CAPACITY ANALYSIS OF SUCTION ANCHORS IN CLAY BY 3D FINITE ELEMENT ANALYSIS

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ABSTRACT: *This paper describes the use of 3D finite element analysis (FEA) to compute the undrained capacity of a suction anchor in clay. A particular issue that this study focused on was use of interface elements to model the possibly reduced strength and slippage along the soil-structure contact surface.*

The suction anchor was first analyzed as a plane strain problem followed by full three dimensional analyses of a 5 m diameter suction anchor. The studies included an evaluation of the effects of the wall interface strength and comparisons with approximate hand calculations. The holding capacity computations were for pure horizontal loading and also for varying loading angles. The load was attached at the optimal load attachment point to produce a failure mode corresponding to pure translation.

These studies have shown that 3D FEA can be used to estimate the capacity of suction anchors. The strategic use of mesh refinement procedures, interface elements and symmetry greatly reduce the discretization error associated with FEA. Isoparametric interface elements are required to accurately model the soil-anchor slippage along curved surfaces and minimize overshoot for this benchmark problem.

1 INTRODUCTION

This article describes the use of 3D FEA to compute the undrained capacity of a suction anchor in clay. Suction anchors are generally large diameter steel cylinders, open-ended at the bottom and closed at the top, used in mooring systems of offshore structures. There is not any well accepted method for calculating the capacity of these structures. However, a comparison of different available methods including two FEA codes was presented in Andersen et al. (2005). The objective of this study was to evaluate the performance of Plaxis 3D Foundation v. 2.2 (Plaxis, 2008) for analyzing this particular problem. The effects of mesh fineness, use of interface elements and the wall roughness on the calculated capacity were also studied. Andersen and Jostad (1999) discuss several other aspects in the design of skirted anchors in clay which are not covered in this article.

A particular issue that this study focused on was the use of interface elements to model the soil-structure contact surface for cylindrical suction anchors. Isoparametric interface elements are required to accurately model the soil-anchor slippage along curved surfaces and minimize overshoot for this benchmark problem.

2 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 mode corresponding to pure translation, i.e. maximum capacity is obtained when there is no rotation of the anchor. The optimal load attachment point z_p generally varies from case to case and can be found by trial and error analyses varying z_p until a non-rotating failure mode is found.

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

$$s_u\,(\text{kPa}) = 1.25 \cdot z\,(\text{m}) \qquad (1)$$

A strength intercept at the surface of 0.1 kPa was used, giving strengths 0.1 kPa higher with depth compared to the strength profile of Equation 1. The soil was modeled as an undrained, cohesive linear elastic- perfectly plastic (Tresca) material. In Plaxis, we used the Mohr-Coulomb strength model with the friction and dilatancy angles equal to zero ($\varphi = \psi = 0$), cohesion equal to the undrained strength ($c = s_u$), and no tensile cut-off strength. Normally consolidated clays display anisotropy in the undrained shear strength. This was not an issue for this study. However shear strength anisotropy should be accounted for in design.

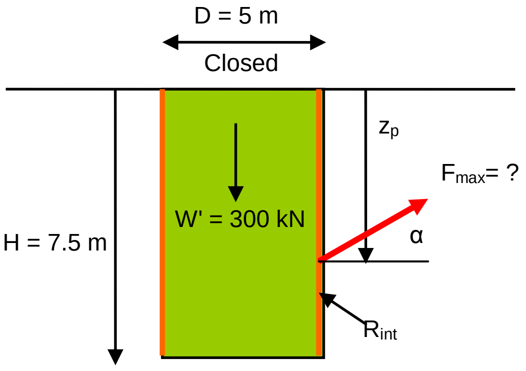

Fig. 1. Description of the suction anchor problem

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. We have used interface elements along the outside skirt walls to allow for slip between the anchor wall and the soil, and to model a possibly reduced strength $s_{u,int} = R_{int} \cdot s_u$ along the outside skirt walls due to the effects of the anchor installation. Recommended values of R_{int} for design situations are given in Andersen and Jostad (2002) and results from centrifuge testing are presented in Chen and Randolph (2007).

3 PLAIN STRAIN ANALYSES

3.1 Presentation of Results

The suction anchor on Figure 1 was first analyzed as a plane strain problem using both Plaxis 2D and Plaxis 3D Foundation. This gives unrealistic capacities. However, the objective was to compare results from the 3D Plaxis code with the more tested 2D code and also to an available hand calculated capacity. An extensive study of the discretization error, and the effects of the interface condition, was also performed. Computations were made with both the 6- and 15-noded element available in Plaxis 2D. Andresen et al (2008) describe the details of these 2D and 3D plane strain analyses.

In the Plaxis 2D FEA, 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 by free coupling the corner nodes in the soil. Wall interface factors R_{int} of 0.65 and 1.0 were used along the outside skirt while full interface strength (R_{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 plane strain anchor was 5 m.

Figure 2 presents the deformed mesh (displacements scaled up 5 times) at the end of one analysis i.e. at the ultimate capacity. A well defined failure surface forms on both the active and passive sides and the suction anchor translates horizontally. This mesh with ~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 effects of mesh fineness, element type and interface condition on the computed suction anchor capacity is further illustrated by Figure 3. For R_{int} of 0.65, 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 percent 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. With about 40,000 nodes, a wall interface factor of 1.0 vs. 0.65 produces a suction anchor capacity of 238 kN/m and the use of no interface elements produces a suction anchor capacity of 242 kN/m.

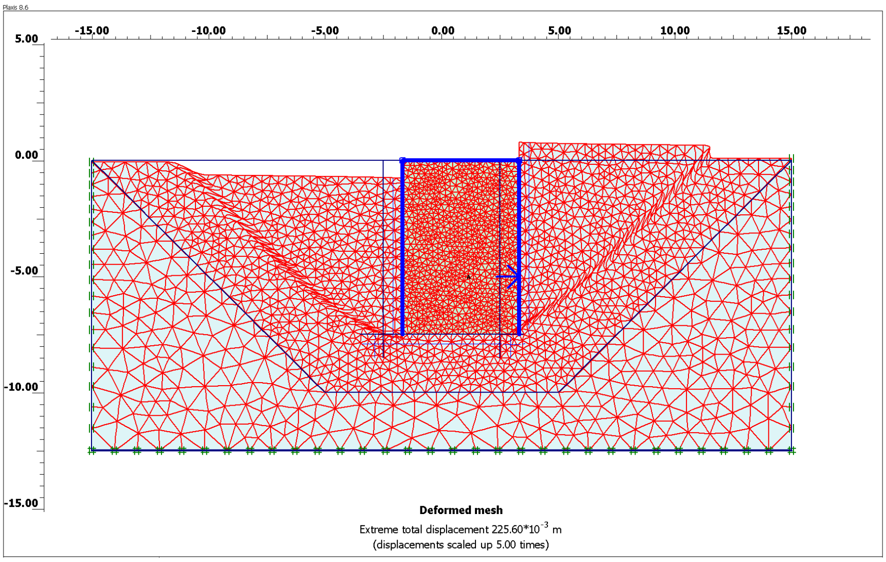

Fig. 2 Plaxis 2D plane strain deformed mesh at the end of the analysis (R_{int} = 0.65)

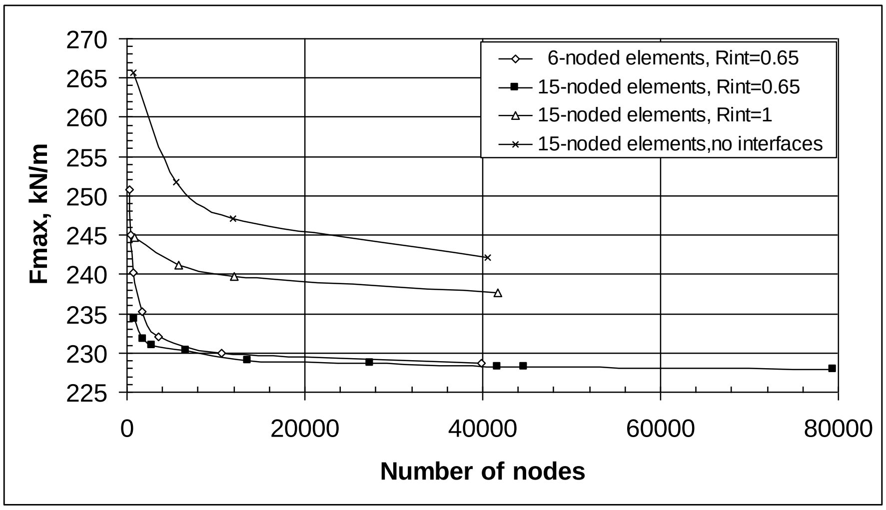

Fig. 3 The effects of mesh fineness, element type and interface condition on computed suction anchor capacity – Plaxis 2D plane strain analyses

The next series of computations utilized Plaxis 3D Foundation to analyze the plane strain problem discussed above to compare its performance with Plaxis 2D. Only one element was used in the out-of-plane direction by using a thickness of only 0.25 m in that direction. The 3D mesh has vertical interfaces along the outside walls with extensions underneath the anchor tip. However Plaxis 3D Foundation v. 2.2 does not allow for horizontal interfaces at the anchor tip level. The vertical interface extensions can be provided by extending but not activating the wall below the anchor tip.

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 computes a capacity of 233 kN/m for R_{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 the capacity because of discretization error. As for the 2D FEA 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 working planes at this depth.

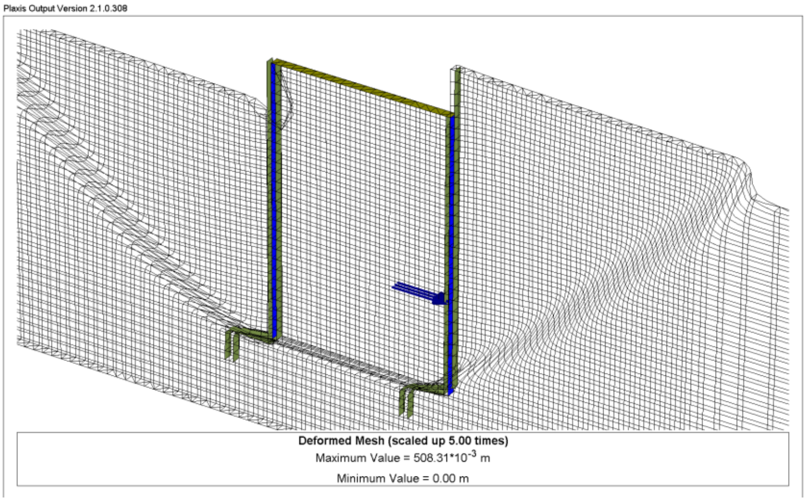

Fig. 4 Plaxis 3D Foundation plane strain deformed mesh at the end of the analysis (R_{int} = 0.65)

3.2 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 in 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 (R_{int} = 1.0) increases the capacities by about 5%.

Table 1 Horizontal plane strain suction anchor capacities (kN/m)

	R_{int} = 0.65	R_{int} = 1.0
Hand calculation	224	232
Plaxis 2D	228	238
Plaxis 3D Foundation	233	244

4 THREE DIMENSIONAL ANALYSES

4.1 Presentation of Results

Plaxis 3D Foundation was then used to analyze the 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. Elements with thickness 0.1 m were generated beneath the anchor tip by using additional working planes. The load was applied at the optimal load attachment point which was found by trial and error to be at a depth of approximately 5 m for horizontal loading.

Andresen et al (2008) discuss the implications of the straight sided interface elements used in an older version of Plaxis 3D Foundation, version 2.1. They observed that because the resulting elements (volume elements, plate elements and interface elements) are not curved (isoparametric), but they have straight sides, the ultimate capacity was overestimated by 5% ($R_{int} = 1.0$) to 10% ($R_{int} = 0.65$) because:

- Any given reduced ($R_{int} < 1.0$) interface shear strength is not taken into effect because slip in the soil-structure contact is prevented.
- Yield is then necessary in the stress points of the adjacent soil volume elements outside the pile, which increases the effective pile diameter.

This should not be an issue with Plaxis 3D Foundation version 2.2 used for these studies because it utilizes isoparametric interface elements.

Figure 5 illustrates the geometry that was used for these analyses and the deformed mesh from one of the computations. Figure 6 summarizes the mesh refinement studies for these 3D FEA studies. These studies show that with strategic refinement, a mesh of ~40,000 elements and ~ 110,000 nodes converge to suction anchor holding capacities of 1710 kN and 1815 kN for $R_{int} = 0.65$ and $R_{int} = 1.0$ respectively. Meshes with 70,000 to 75,000 nodes, Figure 6, produce almost the same results. i.e. these meshes gave only a small discretization error.

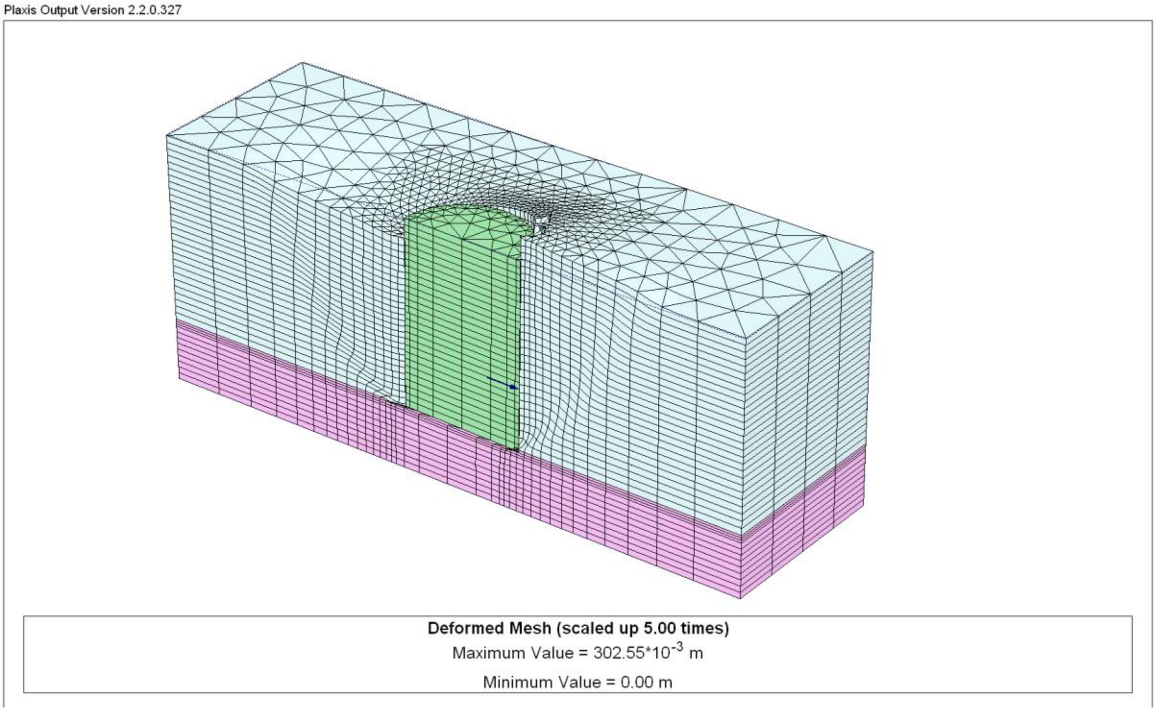

Fig. 5 Plaxis 3D Foundation geometry model and deformed mesh at the end of the analysis - 5 m diameter suction anchor

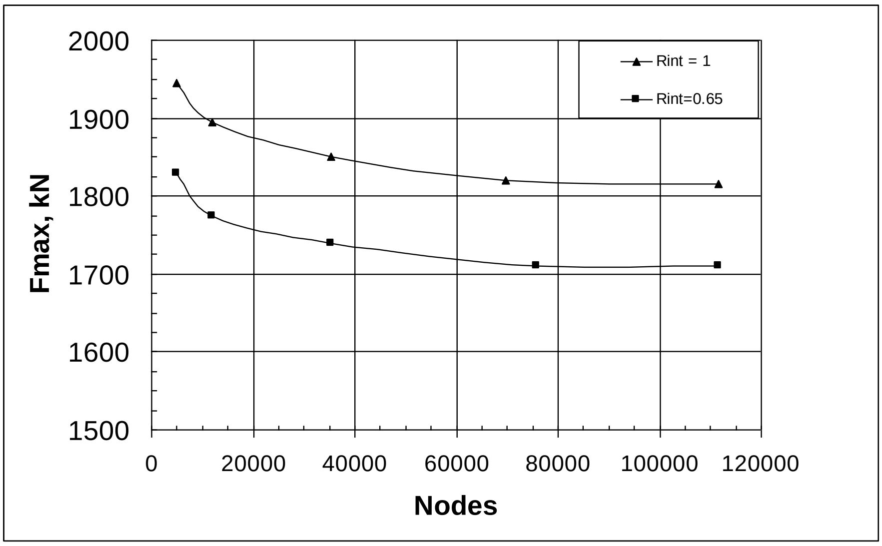

Fig. 6 The effects of mesh fineness and interface condition on computed suction anchor capacity – Plaxis 3D Foundation analyses

These computed capacities were compared with the capacity computed by HVMCap (NGI, 2000). This program is based on the NGI in-house finite element program BIFURC (NGI, 1999) and is specially made 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. It is a plane model with the three dimensional effects modeled by displacement compatible 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 R_{int} = 1.0 was 1578 to 1775 kN depending upon the range of values (a factor between 0.5 and 1.0 times the intact shear strength) assumed for the three dimensional side shear. The capacity computed by BIFURC 3D was 1780 kN. For R_{int} = 0.65, the computed capacities were 1463-1723 kN (HVMCap) and 1665 (BIFURC 3D).

4.1 Discussion of Three Dimensional Analyses

Table 2 compares the suction anchor capacities computed by Plaxis 3D Foundation Version 2.2 for the cylindrical suction anchors with the capacities computed by BIFURC 3D and HVMCap. Results for wall interface factor R_{int} =0.65 and 1.0 are given. For both wall interface factors, the Plaxis 3D results are 2 to 2.5 % higher than the BIFURC 3D results.
The Plaxis 3D results are at the upper end of the range of HVMCap results for R_{int} = 0.65 and slightly higher than the maximum HVMCap capacity for R_{int} = 1.0. The differences are likely due to the fact that the BIFURC 3D and HVMCap computations did not include the 0.1 kPa strength intercept at the seafloor surface. Plaxis 3D might slightly overestimate the suction anchor capacity due to the lack of horizontal interfaces at the anchor tip level. However, the Plaxis 3D Foundation results are reasonable and in particular, indicate that the isoparametric, or curved interface elements accurately model the interaction between curved soil-structure surfaces.

Table 2 Horizontal suction anchor capacities (kN)

Computation	**R_{int} =0.65**	**R_{int} = 1.0**
PLX 3DF Circle 5 m diameter	1710	1815
NGI BIFURC3D FEM Circle 5 m diameter	1665	1780
NGI HVMCap FEM "2D+side shear"	1463-1723	1578-1775

5 NON-HORIZONTAL LOADINGS

Andersen et al. (2005) compared calculation procedures for the undrained suction anchor capacity for varying loading angles α. An interface factor R_{int} of 0.65 was used for all of these computations. All loadings were applied at the optimal loading point to produce a failure corresponding to pure translation. Figure 7 summarizes results from four different FE capacity calculations. NGI used the in house code BIFURC 3D, while the Offshore Technology Research Center (OTRC) and the University of Western Australia(UWA) used ABAQUS (HKS, 2002). The Plaxis 3D Foundation version 2.2 results produced in this study, Figure 7, agree very well with the other benchmark 3D FE results.

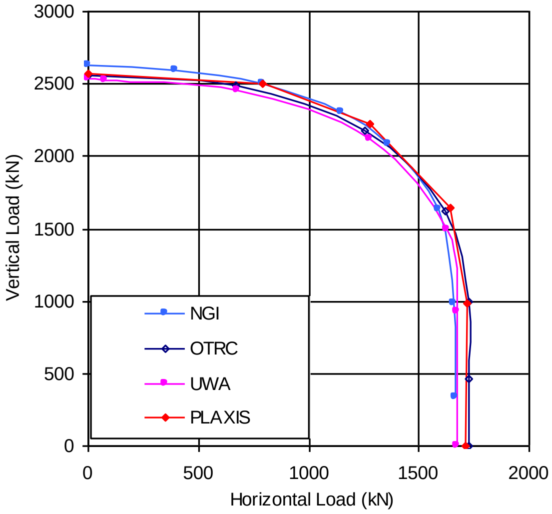

Fig. 7 Comparison of Plaxis 3D Foundation and benchmark suction anchor computations for non-horizontal loadings after Andersen et al (2005) - 5 m diameter suction anchor.

6 CONCLUSIONS

These studies have shown that Plaxis 3D Foundation can be used to estimate the capacity of suction anchors. However, this requires the strategic use of mesh refinement procedures and symmetry to reduce discretization error and interface elements to model anchor-soil slip and reduce interface strength. Isoparametric interface elements are required to accurately model the soil-anchor slippage along curved surfaces and minimize overshoot for this benchmark problem. Detailed conclusions follow.

6.1 Plane Strain Computations

- The Plaxis 2D and Plaxis 3D Foundation capacities agree within about 2 percent and the FE results also agree well with the hand calculation.
- The discretization error always contributes to an overshoot for FE capacity analysis. 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.

6.2 Three-dimensional Computations

- Plaxis 3D Foundation results for horizontal loading agree well with the capacities obtained from BIFURC 3D and NGI HVMCap. The Plaxis 3D Foundation results for inclined loading also agree well with the Andersen et al (2005) benchmark results.
- The isoparametric, or curved interface elements used in Plaxis 3D version 2.2 accurately model the interaction between curved soil-structure surfaces.
- 3D ultimate capacity calculations by FEA are sensitive to discretization error. Insight into the geometry of the governing failure mechanism and the use of interface elements, symmetry, reduced model dimensions and selective 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 it is possible to quantify the discretization error and possibly make it negligible.

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