Suction Caissons : Finite Element Modeling

by

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PREFACE

The project Suction Caissons and Vertically Loaded Anchors was conducted as series of inter-related studies. The individual studies are as follows:

- Suction Caissons & Vertically Loaded Anchors: Design Analysis Methods by Charles Aubeny and Don Murff, Principal Investigators
- Suction Caissons: Model Tests by Roy Olson, Alan Rauch and Robert Gilbert, Principal Investigators
- Suction Caissons: Seafloor Characterization for Deepwater Foundation Systems by Robert Gilbert Principal Investigator
- Suction Caissons: Finite Element Modeling by John Tassoulas Principal Investigator

This report summarizes the results of the Suction Caissons: Finite Element Modeling study

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SUMMARY

This Report presents our final account of the development and validation of a computational procedure for finite-element analysis of suction-caisson behavior, highlighting its unique features and capabilities. The procedure is based on a description of soil as a two-phase medium: a water-filled porous solid. Nonlinear behavior of the solid phase is represented by means of a bounding-surface plasticity model while a frictional-contact algorithm is used in handling soil-caisson interaction. Furthermore, specially devised remeshing schemes help track the caisson penetration path and avoid numerical complications with heavily distorted finite elements in the vicinity of the caisson-soil interfaces. The procedure has been applied to simulations of several tests involving caisson installation, set-up and pullout. Computational results and experimental data are in good agreement.

INTRODUCTION

Suction caissons are hollow cylinders (tubes) capped at the top. They are allowed to penetrate the sea-bottom sediments under their own weight, and then pushed to the required depth with differential pressure applied by pumping water out of the interior. The use of suction caissons as foundations for deep-water offshore structures and anchors for mooring lines has been increasing in the last decade. Suction caissons are an attractive option in providing anchorage for floating structures in deep water. They are easier to install than impact-driven piles and can be used in water depths well beyond where pile driving becomes impractical. Suction caissons have higher load capacities than drag embedment anchors and can be inserted reliably at preselected locations and depths with minimum disturbance to the seafloor environment and adjacent facilities (Sparrevik 2001).

Better understanding of suction-caisson behavior has been sought by means of field tests, laboratory tests, and numerical simulations. Extensive field tests on small-scale and full-scale caissons have been carried out to determine their installation characteristics and axial as well as lateral load capacities, e.g. Hogervorst (1980), Tjelta et al. (1986), Tjelta (1995). Field tests are valuable in obtaining geotechnical information relevant in the design of future caissons, but they are expensive and time-consuming. On the other hand, laboratory testing of model suction caissons can be employed to investigate performance of the caissons under a variety of conditions. Geotechnical centrifuge tests on model suction caissons have been carried out to simulate the stress conditions and soil response at the field scale (see Clukey et al. 1995, Randolph et al. 1998). These are quite costly and remain subject to various

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limitations. Model suction caissons have been tested under 1-*g* and controlled laboratory conditions (Wang et al. 1977, Steensen-Bach 1992, Rao et al. 1997, El-Gharbawy and Olson 1999, El-Gharbawy et al. 1999, Whittle et al. 1998, Byrne and Houlsby 2002). The caissons studied were of aspect ratio (length-to-diameter ratio) in the range of 2-12 and were tested under various loading conditions. Laboratory tests on model suction caissons conducted by Wang et al. (1977) were focused on studying caisson efficiency and feasibility and identifying important parameters governing their performance. The recent laboratory tests (Rao et al. 1997, El-Gharbawy and Olson 1999) were focused on improving the design methodology.

Studies of suction caisson behavior involving extensive axisymmetric and three-dimensional numerical simulations (Sukumaran et al. 1999, Erbrich and Tjelta 1999, El-Gharbawy and Olson 2000, Deng and Carter 2002) have been carried out to determine their capacity under different loading and drainage conditions. Sukumaran et al. (1999) and Erbrich and Tjelta (1999) used the commercial finite element code ABAQUS (www.hks.com), El-Gharbawy and Olson (2000) used the commercial finite element code PLAXIS (http://www.plaxis.nl) developed for geotechnical computations, and Deng and Carter (2002) used the finite element software AFENA developed at the Center for Geotechnical Research at the University of Sydney (http://www.civil.usyd.edu.au/cgr). In all cases, the stress-strain behavior of the soil skeleton was represented by means of plasticity models such as the modified cam-clay model. The suction caisson was wished in place, with no attempt to simulate the installation process. Perfect interface bonding was assumed between the caisson and the surrounding soil skeleton. The initial state of stress in the soil skeleton was typically estimated in terms of the submerged unit weight and the lateral earth pressure coefficient at rest (Deng and Carter 2002).

The computational procedure developed in the course of our project (Vásquez 2000, Maniar 2004) and reported herein simulates suction-caisson installation and estimates the axial and lateral capacities. An axisymmetric formulation was implemented in a computer code for analysis of installation and axial-pullout problems. On the other hand, a three-dimensional analysis formulation that utilizes the general-purpose finite-element analysis code ABAQUS (http://www.hks.com) but imports the state of the state of the soil-caisson system from axisymmetric installation computations was adopted for lateral-pullout problems. The computed caisson behavior is compared with measurements from laboratory tests conducted during a concurrent research project at the Offshore Technology Research Center (Mecham 2001, Luke 2002, Coffman 2003, Coffman et al. 2004, and El-Sherbiny 2004).

GOVERNING EQUATIONS

The response of saturated, porous, clayey soil can be described using the Biot theory of porous media (Biot 1941, 1955, Atkin and Craine 1976, Bowen 1976, Prevost 1980, 1981) that accounts for coupling between deformation of the solid phase and flow of the pore fluid. Vásquez (2000) and Maniar (2004) provide detailed accounts of the governing equations and the corresponding weak statements that form the basis of our finite-element modeling. Solid displacements, Darcy's velocities and excess pore-fluid pressure are the field quantities. One set of equations imposes conservation of *linear momentum of the mixture*. Another set specifies conservation of *linear momentum of the fluid phase*. The last equation expresses conservation of *mixture mass*. Although these equations have been applied in earlier studies of flow and deformation in porous media, we must point out that we have introduced an equivalent arrangement that facilitates the description of frictional contact in terms of the effective (normal) stress component on the caisson-soil interfaces (Vásquez 2000 and Maniar 2004).

FINITE-ELEMENT DISCRETIZATION

Axisymmetric soil discretization is accomplished with eight-node, quadratic, isoparametric, underintegrated finite elements for solid displacements, and Darcy's velocities. Spatially continuous discretization of excess pore-fluid pressure is applied using four-node linear finite elements. The caisson is represented using conventional, axisymmetric, solid finite elements: eight-node, quadratic, isoparametric elements for displacements. As explained by Vásquez (2000) and Maniar (2004), our choice of identical interpolation functions for solid displacements and Darcy's velocities, along with the arrangement of the governing equations referred to above, lead to straightforward calculation of *effective* nodal forces on any soil boundary. This is particularly significant when dealing with the caisson-soil interface where the frictional-contact algorithm requires effective forces (the ones corresponding to soil effective stress components). It is worth emphasizing that the frictional-contact algorithm implemented in our formulation is not available in general-purpose computer codes. In the latter, only *total* nodal forces can be readily determined and the resulting description of frictional contact becomes unrealistic in the presence of pore-fluid pressure.

SOIL CONSTITUTIVE MODEL

The nonlinear behavior of clayey soil is described on the basis of a bounding-surface plasticity theory for isotropic cohesive soils (Dafalias and Herrmann 1982, Dafalias 1986, Dafalias and Herrmann 1986, Kaliakin and Herrmann 1991). Utilizing concepts and principles of critical state soil mechanics, the bounding-surface theory is a reliable and versatile tool for representation of clay behavior along arbitrary stress and strain paths. The constitutive model provides the relationship between effective stress and strain increments.

CAISSON-SOIL INTERFACES

The interior and exterior soil-caisson interfaces are modeled with a contact algorithm based on a slide-line formulation (Hallquist et al. 1985), which allows for large relative displacements between the caisson and the soil. The slide-line formulation involves nodes on the soil side of the interface and surface elements on the caisson side.

In the contact algorithm, penetration of soil nodes into the caisson is prevented with constraints imposed on the solid displacements, Darcy's velocities, and the excess pore-fluid pressure using Lagrange multipliers. Friction between the soil and the caisson is assumed to obey the classical Coulomb law. "Stick" and "slip" conditions are distinguished on the basis of the level of interface frictional force in comparison with the Coulomb force, which is taken equal to the effective compressive (normal) force multiplied by the soil-caisson interface friction coefficient. The slide-line contact formulation is in terms of effective forces on the interfaces (integrals of the effective traction components on the interface weighted by the interpolation functions). By the arrangement of the governing equations and the corresponding weak statements, and the choice of interpolation functions for solid displacements and Darcy's velocities, it is straightforward to extract these effective forces (Vásquez 2000 and Maniar 2004).

POTENTIAL FLOW

During installation of the caisson, by self-weight or suction, water flows out of the caisson interior through outlets in the cap. The size of the outlets is considerably smaller than the interior cross section of the caisson. Therefore, water cannot flow freely and some nonuniformity of pressure is expected in the interior of the caisson. To simulate this phenomenon, we used a potential flow formulation to estimate the pressure at the top of interior soil (Vásquez 2000). The potential flow formulation was developed assuming that the fluid is incompressible and inviscid and its flow is irrotational.

REMESHING

We developed a remeshing tool in order to eliminate the need for a priori specification of the caisson penetration path. As installation of the caisson progresses, the finite-element mesh is adjusted so that the line of nodes below the tip remains straight in the axial direction. This line of nodes is also the "seam" in the mesh where separation of soil interior and exterior occurs during penetration. With this adjustment, overconfinement of the soil in the caisson interior is eliminated, and the path of caisson penetration in the soil is determined in the course of the installation process (Maniar and Tassoulas 2002, Maniar 2004).

Unlike other numerical simulations in which the caisson is "whished" into position within the soil, our approach not only leads to the caisson penetration path but provides the force required for installation and its distribution on the interior and exterior caisson-soil interfaces. Furthermore, our detailed treatment of caisson penetration, enhanced by this remeshing tool, enables evaluation of the significance of fine caisson characteristics, such as the tip geometry, that may affect the installation process.

Another remeshing tool was developed in order to adjust the finite-element mesh next to the caisson-soil interfaces. This tool is intended for eliminating distortion of the soil elements in the vicinity of the caisson-soil interfaces and is convenient and helpful in cases where a high coefficient of friction leads to significant finite-element distortion.

SIMULATION PROCEDURE

Computations carried out using our procedure are arranged in a sequence that closely follows laboratory and field tests. The steps are: a) preparation of the soil test bed via slurry consolidation, b) installation of the caisson by self-weight and suction, c) set-up of the caisson (reconsolidation of the caisson-soil system, and d) pullout of the caisson at various speeds. For each of the steps b-d, the initial state of the soil is the one computed at the end of the previous step.

RESULTS

Complete records of our computational experience are provided by Vásquez (2000) and Maniar (2004). In this report, we limit the presentation to results related to caisson installation as this is the stage for which our procedure possesses unique features and capabilities. It is worth noting that computed pullout capacities under both axial and lateral loads are in very good agreement with test data (see Vásquez 2000 and Maniar 2004).

Installation by Self-Weight

Fig. 1(a) shows the penetration path computed using our procedure for a 4-in-diameter model caisson installed in about 200 sec to depth of 32 in by self-weight (Luke 2002). In the context of this test, “self-weight” refers to caisson weight plus additional ballast required for installation to the specified depth. In this particular case, the caisson weight alone will produce penetration of about 11 in (Maniar 2004). The fine dashed lines in Fig. 1(a) represent the interior and exterior walls of the caisson while the relatively coarse dashed line is at mid-thickness of the caisson. In the present computations, the caisson tip (actually, a circular rim) is located at mid-thickness. Therefore, it is of interest to examine soil movement during installation with respect to the coarse dashed line. If conditions of perfect symmetry between interior and exterior soil regions (soil to the left of the interior wall and to the right of the exterior wall) prevailed in the neighborhood of the caisson tip, the cut through the soil, during installation, would occur along the coarse dashed line (no soil would cross this line). During self-weight installation, such symmetry is approached as the caisson thickness-to-radius ratio goes to zero (infinitely thin caisson, infinite diameter-to-thickness ratio). For the caisson (of finite thickness) that we are dealing with here, our computations show that the cut through the soil occurs along the solid line (curve) in Fig. 1(a). It is important to keep in mind that this is a line in the *undeformed* soil domain, separating the portions of soil that, during installation, are placed in the interior and exterior of the caisson. We refer to this line as the “penetration path,” and note that during self-weight installation it is entirely to the left of the coarse dashed line. This result implies that, during self-weight installation, soil from the left is pushed by the caisson to the right of the coarse dashed line, i.e., outwards. The cumulative volume of soil displaced from the interior to the exterior is shown in Fig. 1(b) vs. the caisson tip location. Configurations of the caisson-soil system at the beginning and end of self-weight installation are provided in Fig. 2. As can be seen, our numerical simulation of the test indicates that the top of the soil plug is lowered during this self-weight penetration.

Fig. 3 shows computed forces required for installation along with a measurement from the test by Luke (2002). The friction coefficient ($\mu = 0.16$) used in the computations on both interior and exterior interfaces was obtained by calibration of our procedure using another test by El-Sherbiny (2004). It can be seen that the computed soil resistance is reasonably close to the one reported from the test up to penetration of about 16 in but becomes significantly higher near the end of the installation process. Measurements of the friction coefficient (Pedersen et al. 2003) suggest values higher than the one used in the computations. Therefore, it is likely that the discrepancy is due to differences (between the simulation and the test) in the state of the soil prior to installation.

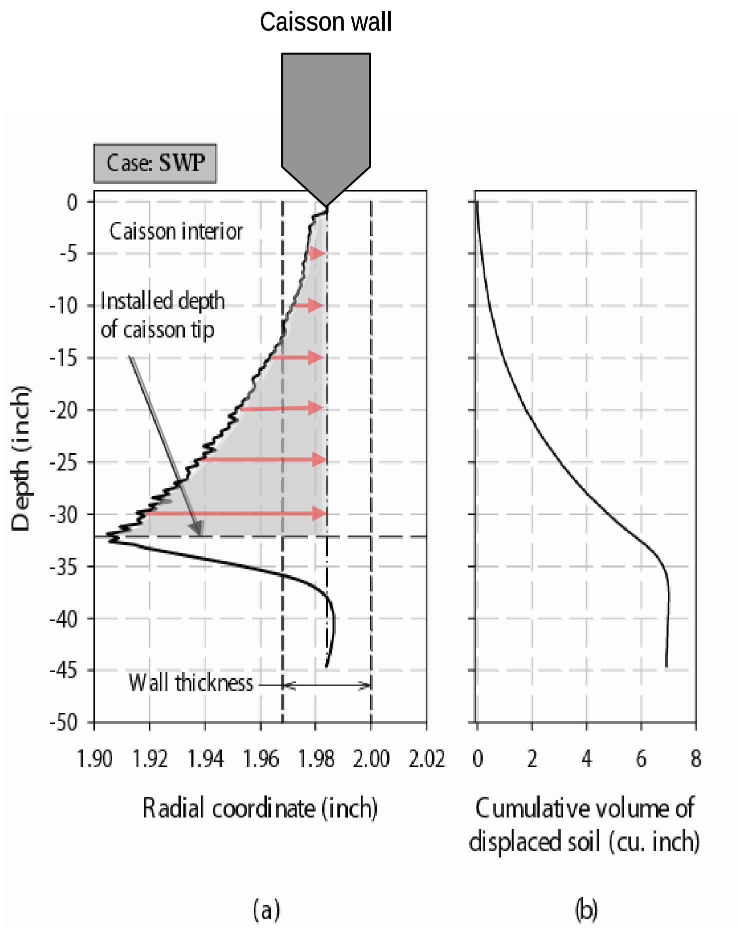

Figure 1: Self-weight penetration path (a) and cumulative volume of displaced soil (b).

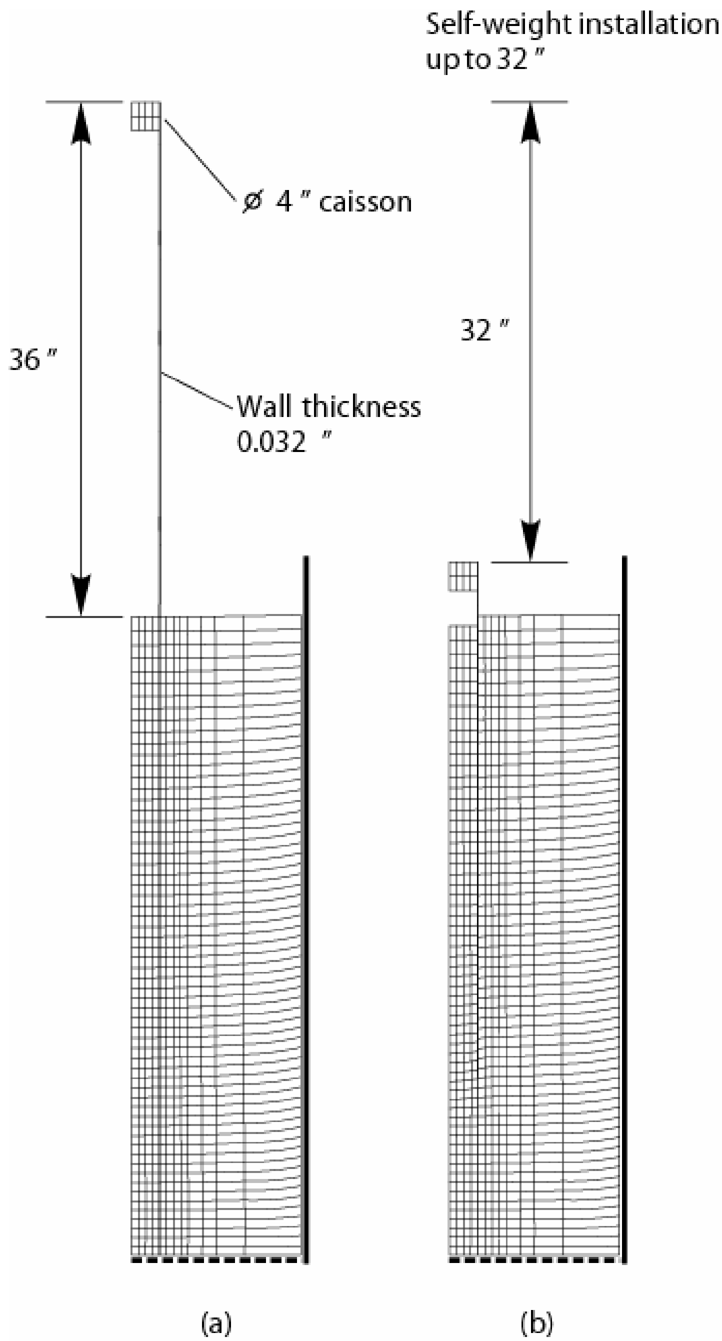

Figure 2: Self-weight installation: initial and deformed configurations. Notice that the soil plug moves downwards in this simulation.

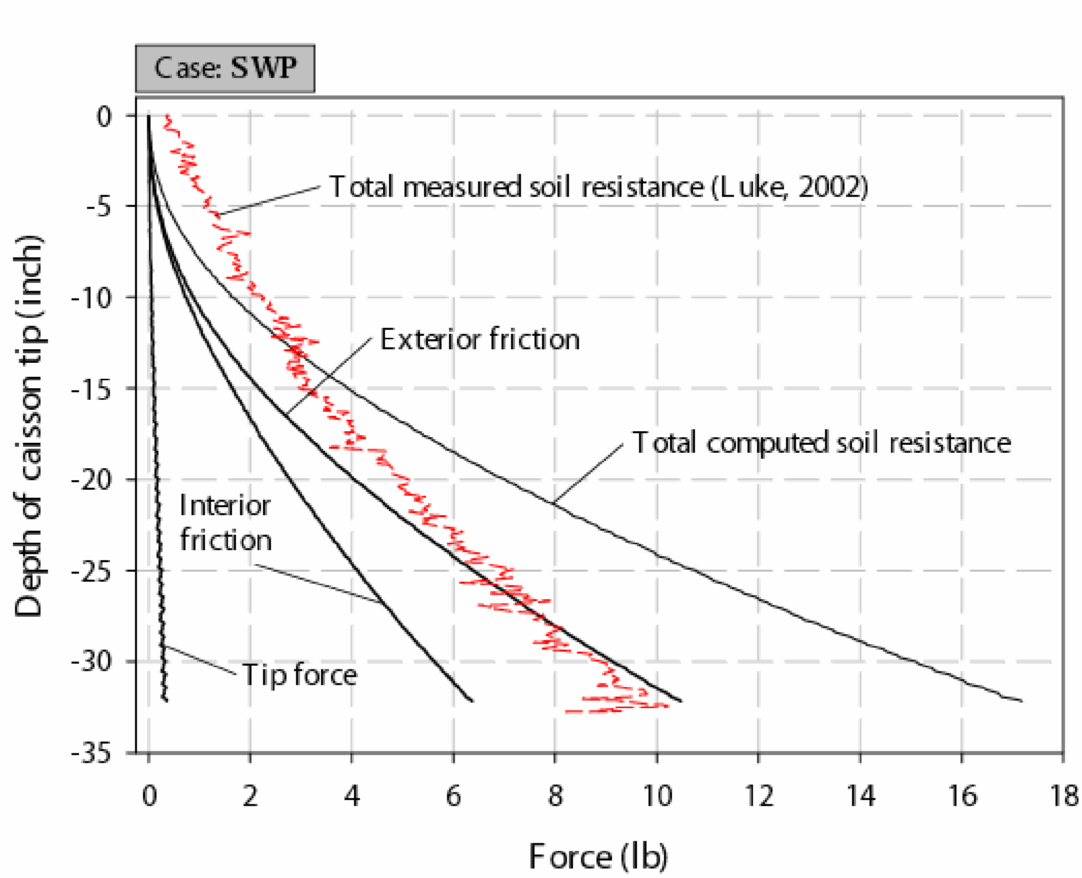

Figure 3: Computed and measured forces during self-weight installation.

It is worth commenting on the contrast between the exterior and interior components of soil resistance during self-weight installation. Consistently with the outward displacement of the soil noted in Fig. 1(a), the exterior friction is seen to be substantially higher than the interior component (about 60% higher near the end of the installation process, Fig. 3).

Suction Installation

Fig. 4(a) shows the penetration path computed using our procedure for a 4-in-diameter model caisson installed to depth of 32 in by suction (Luke 2002). Although this test is classified as "suction installation," the caisson was first pushed to 16 in penetration by self-weight (plus additional ballast) and then to the final depth of 32 in by suction. Thus, the simulation of the initial 16-in penetration is the same as in the case of self-weight installation discussed above. As can be seen in Fig. 4(a) shows, soil is initially pushed outwards (self-weight installation portion) but, after suction is applied, inward soil movement occurs, in contrast with the case of self-weight installation (the penetration path crosses the coarse dashed line; compare with Fig. 1(a)). The cumulative volume of displaced soil displaced is shown in Fig. 4(b) vs. the caisson tip location. Configurations of the caisson-soil system prior to installation, at the intermediate position attained by self-weight installation and at the final penetration by suction can be seen in Fig. 5. Our numerical simulation of the test indicates that the top of the soil plug rises during this suction installation.

Computed forces required for installation along with a measurement from the test by Luke (2002) are shown in Fig. 6. The friction coefficient (μ = 0.16) used in the simulation of self-weight installation was specified in this case as well, on both interior and exterior interfaces (as mentioned earlier, the value of this parameter was obtained by calibration of our procedure using another test by El-Sherbiny 2004). It can be seen that the computed soil resistance is reasonably close to the one reported from the test up to penetration of about 16 in, the segment corresponding to self-weight installation, but does not exhibit the drop associated with suction installation. As in the case of self-weight installation, it is likely that the discrepancy is due to differences (between the simulation and the test) in the state of the soil prior to installation. Fig. 6 also shows the exterior and interior components of soil resistance. In this case, the interior friction is about the same as the component on the exterior (in contrast to the self-weight installation case, Fig. 3).

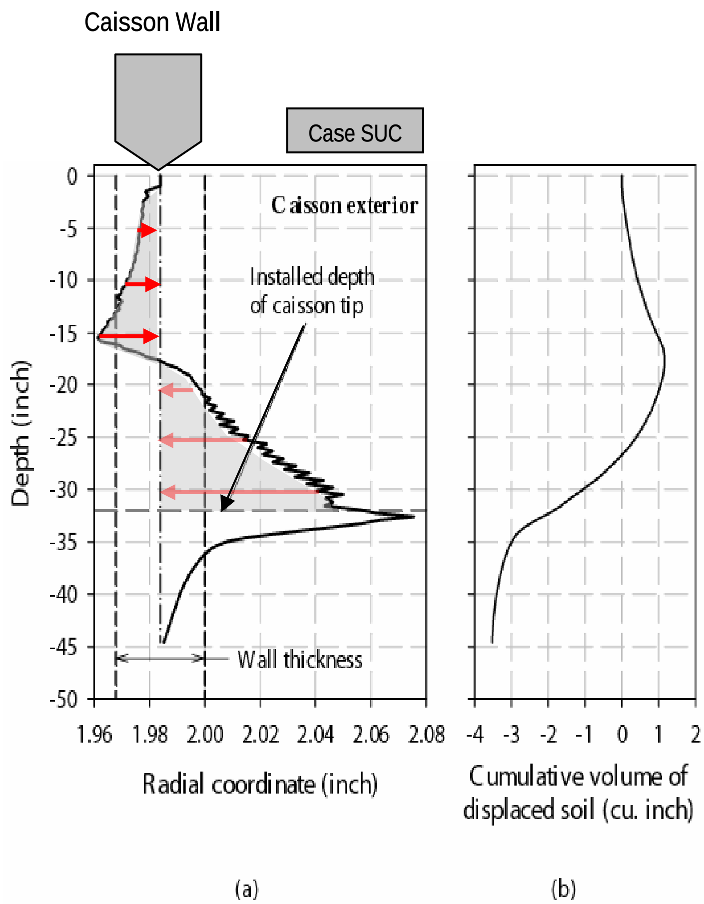

Figure 4: Suction penetration path (a) and cumulative volume of displaced soil (b).

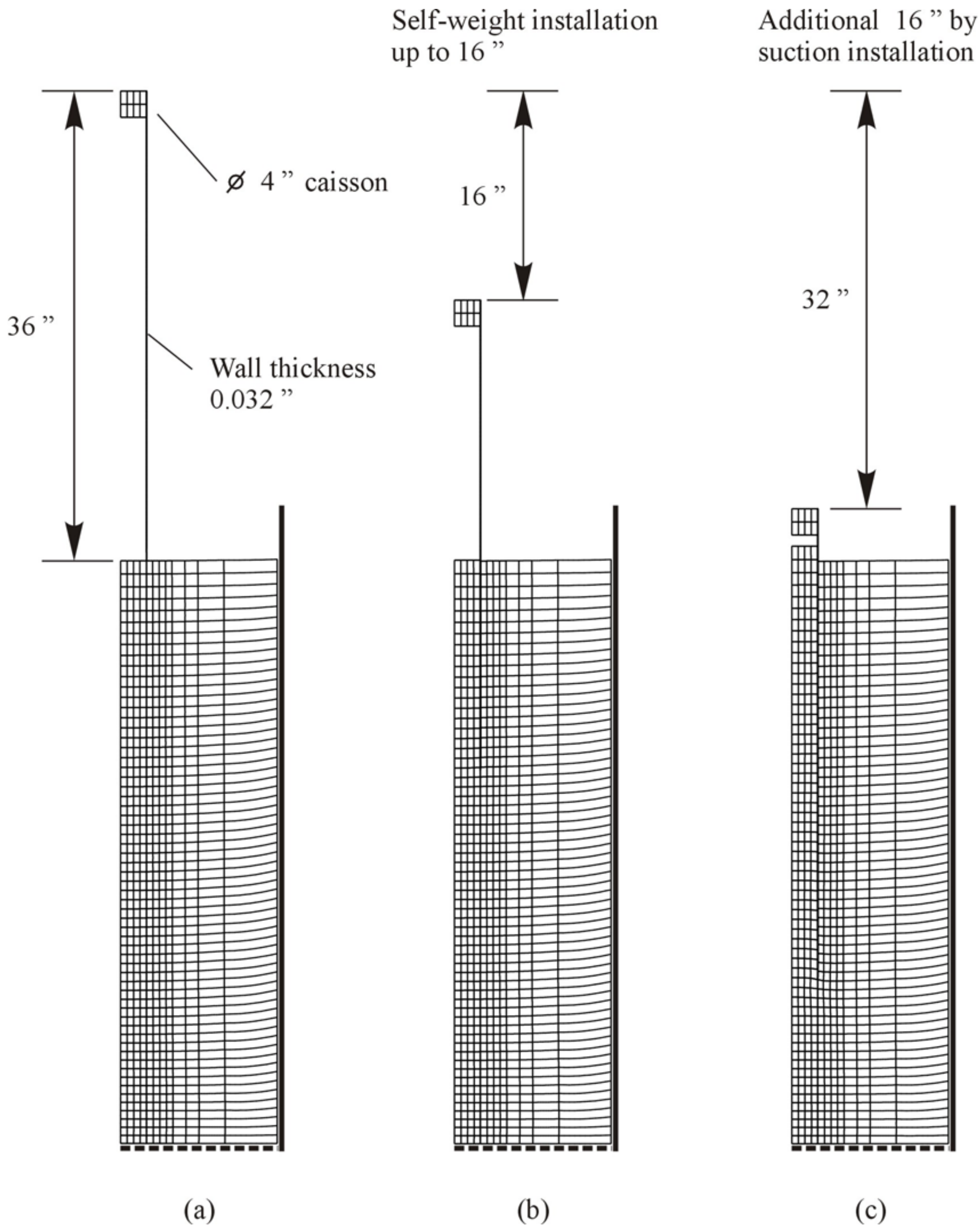

Figure 5: Suction installation: initial (a) and deformed configurations (b) (after 16-in self-weight penetration) and (c) (after penetration to 32 in by suction). Notice that the soil plug rises during this simulation.

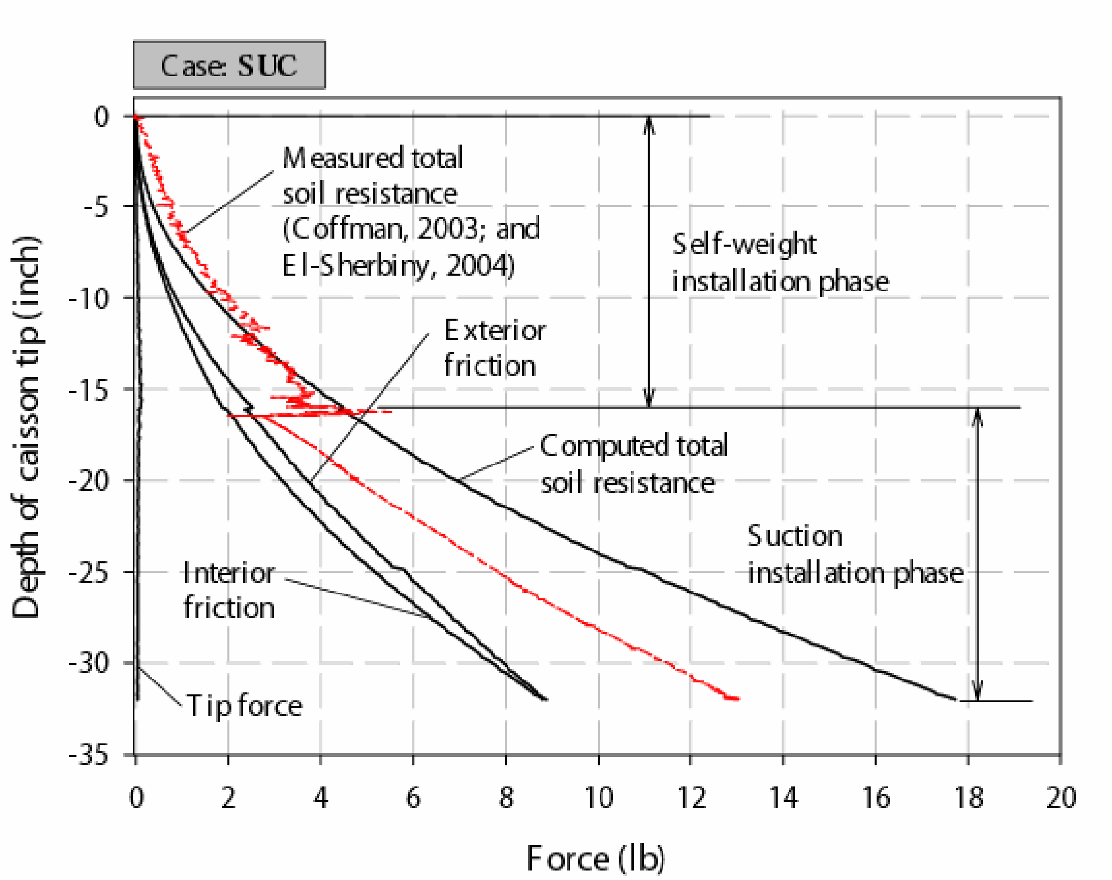

Figure 6: Computed and measured forces during suction installation.

CONCLUSIONS

A computational procedure has been developed at the Offshore Technology Research Center for the analysis of suction caisson behavior under both axial and lateral loads. The procedure has been applied successfully to laboratory tests of suction caissons. Computational results and experimental data are in good agreement. Particularly notable are the capabilities of the procedure in simulating the installation process and providing estimates of the force required and its components on the interior and exterior caisson-soil interfaces. Discrepancies between computed and measured soil resistance are likely due to differences in the state of the soil prior to installation. The uncertainty in the values of bounding-surface plasticity model parameters is also a very probable source of the deviations noted between computations and experiments. Finally, the characterization of caisson-soil interfaces on the basis of the frictional-contact algorithm adopted in our work may require modifications that better reflect the condition of the soil in the vicinity of the caisson (especially during installation).

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