International Journal of GEOMATE, July, 2018 Vol.15, Issue 47, pp.14-21
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2018.47.3695
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

INSTALLATION CONSTRAINTS OF SUCTION ASSISTED FOUNDATIONS AND ANCHORS FOR OFFSHORE ENERGY DEVELOPMENT

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*Kingsley Osezua Akeme, Received: 30 May. 2017, Revised: 27 Jul. 2017, Accepted: 14 Aug. 2017

ABSTRACT: The application of suction caissons has increased over the last two decades for offshore energy developments. Their installation challenges in different seabed types affect their execution process and load-bearing capacity. Hence, the identification of these challenges and understanding their root causes are highly important. As such, this paper aims to review the recorded installation constraints due to different seabed conditions, discuss the various factors related to each of these constraints, and finally provide some suggestions to rectify each constraint and/or its relevant factors. To do so, the approach is to evaluate the geological (geophysical and geotechnical) conditions in multiple case studies and analyze the stability of suction caisson installation in different soil types. Results show that some factors such as plug heave contributes about 29% of the installation issues in both homogeneous clay soils and layered clay soils, soil piping and bottom resistance failure contribute about 16% and 10% respectively of the installation issues in both sand and layered sand soils, while high penetration resistance contributes about 23% of installation issues in layered soils. Also, the uncertainty of soil parameters or behavior is a complementary factor which adds more complexities to the above-mentioned factors. Therefore, a good understanding of the seabed conditions and soil parameters before and during installation, as well as constant monitoring of the induced suction created during penetration with respect to the penetration depth is essential to mitigate the likely issues.

Keywords: Suction, Plug Heave, Soil Piping, Penetration Resistance, Bottom Resistance Failure.

1. INTRODUCTION

1.1 Definition

Suction-assisted caissons have been defined as large cylindrical steel structures with large diameter opened at the base and closed by a lid at the top. The top contains a “valve controlled vent” which allows the escape of water from the caisson during installation [1], [2], [3]. However, in more detail, they are defined as foundation structures that are installed because of a differential pressure created within the caisson compartment through the application of a pump attached to the caisson top which reduces the internal pressure within the caisson compartment as shown in Fig 1.

Suction caissons are classified into two categories based on their application and function. By application, they are classified as *(1)* Compression caisson foundations when they are used in shallow water applications as the foundation supports, and as *(2)* Suction anchors when they are used in deep water applications as mooring and anchoring support [4], [5].

In terms of their function, they are classified either as *(1)* an integrated foundation structure when they are attached to the base of a foundation structure e.g the Gullfak C platform, or as *(2)* a standalone structure when used for mooring and anchorage support [6]. Some examples of other suction assisted foundation and anchors include a suction anchor, suction pile, bucket foundation, skirted foundation and skirt piles etc.

Fig 1 A Cluster of suction anchors adapted from [6]

1.2 Installation Procedure

In general, suction assisted foundations and anchors have the same installation principle in which a suction-induced force is required for their penetration into the seabed. Also, their installation process occurs in two stages. *In the first stage,* they penetrate the seabed by their self-weight. As the process occurs, the water displaced inside the caisson is evacuated through an open vent. The velocity of water that can be discharged through the open vent with respect to the overpressure within the suction caisson is given by the following equation:

When an Orifice is used

$$V=C\sqrt{\frac{2P}{\rho_{S\omega}}} \quad (1)$$

When a piping system (valve) is used

$$V=\sqrt{\frac{2P}{\rho_{S\omega}\ \Sigma K_i}} \quad (2)$$

Where V= steady velocity of water flow, C= Coefficient of discharge (C=0.61 for sharp-edged orifice surface and C= for sharp-edged orifice surface with short tube), P= overpressure in the suction caisson, $\rho_{S\omega}$= sea water density, and K_i = Resistance coefficient for the piping system ($\sum K_i$= 1.7 - 1.8 for a 2 ft or 3 ft diameter butterfly valve system).

However, suction caisson would stop penetrating under its own weight when the soil resistance, including external and internal frictional resistances and tip resistance, is equal to the weight of the suction caisson [7].

An important phenomenon in this stage is the formation of a *seal* between the seabed surface and the caisson. The importance of the seal is to prevent the formation of *localized piping and loss of suction* during penetration. It is thus important that the seal formed must be sufficient to guarantee suction assisted penetration. However, if an insufficient seal is formed this would result in the failure of the entire installation process [4], [8].

The second stage consists of the later part of the penetration process of arriving at the design depth. This is achieved by the application of an additional installation force which is provided in the form of an under pressure or suction created by pumping water out of the caisson through a "submersible pump" attached to the top of the caisson as shown in Fig 2 [4], [8], [9]. The suction generated, is the total pressure difference between the caisson internal vacuum pressure and the external hydrostatic pressure. If the pressure difference created is relatively higher than the external hydrostatic pressure, the suction caissons may *buckle* during installation. Also, an excessive under pressure or suction created within the caisson compartment could result in the upward movement of the internal soil within the caisson which could lead to *plugging failure*. Therefore, the amount of suction available for penetration ranges from a minimum value when the caisson internal pressure is at zero absolute pressure to a maximum value *(allowable suction)* which corresponds to the point where the water within the caisson begins to vaporize. This maximum value is equal to sum of the atmospheric pressure and hydrostatic pressure outside the caisson. Once the design depth has been reached, the valve at the top is closed and a passive suction is generated within the caisson. This passive suction increases the holding capacity (pull- out resistance) of the caisson by engaging negative pore pressure from the soil plug inside and at the bottom of the caisson [4], [8], [10], [11].

Generally, the allowable suction for caisson penetration before plug failure (Reverse end bearing failure) occurs can be calculated using the following equation:

$$P_{all} = F_{in} / A_{in} + Q_u / (A_{in}\ \mathrm{FS}) \quad (3)$$

Where P_{all} = allowable suction, F_{in} = internal caisson wall frictional resistance, A_{in} = Caisson internal crossectional area, Q_u = reverse end bearing over the all soil plug area at the caisson tip, FS = factor of safety [7].

Once the suction assisted foundation has been installed, a setup time is allowed to enable the surrounding soil to regain some of its strength lost during installation before any load attachment is done. During this period, the caisson remains unloaded. Set up time is mostly observed during mooring application [5].

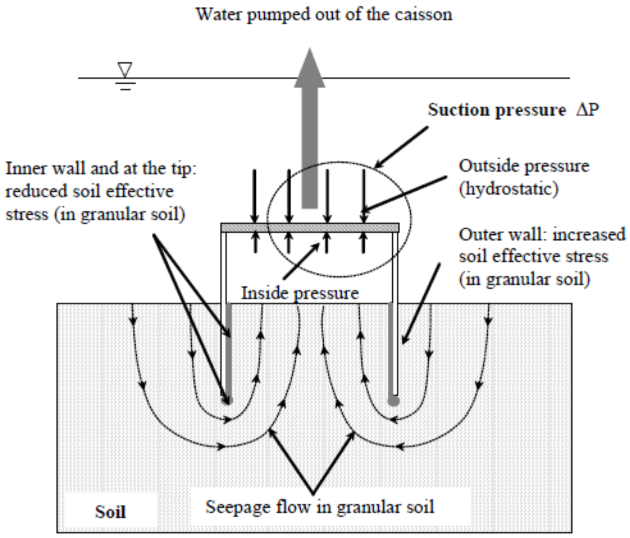

Fig 2 Suction installation process adapted from [6]

METHODOLOGY

The approach adopted in achieving the objectives of this paper is carried out in two parts. The *first part* is a review of the geological (geotechnical and geophysical) survey conducted before and during installation as well as the stability assessment of suction caisson during installation. While the *second part* is a comparative analysis of the installation issues of suction-assisted foundations and anchors obtained from literature reviews and over 50 case study field reports.

2.1 Geological Properties of Soil That Affects the Installation of Suction Caissons

Prior to the installation of suction caissons, a proper site investigation is conducted to select the right location for installation and to establish the geotechnical installation parameters needed for a successful installation campaign. To this end, a geotechnical survey involving in-situ and laboratory tests are conducted to obtain information about the soil properties such as soil index properties, in-situ stresses and stress history, the soil shear strength profile (undrained and undrained conditions) etc.

The following geotechnical soil attributes below are considered very important during the installation of suction caissons at the design stage to accurately predict the likely installation issues that may be encountered during installation. These soil attributes are:

2.1.1 Set up/consolidation effects

This is a phenomenon due to the timely dissipation of excess pore water from the soil particles which results in an increase in the soil effective stress. The time of soil consolidation, need to be accurately predicted and monitored during installation to understand the soil strength conditions during penetration to regulate the rate at which suction is applied to avoid a *punch through* or *plug failure* during installation. For example, the soil strength gained during self-weight penetration takes much longer time than the soil strength gained during suction assisted penetration for different soil types. Also, the rate of soil strengths gained by soil particles outside the caisson wall is faster when compared to the soil strength gained by soil particles inside the caisson wall due to the differences in their drainage paths [8], [12].

2.1.2 Soil permeability profile

The permeability of the subsurface soil and drainage paths determines the magnitude of suction the caisson can accommodate and sustain. The more permeable the soil is, the faster the loss of suction under sustained tension loads. The permeability of the soil is very important especially in the sand during installation to avoid *soil piping* and the possibility of having a *bottom resistance failure* [7].

2.1.3 Soil strength profile

This comprises of the drained and undrained shear strength profile of the soil from the mud line down to the seabed. This is very important to know especially in homogeneous clay soils and in layered structured soils to avoid *plug heave* and *punch through* during penetration [7].

2.1.4 Seabed topographical irregularities

The uneven nature of the seabed could cause a problem during installation especially for suction caissons in cluster from where *cracks* are formed in the caisson walls during penetration. To overcome this challenge, an optimal leveling procedure of the suction caisson should be done immediately after self-weight penetration process but before the suction assisted penetration process begins. The leveling of the uneven section of the caisson should be carried out in small monitored steps [1], [8],[12].

2.1.5 Penetration resistance

This is a measure of the soil shear strength conditions (drained and undrained conditions). The soil shear strength increases gradually with depth depending on the soil density profile. The soil penetration resistance is the sum of the penetration resistance experienced during self-weight and suction assisted penetration(s). It comprises of the total internal and external caisson wall resistance and the caisson tip resistance altogether.

The following Eq. (4) – (7) shows the relationship between penetration resistance and the penetration depth that could be achieved during installation in clay and sandy soils.

For self-weight penetration in clay soil

$$V'= \mathrm{h}\,\alpha_o S_{u1}(\pi D_o) + \mathrm{h}\,\alpha_i S_{u1}(\pi D_1) + (\gamma'\mathrm{h} + S_{u2} N_c)(\pi D t) \tag{4}$$

For suction assisted penetration in clay soil before reverse bearing failure (plug failure) occurs

$$V' + N_c^* S_{u2} \frac{\pi D_i^2}{4} = \mathrm{h}\;\alpha_o S_{u1}(\pi D_o)\left[1 + \frac{D_1^2}{(D_m^2 - D_o^2)}\right](\gamma'\mathrm{h} + S_{u2} N_c)(\pi D t) \tag{5}$$

For self-weight penetration in sand considering the effect of stress enhancement along the caisson walls and tip

$$V' = \int_o^h \sigma' v_o \,\mathrm{dz}\ (K tan\delta)_0\ (\pi D_0) + \int_o^h \sigma' v_1 \,\mathrm{dz}\,(K tan\delta)_i (\pi D_i) + \sigma'_{end}(\pi D t) \tag{6}$$

For suction assisted penetration in the sand before reverse bearing failure (plug failure) occurs while considering the effect of stress enhancement along the caisson walls and tip

$$V' + S\left(\frac{\pi D_i^2}{4}\right) = \int_o^h \sigma' v_o \, dz \, (Ktan\delta)_0 \, (\pi D_o) + \int_o^h \sigma' v_1 \, dz \, (Ktan\delta)_i \, (\pi D_i) + \left(\sigma' v_1 N_q + \gamma' t N_\gamma\right)(\pi D t) \quad (7)$$

Where V' = Effective vertical load, h= installed depth of caisson, α_o= adhesion factor on outside caisson wall, α_i = adhesion factor inside of caisson wall, S_{u1} = average shear strength over depth of skirt, S_{u2} = shear strength at caisson skirt tip, D_o = caisson diameter outside, D_i = caisson diameter inside, D = caisson diameter, t= caisson wall thickness, N_c = Bearing capacity factor (cohesion), π = 22/7, N_c^* = Bearing capacity failure factor, γ' = effective unit weight of soil, D_m = caisson diameter as a result of enhanced stress, k = factor relating vertical stress to horizontal stress, $\sigma' v_o$ = effective vertical stress outside the caisson, $\sigma' v_1$ = effective vertical stress inside the caisson, σ'_{end} = effective vertical stress at the caisson tip, δ = interface friction angle, s = suction within the caisson with respect to the ambient seabed water pressure, N_q = Bearing capacity factor (over burden), N_γ = Bearing capacity factor (self-weight) [13].

2.1.6 Soil sensitivity

This refers to the soil- stress conditions during penetration. It is very important during suction caisson installation. The sensitivity of the soil is critical in predicting the self-weight penetration depth of the caisson, and in estimating the caisson's pull-out capacity immediately after installation [7].

2.1.7 Set down scour

This is an uneven seabed condition which could likely occur very rapidly as the caisson approaches the seabed during installation. During self-weight penetration, set down scour decreases the soil resistance (soil strength) of the soil around the caisson where it occurs. This could lead to *punch through failure* during penetration [14], [15].

2.1.8 Soil stiffness

This parameter is used to analyze the horizontal displacement of suction caisson under loading conditions. Fig 3, demonstrates how large horizontal deflections are generated which alters the stress state of the soils around the caisson thereby leading to the formation of soil gaps around the back of the caisson. The gap created around the caisson could become a channel path for the flow of seawater into the caisson which could result in *soil piping or boiling failure.* Therefore, predicting accurately the caisson lateral displacement and the associated moment distribution along the caisson length is a critical factor in determining the suction caisson load-bearing capacity [7].

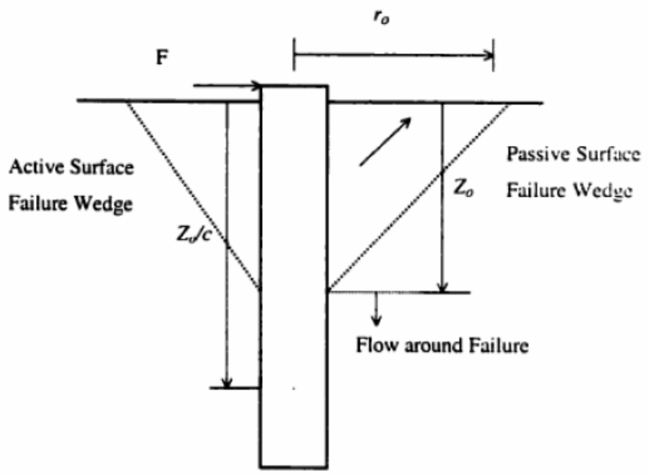

Fig 3 Failure mechanism and padeye optimization adapted from [6]

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2.2 **Design and Installation factors that affect the Load Bearing Capacity of Suction Caissons**

From the review of the literature and practical research works, some key factors that could affect the load-bearing capacity of suction caisson were identified. These factors include:

2.2.1 Loading condition

Suction caissons are subjected to vertical, horizontal and moment loads during installation which may affect their load-bearing capacity. These loads have different loading duration which produces different drainage conditions. Thus, they require continuous monitoring of the load patterns during installation especially the hydrodynamic horizontal and moment loads [7].

2.2.2 Suction caisson geometry- (Aspect ratio-L/D)

The aspect ratio (L/D) is the limiting factor for the maximum penetration depth during installation [11]. Suction caissons with high aspect ratios may be prevented from reaching the design penetration depth during installation when a failure such as a *plug heave* or *buckling* occurs. Another area of concern is the retrieval process where suction caissons with high aspect ratios are difficult to retrieve. It is therefore very important that during the installation process, the soil conditions are monitored and the rate of suction application is controlled [1].

Table 1 below shows the aspect ratios for specific foundations systems and anchors with respect to the water depth, while Table 2 shows the range of Aspect ratios to be applied in different seabed locations as analyzed from the review of over 50 case study field reports

Table 1 Suction caissons applications vs aspect ratios from case studies reviewed from 1958 – 2014 adapted from [1], [6]

Foundation System	Aspect Ratio	Water Depth (m)	Type of Suction Caisson	Platform Fixed/ Floaters
Foundation	0.3-1.7	25-220	Skirt Pile and Suction Buckets	Fixed
Anchoring	0.71-5.3	20-1800	Suction Anchors and Suction Pile	Floaters
Mooring	1.4-5.6	30-1920	Suction Anchors and Suction Pile	Floaters

Table 2 Aspect ratio Vs seabed location from case studies reviewed from 1958 – 2014 adapted from [1], [6]

Seabed Location	**Soil Types**	**Aspect Ratio**	**Water Depth (m)**
Gulf of Mexico	Soft Clay	5 - 5.6	1800 - 1920
West Africa	Soft Clay	2.2 - 4	350 - 1400
North Sea	Soft Clay, Dense Sand, Layered Clay (Soft Clay overlying Stiff Clay), Dense Sand overlying Stiff Clay, Soft Clay overlying Dense Sand	0.36 - 3	40 - 1060
South China Sea	Soft Clay	2	30
Japan	Layered Soil (Sand overlying Clay)*	0.3	25
Timor Sea	Carbonate (Soft Clay overlying Cemented Soil Layers)	24	400
Irish Sea	Sand (Dense/Loose)*, Layered Soil (Clay overlying Sand)*	0.6	33
UK Lakes	Soft Clay	2.7	20 - 80
Baltic Sea	Clay overlying Sand	2.1	357 - 384
Brazil	Soft Clay	1.7 - 3.6	720 - 1200
Adriatic Sea	Layered Clay (Soft Clay overlying Stiff Clay)	3.2 - 3.6	850

*= Not clearly stated

2.2.3 Mooring/chain line attachment point (padeye)

This is a very critical aspect during the installation of suction caissons when they are used as mooring or anchorage support. A mooring system under tension loads from a floating structure transfer the tension loads to the suction caisson via steel chains attached to the padeye. The padeyes are located along the caisson wall and they occupy about 5 to 10% or more of the caisson length. During installation, the padeyes alongside with the steel chain creates a groove in the soil as the suction caisson penetrates deeper into the soil. The groove created could also be a drainage path for soil piping failure to occur.

After the design penetration depth has been reached, the steel chain assumes the shape of a reverse catenary because of: *(1)* the tension loading on the steel chain, *(2)* the soil bearing resistance, *(3)* the frictional resistance along the embedded chain length, *(4)* the chain angle at the mud line, and *(5)* the chain weight during penetration.

To ensure that there is no rotational movement of the suction caisson during ultimate loading conditions, the mooring lines or chains should be attached to the padeye at the *optimal position*. This is important because a larger amount of the ultimate load (weight of the floating platform + environmental loads) is transferred in the lateral direction to the caisson. This ensures that the caisson is operating at full capacity. However, if they are attached below or above the optimum load attachment point, the caisson will be operating at low capacity. This is because more of the foundation loads will be transferred in the vertical direction resulting in the vertical and rotational movements of the suction caisson. This would cause the caisson to buckle, or become unstable which may eventually reduce its load bearing capacity as shown in Fig 4 [1], [7], [12], [16].

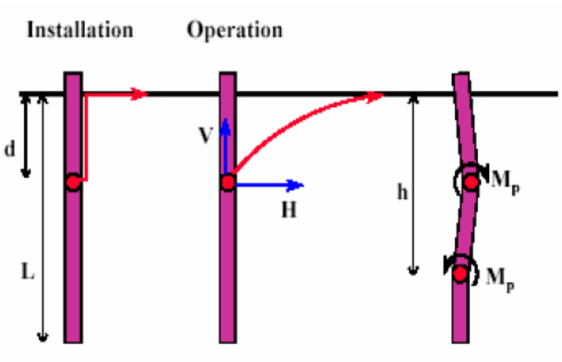

Fig 4 Buckling of anchor piles under tension loading adapted from [12]

2.2.4 The “required suction” for penetration

This is the suction created within the caisson when water is pumped out through the pump during the suction assisted penetration stage. The amount of suction that can be accommodated and sustained during this process greatly depends on the permeability of the subsurface soil and drainage paths. For example, highly permeable soils experience a higher suction decrease compared to less permeable soils. Thus, the required suction to install the caisson to the required depth is given by using the limit equilibrium equation:

$$P_{req} = (R - W_p)/A_{in} \quad (8)$$

Where P_{req} = required suction, R= soil resistance at different penetration, W_p = submerged suction caisson weight, A_{in} = suction caisson internal top cross-sectional area [7].

As a rule of thumb, the *required suction* for penetration must be less than the maximum suction for all soil conditions. For example, in soft clay soils, the ratio between the maximum suction and the required suction should be equal to at least 1.3 before failure occurs, but when a failure occurs, the ratio should be greater than 1.3 [11].

2.2.5 The maximum allowable suction limit

This is a very critical aspect that is responsible for the installation of suction caissons and the failure modes experienced during their installation. Zen [17], derived the equations to calculate the limiting suction for plug heave in clay as shown in “Eq. (1)” and an equation to calculate the critical suction for piping (boiling) in the sand as shown in “Eq. (2)”.

$$P_{sc} = (d - \partial)\gamma' \quad (9)$$

$$P_{sc} = (2d - \partial)\gamma_\omega i_c \quad (10)$$

Where P_{sc} =Maximum suction or Plug heave suction, d= Diameter of the suction caisson; ∂ = Displacement of the soil surface inside the foundation; i_c= Critical hydraulic gradient (mostly i_c=1); γ'’=Submerged unit weight of soil; and γ_w = unit weight of water [17].

2.2.6 Tilting/misalignment

The risk of misalignment of the caisson during installation could affect the load-bearing capacity of the caisson due to the uneven load distribution because of either the improper levelling of the caissons after touch down, buckling of the caisson, or attaching the steel chain or mooring lines to the padeye above or below the optimal position [12], [18].

2.2.7 The type of installation used

The type of installation used (e.g. lift installed or launched installed) and their associated failure modes (e.g. fatigue and corrosion etc.) could reduce the stiffness and load-bearing capacity of suction caissons [1].

2.2.8 The pump requirement capacity

Identifying the right pump capacity for suction caisson installation in different soil types is very important. The pump capacity is very important in the installation process because it creates the suction required for penetration and the penetration rate limiting factor.

Houlsby [13], proposed a formula for calculating the pumping requirement for caisson installation in clay refer to “Eq. (10)” and in sand refer to “Eq. (11)”

$$Q = \frac{\pi D_i^2}{4} V \quad (11)$$

$$Q = \frac{\pi D_i^2}{4} V + F\frac{SKD}{\gamma_\omega} \quad (12)$$

Where Q= Pump capacity or required flow rate; V= Vertical penetration velocity; Di= Caisson internal diameter; D= Caisson outer diameter; F= Dimensionless quantity that depends on h/D (where h is the penetration depth), K is the sand permeability; s= suction within the caisson with respect to the ambient seabed water pressure, and γ_w = unit weight of water.

The above formula shows that the pumping requirement for sand is greater than that for clay due to the high seepage flow generated during caisson due to the high seepage flow generated during caisson installation in the sand requirement for sand is greater than that for clay due to the high seepage flow generated during caisson installation in the sand.

3. RESULTS

From the review of suction caisson installation from literature reviews and 50 case study field reports, the results obtained are summarized in Table 3 and Fig 4.

These results highlight that, plug heave, soil piping, and bottom resistance failure are the most common failure types amongst suction caissons. Plug heave and buckling contribute about 29% and 20% of installation issues in both homogeneous clay soils, layered clay/sandy soils, and carbonate soils. Soil piping and bottom resistance failure contribute about 16% and 10% respectively of the installation issues in both sand and layered sand soils.

The punching through failure contributes about 2% of installation issues in carbonate soils; while high penetration resistance contributes about 23% of installation issues in layered soils. However, despite these installation issues, suctions caissons are more widely used in clay soils (66%) among all other soil types.

Table 3 Suction caisson installation issues in different seabed conditions adapted from [1] pp 3, [6] pp112, [13], [18], [19], [20]

Soil Types	Installation Issues	Seabed Location
Soft Clay	PH, B, SP, and BRF	GOM, West Africa, Brazil, North Sea, South China Sea and UK Lakes
Stiff Clay	IS, SP, BRF, and HPR	
Soft Clay Over Stiff Clay	HPF, BRF, SP, B and PH	North Sea and Adriatic Sea
Stiff Clay Over Soft Clay	HPR, BRF, IS, SP and PTF	
Loose Sand	I, SP, B, PH and BRF	Irish Sea*
Dense Sand	SP, B, PH, BRF and HPR	Irish Sea* and North Sea
Loose Sand Over Dense Sand	L, SP, B, PH, HPR and BRF	Irish Sea* and North Sea
Dense Sand Over Loose Sand	SP, B, PH, BRF, PT and HPR	
Loose Sand Over Soft Clay	PTF, PH, B, SP and BRF	Japan*
Soft Clay Over Loose Sand	SP, PH, B, BRF and HPR	Irish Sea* and Baltic Sea*
Dense Sand Over Soft Clay	PH, B, BRF, PTF, SP and HPR	Japan* and North Sea*
Soft Clay Over Dense Sand	HPR, BRF, PH, B and SP	North Sea and Baltic Sea*
Stiff Clay Over Dense Sand	HPR, BRF, IS, SP and PTF	
Dense Sand Over Stiff Clay	SP, B, PH, BRF and HPR	North Sea
Silt (Homogeneous / Layered Soil)	HPR, SP, BRF, PH and B	
Soft Clay Over Cemented Soil	SP, B, PH, BRF and HPR	Timor Sea
Cemented Soil Over Sand/Clay Soil	HPR and PTF	

* = Not clearly stated

PH= Plug Heave, B= Buckling, SP= Soil Piping, BRF= Bottom Resistance Failure, HPR= High Penetration Resistance, IS= Insufficient Sealing, PTF= Plug Through Failure, L = Liquefaction

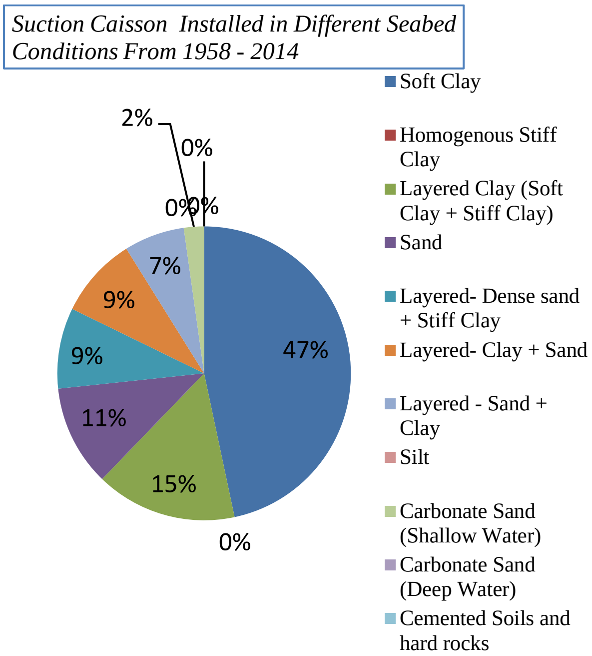

Figure 5 Suction Caisson Installed in Different Seabed conditions from 1958-2014 adapted from [1] pp 3, [6] pp 112.

4. CONCLUSION

From the literature reviewed and analysis conducted, it was observed that the following installation issues such as buckling, plug heave, soil piping, bottom resistance failure and high penetration resistance existed in both homogeneous and heterogeneous seabed conditions. These issues were caused by the amount of suction-induced and the soil attributes exhibited during penetration. The amount of suction-induced is dependent on the seabed condition and the soil attributes exhibited during penetration. Therefore, for these challenges to be mitigated, a good understanding of the seabed conditions and soil parameters before and during installation, together with the constant monitoring of the induced suction created during penetration with respect to the penetration depth is essential.

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5. ACKNOWLEDGMENTS

Appreciation goes to the Authors of this paper for their immense contribution and sacrifice in making this paper worth publishing.

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