Suction-installed skirted foundations, often referred to as suction caissons, are increasingly being used for a variety of offshore applications. In designing a caisson a geotechnical engineer must consider the installation process as well as the in-place performance. The purpose of this paper is to present calculation procedures for the installation of a caisson in clay. For clay sites, the caisson will often be used as an anchor, with the ratio of the skirt length (L) to the diameter (D) as high as 5. Calculation methods are presented for determining the resistance to penetration of open-ended cylindrical caisson foundations with and without the application of suction inside the caisson. Comparisons between predictions and case records are made. A companion paper describes the calculation procedure for installation in sand soils. Finally, comments are made here about installation in a variety of soils other than homogeneous deposits of clay or sand.

NOTATION

- D: caisson diameter
- f: load spread factor for vertical stress enhancement
- h: installed depth of caisson
- hws: height of water above mudline
- K: factor relating vertical stress to horizontal stress
- L: caisson skirt depth
- l: perimeter length of stiffeners within caisson
- m: multiple of diameter that vertical stress is enhanced (i.e. D_m = mD)
- Nq: bearing capacity factor (overburden)
- Nc: bearing capacity factor (cohesion)
- p_a: atmospheric pressure
- s: suction within caisson with respect to ambient seabed water pressure
- s_0: shear strength at mudline
- s_1: average shear strength over depth of skirt
- s_2: shear strength at caisson skirt tip
- t: wall thickness
- V, V': vertical load, effective vertical load
- z: vertical coordinate below mudline
- α: adhesion factor
- γ, γ': unit weight of soil, effective unit weight of soil
- γ_w: unit weight of water
- δ: interface friction angle
- ρ: rate of change of shear strength with depth

Subscripts

- i: inside caisson
- o: outside caisson

1. INTRODUCTION

A suction caisson is a large cylindrical structure, usually made of steel, open at the base and closed at the top. It might be used either as a shallow foundation or as a short stubby pile (often called a suction anchor). The shallow foundation option is more common at sandy soil sites, and the anchor/pile application is more commonly encountered in clay or layered soils.5–10 Fig. 1 shows typical diameter and skirt depths for various projects reported in the literature (the figure is taken from Byrne,11 with further data from Tjelta12). More recently there is an emerging application of caissons as the foundations for offshore wind turbines.13,14

This paper addresses installation in clays and other soils, and a companion paper15 considers installation in sand. In the anchor application the caisson will be designed so that the skirt length (L) is much greater than the diameter (D), and the ratio L/D might be as large as 5 (as shown in Fig. 1). As oil and gas exploration heads further offshore and into deeper water, it is likely that anchor applications will become more common. There are particular advantages to using the suction caisson over other anchoring methods (e.g. drag anchors), in that the caisson can be accurately located, allowing complex mooring line arrangements to be accommodated. The ability to remove a caisson (by simply reversing the installation procedure) allows alteration of mooring line arrangements over the life of a production vessel, and removal at the end of the design life.

After an initial penetration into the seabed caused by self-weight, a suction (relative to seabed water pressure) is applied within the caisson, which forces the remainder of the caisson to embed itself, leaving the top flush with the seabed. The purpose of this paper is to present design calculations for the installation of the caisson. Separate calculations are of course necessary to assess the capacity of the caisson once installed—either as a shallow foundation or as an anchor. Analyses are presented for the magnitude of the self-weight penetration, the relationship between suction and further penetration, and the
limits to penetration that can be achieved by suction. The analyses are ‘classical’ in the sense that they make simplifying assumptions, borrowing techniques from both pile design and bearing capacity theory. More rigorous analyses, using for instance finite element techniques, could be used for particular installations. The analyses presented here should, however, provide a reasonable approximation for design purposes. Similar methods (although differing in some details) to those described below have been published, but our purpose here is to draw together a comprehensive design method and compare it with case records from several sources.

2. INSTALLATION IN CLAY

Figure 2 shows the key variables in the suction caisson problem, so far as the installation is concerned. For the purposes of the installation calculation the strength of the clay is characterised by an undrained strength, which is assumed to increases with depth linearly in the form $s_u = s_{u0} + \rho z$. The methods described below can readily be adapted to more complex strength variations.

2.1. Self-weight penetration

The resistance to penetration is calculated as the sum of adhesion on the outside and inside of the caisson, and the end bearing on the annular rim. The adhesion terms are calculated, following usual practice in pile design, by applying a factor $\alpha$ to the value of the undrained strength. The end bearing is calculated, again following standard bearing capacity analyses, as the sum of an $N_q$ and an $N_c$ term. The result is

$$V = h\alpha_o s_u (\pi D_o) + h\alpha_i s_u (\pi D_i) + (y' h N_q + s_{u1} N_c) (\pi D_i)$$

end bearing on annulus

where $D_o$, $D_i$ and $D$ are the outside, inside and mean diameters respectively, $s_{u1} = s_{u0} + \rho h/2$ is the average undrained shear strength between mudline and depth $h$, $s_{u2} = s_{u0} + \rho h$ is the undrained shear strength at depth $h$, $\alpha_o$ and $\alpha_i$ are adhesion factors on the outside and inside of the caisson (as used in undrained pile design), and $N_c$ is an appropriate bearing capacity factor for a deep strip footing in clay (typically a value of about 9 might be adopted). For undrained analysis $N_q = 1$. 

![Fig. 1. Summary of uses of caisson foundations (from Byrne with further data from Tjelta)](image1)

![Fig. 2. Outline of suction caisson](image2)
2.2. Suction-assisted penetration

Once the self-weight penetration phase has been completed, so that a seal is formed around the edge of the caisson, it will be possible to commence the suction installation phase. The applied suction in the caisson is s relative to seabed water pressure: that is, the absolute pressure inside the caisson is \( p_s + \gamma_s h_w - s \), where \( h_w \) is the water depth. There are a number of practical limits to the maximum attainable value of \( s \). Among these are:

(a) the absolute pressure at which the water cavitates (usually a small fraction of atmospheric pressure)
(b) the minimum absolute pressure that can be achieved by the given pump design
(c) the minimum relative pressure that can be achieved by the pump.

The suction causes a pressure differential across the top plate of the caisson, which results effectively in an additional vertical load equal to the suction times the plan area of the caisson. The capacity is again calculated as the sum of the external and internal friction, and end bearing term. Note that the overburden term is reduced in the end bearing calculation by the suction pressure, assuming that the flow of soil under the rim occurs entirely inwards. The result is

\[
V' + s \left( \frac{\pi D_t^2}{4} \right) = \kappa a_s s_{u1}(\pi D_t) + \kappa a_s s_{u1}(\pi D_t) + (\gamma h - s + s_{u2}N_c)(\pi D_t)
\]

which is readily rearranged to

\[
V' + s \left( \frac{\pi D_t^2}{4} \right) = \kappa a_s s_{u1}(\pi D_t) + \kappa a_s s_{u1}(\pi D_t) + (\gamma h + s_{u2}N_c)(\pi D_t)
\]

Note that if the variation of soil strength is not simply linear, all that is necessary is to replace \( s_{u1} \) with the average strength from mudline to depth \( h \), and \( s_{u2} \) with the strength at depth \( h \). Equation (2) gives a simple relationship between suction and depth. For constant \( V' \) and a linear increase of strength with depth (so that \( s_{u1} \) and \( s_{u2} \) are linear functions of \( h \)), \( s \) is a quadratic function of \( h \).

2.3. Limits to suction-assisted penetration

In addition to the limit imposed by the maximum available suction, there is a limit to the depth of penetration that can be achieved by the action of suction. If the difference between the vertical stress inside and outside the caisson, at the level of the caisson tip, exceeds a certain amount, then local plastic failure may occur, and further penetration may not be possible. The mechanism may be thought of as a 'reverse' bearing capacity problem, in which the soil flows into the caisson.

The average vertical stress (relative to local hydrostatic) inside the caisson at tip level is relatively straightforward to estimate as

\[
-s + \gamma' h + \frac{\pi D_t \kappa a_s s_{u1}}{\pi D_t^4/4}
\]

The third term in this expression arises from the downward friction inside the caisson, and here it is assumed (for simplicity) that this results in a uniform increase of vertical stress at all radii in the caisson. Note that the assumption of a uniform increase in vertical stress within the caisson is clearly unreasonable at small values of \( h/D \), but it will be seen below that this calculation is only needed at \( h/D \) values greater than about 2, for which the uniform increase may be a reasonable approximation.

The relevant stress outside the caisson is much harder to estimate, as the downward load from adhesion on the outside of the caisson will enhance the stress in the vicinity of the caisson, but this enhancement is difficult to calculate. However, we make the simplifying assumption that the downward load from the adhesion is carried by a constant stress over an annulus with inner and outer diameters \( D_a \) and \( D_m \), although the latter cannot be determined with any certainty. The enhanced stress (again relative to local hydrostatic) may be calculated as

\[
\gamma' h + \frac{\pi D_t \kappa a_s s_{u1}}{\pi (D_m^2 - D_a^2)/4} = \gamma' h
\]

Thus the 'reverse bearing capacity' failure would occur when

\[
-s + \gamma' h + \frac{\pi D_t \kappa a_s s_{u1}}{\pi (D_m^2 - D_a^2)/4} = \gamma' h - \frac{\pi D_t \kappa a_s s_{u1}}{\pi (D_m^2 - D_a^2)/4} - N^* s_{u2}
\]

where \( N^* \) is a bearing capacity factor appropriate for uplift of a buried circular footing. Substituting the solution for \( s \) into equation (2) and simplifying gives

\[
V' + N^* s_{u2} \frac{\pi D_t^2}{4} = \kappa a_s s_{u1}(\pi D_t) \left( 1 + \frac{D_t^2}{D_m^2 - D_a^2} \right) + (\gamma' h + s_{u2}N_c)(\pi D_t)
\]

which can be solved for \( h \). Note, however, that although the above equation appears linear in \( h \), in fact \( s_{u1} \) and \( s_{u2} \) are themselves linear functions of \( h \), so that the solution again involves solving a quadratic. Furthermore it would be rational to assume that \( D_m \) increases with penetration, for instance in the form \( D_m - D_a = 2f_s h \), where \( f_s \) is a constant ‘loadspsread’ factor, and this is the procedure we recommend. A further development would be to allow the enhancement of the stress to vary (say linearly) from zero at \( D_m \) to a maximum at the caisson surface \( (D_t) \).

It is worth, however, considering some approximate solutions for the maximum penetration. For many cases the final term

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(the end bearing) is small. We consider also the case where the applied load \( V \) is small, and make the approximation \( D_i \approx D \). If we write \( D_m = mD \) (so that \( m = 1 + 2f \varepsilon h/D \) if we use the procedure recommended above), then equation (7) leads to the following result for this simplified case:

\[
\frac{h}{D} \approx \frac{N_u}{4\alpha_c s_{u2}} \left( 1 - \frac{1}{m^2} \right)
\]

The factor \( N_u/4\alpha_c s_{u2} \) is likely to be in the region of about 4, although it could vary considerably, as it varies from about 3 to 7. The factor \( s_{u2}/s_{u1} \) would be 1-0 for a homogeneous soil, and 2-0 for the extreme of a soil with a strength increasing linearly with depth from a value of zero at the surface. The final factor varies from 1-0 if \( m \) is assumed to be very large, to 0-75 if say \( m = 2 \). The overall result is that the calculated maximum attainable value of \( h/D \) is likely to be from about 3 for stiff clays (with strengths approximately uniform with depth) to 6 for soft normally consolidated clays (with strengths approximately proportional to depth), although with some considerable variability depending on the \( N_u/4\alpha_c \) value. The effect of accounting for the external load \( V \) would be to increase these values. Equation (8), however, provides a useful estimate of the maximum \( h/D \) ratio of a suction-installed caisson that could be reliably installed in clay. If different assumptions are made about the way the external adhesion enhances the vertical stress, the same broad conclusions arise, although the precise figures will vary.

It should be noted that some measured values of installations indicated that higher \( h/D \) ratios than implied by the above calculation may be achievable. The above may therefore be treated as a conservative calculation.

Note also that the end bearing calculation in equations (1) and (2) does not take into account any enhancement of the stress level inside or outside the caisson due to the frictional terms. This follows conventional piling design calculations, in which no such correction is usually included. If this effect was to be taken into account, the factor \( \gamma' h \) in equation (1) would be replaced by whichever is the smaller of

\[
\gamma' h + \frac{\pi D_i h \alpha_c s_{u1}}{\pi (D_m^2 - D_i^2)} / 4
\]

or

\[
\gamma' h + \frac{\pi D_i h \alpha_c s_{u1}}{\pi D_i^2} / 4
\]

(almost invariably the former). Once suction is started, \( \gamma' h - s \) in equation (2) is replaced by the smaller of

\[
\gamma' h - s + \frac{\pi D_i h \alpha_c s_{u1}}{\pi (D_m^2 - D_i^2)} / 4
\]

or

\[
\gamma' h - s + \frac{\pi D_i h \alpha_c s_{u1}}{\pi D_i^2} / 4
\]

(usually the latter except at very small suction). In practice these changes make very small differences to the calculation.

2.4. The effect of internal stiffeners

Most suction caissons include some internal structure, usually consisting of either vertical plates or annular plates, to provide strength and stiffness to the cylindrical shell, either to suppress buckling during suction-assisted penetration, or (in the case of a caisson anchor) to reinforce the caisson at the pad-eye connection. The analysis for the case of annular stiffeners is not considered here, but the use of vertical stiffeners results in only a small change in the calculation.

In principle, stiffeners could be located on the outside of the caisson, but this option does not usually seem to be adopted. The additional resistance offered by the stiffeners can be taken into account by an adhesion term of the form \( h \alpha_c s_{u2} \), where \( i \) is the perimeter length of the stiffeners (usually approximately twice the plate length for thin plate stiffeners), and an end bearing term of the form \( \gamma' h + s_{u2} \alpha C(A) \), where \( A \) is the end area of the stiffeners. The area on which the suction acts (on the left side of equation (2)) should also be reduced by \( A \), although this correction will usually be tiny.

Note that if the stiffeners do not extend the full depth of the caisson, appropriate corrections are required for the value of \( h \) used in the contribution from the stiffeners, and in the appropriate \( s_{u1} \) and \( s_{u2} \) values.

In the calculation of the maximum attainable depth using suction, note that the terms involving adhesion on the inside of the caisson cancel, and have no overall effect on the calculation. The same is true for terms resulting from the resistance from internal (but not external) stiffeners, so for internal stiffeners only equation (8) can still be used.

Example 1. Consider a suction caisson of outside diameter 12 m, wall thickness 45 mm and depth 5 m. Such a caisson might be considered as a foundation for an offshore structure. The caisson is stiffened by 30 plates 25 mm thick and 200 mm deep welded as radial fins on the inside of the caisson, and extending for the top 4 m of the caisson only. The soil profile is idealised as a layer 2 m thick of constant strength 20 kPa, with below that a linear increase of strength from 25 kPa at the surface to 30 kPa at 2 m at a rate 2-5 kPa/m. The buoyant unit weight is taken as 6 kN/m³. The end bearing factor \( N_i \) is taken as 9, and the adhesion factor \( \alpha \) as 0-6 for the outside of the caisson and 0-5 for inside and for the stiffeners. The maximum applied vertical load (including the weight of the caisson and buoyancy effects) is 1000 kN, and the water depth is 50 m.

The calculations described above have been implemented in a spreadsheet-based program SCIP (Suction Caisson Installation Prediction). Fig. 3 shows the calculated loads required to install the caisson in the absence of suction. Fig. 4 shows the predictions from the spreadsheet program of the variation of suction with depth required for installation, and in this case the maximum suction required is 49 kPa.
suction pressure required is 143.9 kPa. An adhesion factor of weight penetration amounts to 41 mm, and the maximum investigate plug failure during installation of suction caissons consolidated clay. The experiments were carried out at 120 tests on the centrifuge at the University of Western Australia, investigating the installation of suction caissons in normally consolidated clay. They investigated three caissons in normally consolidated clay. They investigated three caissons with diameters 10.4 mm, 15.9 mm and 37.2 mm. All caissons had a wall thickness of 0.4 mm and an L/D ratio of 8.

In Fig. 7 a comparison is made between calculated and measured suction pressures required to install the 15.9 mm diameter caisson. The soil strength profile was estimated by House et al.\textsuperscript{17} to be 75 kPa/m and the effective unit weight to be 5.9 kN/m\textsuperscript{2}. The caissons were initially pushed into the clay to a penetration of approximately one diameter before the

**Example 3: Prediction of plug failure.** A series of tests were conducted by House et al.\textsuperscript{15} on the laboratory floor to investigate plug failure during installation of suction caissons in normally consolidated clay. The experiments were carried out at 120g. The strength profile of the clay could be idealised as zero at the surface, increasing with depth at a gradient of 144 kPa/m to a depth of 67 mm and then at 204 kPa/m (at prototype scale these represent rates of increase of 1.2 kPa/m and 1.7 kPa/m). The effective unit weight of the soil (accounting for the 120g acceleration) was determined to be 792 kN/m\textsuperscript{3}. The dimensions of the caisson were 30 mm diameter, 0-5 mm wall thickness and 120 mm skirt length (equivalent prototype dimensions 3-6 m diameter, 60 mm wall thickness, 14-4 m skirt length). An effective vertical load of 15-3 N was applied to the caisson.

Figure 5 shows the penetration resistance for the caisson without the use of suction, showing that most of the resistance is in the skirt friction. Fig. 6 shows an estimated suction penetration curve, which shows good agreement with the experimental data reported by House and Randolph.\textsuperscript{18} The self-weight penetration amounts to 41 mm, and the maximum suction pressure required is 143.9 kPa. An adhesion factor of 0-5 was used for both internal and external walls.

**Example 2: Predicted installation pressures compared with centrifuge tests.** House and Randolph\textsuperscript{18} conducted a series of tests on the centrifuge at the University of Western Australia, investigating the installation of suction caissons in normally consolidated clay. The experiments were carried out at 120g. The strength profile of the clay could be idealised as zero at the surface, increasing with depth at a gradient of 144 kPa/m to a depth of 67 mm and then at 204 kPa/m (at prototype scale these represent rates of increase of 1.2 kPa/m and 1.7 kPa/m). The effective unit weight of the soil (accounting for the 120g acceleration) was determined to be 792 kN/m\textsuperscript{3}. The dimensions of the caisson were 30 mm diameter, 0-5 mm wall thickness and 120 mm skirt length (equivalent prototype dimensions 3-6 m diameter, 60 mm wall thickness, 14-4 m skirt length). An effective vertical load of 15-3 N was applied to the caisson.

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suction was applied. Assuming a circular end bearing capacity factor of 8-5, the maximum penetration calculated by the spreadsheet program that is possible before a plug failure is expected is 83 mm or h/D = 5-2. This can be compared with conclusions drawn by House et al. They compare the volume of water withdrawn from the caisson cavity during installation with the displaced volume within the caisson (assuming heave has not occurred). When more water is evaporated than can be accounted for by the installed portion of the caisson, they infer that plug heave has occurred. Fig. 8 shows, for two installations of the 15-9 mm diameter caisson, the excess volume of water removed, plotted against normalised penetration. For the cases shown, House et al. deduced that plug failure occurs at an L/D ratio between 4 and 5, which agrees with the prediction given above. Again an adhesion factor of 0-5 was used. Note that although plug failure occurred it was still possible to install the caisson further. Installation continues until all water has been withdrawn from the internal cavity. The consequence of plug failure is that the caisson cannot be installed to its full design depth.

**Example 4: Nkossa Field installation.** This calculation involves some modification to the basic procedures described above to account for the geometry of the caissons used in the Nkossa Field off the coast of West Africa. Two different anchor sizes were used, depending on the loading conditions. We shall consider only the installation of the smaller of the two, defined by Colliat et al. as a Type I anchor. The geometry of the caissons is unusual, as they have a step change in diameter part way down the caisson. The bottom section is 4 m in diameter and extends for 4-0 m, whereas the top section is 4-5 m in diameter and is 7-5 m long. The anchor chain lug is located at the change in caisson diameter. The wall thickness for the pipe sections was 15 mm and the design penetration was 11-8 m. The larger top section was to accommodate any soil heave that occurred during installation. Internal stiffening plates are also believed to have been used. However, these are omitted in the calculation here, as there is insufficient information about the detailed geometry of the stiffeners. The weight (in air) of the caisson is given as ‘41 tons’, which converts to a submerged weight of approximately 350 kN.

Colliat et al. give a summary of the soil conditions, which includes average shear strengths as well as upper- and lower-bound strength envelopes. For the purpose of this calculation the average strength is taken and is 5 kPa at the surface, increasing at 1-0 kPa/m for the first 5 m, below which the gradient changes to 1-67 kPa/m. The effective unit weight of the soil is taken as 6 kN/m³. Colliat et al. suggest an adhesion factor of 0-3 based on model scale field tests, but the calculations here show an excellent agreement with the measurements if an adhesion factor of 0-45 (which seems quite reasonable) is used. To account for the effect of the increase in diameter of the top section of the caisson, the internal adhesion factor was set to zero for the top section. End bearing is also taken into account at the step between the two diameters. Fig. 9 shows the suction pressures required compared with the average and range measured during the field installation (on the basis of data presented by Colliat et al.). The slight underestimation of the required suction may be because the stiffeners are not taken into account.

In the three example calculations where it is possible to compare with data, it is clear that a good relation exists between predicted and observed behaviour, using reasonable estimates of soil parameters. Obviously the key parameter that is required for predictions of caissons in clay is the undrained strength profile, and an estimation of the adhesion factor $\alpha$. The $\alpha$ factor is often estimated as $1/S_t$, where $S_t$ is the sensitivity, on the basis that the material immediately adjacent to the caisson becomes fully remoulded. This would suggest of course quite low factors in some clays. We have found above, though, that a factor in the region of 0-5 provided a satisfactory comparison with the case histories we examined.

### 3. INSTALLATION IN OTHER MATERIALS

We include here some comments on possible installation of suction caissons in other materials, as clearly conditions encountered in the field will often be more complex than those we have so far addressed. The comments below are, however, to a certain extent speculative because of the paucity of hard data in these areas.

#### 3.1. Layered materials

Figure 1 shows that a number of installations have occurred in layered materials. We describe briefly the issues that must be considered during the design for these sites.

**3.1.1. Sand over clay.** The sequence of sand over clay probably would not cause problems for installation: typically...
the installation would proceed through the sand (using the calculations given by Houlsby and Byrne\(^{11}\)), and once into the clay the resistance would in most cases be lower, and could be calculated using the same principles as for clay alone (although with a modification to the calculation of the friction).

3.1.2. Clay over sand. Clay over sand is likely to be more problematical. The caisson penetrates through sand when the applied suction creates gradients in the sand, which degrades the tip resistance to almost zero. The pressure differential also provides a net downward force on the caisson, but this contributes less significantly to the installation. Without the flow field in the soil it might be impossible to install the caisson, owing to the high bearing resistance of the sand (especially if it is very dense). During installation in clay it is the net downward force caused by the pressure differential that causes the caisson to be forced into the soil. When the installation occurs in a layered soil there are questions as to whether the caisson will penetrate through a sand layer after it has passed through a clay layer, as it will not be possible to develop the flow regime that degrades the skirt tip resistance to near zero.

There are several field case studies that provide evidence that installation under these conditions may, however, still be possible. The most notable is the large-scale deepwater penetration test that was conducted during the investigations for the Gullfaks C platform.\(^{20}\) The soil profile consists of a number of layers of medium to dense sand and clay. The cone tip resistances reach 20–24 MPa in the denser sand layers, 4–10 MPa in the medium sand layers and 1–2 MPa in the clay layers. The foundation consists of two 6.5 m diameter cylinders joined by a concrete beam, the structure being 22 m in depth. A maximum suction of about 480 kPa (linearly increasing with depth) was required to install the caisson to its full depth. A water jetting system at the caisson tip was used during the penetration of the initial sand layer, thus reducing the tip resistance. Removal was also possible, requiring approximately 250 kPa of overpressure (linearly decreasing) at the maximum depth.

Further references to suction anchor installation in layered material can be found in Senpere and Auvergne\(^{11}\) and Tjelta.\(^{12}\) The former describe the installation in the Gorm field, where soil plug failure occurred in all caissons. The installation was nonetheless successful as a jetting procedure was used to remove material from within the caisson. Tjelta describes issues related to the Curlew, YME and Harding fields but does not give specific details.

3.1.3. Finely interbedded materials. There is no particular reason to suppose that finely interbedded materials would pose problems, unless the composition of the beds differed in some extreme way. There are, however, no recorded cases in such materials.

3.2. Stiff (possibly fissured) clay

There is a concern that it might not be possible to install suction caissons in stiff clays. The principal reason is that, given that such materials are often fissured, or are prone to fissuring, it may not be possible to form the necessary seal around the rim of the caisson for penetration to proceed. One possibility is that fracturing may occur, with water simply flowing through the fissures. This problem may be exacerbated by the fact that the penetration resistance in very stiff clays would be high.

Information for this case is relatively scarce. In most cases where stiff clays have been encountered (i.e. in the Visund, Njord and Aquila fields as discussed by Solhjell et al.\(^{8}\)) the soil conditions consisted of a layer of soft clay overlying much stiffer clay. In these cases it appears that the soft clay layer is deep enough for a seal to be created.

Although there is no evidence to support whether or not installation in stiff fissured clay is possible or not, it should be noted that the condition where a stiff clay exists at mudline might be a rather scarce occurrence.

3.3. Coarse materials

For obvious reasons, extremely heterogeneous materials would be likely to cause problems for installation of a suction caisson. Materials with a significant fraction of coarse gravel or larger sizes would almost certainly present an obstacle to installation. Certain (but not all) glacial tills would therefore be problematical. Very open gravels, even if not particularly coarse, would present problems in that flows during pumping would be very high.

3.4. Silts

It is difficult to do calculations for silts, because it is difficult to determine whether drained and undrained behaviour would be appropriate, and partially drained calculations for caisson penetration have not been formulated. However, given that penetration in clays and sands is relatively straightforward, it would be expected that reasonably homogeneous silts would not pose difficulties.

3.5. Carbonate soils

Erbrich and Hefer\(^{10}\) present the case history of the installation of suction anchors at the Laminaria site in the Timor Sea. Although the installation of the nine anchors was successful, the suction pressures measured were significantly lower than those predicted in the original design calculations. Erbrich and Hefer\(^{10}\) report very low values for the adhesion factor (of the order of 0.1–0.2) that arise from the back-analysis of the field data. It is clear that for extremely fine-grained carbonate soils (as at the Laminaria case) the clay calculation is appropriate, whereas for the coarser materials the sand calculation is appropriate. Because of the crushability of carbonate materials, very low values of \(\tan \phi\) would probably be appropriate in the friction calculation.

3.6. Rocks

It is unlikely that suction caissons could be installed into any but the very softest of ‘rocks’.

3.7. Special conditions

The influence of special conditions (e.g. shallow gas deposits within the depth of the caisson, or organic material) is almost unknown, and would have to be dealt with on an ad hoc basis.

4. PUMPING REQUIREMENTS

The flow capacity of pumps for installation in clay needs only to be that necessary (with a suitable margin) to remove the water from the caisson as penetration proceeds: that is,
where \( F \) is a dimensionless factor that depends on \( h/D \) and \( k \) is the sand permeability.  

5. CONCLUSIONS

In this paper we present the calculation procedures that are required for suction caisson installation in clay. Calculations include those for self-weight penetration, penetration under suction, and the limits to the suction-assisted penetration. The calculation procedures are compared with case records, showing good agreement with the measured responses. The paper concludes with discussion of potential issues when installing suction caissons in a variety of other soils.

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