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# NUMERICAL ANALYSIS OF BEARING CAPASITY OF SUCTION CAISSON

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## ABSTRACT

This paper presents a finite element modeling for determination of bearing capacity of a suction caisson subjected to vertical uplift loading. The approach looks at the uplift capacity of the caisson considering a non-uniform cross sectional area to account for a geometry optimization. For this purpose, the numerical simulation is first verified using available data from other research work especially centrifuge data. Parametric studies are then performed to investigate the role of influencing factors including taper angel. The results show that the bearing capacity of caisson increases with increasing the taper angle.

**KEY WORDS**: Suction caisson; finite element; taper angle, bearing capacity, inclined load; uplift load.

## INTRODUCTION

In recent years, suction caissons have been increasingly applied in offshore engineering in deep water. It has been common in the past to use traditional piles and had many problems in installation. Due to these difficulties, a new type of foundation, the suction caisson, has been developed and used in cases where uplift loads are present.

A suction caisson is open at the bottom and closed at the top, like an inverted top capped hollow cylinder of a fairly large diameter. It penetrates to the see floor by its own weight and then installed by active suction. As soon as there is any indication or pull out movement, the the suction caisson mobilizes significant pullout capacity through the development of negative changes of pore water pressure inside the soil plug and at the bottom of caisson, depending on the soil condition. This is known as passive suction. This passive suction

 

extremely depends on soil drainage conditions and the rate of pullout conditions [1].
The passive suction increases the bearing capacity considerably. Pervious numerical analysis reported in the literature has focused on either vertical or horizontal bearing capacity [2-4]. Interesting results from finite element analyses have also been reported [3, 5]. Such foundations have also been characterized using laboratory and centrifuge tests [6-8].
The present study concentrates on understanding more about the pull out behavior of suction caissons with non-uniform cross sectional area in cohesive soil using finite element methods.

## PROBLEM DESCRIPTION
The study reported in this paper deals specifically with the typical case illustrated in Fig .1.

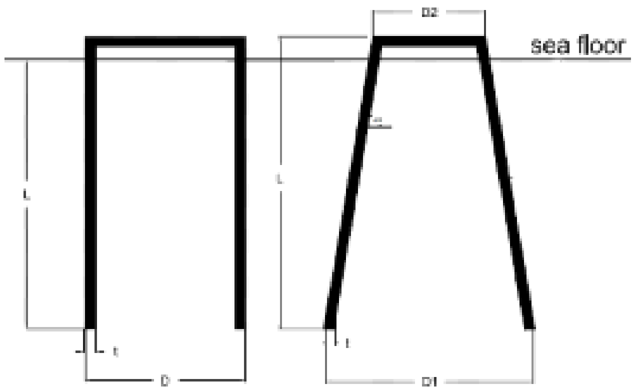


**Figure 1. Typical caissons for study**

The suction caisson is assumed to be cylindrical with an overall diameter of D, embedded length of L, and wall thickness of t, and D/t ratio greater than 80.
For tapered caissons, it is assumed to be conic sections with a diameter of $D_1$ at the top and $D_2$ at the bottom. $\alpha$ is the taper angle with respect to the vertical direction.
The uplift load (displacement controlled) is applied vertically at the top of caisson.
The caisson diameter has been taken as 5.17 m and the length is varried to give an aspect ratio, L/D, of 3.5. A wall thickness of 65 mm is used in all cases.
The caisson is embedded with out top cop flush with the surrounding see floor due to the install process. The caisson has been not completely installed in suction phase, and the soil has had a shape hill under the top of inside caisson.
This paper first initially focuses on the verification of numerically constructed modelling. For this purpose, the data obtained from centrifuge tests reported were used (Cao et al., 2001, 2002). Other data for caisson subjected to inclined load were also used [6].

## DESCRIPTION OF CENTERIFUGE TEST
This centrifuge test was carried out with a scale factor for liner dimensions of 1/100. In this test, the outside diameter of caisson was 5.17 mm and the thickness was .65 mm and thus the aspect ratio was about 3.5. Kaolin normally consolidated clay has been used for the test. The undrained strength ($S_u$) profile for clay was $S_u$=0 at the surface, increasing with depth at rate of approximately 1.14 kPa/m.
The diameter and the thickness of the tested caisson were 904 mm and 320 mm, respectively.
The caisson was carefully installed by self weight and suction. The vertically pulled out load rate of 10 mm/s was used. These dimensions of caisson and soil parameter are used for parametric study in this paper.
The clay soil parameters are presented in Table.1

## FINITE ELEMENT MODEL
For this study Abaqus/standard was used for numerical modeling of suction caisson. Abaqus is very powerfull finite element code supplies an extensive laboratory of element and can model static and transient response of two and three dimensional models. Abaqus contains a wide range of material models for simulation of most typical engineering simulations. For this study, following assumtions are used:

1) Caisson material behavior is assumed to be elastic and rigid.
2) For soil behavior, Modified- cam clay is used.
3) The rate velocity of load is taken higher for the underain condition.
4) Coupled phenomenon is assumed for 2-phase media
5) Contac elelemnts are used tofacilitate possible slip between the soil and the caisson
6) 3-D system is used to model soil-caisson system

## FINITE ELEMENT MESH AND BOUNDARIES
The symmetry assumption is used in this study. Due to symmetry, only half of the geometry is considered. The front face of mesh is shown in Fig 2.
The external faces of the mesh are located sufficiently far, so that no influence is provided for the response of the caisson and thus no constrain is assumed. As a result, zero displacement occurs at the boundaries.
The soil mass is modeled using 8-node triliner to simulate displacement and pore pressure. This reduces the integration (C3D8RP). The caisson was modeled using 8-node linear brick, reduced integration with hourglass control (C3D8R).

 

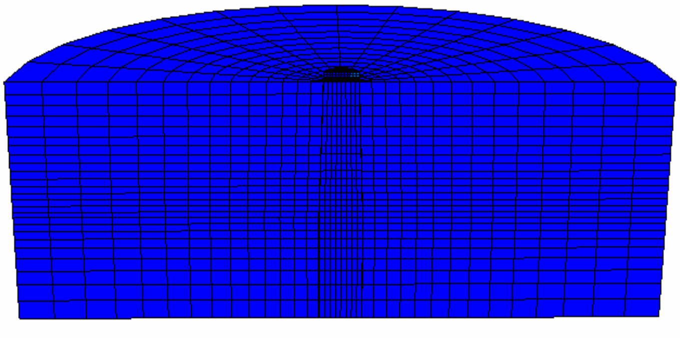

**Figure 2. Typical finite element mesh for $l/D = 3.5$**

The mesh consists of 12345 nodes, 7550 element for soil material and caisson. The total number of degrees of freedoms is typically 39634.

## SOIL MODEL

This study investigats the behavior of suction caisson in normally consolidated clay. The modified Cam-clay model is used to model the stress-strain behavior of the porous soil material. The soil is assumed to be fully saturated with the flow of the pore fluid through its voids. In addition, Darcy's low is assumed to govern.

The modified Cam-clay model variant describes a yield surface shown in Figs 3 and 4 (Hibbitt,1998).

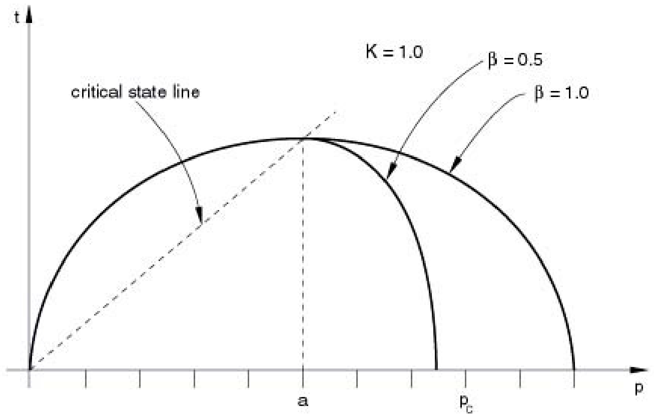


**Figure 3. Modified Cam-Clay yield surfaces in p-t plane**

The yield surface in t-p space in ellipse with Eq. (1) given by:

$$\frac{1}{\beta^2}\left(\frac{p}{a}-1\right)^2+\left(\frac{t}{Ma}\right)^2-1=0 \tag{1}$$

where p=-1/3traceσ is mean effective stress; M is slope of critical state line, t is the deviatoric stress, a is the center of yield surface in p-t plane, and β is a constant used to define the different ellipse on the wet side of the critical state line.

The deviatoric stress measure, t, is defined as Eq. (2).

$$t=q\left[1+\frac{1}{k}-\left(1-\frac{1}{k}\right)\left(\frac{r}{q}\right)^3\right] \tag{2}$$

where $q=\sqrt{\frac{2}{3}s:s}$ is the Mises equivalent stress; r is the $r=(\frac{9}{2}s:s.s)^{\frac{1}{3}}$ third invariant of the stress tensor, and k is the ratio of the flow stress in triaxial tension to the flow stress in triaxial compression. The latter determines the shape of the yield surface in $\pi$ plane.

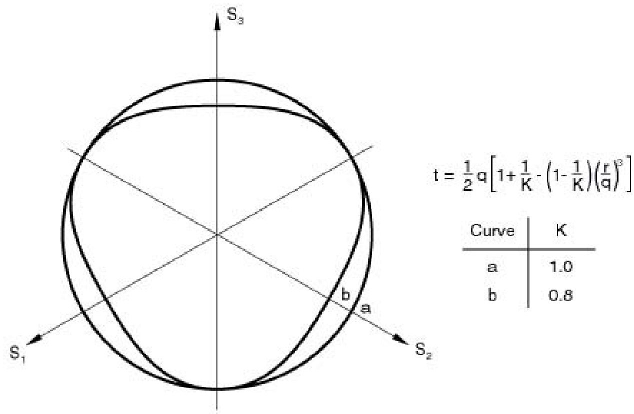


**Figure 4. Modified Cam-Clay yield surfaces section in $\beta$ plane**

The shape can be varied by changing k value. Note that ABAQUS requires that $.778 \le k \le 1.$ to ensure that the yield surface remains convex.

The modified Cam-clay yield surface has the same shape in the $\Pi$ plane as the surface of the original critical state model Fig.4 but in p-t plane, it is assumed to be made up of two elliptic arcs. For equal to "dry" side of the critical state line ($t \succ Mp$), it may be different from on the "wet" side of the critical state line $(B \neq 1)$ and introduces a different ellipse on the wet side of the critical state line.

An associated flow is used in the extended Cam clay model. The size of the yield surface is defined by parameters a given by as Eq. (3).; the evaluation of this variable therefore characterizes the hardening or softening of the material.

$$a=a_0\exp\left[(1+e_0)\frac{1-J^{pl}}{\lambda-\kappa J^{pl}}\right] \tag{3}$$

where $J^{pl}$ is the plastic part of the volume change, J.is the volume change defined as the ratio of current volume to initial volume, $J = J^{pl} + J^{e} = {(1+e)}/{1+e_0}$, $a_0$ is a constant parameter that defines the position of a at the beginning of analysis according to Eq. (4), which is the initial center of the yield surface defined as:

$$a_0 = \frac{1}{2}\exp\left(\frac{e^1 - e_0 - \kappa \ln p'}{\lambda - \kappa}\right) \tag{4}$$

where $e^1$ is the intercept of the normally consolidation line of $p' = 1\ kpa$ in Fig.5

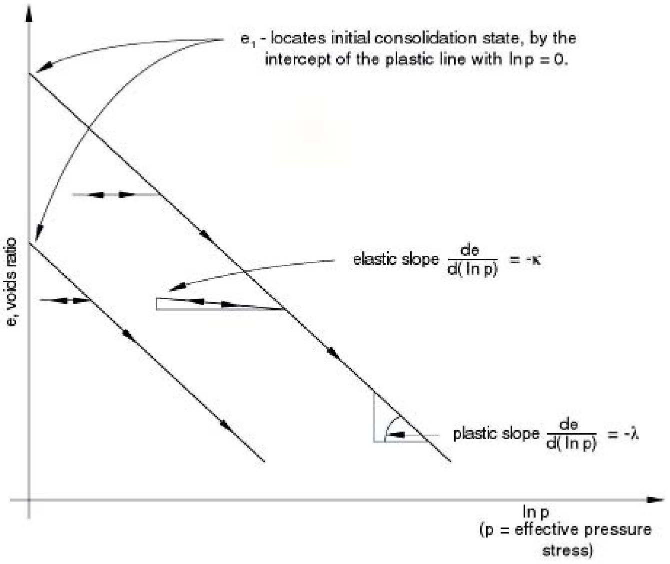


**Figure 5. pore compression behavior for clay model**

Porous elasticity model is suitable for granular materials, which show increases in bulk modulus as they are compacted. It is valid for small elastic strain (normally less than 5%) and is a nonlinear, isotropic elasticity model in which the pressure stress varies as exponential function of volumetric strain. Other parameter in modified Cam-clay in ABAQUS are $\nu$ Poisson ratio, $\kappa$ logharithmic elastic bulk modules for porous material, and $\lambda$ logharthmic hardening modules as show in Fig. 5.

Also the initial void ratio e, the initial effective stress $\sigma_v'$, and coefficient of earth pressure $k_0$ are required.

The parameter used for verification for vertical load and parametric model used in Modified Cam-clay as well as C-CORE's in-house centrifuge data. Table 1 presents a summery of the parameter used in the model [7], [8].

**Table 1. Soil parameters used for modified Cam-clay model**

| Soil parameter | Value used |
|---|---|
| Poisson' ratio, $\upsilon$ | 0.3 |
| Logarithmic elastic bulk modulus, $\kappa$ | 0.02 |
| Logarithmic hardening modulus, $\lambda$ | 0.26 |
| Critical state ratio, M | 0.9 |
| Initial overconsolidation parameter *, $a_0$ | 4.56 kpa/m |
| Wet cap parameter, $\beta$ | 1.0 |
| Third stress invariant parameter, $\kappa$ | 1.0 |
| Initial void ratio *, $e_0$ | 1.1 ≈ 1.48 |
| Coefficient of eart pressure at rest, $k_0$ | 0.64 |
| Friction coefficient at soil/caisson interface, $\mu$ | 0.28 |

(*variable with depth )

### Interface conditions

Frictional behavior between the soil and caisson is considered by adapting the classical coulomb law. Finite sliding contact surface interaction between the caisson and soil was used. Two pair of surface (slave and master) were used to simulate the interaction. A Coulomb type friction contact was used to model share stress between the pair surface Eq. (5).

$$\tau_{\max} = \mu p \tag{5}$$

where $\mu$ is friction coefficient Table 1, and p is effective normal contact pressure equivalent to horizontal effective stress as "Eq.(6).".

$$\sigma_h' = K_0 \sigma_v' \tag{6}$$

## FEM RESULT AND COMPARISON

### Validation of vertical load

For verification of the constructed numerical model for the caisson subjected to vertical load, the numerical data have been commpared with those reported from centrifuge test [7]. Fig. 6 shows this comparison. As seen, the total pullout force obtained from FEM and centrifuge test are in very good agreement. The pick of load was reached after a vertical displacement of about 1% to 1.5% of the caisson diameter with an error of 10.5%.

 

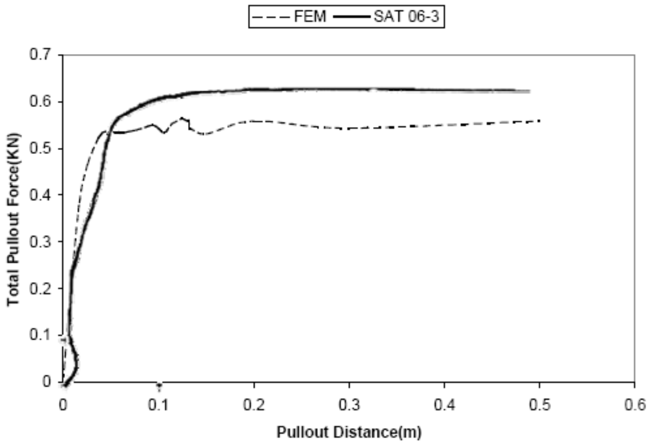


**Figure 6. Comparison of Pullout Force from FEM and and Centrifuge Test**

For further parametric study, the influence of the taper angel on the pullout resistance is investigated. For this purpose, the soil properties shown in Table 1 are used. A suction caisson with an aspect ratio of $l/D$ =3.5 and different values of 1, 2, 3 deg for the taper are considered. Figure 7 shows the load–displacement response for the caisson. The load is normilized by dividing it by a load of $p_0 = 1000\ KN$ . As seen, by increasing $\alpha$ , the ultimate load increases. For $\alpha = 3$ the load carried by the caisson increases by about 24%.
For tapered caisson, the ultimate displacement increases, too.

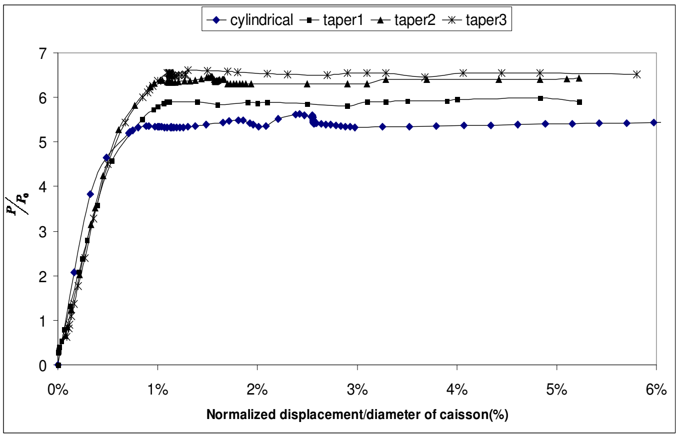


**Figure.7 Variation of Pullout Force versus displacement for caissons with different taper angles**

## CONCLUSIONS

In this paper, finite element analyses have been performed to characterise tapered caissons subjected to axial force using ABAQUS software. The data extracted from constructed numerical modeling hacve been verified using available data fro a centrifuge test, demonstrating the capability of the numerical simulation. Further parametric studies have been performed to determine the influence of the taper angel on the pullout resistance of caissons. The results have shown that the ultimate load carrying capacity by caisson increases with increasing the taper angle.For a taper angle of 3 degrees, the caisson capacity increases by about 24%. This demonstrates the usefulness of geometry modification to achieve greater capacity for caissons.

## NOMENCLATURE

| | |
|---|---|
| a | size of the yield surface is defined by the |
| D | cylindrical with an overall diameter |
| k | ratio of the flow stress in triaxial tension |
| L | embedded length |
| $p$ | is the mean effective stress |
| q | Mises equivalent stress |
| r | third invariant of the stress tensor |
| t | deviatoric stress measure |
| $L/D$ | aspect ratio |
| $a_0$ | constant parameter that defines the position of a at the beginning of analysismaterial |
| $k_0$ | coefficient of earth pressure |
| $e_0$ | Initial void ratio |
| $\alpha$ | angel of caisson body from horizontal |
| $\beta$ | a constant |
| M | critical state ratio |
| $\kappa$ | logharithmic elastic bulk modules for porous |
| $\lambda$ | logharthmic hardening modules |
| $\mu$ | Friction coefficient at soil/caisson interface |
| $\nu$ | Poisson ratio |
| $\sigma_v'$ | vertical effective stress |
| $\sigma_h$ | horizontal effective stress |
| $\tau$ | share stress |

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