# THEORETICAL STUDY ON THE EFFECT OF A WEAK LAYER ON THE VERITCAL BEARING CAPACITY OF SPUDCANS IN CLAY

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ABSTRACT
Soil encountered offshore is usually stratified, often with alternating strong and weak layers. In contrast to a uniform soil profile, the presence of a weaker layer introduces challenges to correctly predict the spudcan load-penetration profile due to alteration of soil failure mechanism. It is therefore important to understand the influence of a weak layer on the vertical load-penetration response and to reflect this influence correctly in design methodologies. This paper presents a numerical study on the effect of the weak layer in both a two layer (weak-strong) and a three layer (strong-weak-strong) soil profile in clay. Normalised parameters, such as relative layer thicknesses and soil shear strength ratios, are investigated. The paper discusses the results of the study in the context of the current industry guidelines and reflects on how the results could be applied in engineering practice.

KEY WORDS: jack-up, spudcan, squeezing, punch-through, foundation assessment

## INTRODUCTION
When predicting the penetration behaviour of a spudcan at a site where layered soils are present, three foundation failure mechanisms are commonly considered ([1], [2] & [3]):

- General shear;
- Squeezing;
- Punch-through.

General shear is the mechanism that occurs where the thickness of the top layer is large when compared with the width of the footing or where the strength of the soil layers do not vary significantly and an average (or similar) strength can be adopted in the bearing capacity equations. Squeezing can occur where a soft clay layer overlies a significantly stronger layer. The last failure mechanism, that of punch-through, concerns the situation where a soft layer underlies a strong layer, which can lead to rapid (uncontrolled) leg penetrations.

Previous research on squeezing and punch-through phenomena has primarily focused on two-layer systems with either infinitely strong and/or thick underlying clay layers (e.g. Meyerhof & Chaplin [4], Brown & Meyerhof [5], Merifield et al. [6], Edwards & Potts [7] and Merifield & Nguyen [8]). For multi-layer systems, the so-called "bottom-up" approach (Xie et al. [9]) is generally used where the penetration behaviour is assessed in a step-wise manner working up from the base of the soil profile using the two-layer soil models. More recently, Hossain [10] presented results from a centrifuge test programme in multi-layer soil profiles, which highlighted the influence underlying layers play in observed penetration response together with the importance of the soil plug, trapped beneath the spudcan.

This paper presents the results from a parametric finite element study (small strain) on the effect of a weak layer in both a two layer (weak-strong) and a three layer (strong-weak-strong) soil profile in clay. The objective of this study was to provide further guidance on how the influence of such a weak layer can be accounted for in engineering practice, in terms of the relative strengths of the soft and strong clay layers and the relative thickness (in terms of the spudcan diameter) of the soft clay layer.

## BACKGROUND THEORY
The general mechanism for the squeezing of a weak clay layer overlying an infinitely strong clay layer is presented in Figure 1. The squeezing of a weak clay layer can be assessed based on the study presented by Meyerhof & Chaplin [4], which for a circular footing is given as follows:

$$q = q_{net} + p_0' = s_{u,weak}\left(\frac{2R}{3T} + N_c - 1\right) + p_0' \quad (1)$$

where:
- q = bearing capacity (or yield pressure)
- $q_{net}$ = bearing capacity excluding overburden pressure
- $s_{u,weak}$ = undrained shear strength of the weak layer
- R = radius of spudcan
- T = thickness of weak clay below spudcan
- $N_c$ = bearing capacity factor for a circular surface footing on a layer of great thickness (6.05)
- $p_0'$ = effective vertical stress at the depth of the spudcan (= 0 at seabed)

Industry guidance ([1] & [2]) for the assessment of squeezing of clay is based on the above formulation, which can be presented as follows:

$$q = q_{net} + p_0' = s_u\left(5 + \frac{0.33 \cdot 2R}{T} + \frac{1.2D}{2R}\right) + p_0' \quad (2)$$

In Eq.2 the term (1.2D/2R) represents the effect of spudcan embedment (D) on the bearing capacity. The lower bound bearing capacity is given by general failure in the weak layer, whilst the upper bound bearing capacity is given by general failure in the underlying strong layer (because the underlying layer is not infinitely strong in practice). Based on this formulation, squeezing occurs when:

$$2R \geq 3.45T\left(1 + 1.1\frac{D}{2R}\right) \quad (3)$$

For a spudcan on the ground surface, Eq. (3) simplifies such that squeezing can be expected when $T \leq 0.29 \cdot 2R$.

Dean [11] has proposed a slightly modified version of the squeezing formulation which differs from the SNAME formulation by up to 14% for depth to diameter ratios in the range of 0 to 3.

Brown & Meyerhof [5] and Merifield & Nguyen [8] present modified bearing capacity factors dependent on the ratio of undrained shear strengths between the strong and weak clay layers and the thickness of the weak clay layer.

Hossain [10] found that the limiting squeezing depth, $h_{sq}$ (equivalent to T in Eq. (3)), is a function of the strength ratio between the layer through which the spudcan is penetrating and at least two successive underlying layers, in addition to the height and strength of the soil plug trapped underneath the spudcan. For a zero height soil plug condition, Hossain reports $h_{sq}/2R$ ratios of 0.17 and 0.28 (the former is for an $s_{u,weak}/s_{u,strong}$ ratio of around 0.24 whilst the latter is for soft clay over sand).

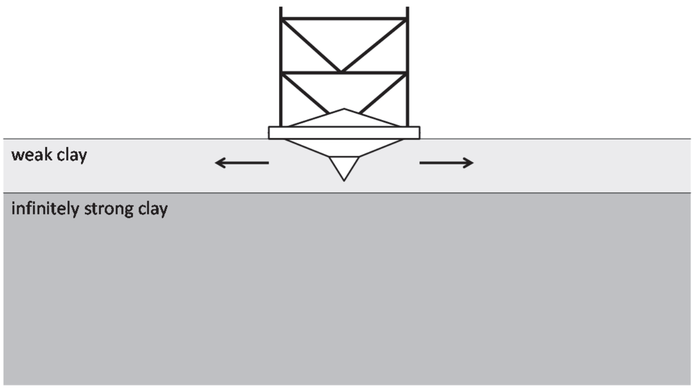



Figure 1: General representation of the squeezing mechanism for a surface footing

The general mechanism for punch-through of a strong clay layer into an underlying weak clay is presented in Figure 2. Industry guidance ([1] & [2]) for the assessment of punch-through for two clay layers is based on Brown & Meyerhof [5], which can be presented as follows for a circular footing:

$$q = q_{net} + p_0' = s_{u,strong}\left(\frac{3H}{2R} + N_c s_d \frac{s_{u,weak}}{s_{u,strong}}\right) + p_0' \qquad (4)$$

where: $s_{u,strong}$ = undrained shear strength of stronger layer
$s_{u,weak}$ = undrained shear strength of weaker layer
H = thickness of stronger layer
$s_d$ = bearing capacity depth factor.

Dean [11] has proposed a slightly modified version of the punch-through formulation where the coefficient "3" in Eq. (4) is replaced by 4α, where α is a factor that can be selected based on judgement and experience. Hossain [10] highlighted the importance of including the influence of the soil plug trapped beneath the spudcan in the assessment of punch-through.

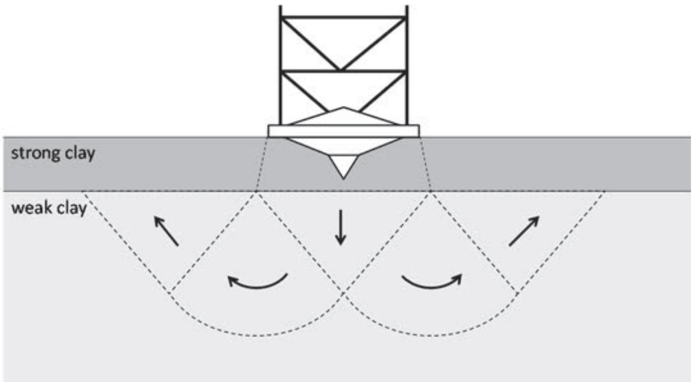



Figure 2: General representation of the punch-through mechanism for a surface footing

FINITE ELEMENT MODEL

The finite element program PLAXIS [12] was used to estimate the bearing capacity of the foundation systems. Key assumptions employed in the analyses were:

- 2D axisymmetric condition;
- Perfectly rough interface between the spudcan and soil;
- Undrained soil conditions;
- Homogenous soil layers.

Two geometric models were considered in the analyses:

- weak-strong model: weak clay overlying strong clay;
- strong-weak-strong model: strong clay overlying weak clay overlying strong clay.

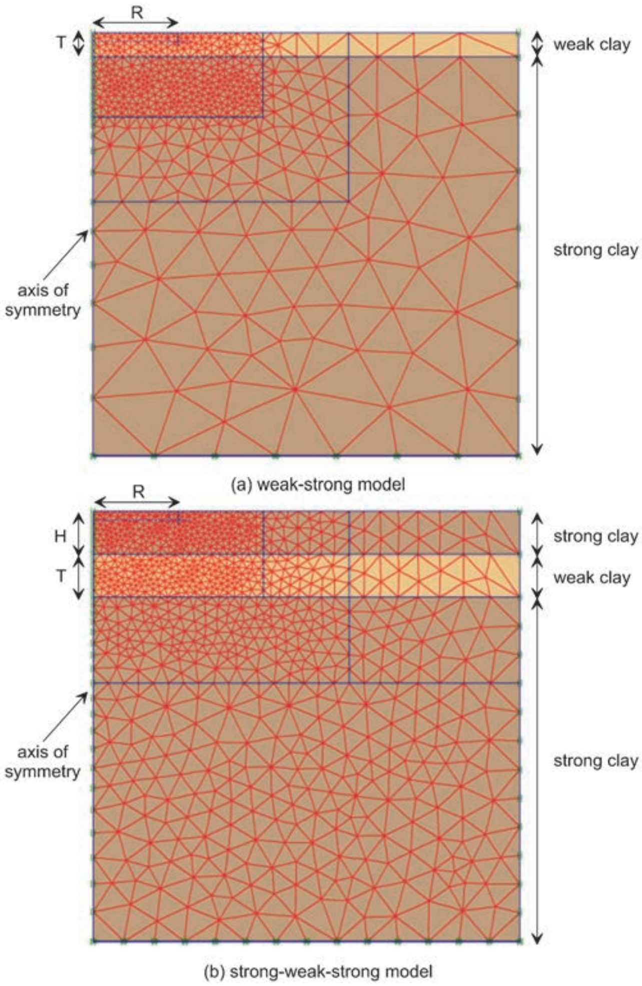


Figure 2: Example finite element mesh geometries

Example model geometries are presented in Figure 2. The spudcan was modelled as a rigid circular footing with a diameter (2R) of 14 m. Houlsby & Martin [13] have shown the undrained shape factor to be constant for conical footings with an apex angle of greater than 110°. Since spudcans typically have equivalent apex angles that are greater than this, modelling the spudcan as a flat circular footing is a reasonable approximation for purely vertical loading.

Interface elements were included between the spudcan and the soil and were modelled to give a perfectly rough interface. For all analyses, the spudcan was resting on the soil surface.

The weak-strong model was analysed to assess how the squeezing mechanism varies with differing weak-to-strong strength ratios. For this model, the thickness of the weak clay layer was varied to give thickness (T) to spudcan diameter (2R) ratios of between 0.02 and 1.0.

The strong-weak-strong model was analysed to assess how the failure mechanism changes when the soft clay layer is positioned between two stronger clay layers. For this model, the thicknesses of the overlying strong clay (H) and the weak clay layer (T) were varied to give H/2R and T/2R ratios of between 0.02 and 2.0.

An elastic-perfectly plastic material model with a Tresca failure criterion was used in the analyses with the parameters selected for use with undrained capacity analyses. The undrained shear strength of the strong clay, $s_{u,strong}$, was set equal to 200 kPa. The undrained shear strength for the weaker layer, $s_{u,weak}$, selected to give weak-to-strong strength ratios ($s_{u,weak}/s_{u,strong}$) of 0.10, 0.18, 0.40, 0.60 and 0.80. Each layer was modelled with constant undrained shear strength.

RESULTS – WEAK-STRONG MODEL

Results from the analyses of the weak-strong model are presented in Figure 3. The results are presented in terms of normalised bearing capacity ($q_{net}/s_{u,weak}$) and a weak clay thickness normalised by the diameter of the spudcan (T/2R). Squeezing calculations according to Meyerhof & Chaplin [4] and SNAME T&RB 5-5A [1] are presented in Figure 3 for comparison, as are the recommendations from Brown & Meyerhof [5] and data from Merifield & Nguyen [8].

Edwards & Potts [4] considered the punch-through bearing capacity of a rough flat-based circular footing resting on a thin strong clay overlying weak clay. Further unpublished analyses by Edwards used the same approach and finite element mesh to investigate the squeezing capacity of a rough flat-based circular footing resting on a thin weak clay layer overlying a strong clay layer, as considered here. The data from those analyses has been shared with the Authors of this paper in order to provide a comparison from the PLAXIS results and are also plotted in Figure 3.

The following points are noted from Figure 3:

1. $q_{net}/s_{u,weak}$ decreases with increasing T/2R;
2. $q_{net}/s_{u,weak}$ decreases with increasing $s_{u,weak}/s_{u,strong}$;
3. Squeezing is observed to occur when $T/2R \leq 0.3$, which compares well with the Meyerhof & Chaplin and SNAME calculations and also with data from Brown & Meyerhof [5], Merifield & Nguyen [8] and Edwards (see above);
4. Very good agreement is observed between the FE results and the Meyerhof & Chaplin and SNAME calculations where $s_{u,weak}/s_{u,strong} = 0.1$;
5. Where $s_{u,weak}/s_{u,strong} > 0.1$, the Meyerhof & Chaplin and SNAME calculations give higher $q_{net}/s_{u,weak}$ ratios than those determined from the FE analyses. A similar trend is evident from the data provided by Edwards.

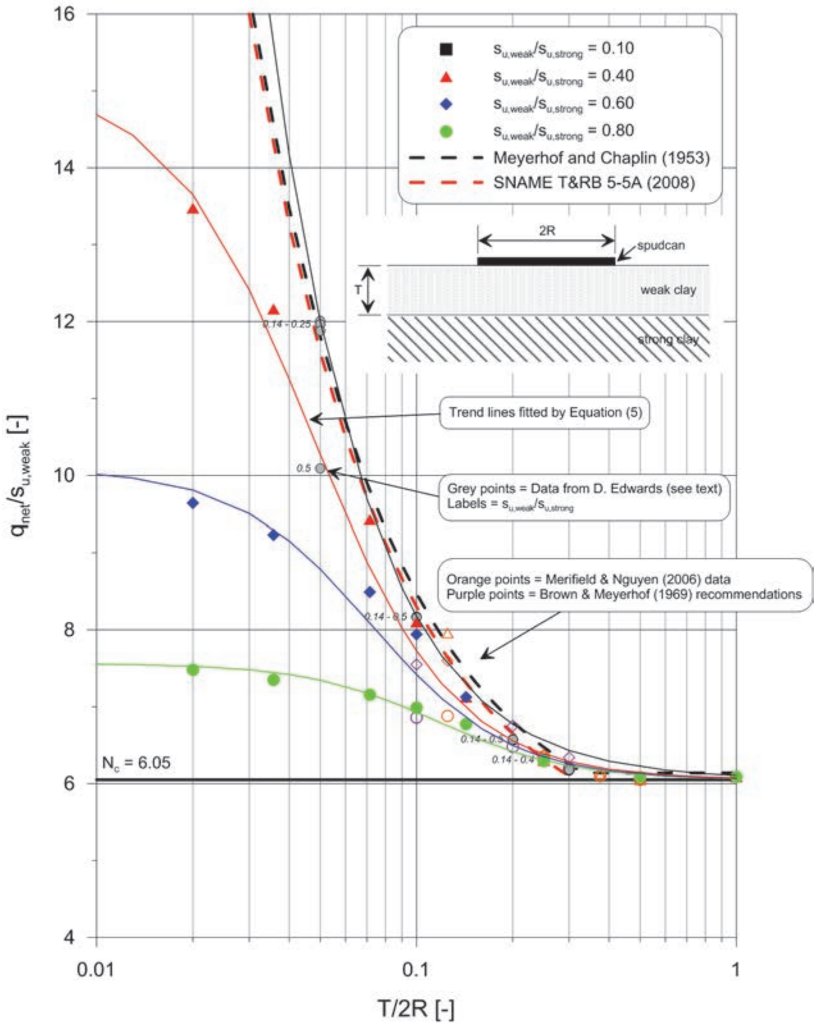



Figure 3: Weak-strong scenario – bearing capacity factor from FE analyses (perfectly rough spudcan)

The difference highlighted in point 5 above is considered attributable to a change in the failure mechanism, with increased mobilised resistance from the underlying strong clay as the $s_{u,weak}/s_{u,strong}$ ratio increases. This is demonstrated in Figure 4 which presents plots of incremental displacements for a geometry of T/2R = 0.1 for different strength ratios.

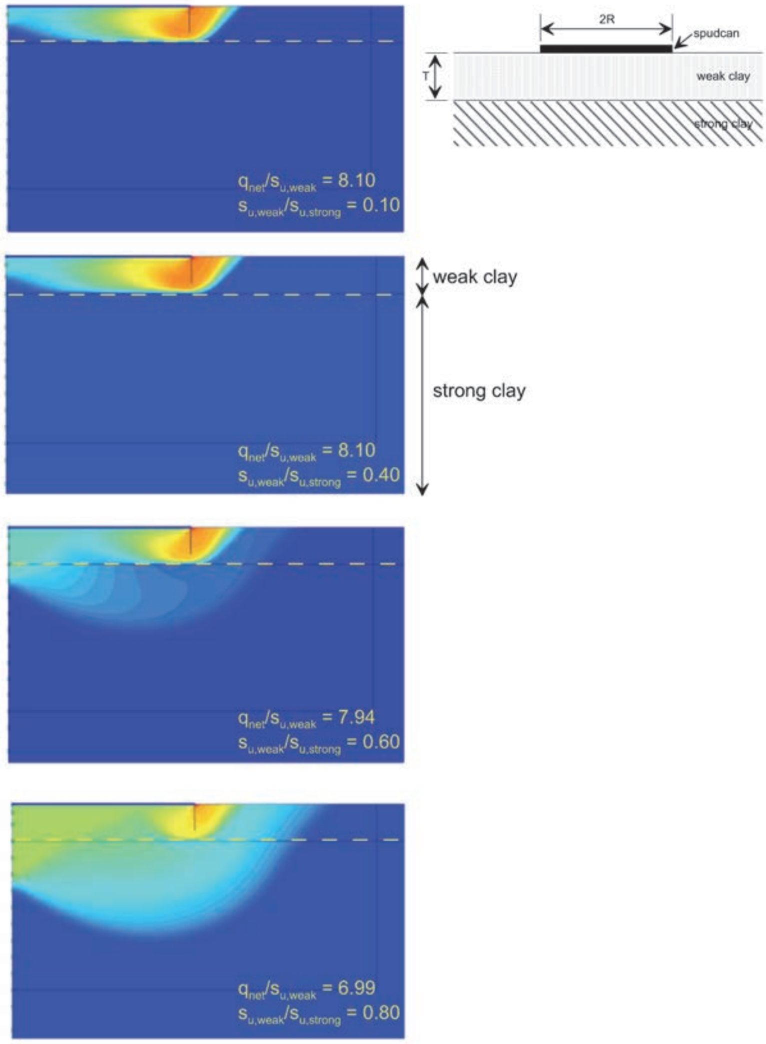
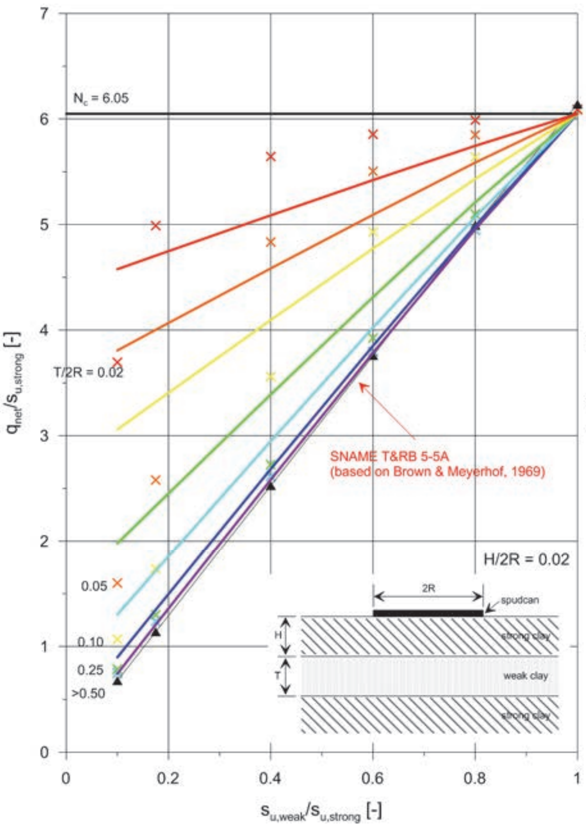



Figure 4: Weak-strong scenario - contours of incremental displacements (T/2R = 0.10; perfectly rough spudcan)

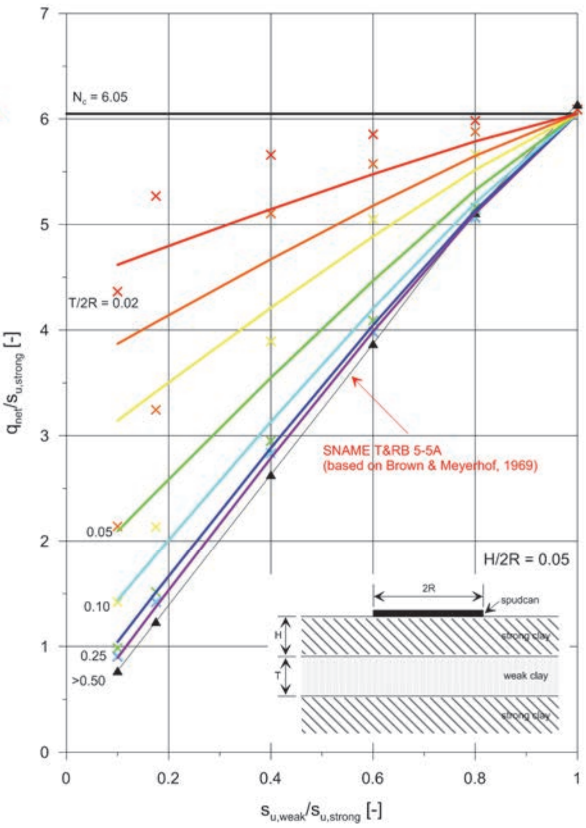
RESULTS – STRONG-WEAK-STRONG MODEL

Results from the analyses of the strong-weak-strong model are presented in Figures 5(a) to (g) for differing thicknesses of the strong surface clay (H/2R). The results are presented in terms of normalised bearing capacity ($q_{net}/s_{u,strong}$), the shear strength ratio ($s_{u,weak}/s_{u,strong}$) and a normalised weak clay thickness (T/2R). Punch-through calculations according to SNAME T&RB 5-5A [1], which are based on Brown & Meyerhof [5] and consider T to be infinitely large, are presented in the figures for comparison.



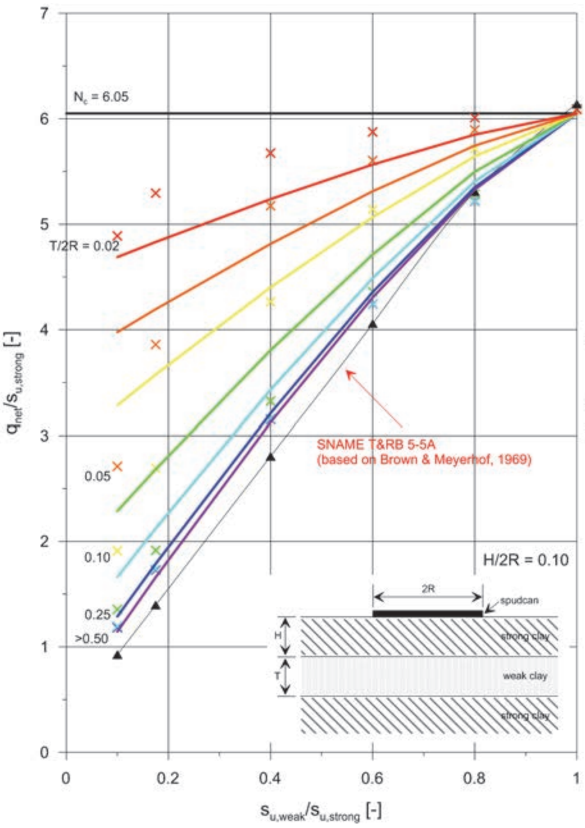
$N_c$ = 6.05
T/2R = 0.02
0.05
0.10
0.25
>0.50
SNAME T&RB 5-5A
(based on Brown & Meyerhof, 1969)
H/2R = 0.02
2R
spudcan
H
T
strong clay
weak clay
strong clay
$q_{net}/s_{u,strong}$ [-]
$s_{u,weak}/s_{u,strong}$ [-]


(a)



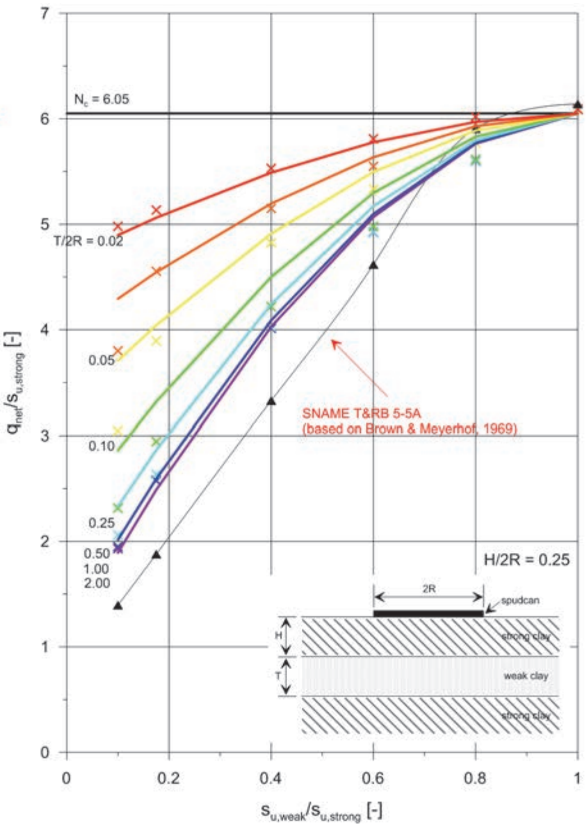
$N_c$ = 6.05
T/2R = 0.02
0.05
0.10
0.25
>0.50
SNAME T&RB 5-5A
(based on Brown & Meyerhof, 1969)
H/2R = 0.05
2R
spudcan
H
T
strong clay
weak clay
strong clay
$q_{net}/s_{u,strong}$ [-]
$s_{u,weak}/s_{u,strong}$ [-]


(b)



$N_c$ = 6.05
T/2R = 0.02
0.05
0.10
0.25
>0.50
SNAME T&RB 5-5A
(based on Brown & Meyerhof, 1969)
H/2R = 0.10
2R
spudcan
H
T
strong clay
weak clay
strong clay
$q_{net}/s_{u,strong}$ [-]
$s_{u,weak}/s_{u,strong}$ [-]


(c)



$N_c$ = 6.05
T/2R = 0.02
0.05
0.10
0.25
0.50
1.00
2.00
SNAME T&RB 5-5A
(based on Brown & Meyerhof, 1969)
H/2R = 0.25
2R
spudcan
H
T
strong clay
weak clay
strong clay
$q_{net}/s_{u,strong}$ [-]
$s_{u,weak}/s_{u,strong}$ [-]


(d)

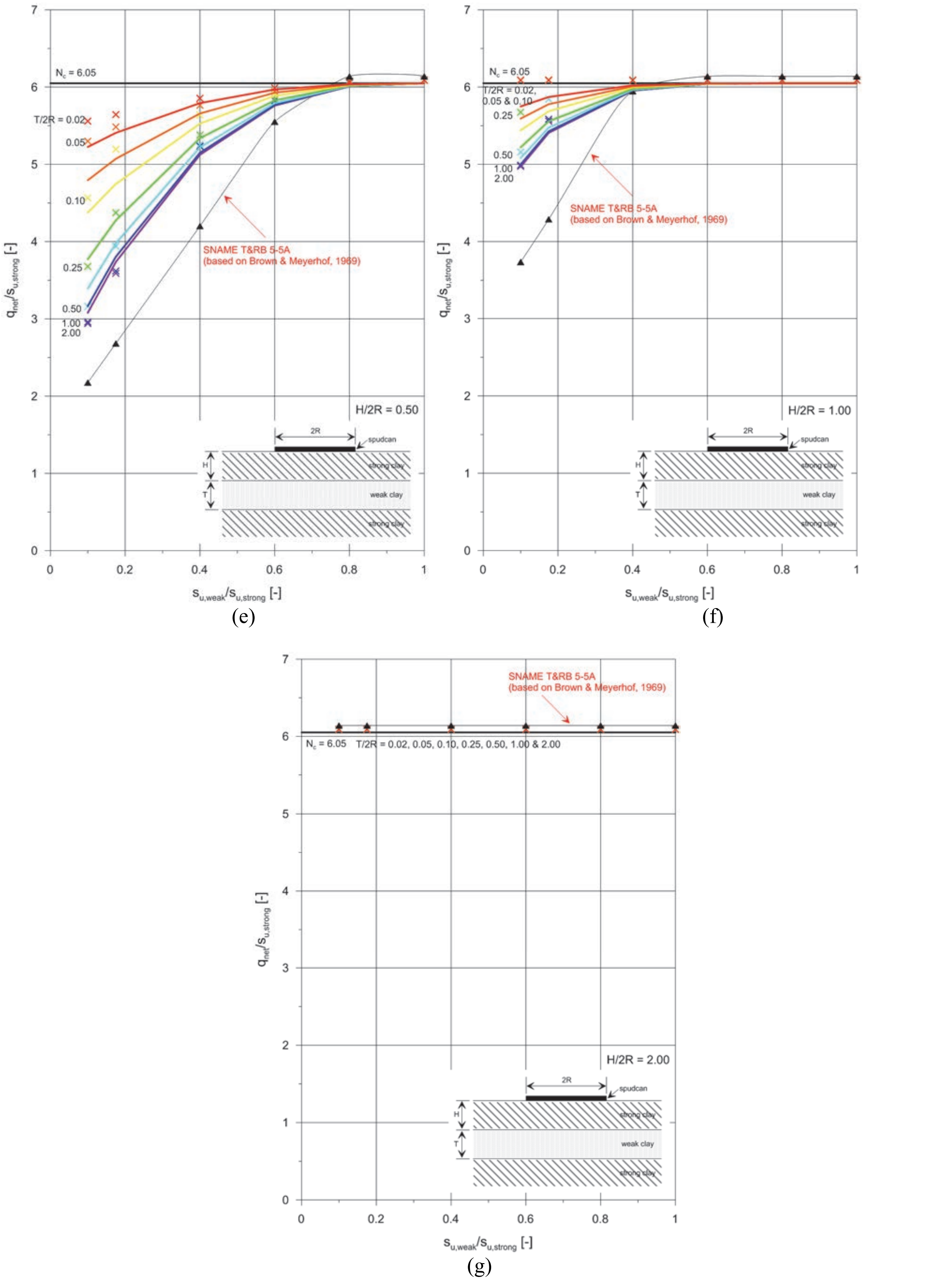



Figure 5: Strong-weak-strong scenario - bearing capacity factor from FE analyses (perfectly rough spudcan) (a) H/2R=0.02, (b) H/2R=0.05, (c) H/2R=0.1, (d) H/2R=0.25, (e) H/2R=0.5, (f) H/2R=1, (g) H/2R=2

The following points are noted from the Figure 5:

1. $q_{net}/s_{u,strong}$ decreases with decreasing $s_{u,weak}/s_{u,strong}$;
2. $q_{net}/s_{u,strong}$ increases with increasing H/2R;
3. $q_{net}/s_{u,strong}$ decreases with increasing T/2R;
4. When H/2R ≥ 2.0, bearing resistance is mobilised entirely within the strong surface clay;
5. When H/2R = 1.0, bearing resistance is mobilised entirely within the strong surface clay except when $s_{u,weak}/s_{u,strong}$ is less than approximately 0.3;
6. For a given H/2R ratio, the variation in $q_{net}/s_{u,strong}$ is essentially consistent when T/2R ≥ 0.5;
7. When T/2R ≥ 0.25, the variation in $q_{net}/s_{u,strong}$ is approximately consistent for H/2R ≤ 0.25;
8. The SNAME T&RB 5-5A [1] punch-through calculations are observed to give lower $q_{net}/s_{u,strong}$ ratios than those determined from the FE analyses (except when $s_{u,weak}/s_{u,strong}$ = 0.80). This observation is consistent with Merifield et al. [6] and Edwards & Potts [7]. The difference between the SNAME calculations and the lowest capacities calculated from the FE analyses increases as H/2R increases.

As with the weak-strong model, the difference between the FE analyses and the SNAME T&RB 5-5A [1] calculations are considered to result from changes in the failure mechanism that depend on the relative strengths and thicknesses of the soft and strong clay layers. This is demonstrated in Figure 6 which presents plots of incremental displacements for a strong surface clay thickness of H/2R = 0.25, a constant strength ratio $s_{u,weak}/s_{u,strong}$ = 0.4 and varying T/2R. For small T/2R ratios (e.g. T/2R < 0.25), the failure mechanism appears to be dominated by squeezing of the weak clay. As T/2R increases, the failure mechanism becomes larger and more like a general shear / punch-through type failure, as evidenced for T/2R ratios of 0.50 and 2.00 in Figure 6. In general, it is considered that squeezing type mechanisms are likely to occur when H/2R ≤ 1.00 and T/2R < 0.25.

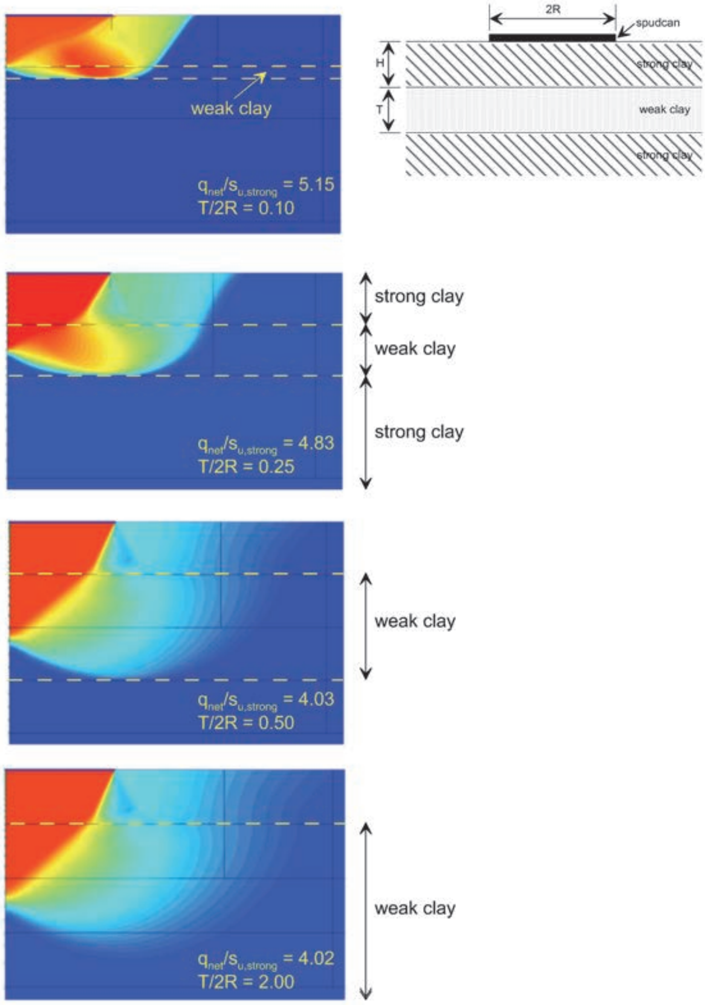



Figure 6: Strong-weak-strong scenario - contours of incremental displacements (H/2R = 0.25; $s_{u,weak}/s_{u,strong}$ = 0.40; perfectly rough spudcan)

APPLICATION IN ENGINEERING PRACTICE

To facilitate application of the results from this study in engineering practice, relationships have been fitted to the numerical results presented above. Results from this exercise are summarised below. Note however that validation of the relationships with field and/or laboratory test data are required in order for the results to be adopted for general use.

*Weak-strong soil scenario*

The modified bearing capacity factor, $N_c^*$, for the weak-strong soil profile can be represented by the following relationship:

$$\frac{q_{net}}{s_{u,weak}} = N_c^* = N_c\left(1+\frac{N}{1+a\left(T/2R\right)^b}\right) \tag{5}$$

where: $q_{net}$ =

$N_c$ = 6.05 = bearing capacity factor for a surface circular footing on the weaker clay layer

$N$ = $(s_{u,strong}/s_{u,weak} - 1)$

$a$ = $-420\cdot\ln(s_{u,weak}/s_{u,strong})$

$b$ = $0.25\cdot\ln(s_{u,weak}/s_{u,strong}) + 2.17$

The coefficient *N* limits $N_c^*$ to a maximum value corresponding to soil failure occurring entirely in the underlying stronger clay layer. The coefficient *a* and exponent *b* are both functions of the shear strength ratio $s_{u,weak}/s_{u,strong}$. Eq. (5) provides a good fit to the numerical results, as shown in Figure 3.

*Strong-weak-strong scenario – fully degraded capacity*

For a strong-weak-strong soil profile, the bearing capacity of a spudcan resting on the surface layer stops decreasing with further increase of the weak layer thickness beyond a certain point for a given normalised top layer thickness (H/2R) and strength ratio $s_{u,weak}/s_{u,strong}$. In this paper, this limiting capacity referred as the *fully degraded* capacity. For an infinitely thick weak layer, the Brown & Meyerhof [5] recommendation corresponds to the fully degraded capacity and can be written in the general format as:

$$q = q_{net} + p_0' = s_{u,strong}\left(\alpha\left(\frac{4H}{2R}\right) + N_c s_d \frac{s_{u,weak}}{s_{u,strong}}\right) + p_0' \le s_{u,strong} N_c s_d + p_0' \tag{6}$$

The Brown and Meyerhof bearing capacity equation assumes that the punching shear capacity consists of two components:1) general shear in the lower layer; 2) shear resistance on the cylindrical punching shear surface formed in the upper layer. A coefficient $\alpha$ is applied to undrained shear strength to derive the shear resistance along the punching shear surface. A constant value $\alpha = 0.75$ is used in the ISO & SNAME guidelines [1 & 2]. The bearing capacity is also limited to the general shear capacity calculated for a uniform profile with the shear strength of the top (strong) layer.

In Figure 5, the Brown & Meyerhof recommended capacity is plotted together with the numerical results. Generally speaking, the Brown & Meyerhof equation provides a reasonable prediction of the fully degraded capacity when the top layer is relatively thin (H/2R < 0.1 approx.), but increasingly underestimates the punch-through capacity as the normalised top layer thickness increases. In order to capture the trend demonstrated by the numerical results, modification is proposed to the Brown & Meyerhof equation:

$$q = s_{u,strong}\left(\left(\frac{4H}{2R}\right)\left(1-\frac{s_{u,weak}}{s_{u,strong}}\right)^A + N_c s_d\left(1-\left(1-\frac{s_{u,weak}}{s_{u,strong}}\right)^A\right)\right) + p_0' \le s_{u,strong} N_c s_d + p_0' \tag{7}$$

The modification is based on the hypothesis that as the strength ratio ($s_{u,weak}/s_{u,strong}$) increases, i.e. difference in soil strengths becomes smaller, the contribution from the punching shear mechanism (first part of the equation) decreases, whereas the contribution from the general shear mechanism in the weak layer (the second part of the equation) increases. The exponent *A* determines the rate of change between the two failure mechanisms and is found to be a function of the normalised top layer thickness, H/2R:

$$A = 1 + 2.5\left(\frac{H}{2R} + \left(\frac{H}{2R}\right)^2\right)$$, valid for H/2R ≤ 1.5 for a surface circuar footing (8)

The quality of the fit to the numerical results for the fully degraded condition is shown to be excellent (purple lines in Figure 5).

It is worth pointing out that the combined capacity due to the two failure mechanisms must be limited by the capacity of a uniform clay layer with the strength of the top layer. For $s_{u,weak}/s_{u,strong}$ =1, the condition is automatically satisfied. For the extreme case of $s_{u,weak}/s_{u,strong}$ =0, the condition is met when:

$$\left(\frac{4H}{2R}\right) \leq N_c s_d \tag{9}$$

For a surface circular footing, $N_c s_d$ = 6.05, which requires H/2R ≤ 1.5 to satisfy the condition. The implication is that if the normalised top layer thickness (H/2R) is greater than 1.5, the bearing capacity of the spudcan is uninfluenced by the underlying weak layer, regardless of its strength or thickness. This seems to be consistent with the numerical results for H/2R = 1 and 2. It can be further proved that as long as H/2R ≤ $N_c s_d$/4 (H/2R ≤ 1.5 for a surface footing), the calculated capacity using Eq. (7) is no greater than the single layer capacity for any $s_{u,weak}/s_{u,strong}$ ratio between 0 and 1.

*Strong-weak-strong scenario – effect of weak layer thickness*

The underlying assumption in the Brown & Meyerhof bearing capacity equation (Eq. 6) is that the underlying weak layer is thick enough (or infinitly thick) that the fully degraded capacity will be experienced. In reality, the thickness of the weak layer is often limited. The numerical results presented in Figure 5 show that as the thickness of the weak layer reduces, $q_{net}/s_{u,\,strong}$ increases (i.e. the influence of the weak layer reduces), which implies that the spudcan capacity could be underestimated using the Brown & Meyerhof equation for such conditions. To capture the effect of the normalised weak layer thickness (T/2R), a so-called *degradation function* is introduced to desribe the decrease (degradation) of foundation capacity with the increase of weak layer thickness. The capacity of a circular footing resting on a soil profile with certain *H/2R*, *T/2R* and $s_{u,weak}/s_{u,strong}$ can be calculated by:

$$q = q_{net} + p_0' = q_{net\_degraded} + \left(q_{net\_uniform} - q_{net\_degraded}\right) f_d + p_0' \tag{10}$$

where $q_{net\_degraded}$ is the fully degraded net bearing capacity moblised for a thick weak layer (Eq. 7); $q_{net\_uniform}$ is the net bearing capacity for a uniform clay layer with the shear strength of the top (strong) layer; $f_d$ is the degradation function and is related to *T/2R* by:

$$f_d = \tanh\left(2\left(\frac{T}{2R}\right)^{0.5}\right) \tag{11}$$

Using Eqs. 10 and 11 it is possible to predict the spudcan bearing capacity for any specific combination of *H/2R*, *T/2R* and $s_{u,weak}/s_{u,strong}$, as shown by the solid lines in Figure 5. It can be seen that the proposed approach offers a reasonable qualitative description of the numerical results. The quality of the fit is generally good for *H/2R* ≥ 0.1 and $s_{u,weak}/s_{u,strong} \geq 0.2$. However, as the top layer thickness becomes small (H/2R < 0.1) or when the strength ratio becomes small ($s_{u,weak}/s_{u,strong}$ < 0.2), the prediction using Eq. 10 can deviate considerably from the numerical results. This is due to the simplicity of the degradation function adopted, which is only a function of the normalized weak layer thickness. In reality, it is likely to be also a function of the top layer thickness (or alternatively the ratio of *T/H*) and the strength ratio.

CONCLUDING REMARKS

The results from a parametric finite element based study on the effect of the weak layer in both a two layer (weak-strong) and a three layer (strong-weak-strong) soil profile in clay have been considered.

Results from the weak-strong analyses have shown that squeezing is observed to occur when the thickness of the weak clay layer is less than about 0.3 times the spudcan diameter. This observation is independent of the undrained shear strength of the weak clay. The results compare well with the Meyerhof & Chaplin [4] and SNAME T&RB 5-5A [1] calculations. Very good agreement is observed between the Meyerhof & Chaplin and SNAME calculations where $s_{u,weak}/s_{u,strong}$ = 0.1. At higher $s_{u,weak}/s_{u,strong}$ ratios, the Meyerhof & Chaplin and SNAME calculations give higher $q_{net}/s_{u,weak}$ ratios than those determined from the FE analyses. This difference is attributed to a change in the bearing capacity failure mechanism, with increased mobilised resistance from the underlying strong clay as the $s_{u,weak}/s_{u,strong}$ ratio increases.

Results from the strong-weak-strong analyses have generally shown that as the thickness of the weak clay layer increases, the failure mechanism appears to change from a squeezing to a general shear / punch-through type failure. As general guidance, it is found that squeezing type mechanisms are likely to occur when the thickness of the weak clay is less than 0.25 times the spudcan diameter and the thickness of the overlying strong clay is less than 1.0 times the spudcan diameter. Comparative SNAME T&RB 5-5A punch-through calculations (based on Brown & Meyerhof [5]) provide a reasonable prediction of the fully degraded capacity when the top layer is relatively thin (H/2R < 0.1 approx.), but increasingly underestimate the punch-through capacity as the normalised top layer thickness increases. This difference is attributed to changes in the bearing capacity failure mechanism.

To facilitate application of the results from this study in engineering practice, relationships have been fitted to the numerical results. It is however noted that validation of the relationships with field and/or laboratory test data are required in order for the results to be adopted for general use. In principle, this approach is applicable to both penetration and bearing capacity analyses. For bearing capacity analyses, consideration also needs to be given to the cyclic strength of the soil.

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