SAND2016-6076R

Sandia National Laboratories

Operated for the U.S. Department of Energy's
National Nuclear Security Administration
by **Sandia Corporation**

Albuquerque, New Mexico 87185

date: 6/17/2016

to: Dr. Sam Weller, University of Exeter

from: Steven Gomez (Org. 01556), Richard Jensen (Org. 06914) and Jason Heath (Org. 06914)

subject: An Investigation of DTOcean Foundation and Anchor Systems

---

1. Introduction

This memo documents the mechanical loading analysis performed to date for the DTOcean program WP4 foundation and anchor systems submodule. FEA simulations were performed to validate design requirements defined by Python based analytic simulations of the WP4 program Naval Facilities Engineering Command (NAVFAC) tool. This FEA procedure focuses on worst case loading scenarios on direct embedment anchor and suction caisson designs produced by WP4. These models include a steel casing and steel anchor with soft clay and dense sand surrounding the steel components respectively.

Model development was created based on a WP4 module which provided soil and foundation system material properties, basic anchor system geometry, as well as boundary conditions on the soil. Two different cases were run using the WP4 program to calculate the aforementioned parameters assuming different foundation and anchor systems, a suction caisson in soft clay and a direct embedment anchor in a dense sand. The dummy scenario is based on a 10x fixed tidal turbines, loosely based on the HS1000 turbine. The environmental conditions on the tidal turbines were computed by WP4 and translated into mooring line loads that were then used by WP4 to select the required size and geometry of the suction caisson and direct embedment anchor. The WP4 input files are attached to the memo. The input files for the suction caisson scenario and direct embedment anchors scenario are named: rpj_shetland_suctCais.py and rpj_shetland_directEmbed.py

The results from this study will be used to inform the DTOcean development program by providing an assessment as to whether the foundation designs will adequately support the specified load requirements. This document will cover the meshing process (including geometry simplification) as well as a look at the simulation/modeling approach.

2. Finite Element Model

Cubit, the Sandia-developed meshing tool, was used for the model creation of this project. The foundation system model geometries were acquired from pre-parameterized metrics set by the WP4 program. Model simplifications were made to the defined parameters in effort to reduce computational cost and allow for increased refinement near stress areas of interest.

The suction caisson and embedment anchor meshes contain 147,368 and 442,046 elements respectively, shown in Figure 1 and Figure 2. To mitigate loading boundary effects, the soil was represented out a distance of 20 times the casing diameter and a depth of 1 times the respective suction caisson and embedment anchor depth.

Axisymmetric geometry was implemented to reduce computational cost and was created

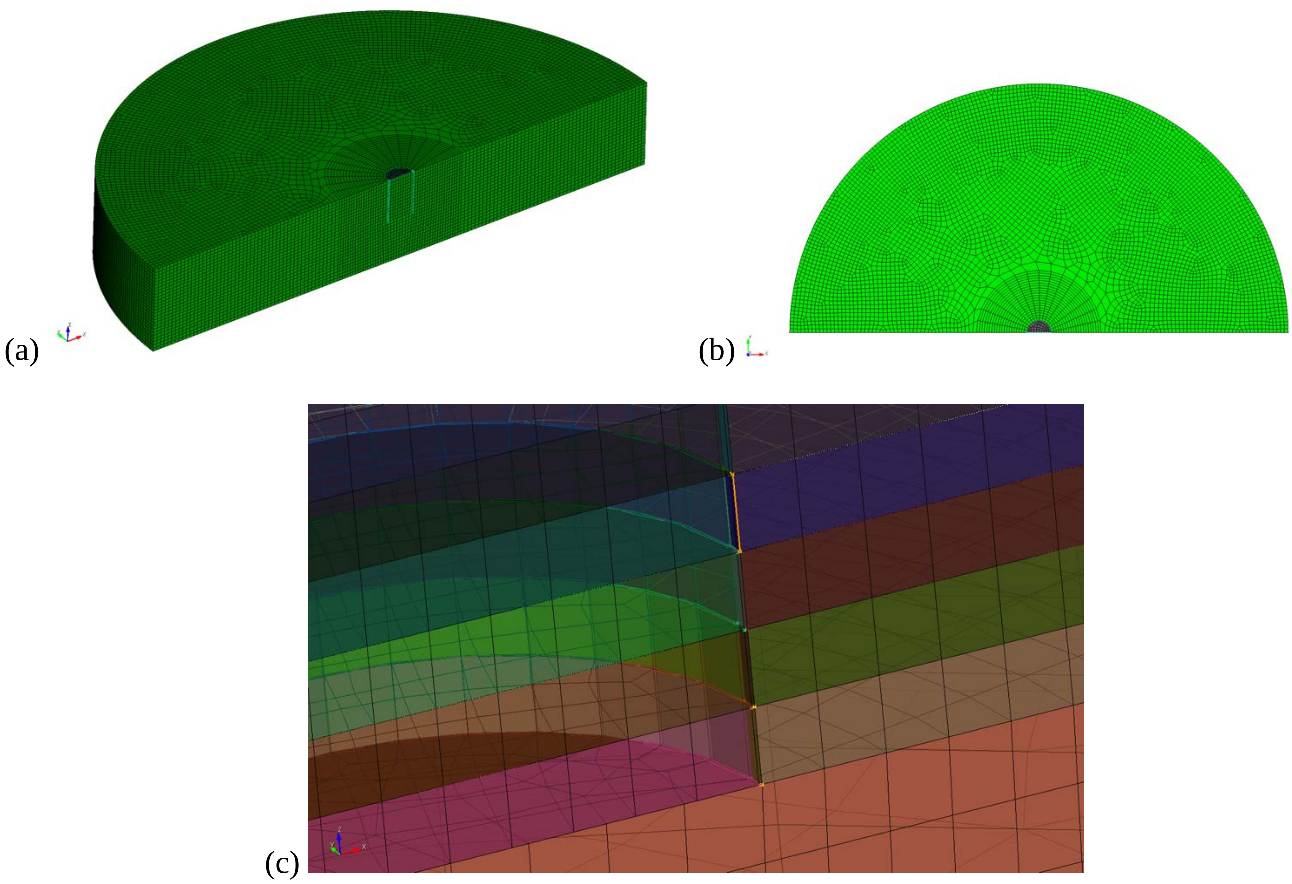


Figure 1: Full mesh of the suction caisson configuration shown in (a) isometric view (b) bird's-eye view and (c) load location of the representative caisson pad eye

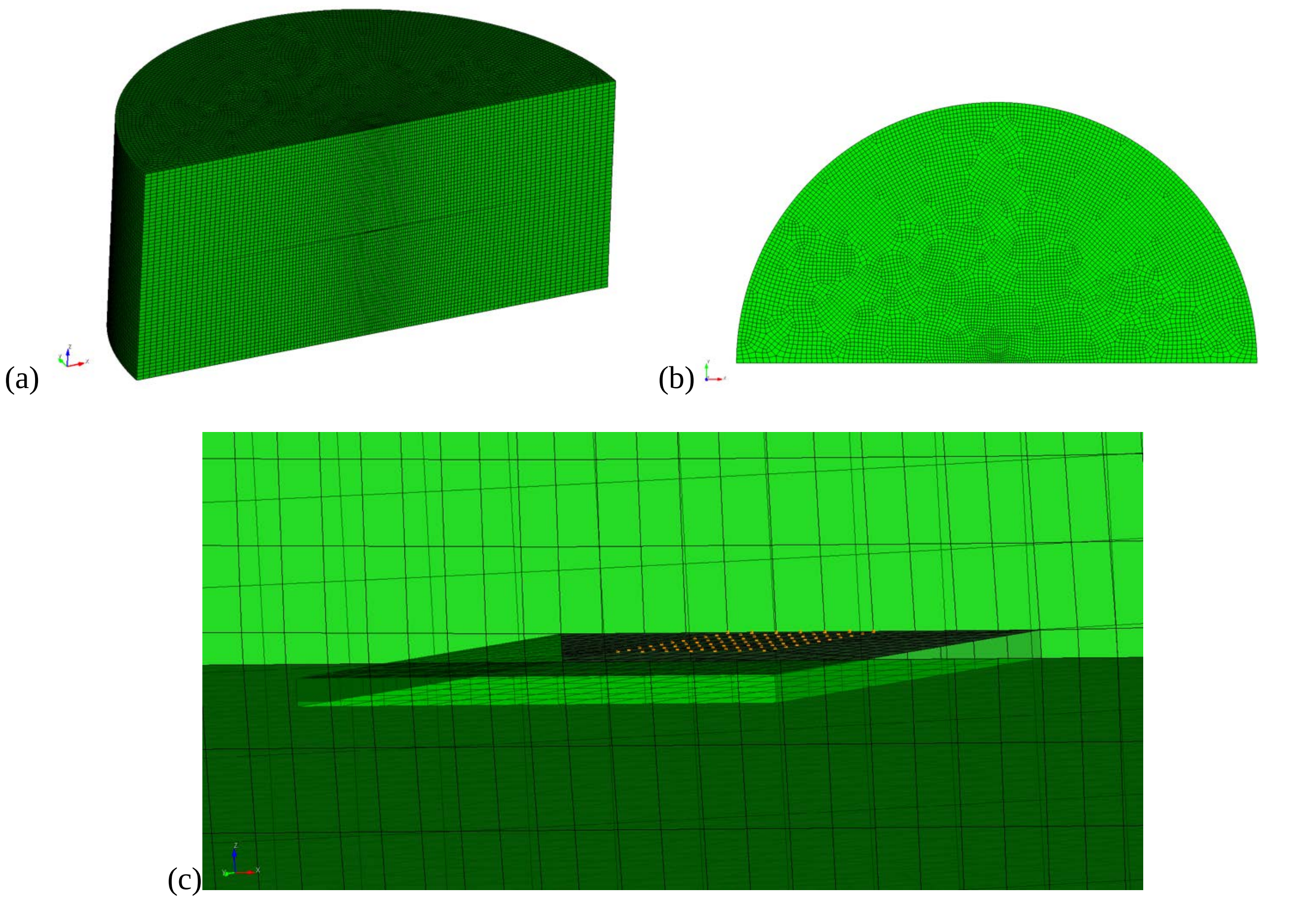


Figure 2: Full mesh of the direct embedment anchor configuration shown in (a) isometric view (b) bird's-eye view and (c) load location of the representative anchor plate pad eye

Nodesets were created to apply the prescribed force along a representative pad eye geometry for the suction caisson and embedment anchor, shown in Figure 1(c) and Figure 2 (c) respectively. The steel anchor components, by where the load was applied, utilized shell elements. These shells were lofted to their respective thickness, shown in Figure 3. Once the assemblies were created in Cubit and exported in the genesis format, the Sierra/SM [2] code was used to perform subsequent analysis.

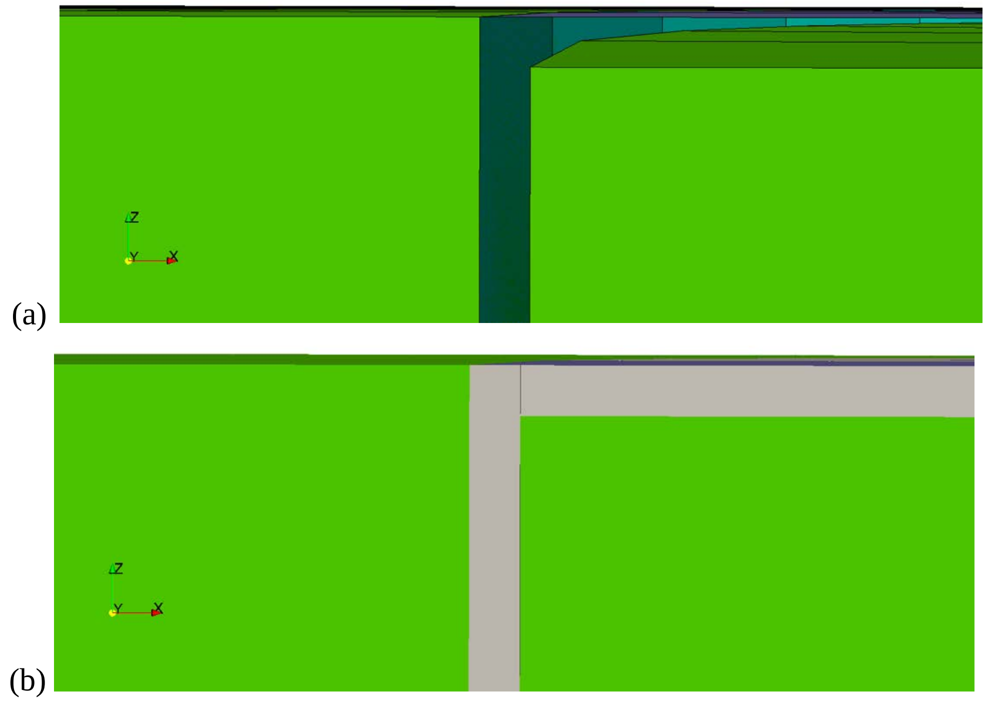


Figure 3: Shell elements were used to represent the thin steel suction caisson and direct embedment geometries. For visualization, the suction caisson plate is shown in an (a) un-lofted (b) lofted configuration.

3. Materials and Methods

3.1. Soil and Crushable Foam Model

The soil and crushable foam material model was originally formulated by Krieg [1] and is currently implemented in Sierra/SM [2], based on PRONTO 3D [3]. The following 3.1 subchapter describing the function of this material model is an excerpt taken from PRONTO 3D [3]:

The yield surface assumed is a surface of revolution about the hydrostat in principal stress space as shown in Figure 4. In addition, a planar end capon the normally open end is assumed. The yield stress is specified as a polynomial in pressure, p (positive in compression)

$$\sigma_{yd} = a_0 + a_1 p + a_2 p^2 \quad (1)$$

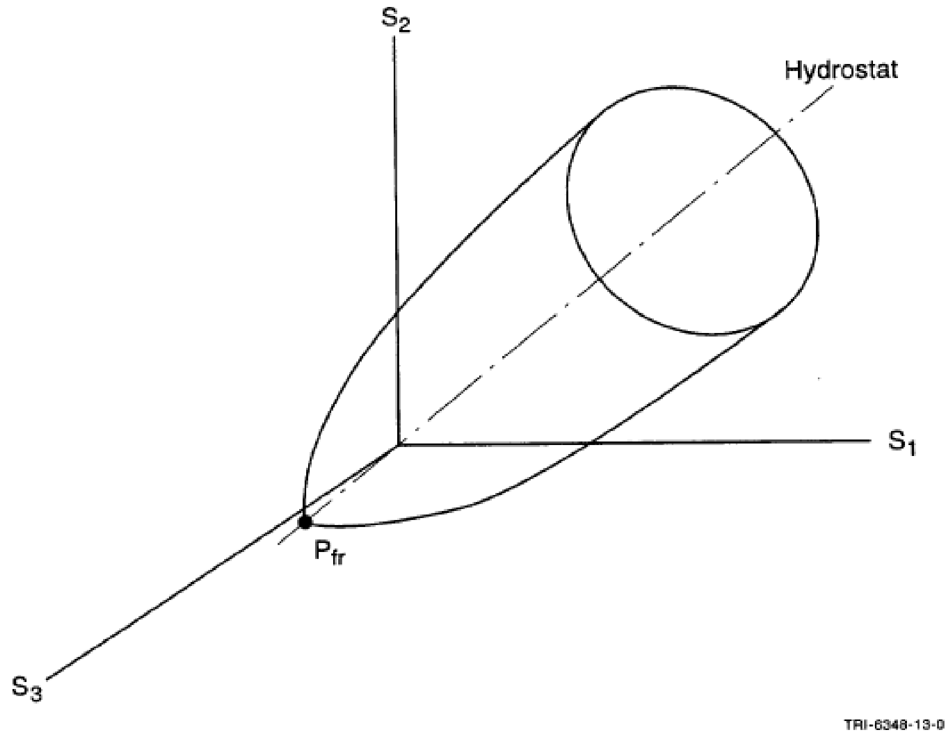


Figure 4: Pressure-dependent yield surface for the soils and crushable foams material model.

The determination of the yield stress from Equation 1 places severe restrictions on the admissible values of a_0, a_l, and a_2. There are three valid cases as shown in Figure 3. First, the user may specify a positive a_0, and a_1 and a_2 equal to zero as shown in Figure 5a. This gives an elastic-perfectly plastic deviatoric response, and the yield surface is a cylinder oriented along the hydrostat in principal stress space. Second, a conical yield surface (Figure 5b) is given by

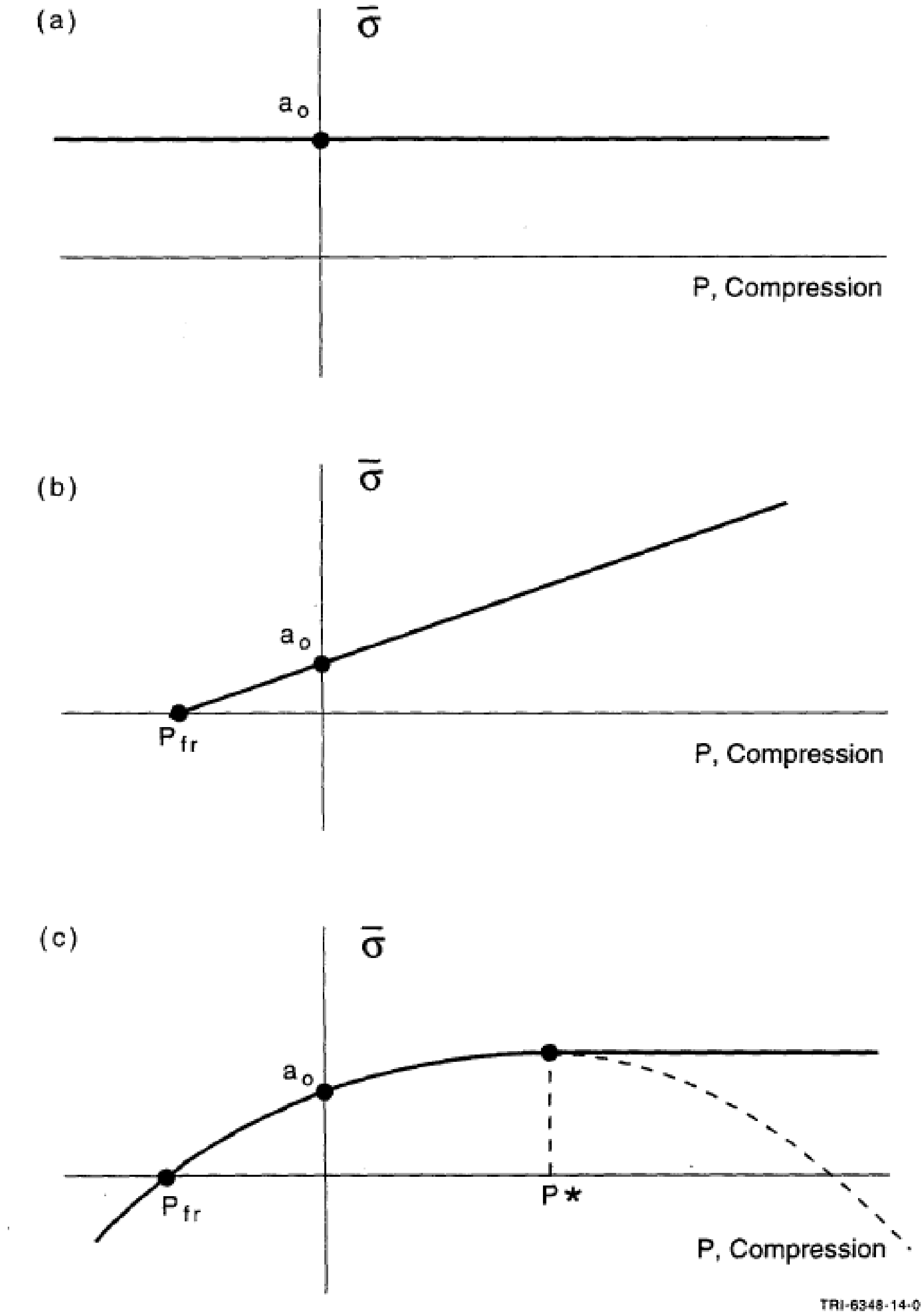


Figure 5: Forms of valid yield surface which can be defined for the soils and crushable foams material model.

setting a_2 to zero and entering appropriate values of a_0 and a_1. The program checks the user's input to determine whether a valid (negative) tensile fracture pressure, P_{fr}, results from the input data. The third case results when all three constants are nonzero and the program detects that a valid negative tensile failure pressure can be derived from the data. This case is shown in Figure 5c. A valid set of constants for the third case results in a parabola as shown in Figure 5c. We have drawn the descending portion of the curve with a dashed line, indicating that the program does not use that portion of the curve. Instead, when the pressure exceeds P^*, the yield stress is held constant as shown at the maximum value.

The plasticity theories for the volumetric and deviatoric parts of the material response are completely uncoupled. The volumetric response is computed first. The mean pressure, p, is assumed to be positive in compression, and a yield function is written for the volumetric response as

$$\phi_p = p - f_p(\varepsilon_V) \qquad (2)$$

where $f_p(\varepsilon_v)$ defines the volumetric stress-strain curve for the pressure as shown in Figure 6. This function is defined by the user with the restriction that the slope of the function must be less than or equal to the unloading bulk modulus, K_o, everywhere. If the user wishes the volumetric response to be purely elastic, he simply specifies no function identification (e.g., FUNCTION ID = 0). The yield function, ϕ_p, determines the motion of the end cap along the hydrostat.

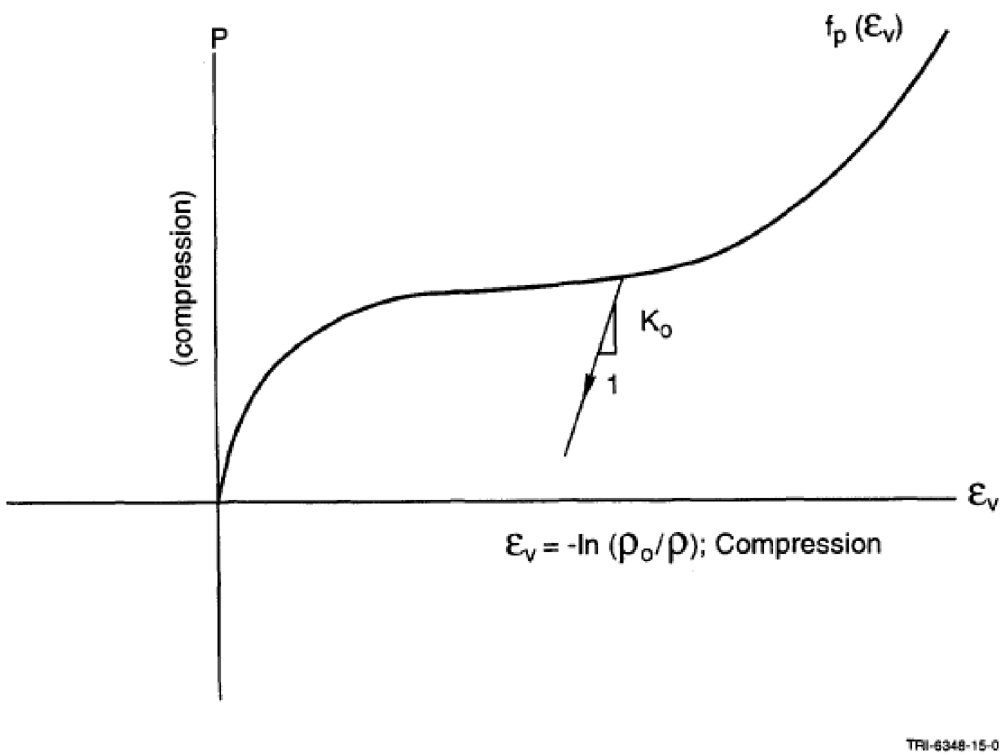


Figure 6: Pressure versus volumetric strain curve in terms of a user-defined curve, F(εv), for the soils and crushable foams material model.

The Soils and Crushable Foams model uses four internal state variables:

EVMAX - maximum compressive volumetric strain experienced (always positive),
EVFRAC - current value of volumetric fracture strain (positive in compression),
EV - current value of volumetric strain (positive in compression),
NUM - integer pointing to the last increment in the pressure function where the interpolate was found.

The PROP array (the input parameters for the soils and crushable foams model) contains the following entries for this material:

PROP(1) - 2μ
PROP(2) - Bulk Modulus, K_0
PROP(3) – a_0
PROP(4) – a_l
PROP(5) - a_2
PROP(6) - Function ID number.

3.2. Model Parameters

The anchor system design parameters used in the FE analysis are shown in Table 1 and Table 2. The embedded anchor pad eye was located in the middle of the anchor plate, axisymmetric across the cross-section.

Table 1: Suction caisson design parameters

Definition	units	Value
Caisson diameter	m	5 x 3.5
Caisson length	m	7.925 x 5.5
Caisson thickness	m	0.0254 x 0.06
Padeye load	N	1.353111E+6
Angle	Degrees	0
Pad eye location	m	5.5
Relative soil depth	m	120
Overburden pressure	Pa	1.177E+6
Pad eye anchor length	m	0.305
Pad eye anchor width	m	0.305

Table 2: Embedded anchor design parameters

Definition	units	Value
Plate width	m	2
Plate length	m	3.5
Plate thickness	m	0.1
Pad eye load	N	1.353E+6
Angle	Degrees	90
Embedded depth	m	8.625
Relative soil depth	m	120
Overburden pressure	Pa	1.177E+6
Pad eye anchor length	m	1.44
Pad eye anchor width	m	0.61

The material properties used to parameterize the FE model are shown in Table 3. The Suction caisson implemented the soft clay soil and foam material model parameters and the embedded anchor analysis implemented dense sand. Both anchor systems utilized identical steel properties.

Table 3: Material model parameters

Definition	Units	Soft Clay	Dense sand	Steel
Density	$\frac{kg}{m^3}$	1762	2163	7860
Young Modulus	Pa	13.41E+6	65E+6	1.999E+11
Poisson’s Ratio	-	0.45	0.35	0.3
A0	Pa	35910	0	-
A1	Degrees	0	38.5	-
A2	Degrees	0	0	-
Yield Stress	Pa	-	-	427.7E+6

3.3. Loading and Boundary Conditions

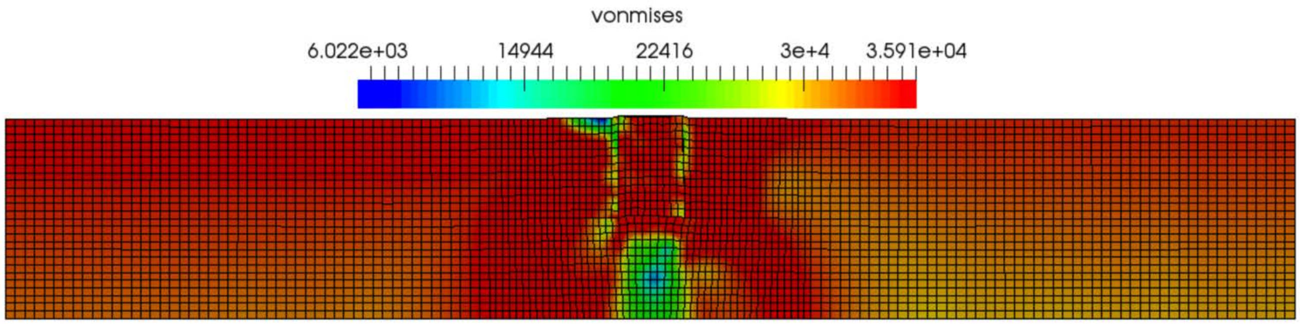
The simulation approach implemented the loadings described in the model dimensions and loading levels denoted in Table 1 and Table 2. Both anchor systems applied the pad eye load evenly distributed across pad eye anchor. This was accomplished by dividing the prescribed load across the respective node surface of the pad eye. The soil mass bottom faces were fixed in the vertical direction, the front cross section faces were fixed normal to their surfaces, and the outer circumferential surfaces of the soil mass were allowed to move only in the vertical orientation. Sierra/SM [2] explicit quasistatic mode solver was utilized for these simulations. A uniform seafloor friction coefficient of 0.5 was implemented in the design studies.

4. Results

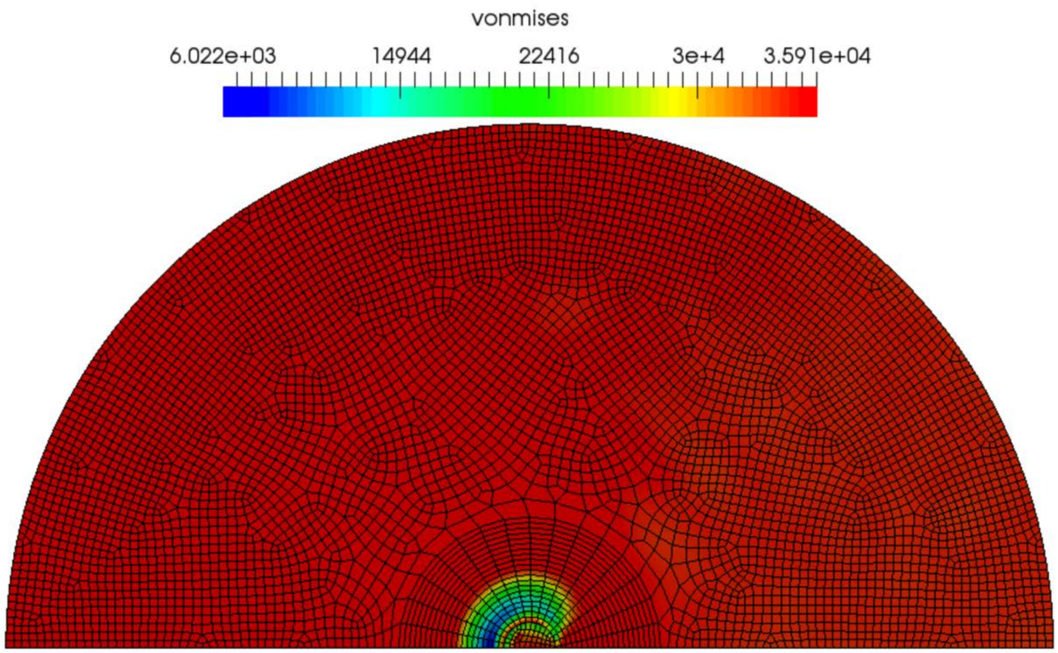
Contour plots of Von Mises stress, Equivalent Plastic Strain (EQPS), and Maximum Compressive Volumetric Strain (EVMAX) are shown in Figure 7 through Figure 12 for the suction caisson and direct embedment anchor designs. Non-magnified displacements are shown in these figures.

The suction caisson design results show the Von Mises stress reaches a maximum of approximately 36 kPa near the caisson load application and a minimum of 6 kPa along the caisson border top soil opposite of the caisson load application. Localized plastic strain is present around the right-hand side caisson where the load is applied, reaching approximately 0.4 EQPS in the bottom back corner of the caisson and averaging approximately 0.2 EQPS in the soft clay bordering the caisson. The EQPS quickly dissipates to zero around the outer surrounding clay mass. Maximum compressive volumetric strain for the caisson design reaches 0.036 and occurs at the bottom caisson corner near the applied load.

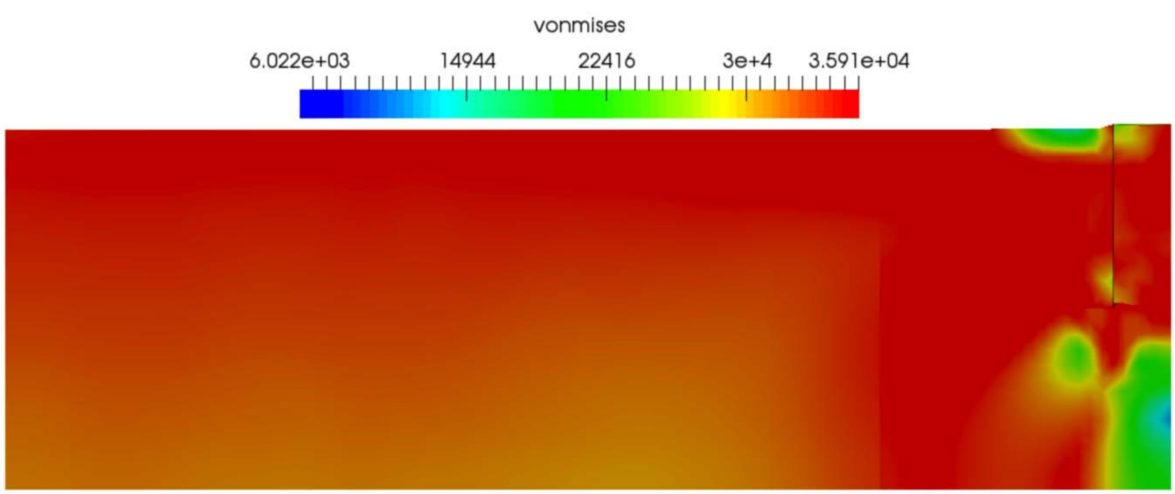
The direct embedment design results show the Von Mises stress near the area of the plate edge loading reaches a maximum of approximately 1 MPa and dissipates to 0.24 MPa around bottom of the anchor. Near this area of high stress, localized plastic strain reaches approximately 0.015 EQPS, reducing to 0.008 EQPS in the dense sand below the embedment anchor, and dissipating to zero around the surrounding sand. Maximum compressive volumetric strain for the caisson design reaches 0.016, localized directly above location of the embedment anchor. A significant source of volumetric strain and stress shown in the suction caisson and direct embedment design is induced by the constant overburden pressure of 1.18 MPa.



(a)



(b)



(c)

Figure 7: Von Mises stress (Pa) shown in (a) front view (b) bird's-eye view and (c) sliced midway through the suction caisson.

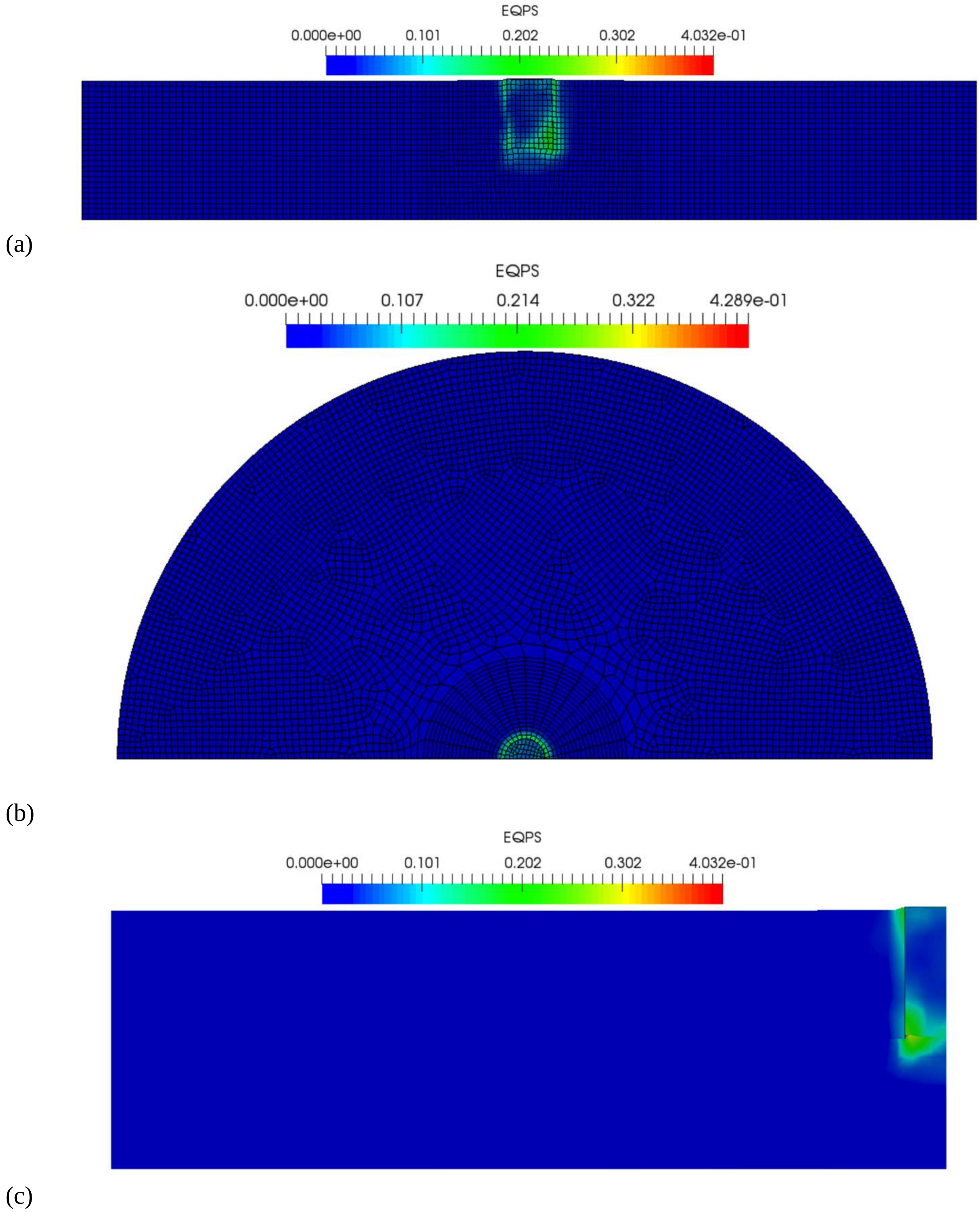
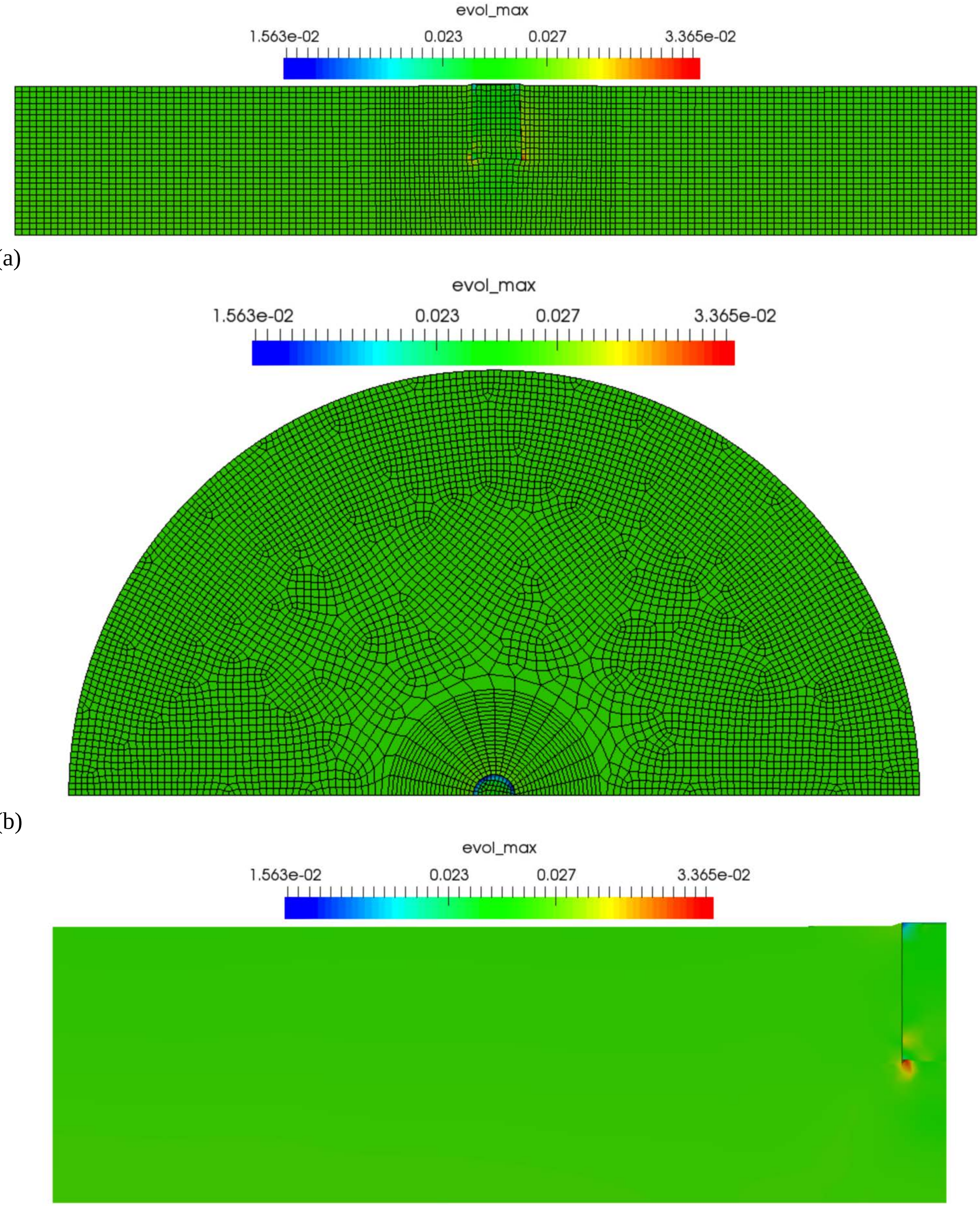


Figure 8: EQPS shown in (a) front view (b) bird's-eye view and (c) sliced midway through the suction caisson.

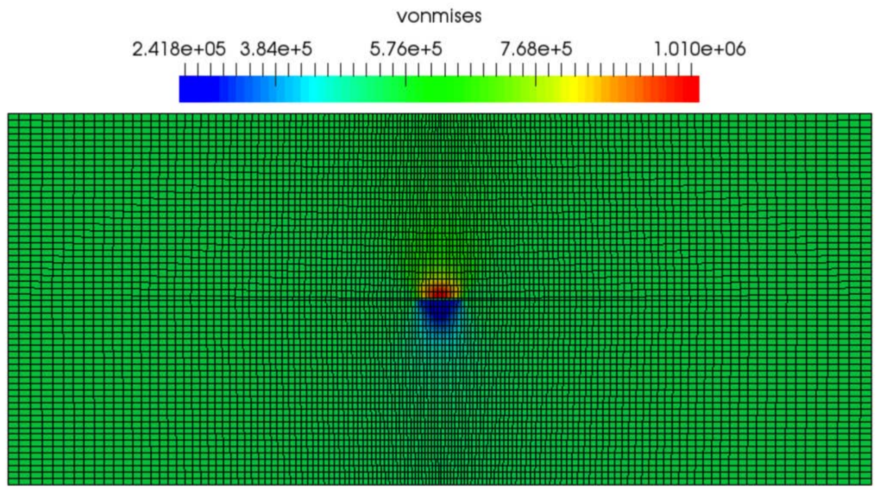


(a)

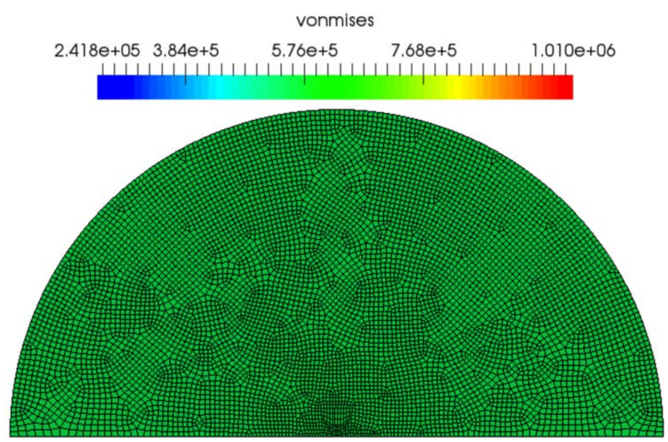
(b)

(c)

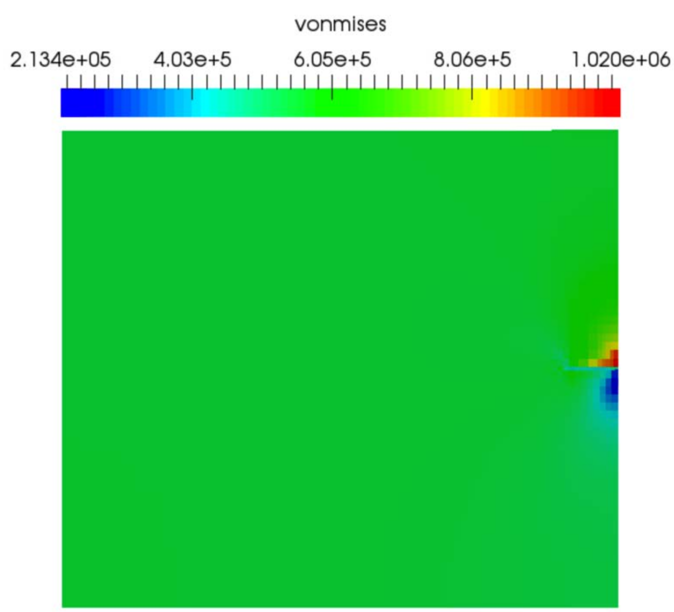
Figure 9: Maximum compressive volumetric strain shown in (a) front view (b) bird's-eye view and (c) sliced midway through the suction caisson.



(a)

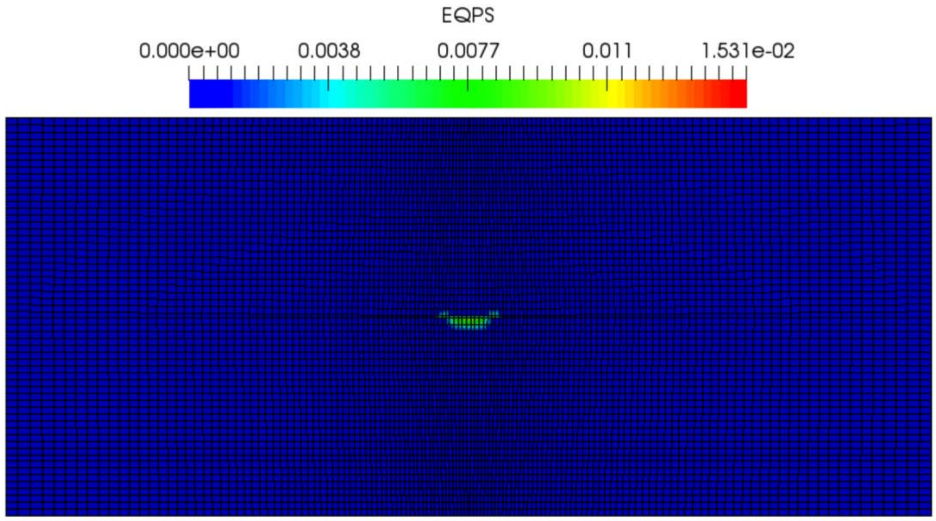


(b)

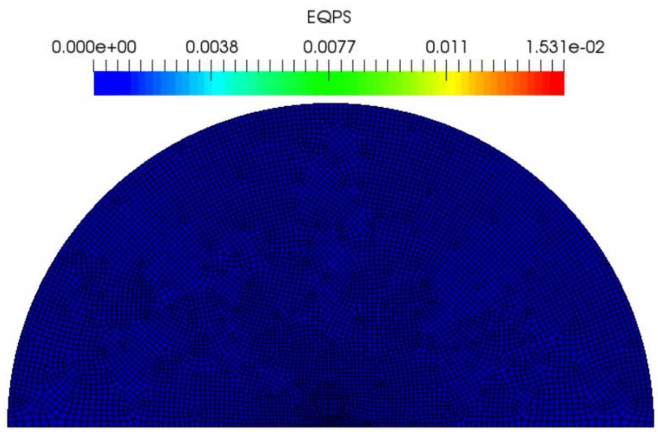


(c)

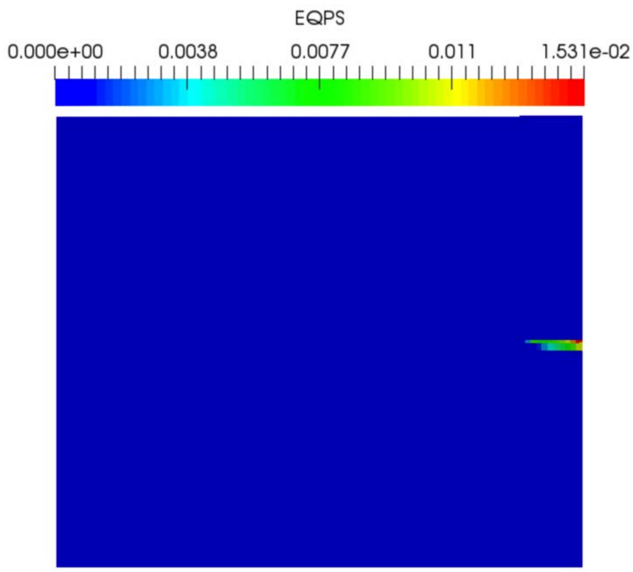
Figure 10: Von Mises stress (Pa) shown in (a) front view (b) bird's-eye view and (c) sliced midway through the direct embedment anchor.



(a)

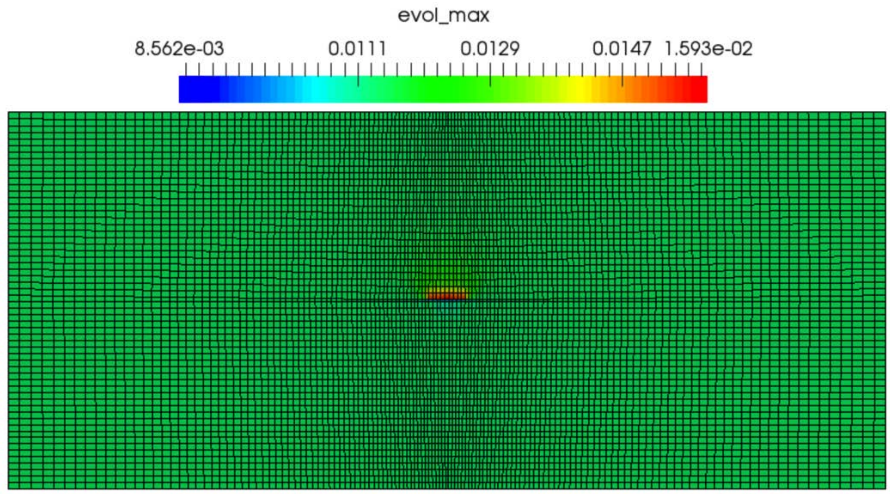


(b)

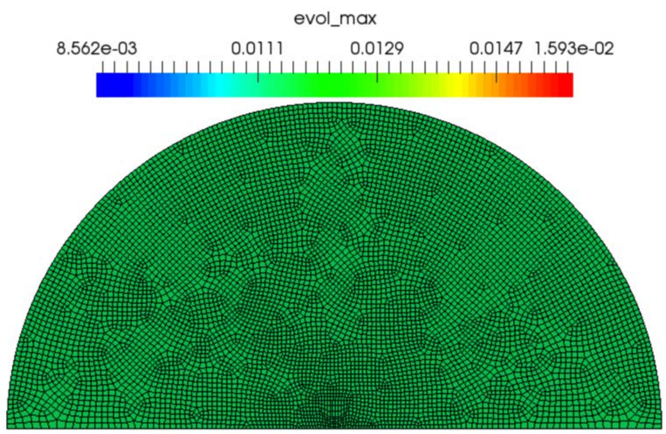


(c)

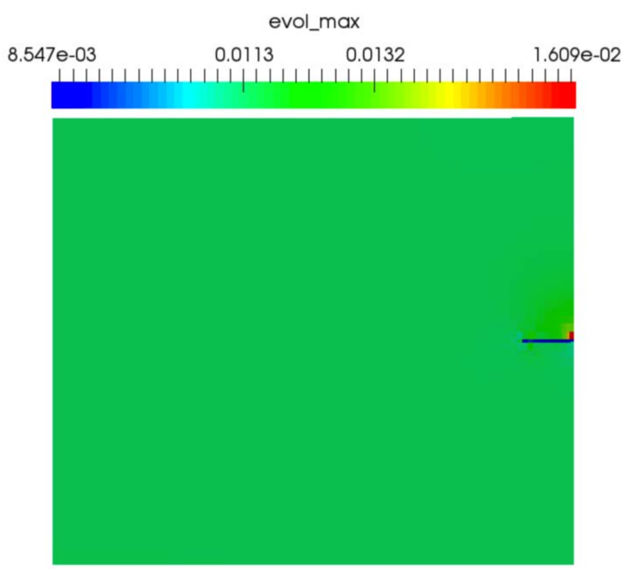
Figure 11: EQPS shown in (a) front view (b) bird's-eye view and (c) sliced midway through the direct embedment anchor.



(a)



(b)



(c)

Figure 12: Maximum compressive volumetric strain shown in (a) front view (b) bird's-eye view and (c) sliced midway through the direct embedment anchor.

5. Conclusions and Future Work

The suction caisson and direct embedment anchor designs show localized stress and strain under the prescribed loading conditions, but the respective soft clay and dense sand soil masses do not fail throughout the soil volume. The proposed designs should provide as adequate anchor systems for the respective load scenarios proposed.

Further review and diligence of the WP4 program material conversion to the Sierra/SM [2] soil and foam material model is desired. Additionally, the physical loading process of these anchors should be better understood to replicate FE boundary conditions with higher fidelity. Field data and/or data from NAVFAC based analytic tools would provide a means of model comparison and potentially allocate a baseline calibration model. Further FEA is recommended for exploring model sensitivity and parameter range variability such as load magnitude, load application site, and soil material definition.

Internal Distribution

MS-0346	S. Gomez	Org. 01556
MS-1124	J. Roberts	Org. 06122
MS-0751	R. Jensen	Org. 06914
MS-0750	J. Heath	Org. 06914
MS-0828	M. Ross	Org. 01557
MS-0346	D. Peebles	Org. 01556
MS-0735	M. Lee	Org. 06914

Acknowledgments

This work was funded by the Department of Energy’s (DOE) Energy Efficiency and Renewable Energy (EERE) Program’s Wind and Water Power Technologies Office.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND Number: 2013-6867 C.

References

1. Krieg, R.D., (1978) "A Simple Constituive Description for Soils and Crushable Foams," SC-DR-72-0883. Albuquerque, NM and Livermore, CA: Sandia National Laboratories.
2. SIERRA Solid Mechanics Team (2016). Sierra/SolidMechanics 4.40 User’s Guide. SAND Report 2016-2707. Albuquerque, NM and Livermore, CA: Sandia National Laboratories.
3. Taylor L.M. and Flanagan, D.P., (1989). Pronto 3D A Three-Dimensional Transient Solid Dynamics Program: SAND87-1912. Albuquerque, NM and Livermore, CA: Sandia National Laboratories.

Attachments

SNL_validation_cases.zip