PORT-SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering - Port Said University
Volume 23 No. 1 March 2019 pp: 39:46

Spud-Can Penetration Response in Double Layered Soil By Press-Replace Technique

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ABSTRACT

One of the most important factors in the process of jack-up rig installation is the good expectation of the amount of spud-can penetration into soil layers under the varying loads. It is important to insert the spud-can through soil layers up to the expected stability depth during the installation process to guarantee enough soil stability reaction. The Press-Replace Technique (PRT), which is considered a kind of small-deformation nonlinear-material finite-element analysis, is applied in this paper to track the full load-penetration response of a spud-can in double-layered soil. A parametric study was carried out by using Plaxis 2D Vr.8.6 to evaluate the effect of the strength properties of soil on the Punch-through phenomenon and the bearing capacity of soil spud-can system by applying the Press Replace Technique (PRT). This study is also concerned with the penetration of a circular spud-can in stiff clay over either soft clay or loose sand soil. Among the considered properties of the soil, it was demonstrated that the undrained shear strength of top stiff clay layer is the most important parameter that affects the penetration response of spud-can in this case, where the properties of the lower soft clay layer do not have major effect.

Keywords: Jack-up Rig, Spud-Can, Penetration, Offshore Engineering, Punch-Throw, Backflow, Plaxis.

1. INTRODUCTION

For many decades, during the installation process of jack-up rig, the penetration-response of a spud-can could be tracked by the conventional analysis method. However, the classical conventional method does have many limitations, and it is certainly not valid for the penetration in multi-layered soil. Therefore, numerical modeling methods became necessary in order to investigate the penetration-response of a spud-can in multi-layered soil. Initially, the legs of a jack-up rig are placed on the seabed surface while the rig is floating to get the first stage of stability, as shown in Figure 1. Then the rig hull is elevated up under the effect of its own weight to achieve the second stage of stability. Finally, the preload stage is finished when a complete balance between the capacity of the soil and the forcing loads is fulfilled. The current study aims to investigate the spud-can penetration into soil layers during the preloading case. From the previous experience, it was found that the penetration depth in sand has mostly small orders, if compared to the penetration in clay. For instance, the recorded depth of penetration in soft clay has reached 55m in the Mississippi Delta [1]. For the penetration in particular soil conditions; like strong soil over soft soil, the bearing capacity of soil increases continuously with the penetration depth; until a sudden drop in the bearing capacity is encountered (punch-through phenomenon). This may lead to a sudden rapid penetration and a total loss of the spud-can balance. Therefore, a trail is made in this research to get a thorough understanding to this phenomenon and to investigate the different soil properties that might affect the punch-through of a spud-can that penterates in a stiff over a weak soil.

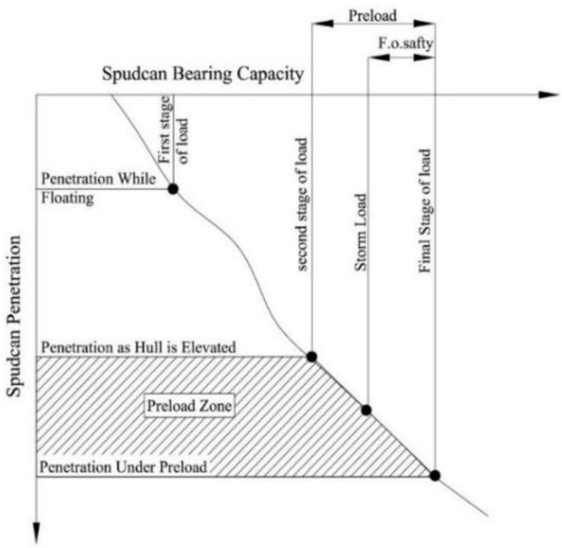

Figure 1. Idealized relationship of soil bearing capacity and Spud-can penetration.

There are many methods and guidance notes to evaluate the load penetration curve of a spud-can at preloading stage. Most of these methods are effective for specific soil conditions: a) a homogeneous single

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layer consists of sand or clay, b) double layer stiff-over-soft clay soil, and c) sand over clay soil (Hossain [2] and [3], Lee et al. [4], and Anandro [5]).

Despite the fact that multi-layered soil profiles are commonly encountered in many offshore areas, only few efforts were made to investigate the problem of installation of jack-up rigs in multi-layered soil conditions. Kellezi et al. [6] studied the penetration of spud-can into multi-layered soil conditions by large deformation finite element analysis under condition of a static vertical load at the center of an idealized spud-can. Hossain [7] used centrifuge modeling to model the penetration of spud-can foundation through 3 to 6 similar clay layers with interbedded stronger clay, silica sand, or carbonate sand layers. His target was to present awareness into the behavior of spud-can foundations in stratified sediments comprising layers of different drainage conditions and mineralogy.

Zhang et al. [8] judged the performance of the current guideline methods for spud-can penetration by comparing their predictions with measurements from selected well-controlled centrifuge experiments. They also analyzed the problem by the large deformation finite element method and compared the numerical results with those of the experimental work. Zheng et al. [9] developed the mechanism-based design methods for surface sand-over-clay deposits to examine the spud-can penetration resistance in an interbedded sand layer between two clay layers. They also carried out a series of large-deformation finite-element analyses to investigate the penetration resistance after adding a strong fourth layer.

However, large deformation numerical analyses such as the Arbitrary Eularian-Lagrangian, Coupled Eularian-Lagrangian, and Material Point Methods are not yet generally available or common for engineering applications, Engin [10]. Therefore, the Press-Replace Technique (PRT) is applied in this work to model the progressive spud-can penetration, since it is classified as a small deformation numerical method, which is based on a small-strain geometry update procedure. Furthermore, PRT can be worked in standard finite element packages commonly used in geotechnical applications. For example, Engin [10] used PRT to model a suction pile penetration in clay. Andersen, et al. [11] also used PRT to study suction anchors in soft clay. In this research, a parametric study was carried out by the PRT to evaluate the effect of shear parameters of the soil, and the variation of thickness of soil layers on the punch-through phenomenon and the bearing resistance of spud-can foundations. This study is concerned with the penetration in double layer soil deposits comprising either stiff clay over soft clay, or stiff clay over loose sand.

2. NUMERICAL MODEL

In this study, the PRT is applied based on a displacement control scheme. The finite element mesh discretization is kept unchanged during the entire penetration process. At the start of each phase, the properties of penetrated soil elements are replaced by those of the spud-can material; resulting in a change of the global stiffness matrix without any need to update the mesh geometry.

The general idea in PRT is to apply the prescribed vertical displacement at each phase by using a group of clusters. The division of clusters must be compatible with the spud-can approximate dimensions. Moreover, the vertical dimensions of the clusters must be equal to the prescribed vertical displacement. If the widest plan area of spud-can touches the seabed surface, the loading will start. After penetrating the soil by the spud-can, the cluster properties must be upgraded to simulate the new penetration phase.

The analysis is repeated for every penetration step until the required penetration of spud-can is reached as shown in Figures 2 and 3. If the spud-can is penetrating in sand, the backfill of sand will start directly once the penetration starts. This phenomenon can be simulated in the numerical model by assigning some carefully selected properties for the clusters of backfill sand accumulated above the spud-can during penetration. The properties of backfill sand clusters can be taken as percentages of their counterparts of the penetrated sandy layer. The stiffness of backfill sand clusters is assumed one-half the stiffness of the original sandy layer. Nevertheless, for the penetration in a surface clay layer, a backflow of clay will take place after the formation of a cavity above the spud-can. The cavity would have a limited height; which can be calculated as follows, Hossain [7]:

$$\frac{hc}{D} = (\frac{S_{uH}}{\gamma' D})^{0.55} + \frac{1}{4}\frac{S_{uH}}{\gamma' D} \qquad \text{Eq.1}$$

$$S_{uH} = S_{um} + p\,h_c \qquad \text{Eq.2}$$

where :

S_{uH} = The shear strength at the backflow depth in kN/m^2,

S_{um} = The shear strength at the seabed level in kN/m^2,

h_c = The cavity height in m,

γ' = The specific gravity weight kN/m^3,

D = The spud-can diameter in m, and

p = Shear strength gradient with soil depth (z).

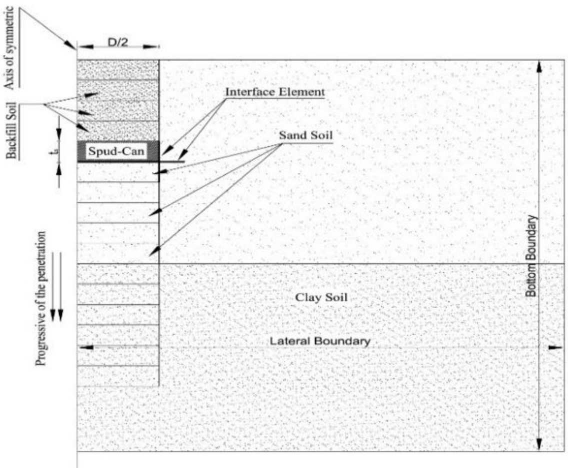

Figure 2. The penetration in case sand above clay by using PRT

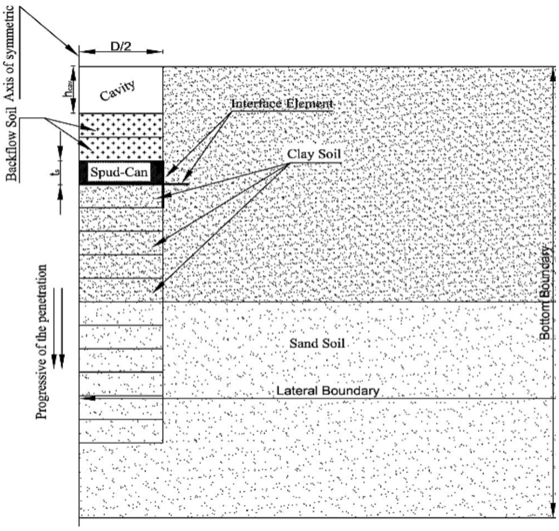

Figure 3. The penetration in case clay above sand by using PRT.

2.1 Basic Assumptions

The finite element package Plaxis 2D Vr.8.6 was chosen to simulate all study cases in this work. The framework of the current study is to improve the PRT to be capable to simulate the spud-can penetration in deep-layered clay and multi-layered soil deposits that could be found in many offshore areas. The following hypothesizes were adopted throughout the present numerical analysis:

- The thickness of each phase (solution step) and the prescribed displacement were taken as one meter.
- The finite element analysis model is axisymmetric.
- The finite element type selected to simulate both the soil and spud-can is 15-node element.
- The density of finite element mesh was taken as a medium coarse type.
- The boundary distance in vertical and horizontal directions was taken at least 4-times the widest diameter of spud-can.
- The contact surface between the spud-can and adjacent soil was simulated by interface elements that were defined by five pairs of nodes for each element. The interface strength was taken as 0.7 as recommended in the Plaxis [12]. The interface elements were extended horizontally and vertically one step size out the corners of spud-can cluster for every phase of the finite element analysis in order to improve the poor quality of stress results arising at the corner points of the spud-can, Anandro [5].
- The spud-can material was taken as a rigid cluster by using linear elastic model type with Young Modulus of 200 Gpa and Poisson's ratio of 0.3.
- The penetration was tracked until penetration reaches 1.5 the maximum diameter of the spud-can.
- The sandy soil was treated as drained type material.
- The clay in the entire numerical model was treated as undrained type material represented by Mohr-Coulomb constitutive soil model. However, the backflow clay was taken as drained type material with Linear Elastic constitutive model. Its specific weight and stiffness modulus were taken as one-half and one-quarter of their original values, respectively. Moreover, the value of Poisson's ratio was taken as 0.3 and 0.45 for backflow clay and original clay, respectively. It must be noticed that the cohesion between the backflow clay and the top-surface of spud-can is very weak, so the strength factor of their interface elements was taken as 0.01 to reflect that weak cohesion.

2.2 Validation of The Model

The proposed numerical model, which is based on the PRT, will be verified against published literature in this section. The penetration of a 12m diameter circular spud-can in a 3-layer soil deposit that was investigated by Hossain [7] using centrifuge modeling. This study case is reanalyzed numerically herein and the results are compared for verification. It was donated by Hossain [7] as FS1.

Table 1 gives the stratification and the main engineering properties of the soil. The soil profile consists of three layers: moderate-, soft-, and stiff clay. It was prepared by Hossain to investigate the effect of an interbedded soft clay layer on the penetration resistance of a spud-can foundation. Figure 4. shows a comparison between the current PRT numerical predictions and those of the experimental work. The spud-can penetration resistance is shown as a relation between the bearing pressure, q_u and the penetration depth, d. During the penetration of advancing spud-can through the upper moderate and soft clay layers, a satisfactory match can be noticed between the numerical PRT predictions and test results. Moreover, both studies showed a minor punch-through at the same level (at d/D = 0.5 approximately). As soon as the advancing spud-can approaches the initial top level of stiff clay layer, the numerical model starts to exhibit smaller displacements showing a higher stiffness than the experimental model. It was noticed experimentally that the advancing spud-can continues penetration through the residues of the upper layers trapped under the spud-can, even after reaching the initial top level of bottom soil layer. It is hard to simulate such a complicated phenomenon in the current small displacement finite element analysis; which ignores the accumulation of strains and deformations occurred in previous phases of the analysis.

In the present analysis by PRT it was assumed that the soil clusters are removed progressively and directly replaced by the spud-can material at each phase of analysis; keeping the original finite element mesh unchanged. In other words, it was assumed in the present analysis that the advancing spud-can would penetrate directly into the lower soil layer as soon as it reaches its initial top level; with no regard to the soil trapped from the upper clay layers. This may be the main reason of stiffer response of the numerical model during the penetration in the lower stiff clay layer. It can also be noticed from Figure 4. that the numerical response that considers clay backflow, is relatively more accurate than the situation when clay backflow is ignored. Moreover, the numerical response with clay backflow taken into account could successfully show a main punch-through like that encountered in the test results. The numerical solution failed to predict the presence of the main punch-through when clay backflow was neglected.

Table.1 Case of multi clay layers (Hossain [7])

Layer	H	γ	S_{um}	S_{inc}	E	H/B
First Layer	Moderate Clay					
	H	γ	S_{um}	S_{inc}	E	H/B
	m	Kn/m³	Kn/m²	Kn/m²/m	Kn/m²	-
	5	16	22.0	-	11000	0.42
Second Layer	Soft Clay					
	H	γ	S_{um}	S_{inc}	E	H/B
	m	Kn/m³	Kn/m²	Kn/m²/m'	Kn/m²	-
	6	16	9.0	-	3150	0.50
Third Layer	Stiff Clay					
	H	γ	S_{um}	S_{inc}	E	H/B
	m	Kn/m³	Kn/m²	Kn/m²/m'	Kn/m²	-
	39	16	37.0	-	11900	3.25

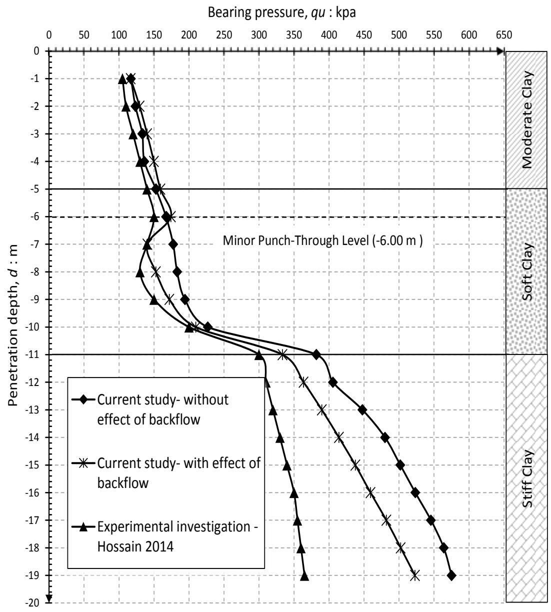

Figure 4. Comparison of current study predictions and published work. (FS1).

3. PARAMETRIC STUDY

In this section, a parametric study is carried out by the present numerical model based on PRT to investigate the effect of the strength parameters of the soil on the punch-through phenomenon and the soil bearing resistance. This study is mainly concerned with spud-can penetration in double-layered soil deposits consisting of stiff-clay underlined by a soft-clay or a loose-sand layer; as shown in Figure 5.

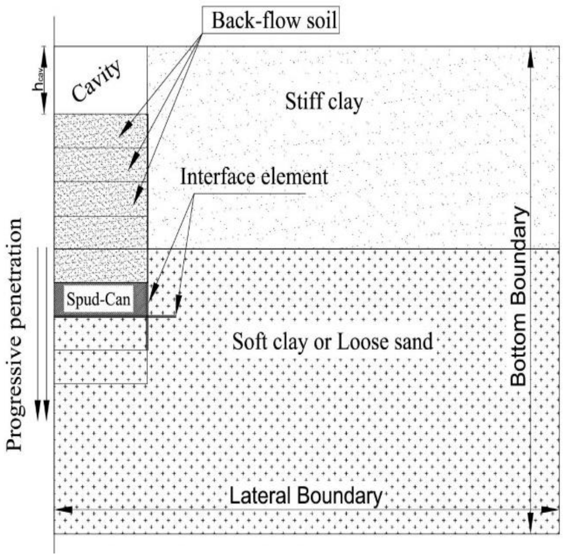

Figure 5. Spud-can penetration into double-layered soil with upper stiff clay layer.

In all study cases hereafter, the diameter of spud-can was taken as constant (D = 12 m). Moreover, the level of water table was kept constant at 50 m above the seabed in all study cases. The main parameters and factors considered in the study are summarized as follows:

Penetration in Stiff Clay over Soft Clay soil:

- Undrained shear strength of the upper stiff clay layer.
- Undrained shear strength of the lower soft clay layer.

Penetration in Stiff Clay over Loose Sand soil:

- Undrained shear strength of the upper stiff clay layer.
- Friction angle of the lower sand layer.

3.1 Stiff Clay over Soft Clay

3.1.1 Undrained shear strength of the upper stiff clay layer

In this section, the effect of variation of undrained shear strength (S_{um}) of the top stiff clay layer on the penetration response of spud-can is studied. Six study cases were considered for which S_{um} of the top clay layer was taken as 50, 80,110,140,170,200 kPa, as given in Table.2 the results are depicted in Figure 6. The cavity height will be a minimum for the study case with least undrained shear strength S_{um}, and it increases with the increase of shear strength of top clay layer (See Eq.1 and Eq.2).

The penetration response of spud-can in each case consists of three main phases:

a) Phase-I (before reaching the cavity height):

In this phase, the soil bearing pressure increases slightly with penetration depth for small values of S_{um}. However, for higher values of S_{um}, the soil bearing pressure decreases with the increasing penetration depth, especially when approaching the cavity height. A minor punch-through may be encountered for higher values of S_{um}.

b) Phase-II (At the cavity height):

When the penetration depth reaches the cavity height, the soil bearing pressure deteriorates rapidly and a main punch-through is encountered. The level at which the punch-through is encountered is not constant as the cavity depth is considerably affected by the variable S_{um} of stiff clay in this series of study cases.

c) Phase-III (After exceeding the cavity height):

At this final phase of penetration, the bearing pressure under the spud-can is controlled by the stiffness of lower soft clay layer. The penetration response curves for the different cases are identical and very close to one another.

Table.2 Undrained shear strength of the upper stiff clay layer.

Upper Layer	H	γ	S_{um}	S_{inc}	E	H/B	
Units	m	kN/m^3	kN/m^2	$kN/m^2/m'$	kN/m^2	-	Stiff Clay
CC01	10	18	**50**	1	8400	5	
CC02	10	18	**80**	1	8400	6	
CC03	10	18	**110**	1	8400	7	
CC04	10	18	**140**	1	8400	8	
CC05	10	18	**170**	1	8400	8	
CC06	10	18	**200**	1	8400	9	
Lower Layer	H	γ	S_{um}	S_{inc}	E	H/B	
Units	m	kN/m^3	kN/m^2	$kN/m^2/m'$	kN/m^2	-	Soft Clay
CC01	40	16	10	1	3000	3.3	
CC02	40	16	10	1	3000	3.3	
CC03	40	16	10	1	3000	3.3	
CC04	40	16	10	1	3000	3.3	
CC05	40	16	10	1	3000	3.3	
CC06	40	16	10	1	3000	3.3	

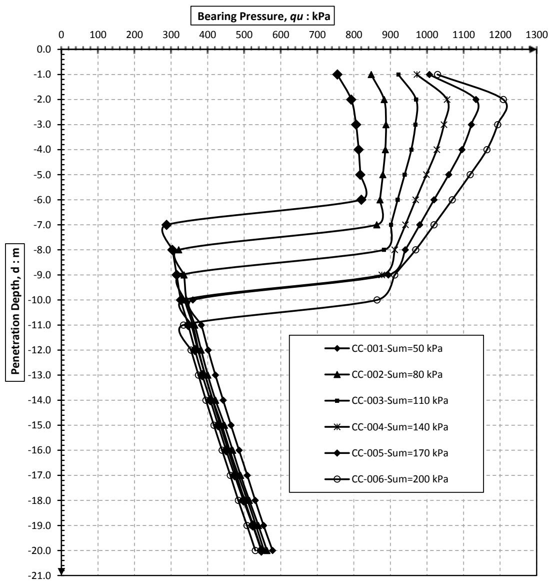

Figure 6. Undrained shear strength of the upper stiff clay layer

3.1.2 Undrained shear strength of the bottom soft clay layer

The effect of the variation of undrained shear strength (S_{um}) of the lower soft clay layer on the penetration response of spud-can is studied in this section. Six study cases are considered as described in Table.3 The undrained shear strength of the lower clay layer ranges from 6 kPa to 16 kPa in steps of 2 kPa. The results are shown in Figure 7. It can be seen that the penetration response of the spud-can is generally the same for all cases with a major punch-through takes place at the same level; irrespective the variations of engineering properties of the lower soft clay layer. The bearing pressure improves slightly with the increase in shear strength of soft clay.

Table.3 Undrained shear strength of lower soft clay

Upper Layer	H	γ	S_{um}	S_{inc}	E	H/B	
Units	m	kN/m^3	kN/m^2	$kN/m^2/m'$	kN/m^2	-	Stiff Clay
CC07	10	18	40	1	20000	0.8	
CC08	10	18	40	1	20000	0.8	
CC09	10	18	40	1	20000	0.8	
CC010	10	18	40	1	20000	0.8	
CC011	10	18	40	1	20000	0.8	
CC012	10	18	40	1	20000	0.8	
Lower Layer	H	γ	S_{um}	S_{inc}	E	H/B	
Units	m	kN/m^3	kN/m^2	$kN/m^2/m'$	kN/m^2	-	Soft Clay
CC07	40	15	**6**	1	**1800**	3.3	
CC08	40	15	**8**	1	**2400**	3.3	
CC09	40	15	**10**	1	**3000**	3.3	
CC010	40	15	**12**	1	**3600**	3.3	
CC011	40	15	**14**	1	**4200**	3.3	
CC012	40	15	**16**	1	**4800**	3.3	

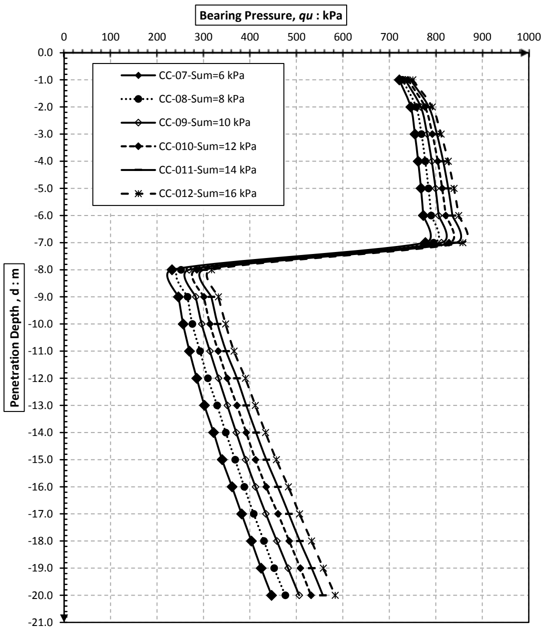

Figure 7. Undrained shear strength of lower soft clay

3.2 Stiff Clay over Loose Sand

3.2.1 Undrained shear strength of the upper stiff clay layer.

This section studies the role of undrained shear strength of the upper stiff clay in spud-can penetration in stiff clay over loose sand soil deposits. The chosen undrained shear strength for clay in this study ranges from 50 kPa to 200 kPa. All data are tabulated in Table.4 and the results are presented in Figure 8. As mentioned before, the minimum height of cavity that could take place for the cases under consideration shall be encountered when the undrained shear strength of the top clay is a minimum. Figure 8. Shows that the location at which the punch-through is encountered becomes deeper, and the soil bearing stress gets better, as the undrained shear strength of the top clay layer becomes bigger. Beyond the punch-through, the rate of improvement in soil bearing stress with the increasing shear strength for top clay; decreases as the penetration depth increases.

Table.4 Undrained shear strength of the upper stiff clay

Upper Layer	H	γ	S_{um}	S_{inc}	E		
Units	m	kN/m^3	kN/m^2	$kN/m^2/m'$	kN/m^2		Stiff Clay
CS01	10	18	**50**	1	8400		
CS02	10	18	**80**	1	8400		
CS03	10	18	**110**	1	8400		
CS04	10	18	**140**	1	8400		
CS05	10	18	**170**	1	8400		
CS06	10	18	**200**	1	8400		
Lower Layer	H	γ	φ	ψ	E_{inc}	E	
Units	m	kN/m^3	°	°	$kN/m^2/m$	kN/m2	Loose Sand
CS01	40	18	25	-	-	20000	
CS02	40	18	25	-	-	20000	
CS03	40	18	25	-	-	20000	
CS04	40	18	25	-	-	20000	
CS05	40	18	25	-	-	20000	
CS06	40	18	25	-	-	20000	

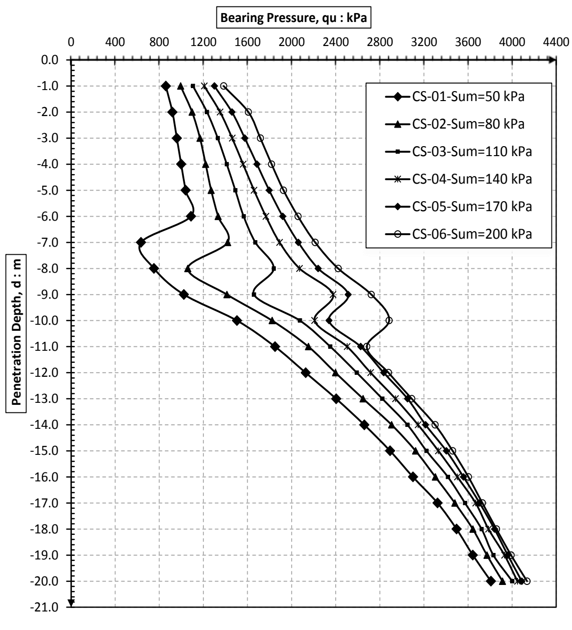

Figure 8. Undrained shear strength of the upper stiff clay layer.

3.2.2 Friction angle φ of the bottom sand layer.

In this section, the influence of variation of the friction angle of lower sand layer on the penetration response of spud-can is studied. Six study cases are considered as given in Table.5. The friction angle φ ranges from 25° to 30° in steps of one degree. The results are shown in Figure 9. It is clear that the effect of friction angle variations on penetration response is trivial before encountering the punch-through. Beyond the punch-through, the soil bearing pressure gets better as the friction angle of lower sand layer increases.

Table.5 Friction angle φ of the bottom sand layer.

Upper Layer	H	γ	S_{um}	S_{inc}	E		
Units	m	kN/m^3	kN/m^2	$kN/m^2/m'$	kN/m^2		Stiff Clay
CS07	10	18	40	1	20000		
CS08	10	18	40	1	20000		
CS09	10	18	40	1	20000		
CS010	10	18	40	1	20000		
CS011	10	18	40	1	20000		
CS012	10	18	40	1	20000		
Lower Layer	H	γ	φ	ψ	E_{inc}	E	
Units	m	kN/m^3	°	°	$kN/m^2/m$	kN/m^2	Loose Sand
CS07	40	18	**25**	-	-	20000	
CS08	40	18	**26**	-	-	20000	
CS09	40	18	**27**	-	-	20000	
CS010	40	18	**28**	-	-	20000	
CS011	40	18	**29**	-	-	20000	
CS012	40	18	**30**	-	-	20000	

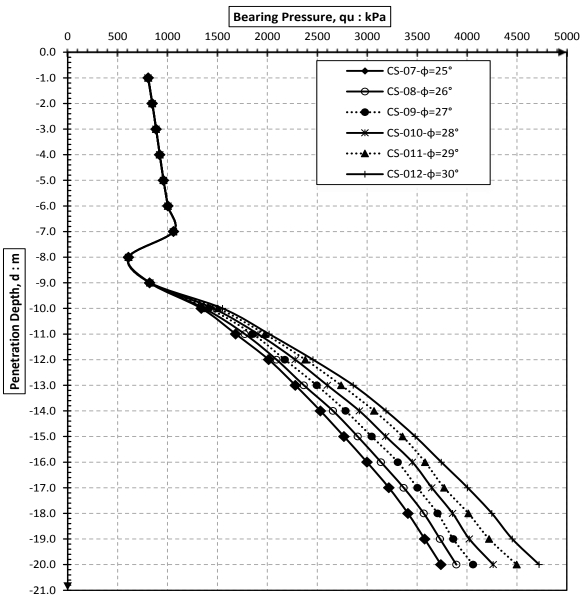

Figure 9. Friction angle φ of the bottom sand layer.

4. CONCLUSIONS

From the studies carried out in this work, it can be concluded that:

- **Spud-can Penetration in Stiff Clay over Soft Clay**

  1) For small values of undrained shear strength of top clay layer (S_{um}), the soil bearing pressure increases slightly as the penetration depth increases. However, for higher values of S_{um} , the soil bearing pressure decreases with the increasing penetration depth, especially when approaching the cavity height. A minor punch-through may be encountered near the seabed level for higher values of undrained shear strength S_{um}.

  2) Variations of the undrained shear strength of the lower soft clay layer do not affect the elevation of the major punch-through. However, the bearing pressure of soil will improve slightly with the increase of shear strength for the lower soft clay layer.

- **Spud-can Penetration in Stiff Clay over Loose Sand**

  1) As the undrained shear strength of the top clay layer increases, the level of major punch-through becomes deeper, and the soil bearing stress beyond the punch-through gets better.

  2) As the friction angle of the lower sand layer increases, the soil bearing pressure increases, if (and only if) the penetration depth exceeds the level of punch-through. Variations of the friction angle of lower sand layer do not affect the soil bearing stress before or during the punch-through phase.

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تأثير اختراق اساسات المنشاءات ذات الرفع الذاتي في التربة ذات الطبقتين باستخدام طريقة استبدال الضغط

يعتبر التوقع الجيد لعمق الاختراق واحداً من العوامل الحيوية الهامة اللازمة لتثبيت أساسات الحفارات من النوع (jack-up)تحت تأثير الاحمال المختلفة، حيث أن عملية تثبيت الحفار تتطلب الوصول بعمق الاختراق في التربة إلى عمق الاتزان المتوقع، وذلك لضمان وجود رد فعل من التربة يكفي لتحقيق الاتزان، ويمكن توقع قيمة الاختراق المطلوب لتحقيق اتزان الأساسات باستخدام الطرق التقليدية، ولكن هذه الطرق قابلة للتطبيق فقط في حالة الاختراق في تربة مكونة من طبقة واحدة متجانسة، أو في تربة ذات طبقتين في حالات محددة مثل (الاختراق في طبقة رمل فوق طبقة من الطين)، غير أن الطرق التقليدية لا تصلح للاستخدام في حالة الاختراق في التربة ذات الطبقتين المكونة من طبقة طين فوق طبقة رمل، وذلك لصعوبة تمثيل تشكلات الطين فوق الاساسات بعد الاختراق، وتقف الطرق التقليدية عاجزة تماماً عن دراسة الاختراق في حالة التربة متعددة الطبقات، ولذلك وللوصول إلى تمثيل مناسب ومقارب للحقيقة يتم اللجوء لاستخدام النمذجة العددية بطريقة العناصر المحددة.

في هذا البحث سوف يتم تطبيق طريقة استبدال الضغط وهي واحدة من طرق التشكلات الصغيرة للتحليل الإنشائي لدراسة اختراق الأساسات في تربة طينية فوق طبقة رملية، وسيتم التحقق من النتائج بتطبيق الطريقة المذكورة على حالة اختراق الأساسات لتربة متعددة الطبقات تم اختبارها معملياً ونشر النتائج في بحوث سابقة، ويتميز النموذج العددي المقترح بقدرته على تمثيل انهيار التربة الذي يحدث في حالة اختراف التربة الطينية. ويشتمل البحث على دراسة بارامترية لفحص تأثير تغير خواص التربة على ظاهرة الاختراق المفاجئ ومقاومة التربة للأحمال المختلفة، تم فحص حالتين محددتين من التربة ذات الطبقتين: الأولى تتناول الاختراق في تربة تتكون من طبقة طين قوي فوق طبقة من الطين الضعيف، والثانية تشمل الاختراق في طبقة الطين القوي فوق طبقة من الرمل السائب.