An analytical parametric study of pipeline embedment into the seabed

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ABSTRACT

Subsea pipelines are a very important part of extracting hydrocarbons from offshore developments. They are an effective way to transport extracted hydrocarbons from offshore platforms back to shore where they can be processed and distributed. When a pipeline is laid across the seabed, it can sink into the seabed by displacing or compacting the solid below it under the heavy weight of the steel pipe, concrete coating, and the pipe contents. Pipeline embedment is affected by the installation method, the weight of the pipeline, the movement of the sea around the pipe and pipe laying vessel, and the rate at which the pipe is laid. It is also important to consider that pipe can be embedded by both vertical and horizontal movement. Different combinations of horizontal and vertical movement can cause deeper embedment and more complex conditions. The addition of content inside of the pipe during a hydrotest or normal operation may also affect pipe embedment since the additional weight may cause the pipeline to sink more.
This paper presents an analytical parametric study that examined the effect of some of the key factors affecting pipe embedment. Variables were changed one at a time while the other variables are kept at default values, and the effects on pipe embedment were monitored and analyzed. The study revealed several important trends. It was observed that several soil and pipe parameters affect the vertical force required for embedment in mostly linear patterns.

RÉSUMÉ

Les pipelines sous-marins jouent un rôle très important dans l'extraction d'hydrocarbures des aménagements offshore. Ils constituent un moyen efficace de transporter les hydrocarbures extraits de plates-formes offshore vers le continent, où ils peuvent être traités et distribués. Lorsqu'un pipeline est posé sur le fond marin, il peut s'enfoncer dans le fond marin en déplaçant ou en compactant le solide en dessous sous le poids lourd du tuyau en acier, du revêtement de béton et du contenu du tuyau. L'installation du pipeline dépend de la méthode d'installation, du poids du pipeline, du mouvement de la mer autour du tube et du navire poseur et de la vitesse à laquelle le tube est posé. Il est également important de considérer que le tuyau peut être encastré à la fois par des mouvements verticaux et horizontaux. Différentes combinaisons de mouvements horizontaux et verticaux peuvent provoquer une incrustation plus profonde et des conditions plus complexes. L'ajout de contenu à l'intérieur du tuyau pendant un test hydrostatique ou normal peut également affecter l'emboîtement du tuyau, car le poids supplémentaire peut faire en sorte que le pipeline s'enfonce davantage.
Cet article présente une étude paramétrique analytique examinant l’effet de certains des facteurs clés ayant une incidence sur l’intégration de la conduite. Les variables ont été modifiées une à la fois, tandis que les autres variables sont conservées à leurs valeurs par défaut. Les effets sur l'intégration du tuyau ont été surveillés et analysés. L'étude a révélé plusieurs tendances importantes. Il a été observé que plusieurs paramètres de sol et de conduite influent sur la force verticale requise pour l’intégration de manière principalement linéaire.

1. INTRODUCTION

Subsea pipeline embedment is an important aspect of pipe-soil interaction. Embedment depth is affected by different stages of the pipeline life cycle. During installation, the embedment depth is affected by the installation method, the weight and stiffness properties of the pipe, the sea state and vessel motion at the time of laying, and the lay rate. Embedment is affected by the orientation of forces acting on the pipe, such as vertical and horizontal forces. When the pipeline undergoes hydrotesting, the increased weight of the pipeline will cause further embedment. During operation, the embedment may be affected additionally.

Many uncertainties exist in modeling embedment and simplifications are necessary. Models exist for approximating pure vertical resistance for undrained and drained soil conditions.
In this study, an analytic parametric study was performed to examine the effect of various pipe and soil parameters has on the vertical force required to embed a subsea pipeline at a given depth. This paper presents an analysis of how the force required to achieve a specified level of pipeline embedment changes as a function of multiple soil properties and pipeline properties. The properties were changed within ranges that were determined based on a review of previous studies related to subsea pipeline embedment and other studies of subsea soil properties. Values of these parameters used by previous studies, or based on field

data and recorded in previous studies, were examined and ranges were decided based on the minimum and maximum values found.

Subsea pipeline embedment is a measure of how far the bottom of a subsea pipeline becomes embedded into the soil after it is laid on the seabed. The embedment occurs when the forces applied by the pipeline onto the soil deform the soil and create a deformity that the pipeline then resides in after it is installed.

The study was completed by using existing models to calculate the force required for embedment. By changing one variable in a model and plotting the effects it has on the required force, an understanding can be made about how that parameter affects embedment. This process was repeated for a variety of parameters. The effects of each parameter on embedment were compared to determine how each parameter had an impact.

2. LITERATURE REVIEW

The effects of various parameters on the embedment of subsea pipelines into the surface of soil on the seabed have been studied thoroughly by various authors in past literature.

The embedment of subsea pipelines has been so thoroughly studied because of its significant impact on the interactions between a subsea pipeline and the seabed. These interactions are important and worth examining because of their effects on the lateral movement of a pipeline, including pipeline walking and lateral pipeline buckling. Another factor contributing to the amount of study done on pipeline embedment into the seabed is the uncertainty inherent in predicting embedment. The ocean is a very dynamic and unpredictable environment by nature, and the operation of laying subsea pipe is one that involves very large material and equipment being manipulated remotely. This uncertainty makes it hard to predict and measure pipeline embedment, so it is important to have an idea of how the pipeline and soil will interact under various conditions.

This paper focuses mainly on the effects of various soil parameters on the depth of pipeline embedment into soil on the seabed, but other factors include the concentration of the force the pipeline applies to the seabed surface during installation and the motion of the pipeline as it is laid onto the seabed (Randolph & White, 2008).

Bruton (2014) found that existing pipeline embedment prediction models tended to underestimate embedment depths when compared to data from the field. This proposed means of addressing this issue include revising existing models to better incorporate "penetration resistance due to buoyancy, heave mounds and bearing capacity at embedment's over one-half diameter, which is a concern in weaker soils".

Another important factor addressed by Bruton (2014) is the reconsolidation of the seabed soil underneath the pipe in the time between the installation of the pipe and the flooding of the pipe. Bruton has posited that this reconsolidation of the soil under the weight of the empty pipe can have a significant impact on the strength of the soil, and so the added embedment caused by the extra weight of content in the pipe that occurs during the flooding process should be assessed using this new reconsolidated soil strength. Bruton found that since existing models did not account for the soil strength being reduced by the remolding that occurred when the pipeline was installed, the additional embedment that would occur when the pipeline was flooded would be significantly underestimated for lightweight pipelines of large diameter, since the weight of content these pipelines would be very significant compared to the weight of the pipeline itself. Bruton (2014) found that by using an estimate of the reconsolidated strength of the soil and accounting for the amount of time required for the soil to consolidate, more accurate predictions of the pipeline embedment after flooding could be found.

Randolph and White (2008) explained that a safe design for a subsea pipeline requires knowledge of the resistance the soil will exert on the pipeline when it is installed, which requires knowledge of how deep the pipeline will become embedded into the soil on the seabed after it has been laid. Being able to predict the amount of pipeline embedment somewhat accurately is important because, unlike some other fields of engineering, it is difficult to assume a conservative value. This is because both deep embedment and shallow embedment have potentially negative impacts on the safety of the pipeline. One example of such a compromise provide by Randolph and White (2008) is how a pipeline that is embedded deeply will have more resistance to lateral movement, which improves on-bottom stability, but will also have less convective heat losses due to being surrounded by soil instead of open ocean, so the effects of thermal expansion of the pipeline will be greater.

Randolph and White (2008) also state that the stresses resulting from the contact between the pipeline and the seabed soil during the laying procedure have a significantly greater impact on the pipeline's embedment into the soil than the embedment caused by the submerged weight of the pipe and the pipe's contents.

The other factor that Randolph and White (2007) identified as being a key factor in pipeline embedment was the movement of the pipeline as it makes contact with the seabed when being laid by the pipe-laying vessel. This movement is caused by the motion of the ocean surface, where waves and the sea-state cause the vessel to move while laying pipe, and by loads applied to the pipe by motion of the ocean below the surface, where waves and currents push water against the surface of the pipeline and apply hydrodynamic forces to the pipe.

Previous literature was also reviewed to form a basis for what reasonable ranges of values would be for the parameters adjusted in this study.

Tseng et al. (2010) examined the stability of soil with concerns for subsea pipelines. Their analysis showed values for the internal friction angle of subsea soil to be

15.2° to 37.3° based on 30 data sets. Senneset and Janbu (1985) suggested that reasonable values for internal friction angles for various types of subsea soils range between 19° and 42° depending on the soil type. Westgate et al. (2010) found the undrained shear strength at the surface of the seabed to range from 0 kPa to 0.5 kPa depending on the site examined.
Westgate et al. (2012) found the undrained shear strength gradient of subsea soil to range from 4 kPa/m to 38 kPa/m based on field observations. Westgate et al. (2010) found values ranging from 1 kPa/m to 20 kPa/m based on geotechnical site investigation depending on the site.
Multiple studies by Westgate et al. (2010, 2012) found values for the submerged unit weight of subsea soil ranging from 3 kN/m^3 to 8.5 kN/m^3.

3. METHODOLOGY

In this study, the vertical force required to embed a subsea pipeline at a given depth was examined. A diagram of an embedded pipeline can be seen in *Figure 1 - Diagram of an Embedded Subsea Pipeline*.

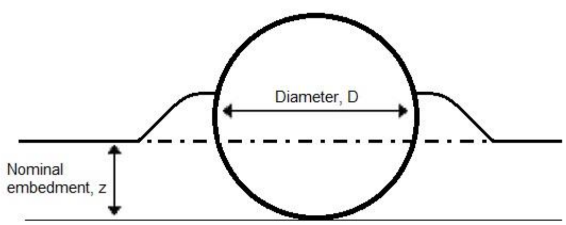

Figure 1 - Diagram of an Embedded Subsea Pipeline

The vertical force required to embed a pipeline is dependent on several factors. The vertical force required is dependent on the nominal embedment depth, z. It is dependent on the diameter of the pipe, D. Several properties of the seabed soil affect the vertical force required for embedment. Undrained and drained clay each have respective parameters that affect the vertical force to embed a pipeline.
To facilitate the analysis, a flowchart describing the algorithm used to calculate the vertical force required to embed a pipeline at a given depth was created. This flowchart can be seen in *Figure 2 - Flowchart of the Parametric Study of Pipeline Embedment*.

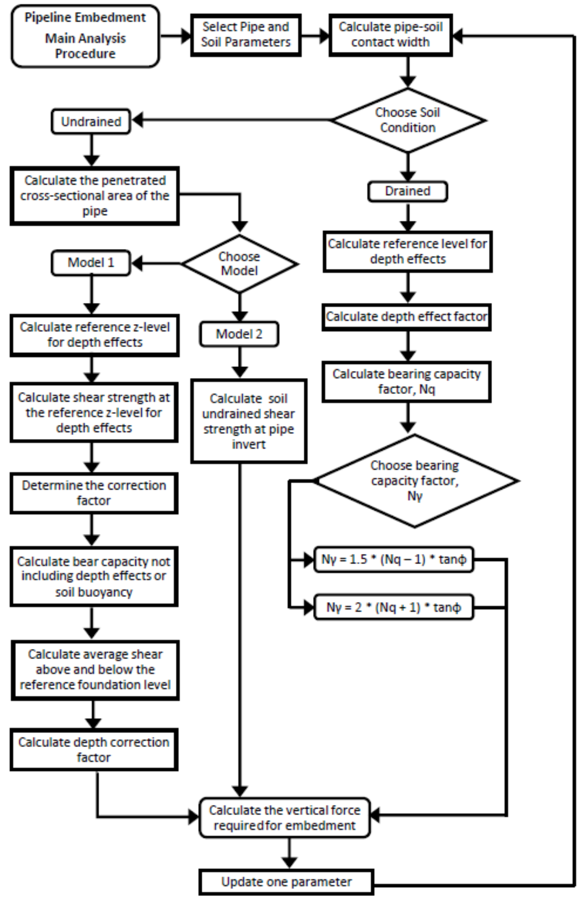

Figure 2 - Flowchart of the Parametric Study of Pipeline Embedment

3.1. UNDRAINED SOIL

Undrained soil is characterized by increasing pore water pressure as an applied load is increased due to water being unable to drain from the soil. There are two calculation models used for calculating vertical embedment force in undrained soils.

3.1.1. MODEL 1

The vertical force required, Q_v, to embed to depth, z, using Model 1 is described by (EH & Booker, 1973),

$$Q_v = Q_{v0}(1 + d_{ca}) + \gamma' A_{bm} \quad (1)$$

where Q_{v0} is soil bearing capacity without depth effects or soil buoyancy, d_{ca} is depth correction factor, γ' is submerged unit weight of soil and A_{bm} is penetrated cross-sectional area of the embedded pipe. The soil bearing capacity without depth effects or soil buoyancy, Q_{v0}, is calculated as,

$$Q_{v0} = F(N_c\, Su_{,0} + \rho B / 4)B \qquad (2)$$

where F is correction factor that is a function of pipe roughness and $\rho B / Su_{,0}$, N_c is bearing capacity factor for clay which was taken as 5.14 for smooth pipes and small penetrations. $Su_{,0}$ is undrained shear strength at the reference z-level for depth effects ρ is gradient of the undrained shear strength with embedment depth, B is pipe-soil contact width.
The pipe-soil contact width is a function of embedment depth, z, and is calculated as,

a) $B = 2\sqrt{Dz - z^2}$ $\quad z < D/2$

b) $B = D$ $\quad z \geq D/2$ $\qquad$ (3)

where D is total outside pipe diameter.
The undrained shear strength at the reference z-level for depth effects, $Su_{,0}$, is taken as,

$$Su_{,0} = Su_{,z=0} + \rho z_{Su_{,0}} \qquad (4)$$

where $Su_{,z=0}$ is undrained shear strength on the seabed, $z_{Su,0}$ is reference z-level for depth effects.
The reference z-level for depth effects is taken as the seabed for shallow penetrations and for deep penetrations is taken as the depth where a tangent line at a 45° angle to the pipe intersects a vertical line through the edge of the soil-pipe contact point. The reference z-level for depth effects can be calculated as,

$For\ z < (D / 2)(1 - \sqrt{2} / 2)$

$$z_{Su,0} = 0 \qquad (5)$$

$For\ z \geq (D / 2)(1 - \sqrt{2} / 2)$

$$z_{Su,0} = z + (D / 2)(\sqrt{2} - 1) - B / 2 \qquad (6)$$

The depth correction factor, d_{ca}, is calculated as,

$$d_{ca} = 0.3(Su_{,1} / Su_{,2})arctan(z_{Su,0} / B) \qquad (7)$$

where $Su_{,1}$ is average shear strength above the reference foundation level and calculated as ($Su_{,z=0} + Su_{,0}/2$, $Su_{,2}$ is average shear strength below the reference foundation level is $Q_{v0} / (BN_c)$.
The penetrated cross-sectional area of the embedded pipe is calculated as,

$For\ z < D / 2$

$$Abm = arcsin(B / D)D^2 / 4 - (BD / 4)cos(arcsin(B / D)) \qquad (8)$$

$For\ z \geq D / 2$

$$A_{bm} = \pi D^2 / 8 + D(z - D / 2) \qquad (9)$$

3.1.2. MODEL 2

The vertical force required, Q_v, to embed to depth, z, using Model 2 is described in past literature (Randolph & White, 2008) (Merifield, White, & Randolph, 2008) (Chatterjee, Randolph, & White, 2012). It can be calculated as,

$$Q_v = \left\{min\left[6(\frac{z}{D})^{0.25}, 3.4(\frac{10z}{D})^{0.5}\right] + 1.5\frac{\gamma' Abm}{Dsu}\right\}DS \qquad (10)$$

3.2. DRAINED

Drained soil is characterized by negligible pore water pressure in the soil as the water is able to drain from the soil. The vertical force required, Q_v, to embed a pipeline to depth, z, is given by (DNVGL-RP-F114, 2017),

$$Q_v = 0.5\gamma' N_\gamma B_2 + z_0 N_q d_q B \qquad (11)$$

where N_q is the bearing capacity factor equal to $e^{\pi tan\varphi} tan^2(45 + \frac{\varphi}{2})$,
N_γ is the bearing capacity factor being between $1.5(N_q - 1)tan\varphi$ to $2(N_q + 1)tan\varphi$,
φ is the friction angle of the soil, d_q is the factor accounting for depth effects and z_0 is the reference z-level for depth effects.
The reference z-level for depth effects is dependent on the friction angle of the soil, φ, and is given by,

$For\ z < (D / 2)(1 - cos(\pi / 4 + \varphi / 2))$

$$z_0 = 0 \qquad (12)$$

$For\ z \geq (D / 2)(1 - cos(\pi / 4 + \varphi / 2))$

$$z_0 = z - D / 2 + [\,(D / 2)/(sin(\pi / 4 + \varphi / 2)) - B / 2]tan(\pi / 4 + \varphi / 2) \qquad (13)$$

The depth factor, d_q, is calculated by,

$$d_q = 1 + 1.2\frac{z_o}{B} tan\,\varphi(1 - sin\,\varphi)^2 \qquad (14)$$

4. PARAMETRIC STUDY

An analytic parametric study of the vertical force required to penetrate a pipe to a given depth for both undrained and drained conditions was completed. Vertical force calculations were analyzed using two calculations models for undrained conditions and minimum and maximum values of the bearing capacity factor used in drained condition calculations. The effect of various pipe and soil parameters on the vertical force was analyzed.
The effect of the following parameters, seen in *Table 1 - Soil and Pipe Parameters*, on the vertical force required to penetrate a pipe were analyzed.

Table 1 - Soil and Pipe Parameters

Parameter	Symbol	Value	Unit
nominal embedment depth	z	1	m
outside pipe diameter	D	0.5	m
undrained shear strength on the seabed	Su,z=0	250	Pa
gradient of the undrained shear strength with embedment depth	ρ	5000	Pa/m
submerged unit weight of soil	γ'	3000	N/m^3
friction angle of the soil	φ	20	deg

Each parameter was individually changed while the remaining parameters were held constant and the effect on the vertical embedment force required was measured.
Since each trial involved changing one parameter while keeping the remaining parameters constant, it is important to note that in reality these soil parameters would normally be related and the change in one parameter would result in the change of the other parameters. For the purposes of the parametric study they are assumed to be independent.
Undrained and drained soil conditions are dependant on the rate of loading and the rate at which pore water can dissipate from space between soil particles. While certain soil types can predominately demonstrate either undrained or drained behaviour, calculation models for both conditions were analyzed despite selected parameters being indicative of either condition.

4.1. EMBEDMENT DEPTH

The embedment depth, z, was changed incrementally from 0 m to 1 m while the remaining parameters were held constant. The vertical embedment force for undrained and drained conditions was measured.
The embedment depth was held constant at 1 m during other trials due to the range of standard pipe sizes ranging from less than 1 m to greater than 1 m which would include unburied, partially buried and totally buried pipeline conditions to be included in the study.

4.2. PIPE DIAMETER

The pipe diameter, D, was changed incrementally from 0.540 in (0.0137 m) to 48.000 in (1.219 m) based on standard pipe sizes (ASME/ANSI B36.10 Welded and Seamless Wrought Steel Pipe) (ASME/ANSI B36.19 Stainless Steel Pipe) while the remaining parameters were held constant. The vertical embedment force for undrained and drained conditions was measured.
The outside pipe diameter was held constant at 0.5 m during other trials due to the range of embedment depths from 0 m to 1 m, which allows for varying burial conditions, from unburied to fully buried, to be included in the study.

4.3. UNDRAINED SHEAR STRENGTH OF SOIL ON THE SEABED SURFACE

The undrained shear strength of the soil on the seabed surface, $S_{u,z=0}$, was changed incrementally from 0 kPa to 0.5 kPa based on (Westgate, White, & Randolph, Pipeline Laying and Embedment in Soft Fine-Grained Soils: Field Observations and Numerical Simulations, 2010) while the remaining parameters were held constant. The vertical embedment force for undrained and drained conditions was measured.
The undrained shear strength of the soil on the seabed surface was held constant at 0.25 kPa during other trials as it is the median of the range being analyzed.

4.4. GRADIENT OF THE UNDRAINED SHEAR STRENGTH WITH EMBEDMENT DEPTH

The gradient of the undrained shear strength with embedment depth, ρ, was changed incrementally from 1 kPa/m to 38 kPa/m based on (Westgate, White, & Randolph, Pipeline Laying and Embedment in Soft Fine-Grained Soils: Field Observations and Numerical Simulations, 2010) (Westgate, White, & Randolph, 2012) while the remaining parameters were held constant. The vertical embedment force for undrained and drained conditions was measured.
The gradient of the undrained shear strength with embedment depth was held constant at 5 kPa/m during other trials. This value was randomly chosen between the selected range.

4.5. SUBMERGED UNIT WEIGHT OF SOIL

The submerged unit weight of soil, γ', was changed incrementally from 3 kN/m^3 to 8.5 kN/m^3 based on (Westgate, White, & Randolph, 2012) (Westgate, Randolph, White, & Li, 2010) (Westgate, White, & Randolph, Pipeline Laying and Embedment in Soft Fine-Grained Soils: Field Observations and Numerical Simulations, 2010) while the remaining parameters were held constant. The vertical embedment force for undrained and drained conditions was measured.
The submerged unit weight of soil was held constant at 3 kN/m^3 during other trials. This value was randomly chosen between the selected range.

4.6. FRICTION ANGLE OF SOIL

The friction angle of soil, ϕ, was changed incrementally from 15.2° to 42° based on (Tseng, et al., 2010) (Senneset & Janbu, 1985) while the remaining parameters were held constant. The vertical embedment force for undrained and drained conditions was measured.
The friction angle of soil was held constant at 20° during other trials. This value was randomly chosen between the selected range.

5. RESULTS

The following results were obtained from completing a parametric study on various parameters influencing subsea pipeline embedment.

5.1. EMBEDMENT DEPTH

As shown in *Figure 3 - Embedment Depth*, the vertical force required for the selected pipeline to penetrate the seabed with soil parameters seen in *Table 1 - Soil and Pipe Parameters* increases approximately linearly as the depth of embedment increases. The vertical force required for undrained soil conditions is larger than the vertical force required to penetrate drained soil.

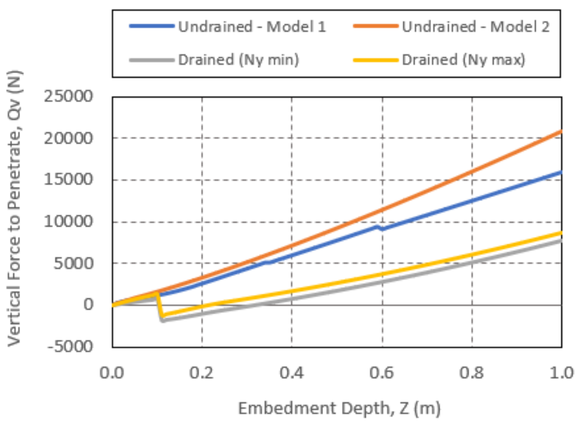

Figure 3 - Embedment Depth

5.2. PIPE DIAMETER

As shown in *Figure 4 - Pipe Diameter*, the vertical force required for a pipeline to penetrate the seabed with soil parameters seen in *Table 1 - Soil and Pipe Parameters* increases approximately linearly in undrained soil conditions as the diameter of the pipeline increases. The vertical force required for undrained soil conditions is larger than the vertical force required to penetrate drained soil. The vertical force to penetrate drained soil begins to peak and decrease as the pipe diameter equals the embedment depth.

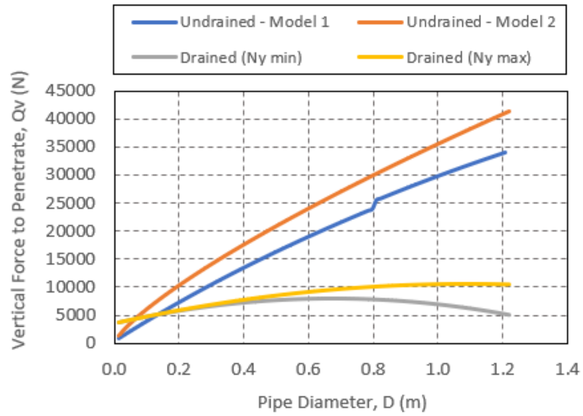

Figure 4 - Pipe Diameter

5.3. UNDRAINED SHEAR STRENGTH OF SOIL ON THE SEABED SURFACE

As shown in *Figure 5 - Undrained Shear Strength on the Seabed*, the vertical force required for the selected pipeline to penetrate the seabed with soil parameters seen in *Table 1 - Soil and Pipe Parameters* increases linearly in undrained soil as the undrained shear strength on the seabed surface increases. The vertical force required for drained soil conditions is not affected by this parameter.

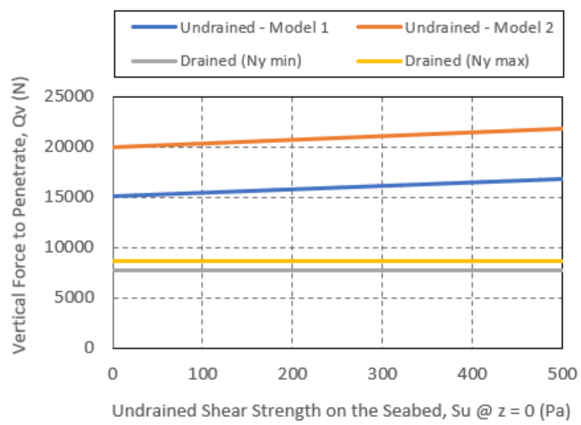

Figure 5 - Undrained Shear Strength on the Seabed

5.4. GRADIENT OF THE UNDRAINED SHEAR STRENGTH WITH EMBEDMENT DEPTH

As shown in *Figure 6 - Gradient of the Undrained Shear Strength with Embedment Depth*, the vertical force required for the selected pipeline to penetrate the seabed with soil parameters seen in *Table 1 - Soil and Pipe Parameters* increases linearly in undrained soil conditions as the gradient of the undrained shear strength with depth increases. The vertical force required for drained soil conditions is unaffected by this parameter.

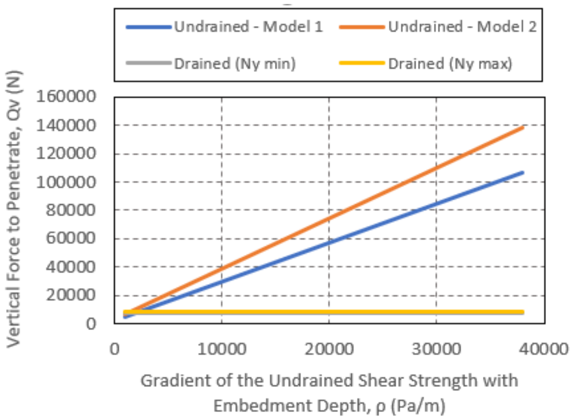

Figure 6 - Gradient of the Undrained Shear Strength with Embedment Depth

5.5. SUBMERGED UNIT WEIGHT OF SOIL

As shown in *Figure 7 - Submerged Unit Weight of Soil*, the vertical force required for the selected pipeline to penetrate the seabed with soil parameters seen in *Table 1 - Soil and Pipe Parameters* increases linearly as the submerged unit weight of soil increases. The vertical force required for undrained soil conditions is initially larger than the vertical force required to penetrate drained soil; however, the vertical force required in drained soil is more affected by the increase in submerged unit weight than for undrained soil conditions.

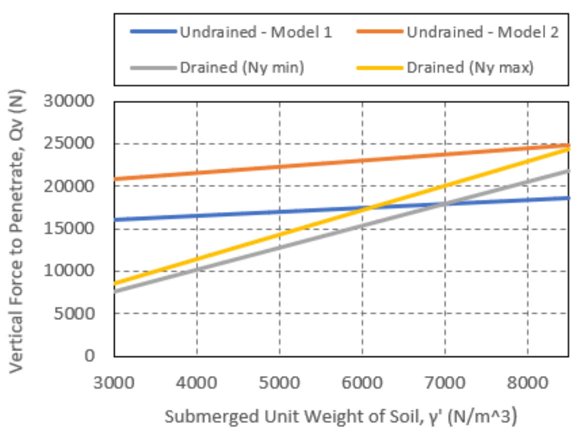

Figure 7 - Submerged Unit Weight of Soil

5.6. FRICTION ANGLE OF SOIL

As shown in *Figure 8 - Friction Angle of the Soil*, the vertical force required for the selected pipeline to penetrate the seabed with soil parameters seen in *Table 1 - Soil and Pipe Parameters* increases exponentially in drained soil conditions as the friction angle of the soil increases. The vertical force required for undrained soil conditions is not affected by this parameter.

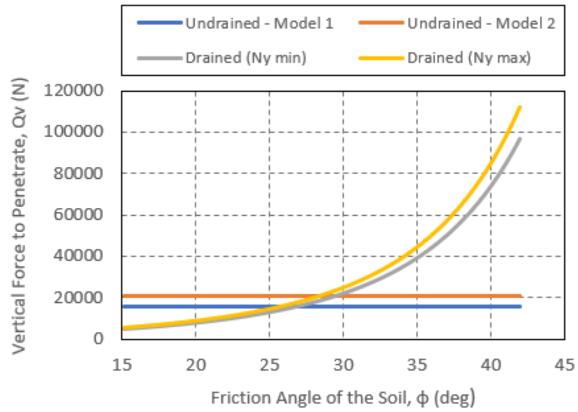

Figure 8 - Friction Angle of the Soil.

6. CONCLUSION

During this study, an analytic parametric study was performed to analyze the effects that various pipe and soil parameters have on the vertical force required to embed a subsea pipeline.

The analytic parametric study was conducted using a selected pipeline diameter penetrating the seabed with soil parameters seen in *Table 1 - Soil and Pipe Parameters*.

Based on the results of the parametric study of the effects of the selected soil and pipe parameters seen in *Table 1 - Soil and Pipe Parameters* on the vertical force required for embedment into the seabed, it was determined that most parameters affect the vertical force linearly.

It was observed that the vertical force required for the pipeline to penetrate the seabed increases approximately linearly as the depth of embedment increases. The vertical force required for a pipeline to penetrate the seabed increases approximately linearly in undrained soil conditions as the diameter of the pipeline increases and the vertical force to penetrate drained soil begins to peak and decrease as the pipe diameter equals the embedment depth.

Also, the force increases linearly in undrained soil as the undrained shear strength on the seabed surface increases and as the gradient of the undrained shear strength with depth increases.

The vertical force increases linearly as the submerged unit weight of soil increases. The vertical force required in drained soil is more sensitive to the increase in submerged unit weight than for undrained soil conditions. Also, the vertical force required for a pipeline to penetrate the seabed increases exponentially in drained soil conditions as the friction angle of the soil increases.

These results are limited and subjective to the chosen constant values of the soil parameters seen in *Table 1 - Soil and Pipe Parameters* which were independently selected within ranges determined by past literature.

More research should be given to analyze the studied relationships using more combinations of soil parameter values.

7. ACKNOWLEDGEMENTS

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