Capacity Analysis of Suction Anchors in Clay by Plaxis 3D Foundation

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Introduction

This article describes the use of Plaxis 3D Foundation v. 2.1 (Plaxis, 2008) to compute the undrained capacity of a suction anchor in clay. The objective of this study was to evaluate the performance of Plaxis 3D Foundation for analyzing this particular problem by comparing the Plaxis 3D Foundation results with results from other software including Plaxis 2D and NGI in-house codes. The effects of mesh fineness, use of interface elements and the wall roughness on the calculated capacity were also studied. There are several other aspects in the design of skirted anchors in clay which is not covered in this article. The reader is referred to Andersen and Jostad (1999). A particular issue that this study focused on was use of interface elements adjacent to cylindrical suction anchors. The lack of isoparametric interface elements in the 2.1 version of Plaxis 3D Foundation is known to introduce some error to problems where curved soil-structure interfaces are defined by the volume pile generator. This issue is described in the "Known issue Plaxis 3D Foundation version 2.1" (www.plaxis.nl).

Description of the Problem Considered

Figure 1 illustrates the cylindrical suction anchor analyzed in this study. It is one of the four hypothetical capacity cases presented by Andersen et al (2005) in an industry sponsored study on the design and analyses of suction anchors in soft clays. The anchor was assumed to have a closed top, no tension crack on the active (windward) side and to be very stiff compared to the soil. The load was attached at the optimal load attachment point at depth z_p to produce a failure corresponding to pure translation, i.e. maximum capacity is obtained when there is no rotation of the anchor.

The soil was assumed to be a normally consolidated clay with an average undrained strength increasing linearly with depth as follows:

$$s_u\ (\text{kPa}) = 1.25 \cdot z\ (\text{m})$$

A strength intercept at the surface of 0.1 kPa was used. The soil was modeled as an undrained, cohesive linear elastic- perfectly plastic (Tresca) material. In Plaxis, we used

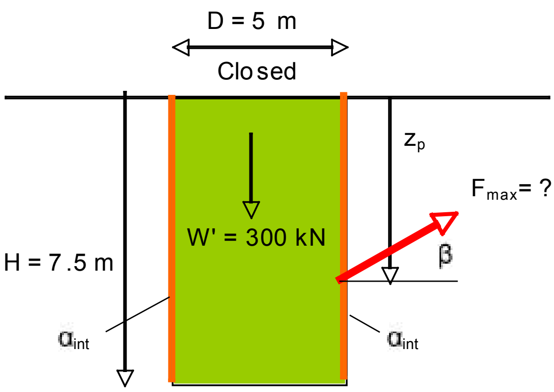

Figure 1: Description of the Suction Anchor Problem

the Mohr-Coulomb strength model with the friction and dilatancy angles equal to zero ($\phi = \psi = 0$), cohesion equal to the undrained strength ($c = s_u$), and no tensile cut-off strength.

The anchor was modeled by linear elastic wall elements with a high stiffness making them virtually rigid. Because the governing failure mechanisms do not involve the soil plug inside the anchor, this soil plug was modeled as a stiff, elastic material. For all the FE-models in this study we have used interface elements along the outside skirt walls. These elements are used to improve the results by allowing for slip between the anchor wall and the soil, and to model a possibly reduced strength $s_{u,int} = \alpha_{int} \cdot s_u$ along the outside skirt walls to account for reduced soil strength due to effects of the anchor installation. Recommended values of α_{int} for design situations are given in Andersen and Jostad (2002) and results from centrifuge testing are presented in Chen and Randolph (2006).

Plane Strain Analyses

The suction anchor on Figure 1 was first analyzed as a plane strain problem using both Plaxis 2D and Plaxis 3D Foundation. The objective was to compare results from Plaxis 3D Foundation with the well established 2D code and to the readily available hand calculated capacity. An extensive study of the discretization error was also performed. Computations were made with both the 6- and 15-noded elements available in Plaxis 2D.

Horizontal interface elements were used along the soil-soil contact underneath the anchor tip in addition to along the outside skirt wall. The vertical and horizontal interfaces were extended 0.2·D outside the anchor. This was to allow possibly full slip around the bottom corners of the anchor. A wall interface factor α_{int} of 0.65 was used along the outside skirt while full interface strength ($\alpha_{int} = 1.0$) was used under the anchor tip and for the interface extensions. The load was applied horizontally at a depth (z_p) of 5 m. The in-plane width D of the anchor was 5 m.

Figure 2 presents the deformed mesh (displacements scaled up 5 times) at the end of one analysis i.e. at ultimate capacity, from a Plaxis 2D plane strain computation. A well defined failure surface forms on both the active and passive sides and the suction anchor translates horizontally.

This mesh with approximately ~5000 15-noded elements (~40 000 nodes) illustrates the degree of mesh refinement necessary for accurate computations although many fewer elements could have been used within the suction anchor. The effect of mesh fineness and element type on the computed suction anchor capacity is further illustrated by Figure 3. More than 40 000 nodes are required for convergence to a capacity of 228 kN/m. However, a mesh with only about 10 000 nodes (15-noded elements) produces an ultimate capacity of 230 kN/m, only 1 % higher than the more accurate value. The discretization error increases dramatically for meshes with less than 5000 nodes (2500 elements). Figure 3 also illustrates that the 6-noded elements produced suction anchor capacities very close to those with the 15-noded elements provided the mesh is refined to have approximately the same number of nodes.

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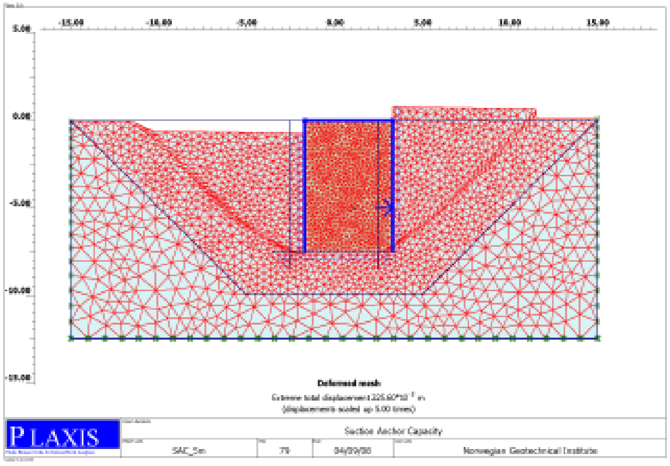

Figure 2: Plaxis 2D Plane Strain Deformed Mesh at the End of the Analysis (α_{int} = 0.65)

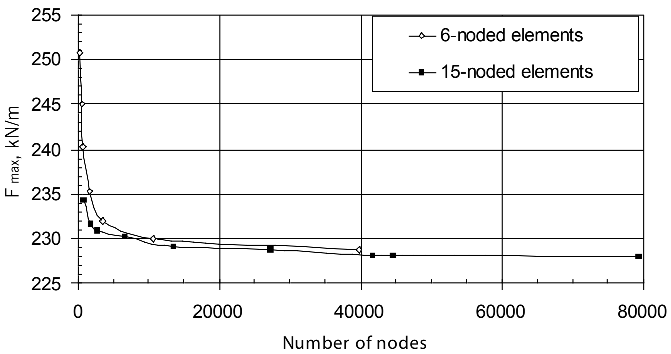

Figure 3: The Effects of Mesh Fineness and Element Type on Computed Suction Anchor Capacity – Plaxis 2D Plane Strain Analyses

The next series of computations utilized Plaxis 3D Foundation to analyze the plane strain problem discussed above as a first step in comparing its performance with Plaxis 2D. Only one element was used in the out-of-plane direction. This was obtained by using a small thickness of 0.25 m in that direction. The 3D mesh has vertical interfaces along the outside walls with extensions underneath the anchor tip but no horizontal interfaces at the anchor tip level.

Interface extension can be provided by deactivated wall extension. Figure 4 shows a deformed mesh (displacements scaled up 5 times) at the end of the analysis i.e. at ultimate capacity from a Plaxis 3D Foundation plane strain computation. A well defined failure surface, similar to the failure surface in Figure 2 for the 2D run, forms and the suction anchor translates horizontally. The mesh shown has ~6700 15-noded wedge elements (~28 000 nodes) and provides a capacity of 233 kN/m for α_{int} = 0.65. Increasing the number of nodes to 80 000 gave nearly the same capacity, while decreasing the number of nodes to less than 10 000 dramatically increased capacity and thus the discretization error. The results from the mesh sensitivity study are shown in Figure 5. As for the 2D calculation the failure mechanism involves a cut-off (thin shear band) at the anchor tip level. It is therefore important to use a thin row of elements at this level to avoid an artificially deeper failure mechanism. This can be enforced by using additional work planes at this depth.

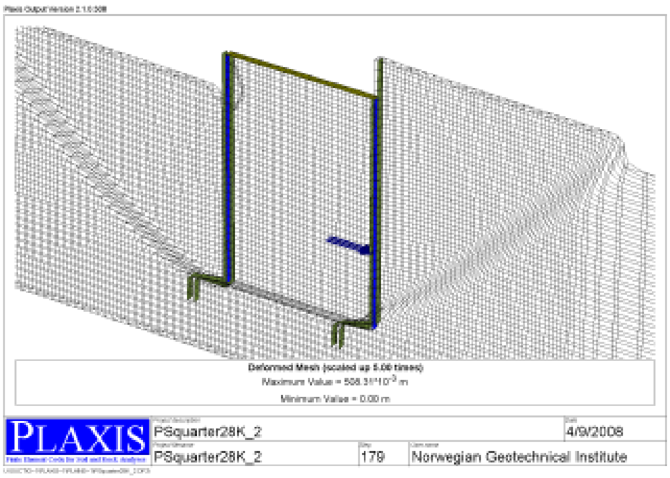

Figure 4: Plaxis 3D Foundation Plane Strain Deformed Mesh at the End of the Analysis (α_{int} = 0.65)

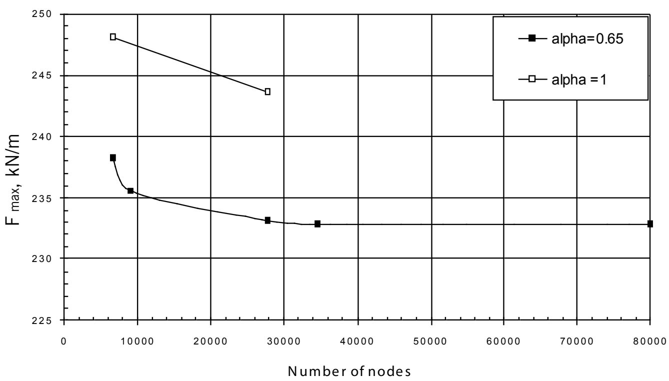

Figure 5: The Effects of Mesh Fineness on Plane Strain Suction Anchor Capacity – Plaxis 3D Foundation

Discussion of the Plane Strain Analyses

Table 1 compares the plane strain suction anchor capacities computed by Plaxis 2D and 3D as well as the capacities estimated by a hand-calculation based on classical earth pressure theory. The capacities of Table 1 are all for the runs where the discretization error is negligible (> 30 000 nodes) and are all in reasonable agreement. The hand-calculation may have some small error because the earth pressure coefficient used is developed for a constant strength profile while the case studied has a linearly increasing strength.

The Plaxis 3D Foundation capacities are about 2 % higher than the Plaxis 2D capacities, probably because of the lack of horizontal interface elements at the bottom of the suction anchor or because of the different element type. The higher wall interface factor ($\alpha_{int} = 1.0$) increases the capacities by about 5%.

	$\alpha_{int} = 0.65$	$\alpha_{int} = 1.0$
Hand calculation	224	232
Plaxis 2D	228	239
Plaxis 3D Foundation	233	244

Table 1: Horizontal Plane Strain Suction Anchor Capacities (kN/m)

Three Dimensional Analyses

Plaxis 3D Foundation was then used to analyze a 5 m diameter cylindrical suction anchor. Only half of the problem was represented in the FE model because of symmetry about the vertical plane in the direction of loading. This feature was important in creating a fine mesh and in reducing computation time. The half cylinder was generated with the volume pile generator. Three rows of elements with thickness 0.1 m were generated beneath the anchor tip by using additional working planes. The mesh refinement studies with strategic refinement led to a mesh of ~26 600 elements and ~76 000 nodes. By plotting the capacity versus the number of nodes as for the 2D calculations it was found that the capacity nearly had converged to a constant value for a mesh with about 76 000 nodes, i.e. this mesh gave only a small discretization error. The load was applied at the optimal load attachment point which was found to be at a depth of approximately 5 m.

As discussed in the "Known issues" section of Plaxis 3D Foundation 2.1, when using the Pile Designer to generate circular piles, the resulting elements (volume elements, plate elements and interface elements) are not curved (isoparametric), but they have straight sides. The ultimate capacity may then be overestimated due to:

- Any given reduced ($\alpha_{int} < 1.0$) interface shear strength is not taken into effect because horizontal slip in the soil-structure contact is prevented.

- The earliest possibility to yield is in the stress points of the adjacent soil volume elements outside the pile, which increases the effective pile diameter.

Therefore, full roughness ($\alpha_{int} = 1.0$) was used along the outside skirt walls and a fine discretization was used along the perimeter of the cylinder to reduce the "effective" pile diameter. Figure 6 illustrates the geometry that was used for these analyses and the deformed mesh from one of the computations. The computed ultimate holding capacity for $\alpha_{int} = 1.0$ was 1870 kN for pure horizontal loading.

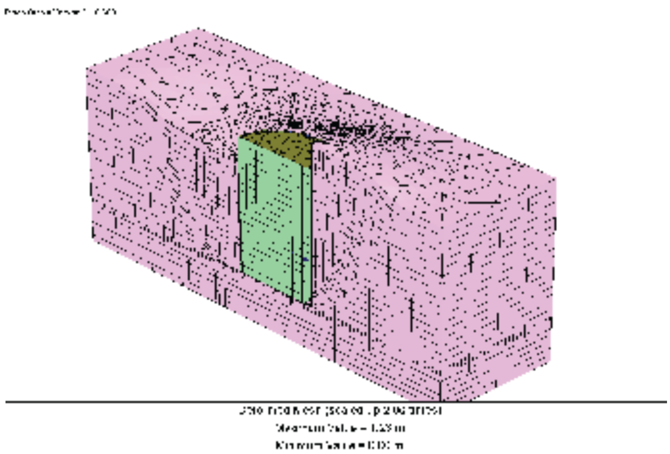

Figure 6: Plaxis 3D Foundation Geometry Model and Deformed Mesh at the End of the Analysis - 5 m diameter Suction Anchor

This computed capacity was compared with the capacity computed by HVMCap (NGI, 2000) and the NGI in-house program BIFURC 3D (NGI, 1999). BIFURC 3D is a general purpose FE program, while HVMCap is a specially made windows program for design analyses of suction anchors, including the effects of reduced interface strength, anchor tilt, tension crack development at the active side, and shear strength anisotropy. HVMCap uses the BIFURC FE program as a calculation kernel. It is a plane model with the three dimensional effects modeled by displacement compatible shear stress factors (side shear) calibrated from full three dimensional finite element studies. The capacity computed by HVMCap for the same case as shown in Figure 1 with $\alpha_{int} = 1.0$ was 1578 to 1775 kN depending upon the range of values (between 0.5 and 1.0) assumed for the three dimensional side shear factors. The capacity computed by BIFURC 3D was 1780 kN.

To avoid the issue with the non-isoparametric elements for the cylindrical anchor, capacities were calculated also for a rectangular anchor having a cross-sectional area equivalent to a 5m diameter circle (3.93 m x 5 m with the 5m width normal to the loading direction). This is believed to be a very good approximation to a cylindrical anchor. Vertical interfaces were used along the outside walls and extended horizontally as shown in Figure 7 to allow full slip around the anchor edges. Thin rows of elements were also used underneath the anchor tip. The computed ultimate holding capacities for $\alpha_{int} = 1.0$ was 1895 kN for pure horizontal loading.

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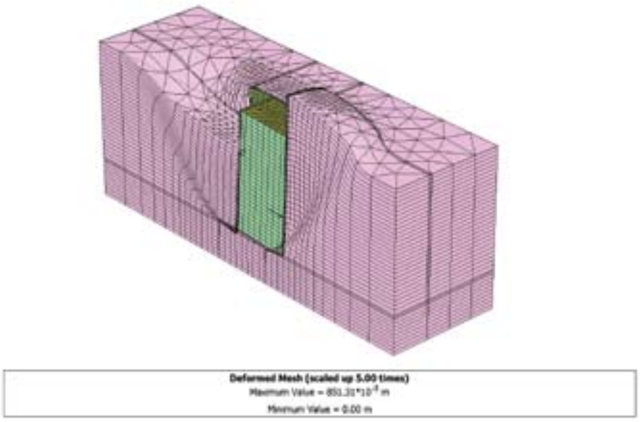

Figure 7: Plaxis 3D Foundation Geometry Model and Deformed Mesh at the End of the Analysis - Rectangular Suction Anchor

Discussion of Three Dimensional Analyses

Table 2 presents the suction anchor capacities computed by Plaxis 3D Foundation for the cylindrical and rectangular suction anchors and the capacities computed by HVMCap and BIFURC 3D. Results for wall interface factor α_{int} =0.65 and 1.0 are given, even if, as noted, it is known that for $\alpha < 1.0$ Plaxis 3D Foundation overestimates the capacity for the cylindrical anchor.

The Plaxis 3D Foundation capacity of 1870 kN for the 5 m diameter cylindrical anchor and 1895 kN for the area equivalent rectangular anchor, both with α_{int} = 1.0, seem reasonable. The minor difference between the rectangular and the circular cross section anchors indicate that the area equivalent rectangle is a good approximation. However, the BIFURC3D results of 1780 kN and the upper bound value of 1775 kN from HVMCap is 5 % less than the Plaxis 3D Foundation result of 1870 kN. As there is no reason to believe that the FEM produce capacities that are too low, this indicates that Plaxis 3D Foundation slightly overestimates the capacity.

Computation	α_{int} =0.65	α_{int} = 1.0
PLX 3DF Circle 5 m diameter	1820[(1)]	1870
NGI BIFURC3D FEM Circle 5 m diameter	1665	1780
PLX 3DF Eqv. area rectangle 5 m x 3.93 m	1715	1895
NGI HVMCap FEM "2D+Side shear"	1463-1723	1578-1775

[(1)]Capacity is too high because of non-isoparametric formulation

Table 2: Horizontal Suction Anchor Capacities (kN)

The recent update Plaxis 3DF version 2.2 includes curved interfaces.

Despite a thorough investigation of the Plaxis 3D Foundation results it has not been possible to identify with certainty what is the cause for the 5 % overshoot. It may be the lack of horizontal interfaces at the anchor tip level that prevents full slip underneath the skirts. For the cylindrical anchor the slightly increased "effective" radius, caused by the non-isoparametric interface elements may also contribute to a small overshoot, although a very fine mesh was used outside the skirt wall.

The Plaxis 3D Foundation result for α_{int} = 0.65 of 1820 kN for the cylindrical anchor is significantly higher than for the equivalent area rectangular anchor and also significantly higher than the BIFURC 3D and HVMCap results. These results confirm that the linear Plaxis 3D Foundation interface elements are too inflexible to model the soil-pile lateral slip along curved surfaces. Later versions of Plaxis 3D Foundation are expected to provide isoparametric, or curved interface elements, for more accurate modeling of curved interfaces.

Non-Horizontal Loadings

Andersen et al (2005) compared calculation procedures for the undrained capacity for varying loading angles β. Figure 8 summarizes results from the independent capacity calculations by three different organizations. The comparison of results from 3D finite element calculations carried out by Norwegian Geotechnical Institute (NGI), Offshore Technology Research Center (OTRC) and the University of Western Australia (UWA) serves as an excellent benchmark for evaluating the performance of Plaxis 3D Foundation.

A series of computations were made to evaluate the performance of Plaxis 3D Foundation when the applied loads are not horizontal. These computations were made for the capacity of the 5 m diameter cylindrical suction anchor. However, an interface factor α_{int} of 1.0 was used for these computations to minimize the effects of non-isoparametric interface issues. All loadings were applied at the optimal loading point to produce a failure corresponding to pure translation.

Figure 8 compares the results of these Plaxis 3D Foundation computations (α_{int} = 1) with the benchmark 3D finite element results (α_{int} = 0.65). Plaxis 3D Foundation shows the same trends with varying load inclination as the other programs but as expected because of the higher interface factor computes higher capacities.

Note that it is only in the lateral direction (z-x plane) that the non-isoparametric elements prevent slip. The interface elements should work well in the vertical direction, thus the capacity for pure vertical loading should not be overestimated. A Plaxis 3D Foundation computation for α_{int} = 0.65 and pure vertical loading produced a capacity of 2570 kN, completely consistent with the benchmark finite element analyses of Figure 13. This agreement occurs because the interface issue described above has little or no effect for vertical suction anchor translation.

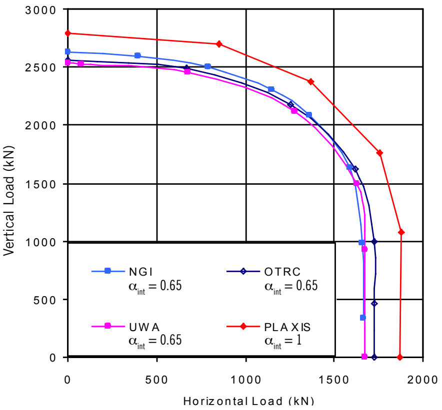

Figure 8:

Comparison of Plaxis 3D Foundation and Benchmark Suction Anchor Computations for Non-horizontal Loadings after Andersen et al (2005) - 5 m diameter Suction Anchor.

Conclusions

For the plane strain computations

- The Plaxis 2D and Plaxis 3D Foundation capacities agree within about 2 % and the Plaxis FE results also agree well with the hand calculation.
- The discretization error always contributes to an overshoot for FE capacity analyses. It was demonstrated how this overshoot can be quantified by plotting the capacity versus the number of nodes. The error was made negligible by the use of interface elements and strategically refining the mesh.
- The 6-noded elements of Plaxis 2D computed the same capacity as the 15-noded elements. However, the 6-noded elements require more mesh refinement so that there is at least an equal number of nodes.

For the three-dimensional computations

- Plaxis 3D Foundation provided a capacity for the 5 m diameter cylindrical suction anchor that is about 5 % higher than the capacities obtained from BIFURC 3D and NGI HVMCap for a wall roughness $\alpha_{int} = 1.0$ and pure horizontal loading.
- The Plaxis 3D Foundation results for inclined loading and $\alpha_{int} = 1.0$ seems reasonable and compares well with the Andersen et al (2005) benchmark results.
- The Plaxis 3D Foundation capacity for a wall roughness $\sigma_{int} = 0.65$ is clearly too high, confirming the expected overestimation from the issue with the non-isoparametric interface elements. We recommend that the Plaxis 3D Foundation program should not be used as the only tool for design of suction anchors until this issue is resolved and correct performance verified.
- Ultimate capacity calculations by FEA are sensitive to discretization error, and in particular 3D problems. Insight in the geometry of the governing failure mechanism and the use of interface elements, symmetry, reduced model dimensions and strategic mesh refinement greatly reduces this error.
- By running a series of calculations for the same problem with varying mesh fineness and plotting the obtained capacities against number of nodes, number of elements or the average element size it is possible to quantify the discretization error and possibly also making it negligible.

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