total length L_T (m)	29.6	15.0	36.4
L_T/D / L_f/D ratio	6.0/5.8	3.8/3.6	6.3/6
Padeye depth, L_i (m)	20.4	9.5	23.5
Line angle at padeye, β	45°	40°	41°
Unfactored padeye load (kN)	8930	2588	12840
Tilt (or verticality)	±5°	±5°	±5°
Misorientation, ψ	±7.5°	±5°	±8°
Set-up (days)	30	14	90
Set-up factor	0.59	0.45	0.63
Cyclic effect	[-]	[-]	-10%
Creep effect	-10%	-25%	[-]
s_u^{DSS}/s_u^C	0.91	0.85	0.925
s_u^E/s_u^C	0.82	0.75	0.805
Design s_u^{DSS} (kPa)	1.9+1.33z	2+1.4z	1+1.15z
γ (kN/m^3)	13-17	15-15	13.5-16

s_u^{DSS}=undrained shear strength measured from direct simple shear tests, s_u^C=undrained shear strength from triaxial compression tests, s_u^E= undrained shear strength from triaxial extension tests, γ=total unit weight of soil, and z=depth below mudline (m).

The aspect ratios range from 3.6 to about 6 with diameters of about 4 m to 6 m. The padeye depth was selected at about two-thirds of the penetration depth. An extra height of 0.5 m to 1.4 m was added to the required penetration depth to account for soil heave after installation. The unfactored critical padeye load was applied at an angle greater than 40°, indicating that a vertical pull-out failure mode was likely to govern the anchor design.

The installation tolerances and available set-up days are in general specified in the design basis. The corresponding set-up factor was estimated according to the procedure by Andersen and Jostad (2002). In the actual analyses, the set-up factor was reduced due to torsion incurred by anchor misorientation.

The clays at all three sites were normally consolidated. Figure 2 shows the similarity of the design s_u^{DSS} profiles of Projects A and B and the base case profile used for the 'proposed design equation'. The shear strength of Project C is lower. In the actual detailed analyses, Projects A and C had multiple linear profiles with depth. These were simplified in this paper with the single linear profiles as shown in Figure 2.

For Projects A and B, no soil degradation due to cyclic loading was included in the actual analyses as it was assumed that the degradation was counterbalanced by the positive rate effects on undrained shear strength due to rapid (~10 sec/cycle) cyclic loading. For Project C, the undrained shear strength was reduced by 10% in the BIFURC design after a detailed study of the cyclic DSS and triaxial test results and the load vs time histories. Creep or negative rate effects due to high constant tension loading lasting for several days may also be an important factor affecting the ultimate holding capacity, especially in the Gulf of Mexico (Clukey et al. 2004). The design shear strength profiles were reduced by 10% and 25% for Projects A and B in the detailed design. No further reduction was made for Project C due to creep.

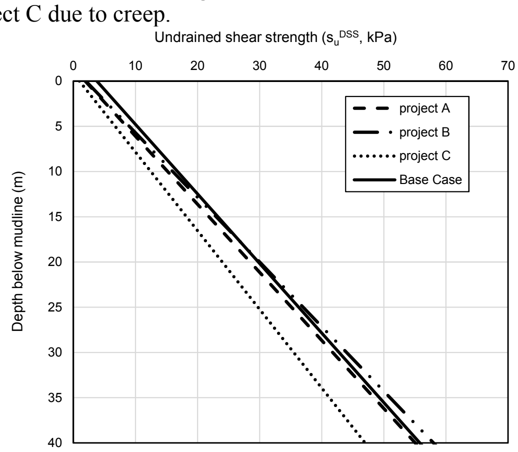

Figure 2. Comparison of design undrained shear strength profiles of the three verification projects and the base case profile.

5 VERIFICATION

Using the proposed design equation with the set-up factors and the information in Table 2, the holding capacity and safety factor for each of the three verification projects were evaluated with the following procedure: (1) find coefficients *a, b* and *c* corresponding to the set-up factor; (2) derive the normalized design equation; (3) find the interaction capacity curve using the gross area of the anchor and the undrained shear strength at pile tip level; (4) find a new shear strength at anchor tip level that leads to a maximum vertical load on the failure envelope; and (5) calculate a reduction factor equal to the ratio of the new shear strength in Step (4) to the design undrained shear strength.

The results of the verification analyses are presented in Figure 3 for Projects A, B and C. In the reevaluation, the factor of safety was estimated in terms of a 'reduction factor' on the ultimate capacity curve to the failure envelope that passes through the unfactored governing padeye load. The overall factor of safety is then equal to the inverse of the reduction factor. The overall factors of safety were estimated as 2.04 (=1/0.49), 2.18 (=1/0.46) and 2.38 (=0.42) for Projects A, B and C, respectively.

Table 3 summarizes the factors of safety from the two approaches. The additional safety margin was estimated from the original detailed FEM designs with BIFURC. The reduced design shear strength profiles by the corresponding percentage due to either creep or cyclic loading were used in the actual BIFURC calculation. The critical load condition and required factors of safety used in the numerical analyses are also shown in Table 3.

The BIFURC lumped factor of safety was taken equal to the square root of the factors of safety in the vertical and horizontal directions because the failure mode was essentially the vertical pull-out mode. For example, the Project A 'lumped' factor of safety is 2.19 ($=\sqrt{(1.2 \cdot 1.14)^2 + (1.5 \cdot 1.14)^2}$).

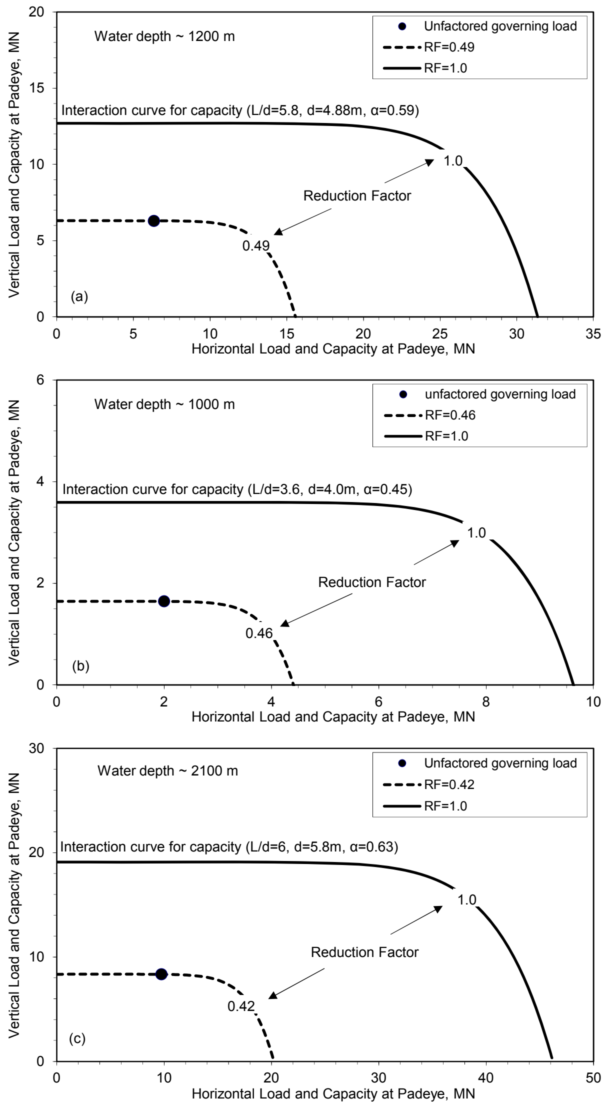

Figure 3. Interaction capacity and failure envelopes for (a) Project A, (b) Project B and (c) Project C. RF = Reduction Factor.

Table 3. Summary of factors of safety.

Approach	Factor of safety	Project A	Project B	Project C
Require-ments	Governing load condition	Damaged	Damaged	Intact
	Required FS (horizontal)	1.2	1.2	1.6
	Required FS (vertical)	1.5	1.5	2.0
BIFURC (FEM)	Additional safety margin	1.14	1.13	1.02
	Lumped factor of safety$^{(1)}$	2.19	2.17	2.61
Eq. 2	Reduction factor	0.49	0.46	0.42
	Overall factor of safety$^{(2)}$	2.04	2.18	2.38
	Difference between $^{(1)}$ and $^{(2)}$	-6.8%	+0.5%	-8.8%

The differences between the 'design equation' overall factor of safety and the BIFURC 'lumped' factor of safety were 6.8%, +0.5% and -8.8% for Projects A, B and C, respectively. The differences can, to a great extent, be attributed to the differences between a design shear strength profile and the base case profile. Therefore in a new anchor design using the 'design' equation, the closer the shear strength profile to the base case, the more accurate the factor of safety will be.

The very good agreement, given the complexities and level of detail in the numerical analyses, indicates that the approximate design equation can provide a simple but efficient solution for preliminary calculations of holding capacity of suction anchors in soft deep water clays. The simpler design equation can also be used to check results from design calculations using FEM.

6 CONCLUSION AND RECOMMENDATIONS

This paper proposes an approximate design equation that can be used for preliminary sizing of suction anchors in soft clays. The equation was derived through an extensive analytical study of the holding capacity of suction caissons with different aspect ratios. The equation is validated by comparing the results of detailed numerical studies and the proposed design equation for three projects. The proposed design equation does not require specific knowledge about plasticity and numerical theory.

The comparison shows an excellent agreement between the factors of safety from the detailed analysis and the design equation-based design. The good agreement suggests that the design equation can provide a simple but efficient solution for the calculation of the holding capacity of suction anchors in soft clay in preliminary design or even early design phases of a project (e.g., bidding, pre-FEED). The proposed approximate design equations should however not be used for final design.

Caution should be exercised if using the design equation for the following cases: (1) if the soil shear strength profile cannot be simplified to a linearly increasing shear strength with depth (e.g., layered soil) and (2) if the aspect ratio is outside the range from 3 to 6. For such conditions, other design methods than the proposed design equation are preferred.

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