An analytical parametric study of lateral pipeline-soil interaction in partially embedded pipelines

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ABSTRACT
Pipelines can transport either liquid hydrocarbon or natural gas products and are a key component in offshore oil and gas development. Offshore pipelines are often laid on the seabed. However, factors such as the hydrodynamic force, the weight of the pipe and its contents, and laying effects, can cause a portion of the diameter of the pipeline to penetrate the seabed. A pipeline which was designed to lay on the seabed or be buried can become a partially embedded pipeline due to seabed mobility. Accounting for lateral pipeline soil interaction in partially embedded pipelines is therefore an important consideration for offshore pipeline design. Closed form solutions such as an analytical parametric study are an effective way of understanding engineering problems such as lateral pipeline-spill interaction in partially embedded pipelines. Although advanced experimental studies or finite element analysis would be able to more accurately predict the effects lateral pipeline-soil interaction in partially embedded pipelines, these approaches can be quite costly and impractical. An analytical parametric study was conducted to investigate the order of magnitude of various key parameters influencing soil interaction in partially embedded pipelines. Both drained and undrained conditions were studied and plots relating lateral breakout resistance to penetration were produced. For the undrained condition, the undrained shear strength was manipulated and three different models were plotted. For the drained condition, the angle of internal friction was varied to show the change in drained lateral breakout resistance with penetration for each of the roughness parameters. Two different models were plotted. Environmental and seabed soil properties were selected from Canadian offshore regions. The study revealed interesting trends, which can be useful for engineers designing pipelines in an offshore environment.

RÉSUMÉ
Les pipelines peuvent transporter des produits d'hydrocarbures liquides ou du gaz naturel et sont un élément clé du développement pétrolier et gazier en mer. Les pipelines en mer sont souvent posés sur le fond marin. Cependant, des facteurs tels que la force hydrodynamique, le poids du tuyau et son contenu, ainsi que les effets de pose, peuvent faire pénétrer une partie du diamètre du pipeline dans le fond marin. Un pipeline conçu pour reposer sur le fond de la mer ou être enterré peut devenir un pipeline partiellement intégré en raison de la mobilité du fond de la mer. La prise en compte de l'interaction sol-pipeline latérale dans les pipelines partiellement intégrés est donc une considération importante pour la conception d'un pipeline offshore. Les solutions sous forme fermée, telles que les études paramétriques analytiques, constituent un moyen efficace de comprendre des problèmes techniques tels que l'interaction latérale pipeline-déversement dans des pipelines partiellement encastrés. Bien que des études expérimentales avancées ou l'analyse par éléments finis soient en mesure de prédire plus précisément les effets de l'interaction latéral pipeline-sol dans des pipelines partiellement encastrés, ces approches peuvent être assez coûteuses et peu pratiques. Une étude paramétrique analytique a été menée pour étudier l'ordre de grandeur de divers paramètres clés influençant l'interaction des sols dans des pipelines partiellement encastrés. Les conditions drainées et non drainées ont été étudiées et des parcelles présentant une résistance à la pénétration latérale à la pénétration ont été produites. Pour la condition non drainée, la résistance au cisaillement non drainée a été manipulée et trois modèles différents ont été tracés. Pour la condition drainée, l'angle de frottement interne a été modifié pour montrer le changement de la résistance à l'évasion latérale drainée avec pénétration pour chacun des paramètres de rugosité. Deux modèles différents ont été tracés. Les propriétés environnementales des sols et des fonds marins ont été sélectionnées dans les régions extracôtières du Canada. L'étude a révélé des tendances intéressantes pouvant être utiles aux ingénieurs qui conçoivent des pipelines dans un environnement offshore.

1 INTRODUCTION

Pipeline geotechnics is an important aspect to consider in the design of subsea pipelines. This entails the way in which a pipeline interacts with the surrounding soil. Within this field of study, some important components include lateral pipeline-soil interaction and axial pipeline-soil interaction. Both are applicable to buried and partially embedded pipelines. The condition of the seabed is generally classified as either drained or undrained. The drained condition is typically coarse-grained soils such as sand and gravel and the undrained condition refers to fine-grained soil such as clay.

This paper focuses on the lateral pipeline-soil interaction in partially embedded pipelines, for both drained and undrained conditions. Pipeline embedment begins during pipe lay and may increase with time due to hydrodynamic forces, pipe content load and creep (Shiri 2019). Environmental conditions such as waves and currents lead to lateral forces (Shiri 2019). There are two stages of lateral pipe-soil response behaviour. The first stage is the first load displacement (monotonic), which is characterized by a breakout resistance and a steady residual resistance. The second stage involves cyclic displacement, which is characterized by the growth of soil berms at the limits of the pipe displacement range, with the pipe descending into a shallow trench. Embedment is primarily an issue of penetration bearing capacity failure until the soil resistance is sufficient to resist the load applied by the pipeline (Shiri 2019).

There are a number of different approaches to assess the lateral resistance among partially embedded pipelines. Three of the most notable approaches are as follows: single “friction factor” approach (lateral resistance is related to the submerged weight of the pipeline and the soil type), two component model consisting of a sliding resistance component and a lateral passive pressure component frictional model supplemented with passive resistance of the wedge of soil (Nyman 1984, Wagner et al. 1987, Lieng et al. 1988, Verley & Sotberg 1992, Verley & Lund 1995), and the plasticity model approach (Zhang et al. 1999, 2002, Cassidy 2004) (Shiri, 2019). As previously stated, this paper will examine the lateral pipeline-soil interaction in partially embedded pipelines, for both drained and undrained conditions. The magnitude of various key parameters that influence soil interaction are manipulated and plots relating lateral breakout resistance to penetration were produced.

2 LITERATURE REVIEW

Cheuk, White, & Bolton, 2007, conducted a series of large-scale model tests to study the relationship among large amplitude cyclic movements and partially embedded pipelines in soft clay. They identified four key stages in force-displacement response, breakout, suction re-lease, steady berm growth, and dormant berm collection. Cheuk, White, & Bolton also found that a peak value of resistance occurred at breakout, followed by a sudden drop due to tensile failure which was linked to a loss of suction as the pipe separated from the soil behind it (2007). When considering the lateral breakout resistance, various parameters affect the behaviour observed in a pipeline. Some of the key parameters explored in this paper which influence the lateral breakout resistance of a pipeline include; pipeline weight, degree of embedment, pipe surface roughness, and soil strength.

Verley and Sotberg, 1994 generated a soil resistance model for pipelines placed on sandy soils. Their model is capable of predicting the development of pipe penetration into the soil and the associated soil resistance that may be mobilized against the horizontal pipe motions. In their study, Verley and Sotberg also state that when a pipe is placed on a sandy soil and subject to oscillatory forces as a result of waves and currents, there is a complex interaction between pipe movements, penetration into the soil and soil resistance. Small movements cause penetration and large movements cause the pipe to break out of the soil (Verley & Sotberg, 1992). This demonstrates the complex relationship, which exists in lateral pipeline-soil interactions for partially embedded pipelines on the sea floor.

Chatterjee, White, & Randolph, 2011 explored the soil interaction during large lateral movements on clay by undertaking a parametric study varying the initial vertical embedment’s and level of overloading. They considered five different values of initial embedment (w/D = 0.1, 0.2, 0.3, 0.4 and 0.5) and five levels of overloading (V = 0.1 V_{max}, 0.2 V_{max}, 0.4 V_{max}, 0.6 V_{max} and 0.8 V_{max}). Where w is pipe invert embedment; D is pipe diameter; V is vertical force and V_{max} is vertical bearing capacity. They found that the heavier the pipeline, the greater the lateral resistance, when normalized by the local initial strength, because the heavier pipelines create a higher berm ahead (Randolph, White, & Chatterjee, 2012). This paper only considered a pipe of 406.4 mm diameter and thickness of 12.7 mm with a 5 mm enamel coating and 7 cm thick concrete layer. As such, the results obtained from this parametric study reflect only those of a medium weight pipeline as explored by Chatterjee, White, & Randolph. Chatterjee, White, & Randolph 2011 also found that the effect of embedment had a greater contribution to initial breakout resistance than the effect of weight (Randolph, White, & Chatterjee, 2012). Therefore, in varying the value of embedment for a constant diameter pipe, the lateral pipeline-soil interaction was modelled effectively.

Gao, Yan, Yang & Luo, 2010, studied the effects of pipe surface roughness and pipe initial embedment in relation to the lateral soil resistance for a sandy seabed. When studying the relationship between initial embedment (e_0/D) and lateral-soil resistance, Gao, Yan, Yang & Luo, 2010, considered test pipes with various initial embedments. The test pipes had a fixed value of submerged weight and diameter. Gao, Yan, Yang & Luo concluded that the initial embedment of the pipe is variable and would have on influence on the lateral stability of the pipe. For high values of initial embedment, there is a decrease in soil lateral resistance (Gao, Yan, Yang & Luo, 2010). Although initial embedment was not specifically studied for this paper, during this study, various embedment ratios were assumed to model the whole spectrum of pipeline embedment.

When studying the effects of pipe surface roughness, Gao, Yan, Yang & Luo considered two values of pipe surface roughness (k), k = 1.06 x 10^{-4} m and k = 1.25 x 10^{-5} m. Gao, Yan, Yang & Luo found that lateral soil resistance is greater for a rougher pipe. This analytic parametric study of lateral pipeline-soil interaction only considered steel pipes with a pipe-soil interface roughness factor, $r_{pipe\text{-}soil}$ of 0.6. As such, the variance in roughness for pipelines of different materials was not modelled in this study.

Wagner, Murff, Brennodden, & Sveggen, 1989 developed a model that predicts the soil resistance to lateral motions of untrenched submarine pipelines. This model was developed in the PIPESTAB Pipe-Soil

Interaction Project and improves upon previous estimations such as the coulomb friction estimation as it considers soil strength information and pipe displacement history (Wagner, Murff, Brennodden, & Sveggen, 1989). The coulomb friction estimation predicts the lateral soil resistance by considering the effective submerged pipeline vertical force, which is the submerged weight minus the hydrodynamic lift force, and the soil friction coefficient (Wagner, Murff, Brennodden, & Sveggen, 1989). The soil friction coefficient is commonly taken as 0.5 for clay and 0.8 for sand (Wagner, Murff, Brennodden, & Sveggen, 1989). The scope of the project undertook by Wagner, Murff, Brennodden, & Sveggen considered various soil conditions, which include loose silty fine sand, loose medium/ coarse sand, dense medium/coarse sand, soft clay and stiff clay. Like the paper by Wagner, Murff, Brennodden, & Sveggen, this analytic parametric study focuses on both clays and sands as it considers both the undrained and drained conditions of soils. The drained study looks at lateral breakout resistance for various internal angles of friction.

The general conclusion drawn from the tests on sand, as stated by Wagner, Murff, Brennodden, & Sveggen is that all cyclic loading causes additional penetration and soil mounding and therefore lateral soil resistance is increased. The magnitude of penetration is an important factor to consider in drained soil conditions (sand). As embedment is an important factor, the analytic parametric study presented in this paper considered the entire range of partial embedment (from unburied pipelines to fully buried pipelines).

For clay, increasing clay shear strength decreases the lateral soil resistance (Wagner, Murff, Brennodden, & Sveggen, 1989). Pipeline penetration/ embedment is also an important factor for undrained soils. Pipeline embedment can be more important for the lateral soil resistance than clay strength (Wagner, Murff, Brennodden, & Sveggen, 1989). Significant pipe penetration was observed in soft clay. Pipe weight causes larger penetration in soft clays and can cause a significant lateral earth pressure contribution to the total soil resistance (Wagner, Murff, Brennodden, & Sveggen, 1989). Additional pipe penetration due to cyclic loading, significantly increased the lateral soil resistance. For stiff clays, lower levels of soil resistance were observed which is largely attributed to reduced levels of penetration. Wagner, Murff, Brennodden, & Sveggen studied soft clay with an undrained shear strength of 1 kPa. The stiff clay studied by Wagner, Murff, Brennodden, & Sveggen had an undrained shear strength of 70 kPa. The analytic parametric study of undrained soil conditions presented in this paper considered soils with undrained shear strengths ranging in between those presented by Wagner, Murff, Brennodden.

The studies discussed in this literature review identify that the weight of the pipe, degree of embedment, pipe roughness, and soil strength, all influence lateral pipeline-soil interaction. Figure 1 shows the embedment (z) for a partially buried pipeline, along with the shear strength outside and underneath the pipe. It also shows the pipe-soil interface roughness.

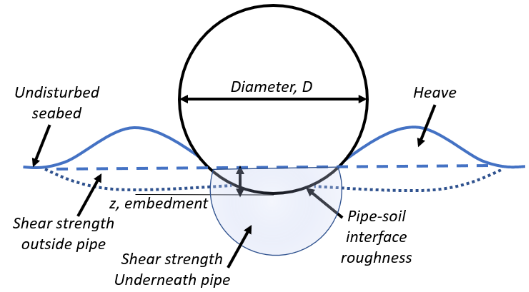

Figure 1. Lateral pipeline soil Interaction - partially embedded pipelines

3 METHODOLGY

An analytic parametric study was completed for the undrained and drained lateral breakout resistance of soils in partially embedded pipelines. The study followed equations outlined by DNV GL in the recommended practice DNVGL-RP-F114, "Pipe-soil interaction for submarine pipelines" (2017). The effects of lateral breakout resistance on partially embedded pipelines as described in Section 4.4 Lateral pipe-soil interaction of DNVGL-RP-F114 was the focus of this paper. Consideration for lateral residual resistance for the undrained and drained conditions was outside of the scope of this study.

Several forces act on subsea pipelines as shown in Figure 2. Friction created on the contract surface between the pipeline and underlying soil is one of the two main contributors to lateral breakout resistance. This friction is largely dependent on the weight of the pipeline. The design parameters used to determine the vertical pipe-soil force (submerged weight of pipe) are given in Table 1. The submerged weight of the pipe was determined using the principles of statics for the free body shown in Figure 2. The vertical pipe soil force was determined to be 2.71 kN.

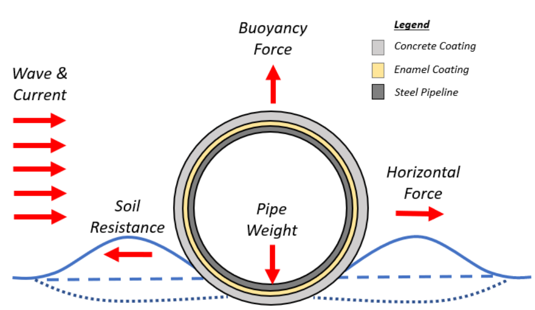

Figure 2. Partially embedded pipeline free body diagram

Table 1. Determination of vertical pipe-soil force, submerged weight of pipe inputs

Parameter	Symbol	Value	Unit
Outer diameter	D_o	0.4064	m
Wall thickness	t	0.0127	m
Concrete coat	$t_{concrete}$	0.07	m
Enamel coating	t_{coat}	0.005	m
Steel density	ρ_s	7850	kg/m^3
Concrete density	$\rho_{concrete}$	2800	kg/m^3
Enamel coating	ρ_{coati}	1200	kg/m^3
Content density	$\rho_{content}$	830	kg/m^3
Water density	ρ_{water}	1025	kg/m^3
Weight of steel	W_{steel}	1210	N
Weight of concrete	$W_{concrete}$	2938	N
Weight of enamel	W_{coat}	76	N
Weight of content	$W_{content}$	928	N
Weight of water	W_{water}	2445	N
Submerged weight	W_S	2707	N

3.1 Undrained Lateral Breakout Resistance

Undrained lateral breakout resistance was graphed using two models. The first model determined undrained lateral breakout resistance ($F_{L,brk,u}$) as the sum of the shear resistance on a horizontal surface underneath the pipe ($F_{L,brk,u,fric}$) and a remaining resistance due to mobilization of the soil in front of the pipe and at the rear due to suction ($F_{L,brk,u,remain}$). This model was used to show the effects of two assumptions on partially embedded pipelines, 1) no suction at the rear; and 2) suction at the rear. The flow chart in Figure 3 shows the methodology utilized for determining undrained lateral breakout resistance following model 1 for this study on partially embedded pipelines. Model 2 involved solving equation 4 presented in section 4.1 of this parametric study and assumes no suction at the rear.

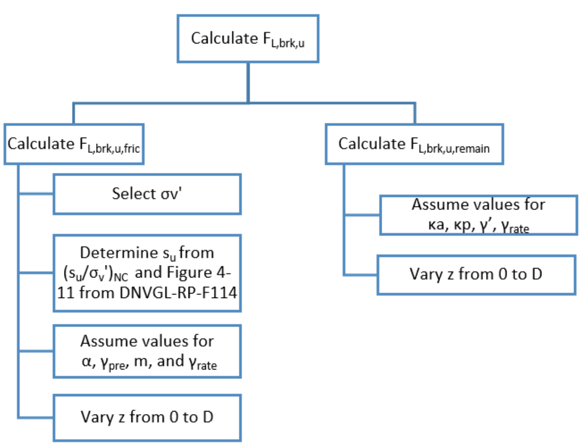

Figure 3. Determination of undrained lateral breakout resistance model 1 flow chart

3.2 Drained Lateral Breakout Resistance

Drained lateral breakout resistance for partially embedded pipelines was ($F_{L,brk,d}$) was modeled using two methods. The methodology for the first model considered in this paper is outlined in Figure 4. Drained lateral breakout resistance is the sum of the friction between the pipe and the soil underneath it ($F_{L,brk,d,fric}$) and the passive earth pressure caused by lateral soil movement($F_{L,brk,d,passive}$). In this paper, the drained frictional angle of soil, φ, was varied to study its effects on lateral breakout resistance. Method two models breakout resistance into a frictional and a passive component that provides increasing resistance with penetration. Refer to section 4.2.

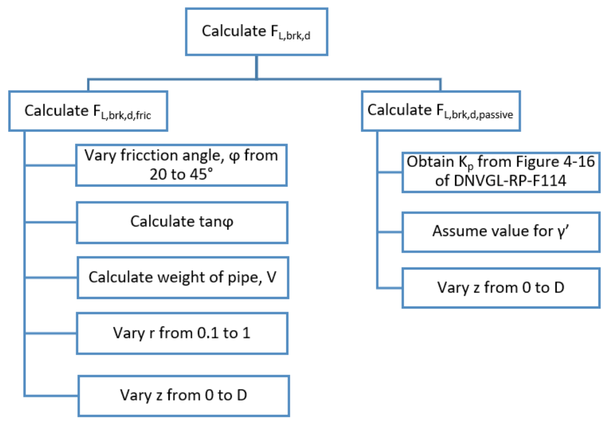

Figure 4. Determination of drained lateral breakout resistance model 1 flow chart

4 PARAMETRIC STUDY

An analytic parametric study of the lateral pipeline-soil interaction in partially embedded pipelines, for both drained and undrained conditions was conducted. The magnitude of various key parameters that influence soil interaction were manipulated and plots relating lateral breakout resistance to penetration were produced for both conditions. The undrained and drained parametric studies are discussed subsequently.

4.1 Undrained Lateral Breakout Resistance

The undrained lateral breakout resistance ($F_{L,brk,u}$) given in equation 1 is the sum of the shear resistance on a horizontal surface underneath the pipe, ($F_{L,brk,u,fric}$) given in equation 2, and a remaining resistance due to mobilization of the soil in front of the pipe and at the rear due to suction (equation 3).

$$F_{L,brk,u} = F_{L,brk,u,fric} + F_{L,brk,u,remain} \qquad [1]$$

$$F_{L,brk,u,fric} = \alpha \cdot \left(\frac{s_u}{\sigma_v'}\right)_{NC} \cdot \gamma_{pre}^{m} \cdot \gamma_{rate} \qquad [2]$$

$F_{L,brk,u,remain} = z \cdot \left(\kappa_a \cdot \overline{s}_{u,active} + \kappa_p \cdot \overline{s}_{u,passive}\right) \cdot \gamma_{rate}$
(allowing for suction at the rear of the pipe)

[3]

$F_{L,brk,u,remain} = z \cdot \left(\kappa_p \cdot \overline{s}_{u,passive} + \frac{1}{2} \cdot \gamma' \cdot z\right) \cdot \gamma_{rate}$
(not allowing for suction at the rear of the pipe)
(DNV GL, 2017)

Where α is the pipe-soil roughness or adhesion factor which represents the reduction in soil-interface strength compared to soil-soil strength (DNV GL, 2017). The adhesion factor was taken as 1 assuming peak resistance (Shiri, 2019). $\left(\frac{s_u}{\sigma_v'}\right)_{NC}$ is the normally consolidated shear strength ratio (ratio of the normally consolidated shear resistance to the consolidated vertical effective stress). Typical range is from 0.25 to 0.5 (non-carbonate soils) (Anderson, 2015). The normally consolidated shear strength ratio was varied from 0.2 to 0.35. This is the typical range as presented in Table 4-11 Stress dependency on shear strength ratio, typical range of DNVGL-RP-F114 for a pipeline with the effective vertical stress, σ_v' of 30 kPa. A vertical effective stress of 30 kPa was assumed to model a range of soil shear strengths. This normally consolidated shear strength ratio multiplied by the effective vertical stress to determine the shear strength of soil.

γ_{pre}^{m} is the consolidation preloading effect raised to the power of m (a factor that accounts for the long-term effect of overconsolidation) (DNV GL, 2017). The preloading effect is the ratio between preloading (e.g. water filled condition), and the static pipe-soil force, V for the condition under consideration (i.e. the overconsolidation ratio, OCR, of the soil under the pipe) (DNV GL, 2017). γ_{pre}^{m} was taken as 1 as it was assumed that the load experience by the soil due to the laying of the pipe was the largest that it had experienced historically. Values of m are less than one (typical range of 0.65 to 0.9) (DNV GL, 2017). As such, m was assumed to be within this typical range (0.775).

γ_{rate} is the rate factor which accounts for the speed of loading due to undrained failure (taken as 1.0 for a reference speed of 2 hours to failure and increased by 10-15% per log cycle) (DNV GL, 2017). γ' is the submerged unit weight of soil.

κ_a and κ_p are soil pressure resistance coefficients which can range from 2 to 2.5 (DNV GL, 2017). As such, these values were taken as 2.25.

$\overline{s}_{u,active}$, $\overline{s}_{u,passive}$ are the average undrained shear strength within the active and passive failure zones, respectively (typically at depth z/2) (DNV GL, 2017). It was assumed that the sea floor would have the same soil material in the active and passive zones, with the same undrained shear strength. The undrained shear strengths in both zones were determined from the normally consolidated shear strength ratio.

Equation 4 shows an alternative undrained lateral breakout resistance model. In this equation, s_u is the undrained shear strength at the pipe invert depth and D is the pipe outer diameter (including coating). The input parameters for the undrained lateral breakout analytic study are given in Table 2. These values apply for both model 1 and model 2 and were used to generate Figure 5. Undrained lateral breakout resistance with penetration in section 5.1.

$$\frac{F_{L,brk,u}}{s_u \cdot D} = 1.7 \cdot \left(\frac{z}{D}\right)^{0.61} + 0.23 \cdot \left(\frac{V}{s_u \cdot D}\right)^{0.83} + 0.6 \cdot \left(\frac{\gamma' \cdot D}{s_u}\right) \cdot \left(\frac{z}{D}\right)^2$$
(DNV GL, 2017) [4]

Table 2. Undrained lateral breakout resistance parametric study inputs

Parameter	Symbol	Value	Unit
Hydraulic Diameter	D_{HYD}	0.5654	m
Submerged pipe	V	2.71	kN/m
Submerged unit	γ'	8	kN/m^3
Shear strength of soil	s_u	Varies	kPa
Adhesion factor	α	1	-
Effective stress	σ_v'	30	kPa
Normally shear strength ratio	$\left(\frac{S_u}{\sigma_v'}\right)_{NC}$	Varies	-
Preloading effect	γ_{pre}	1	-
Consolidation factor	m	0.775	-
Rate factor	γ_{rate}	1	-
Soil pressure	κ_a	2.25	-
resistance	κ_p	2.25	-

4.2 Drained Lateral Breakout Resistance

The drained lateral breakout resistance ($F_{L,brk,d}$) given in equation 5 is the sum of the friction between the pipe and the soil underneath it ($F_{L,brk,d,fric}$) and the passive earth pressure caused by lateral soil movement (equation 6). In equation 6 K_p is the passive earth pressure coefficient (as determined by classical earth pressure theory). The K_p given in Table 3, is Rankine's passive earth pressure coefficient (Das & Sobhan, 2014). The values given in Table 3 were determined from Figure 4-16 Passive earth pressure coefficient according to classical earth pressure theory in DNVGL-RP-F114. The passive earth pressure coefficient varies with friction angle, φ. The frictional contribution to drained lateral breakout resistance is given in equation 7. It is affected by the roughness parameter between the pipe and soil ($r_{pipe-soil}$). The roughness between the seabed and steel pipe is 0.6 (DNV GL, 2017).

$$F_{L,brk,d} = F_{L,brk,d,fric} + F_{L,brk,d,passive} \quad [5]$$

$$F_{L,brk,d,passive} = (1/2) \cdot K_p \cdot \gamma' \cdot z^2 \quad [6]$$

$$F_{L,brk,d,fric} = r_{pipe-soil} \cdot tan\varphi \cdot \left(V - r \cdot tan\varphi \cdot F_{L,brk,d,passive}\right) \quad [7]$$

Table 3. Relationship between roughness parameter, r and passive earth pressure coefficient, Kp

Roughness parameter,	Friction Angle, Φ					
	20	25	30	35	40	45
r	Passive earth pressure coefficient, Kp					
0	2	2.2	2.9	3.5	4.6	5.9
0.1	2.08	2.35	3.11	3.8	5	6.6
0.2	2.16	2.5	3.32	4.1	5.4	7.3
0.3	2.24	2.65	3.53	4.55	5.65	8.45
0.4	2.32	2.8	3.74	5	5.9	9.6
0.5	2.4	2.95	3.95	5.5	7.1	11.2
0.6	2.48	3.1	4.16	6	8.3	12.8
0.7	2.56	3.25	4.37	6.45	9.25	14.5
0.8	2.64	3.4	4.58	6.9	10.2	16.2
0.9	2.72	3.55	4.79	7.05	10.6	17.1
1	2.8	3.7	5	7.2	11	18

As explored by Chatterjee, White, & Randolph, the weight of the pipe has an effect on the area of the berm, and thus depth of penetration. Often times in the drained condition, when the pipe becomes embedded within the soil, berms form on either side of the pipeline. The area of these berms is calculated using equation 8.

$$A_{berm} = (A_{bm}/2) + a \cdot z \qquad [8]$$

Where A_{bm} is the penetrated cross-sectional area of the pipe, as given in equation 9 and is a function of the diameter of the pipe, embedment depth, and the contact width between the pipe and the soil (B). The berm area cab be assumed to be evenly distributed over the extent of the failure surface, which leads to a modified height, z_{mod}. This modified height z_{mod} is meant to replace the embedment depth z in equation 6 to achieve more accurate results. A limitation of this study is that the modified height z_{mod} was not explored.

$$A_{bm} = arcsinc(B/D) \cdot D^2/4 - B \cdot D/4 \cdot cos\,(arcsin\,(B/D)) \qquad For\ z < D/2$$

$$A_{bm} = \pi \cdot D^2/8 + D \cdot \left(z - (D/2)\right) \qquad For\ z \geq D/2 \qquad [9]$$

(DNV GL, 2017)

Table 4 shows the input variables used to produce the graph shown in Figure 6. The angle of internal friction was varied to show the change in drained lateral breakout resistance with penetration for each of the roughness parameters outlined in Table 3. This allowed for conclusions to be drawn about the effects of the roughness parameter and penetration on drained resistance, as discussed in section 5.2.

Table 4. Drained lateral breakout resistance parametric study inputs

Parameter	Symbol	Value	Unit
Hydraulic Diameter	D_{HYD}	0.5654	m
Submerged pipe	V	2.71	kN/m
Submerged unit	γ'	8	kN/m^3
Friction angle of sand	Φ	Varies	-
Pipe-soil interface	$r_{pipe\text{-}soil}$	0.6	-

Equation 10 (model 2) relates drained lateral breakout resistance based on calibration to full-scale model tests performed on siliceous sands as proposed by Verley and Sotberg. This equation gives the lateral fore at breakout in drained soil conditions ($F_{L,brk,d}$). In this model, the lateral breakout resistance is broken down into a friction and passive component. The passive resistance, F_p is given by equation 11. Model 2 had the same inputs as those presented in Table 4.

$$F_{L,brk,d} = 0.6\,V + F_p \qquad [10]$$

$$F_p = \gamma' \cdot D^2 \cdot \left(5 - \frac{0.15\,\gamma' \cdot D^2}{V}\right) \cdot \left(\frac{z}{D}\right)^{1.25} \quad for \quad \frac{V}{\gamma' \cdot D^2} \geq 0.05$$

$$F_p = 2 \cdot \gamma' \cdot D^2 \cdot \left(\frac{z}{D}\right)^{1.25} \quad for \quad \frac{V}{\gamma' \cdot D^2} < 0.05 \qquad [11]$$

5 RESULTS AND DISCUSSION

Plots were generated to summarize the results of the analytic parametric study for undrained and drained breakout resistance. The input variables for the graphs shown in Figure 5 and Figure 6 are given in Table 2 and Table 4, respectively. The outcomes of this study are discussed.

5.1 Undrained Breakout Resistance Results

Normalized penetration (z/D) was plotted against undrained lateral passive resistance (kN/m) for three conditions as shown in Figure 5. Two of the conditions were plotted using the undrained model 1 (equation one), assuming no suction at the rear and assuming suction at the rear. The third condition that was plotted is the undrained alternative method, model 2, presented in equation 4.

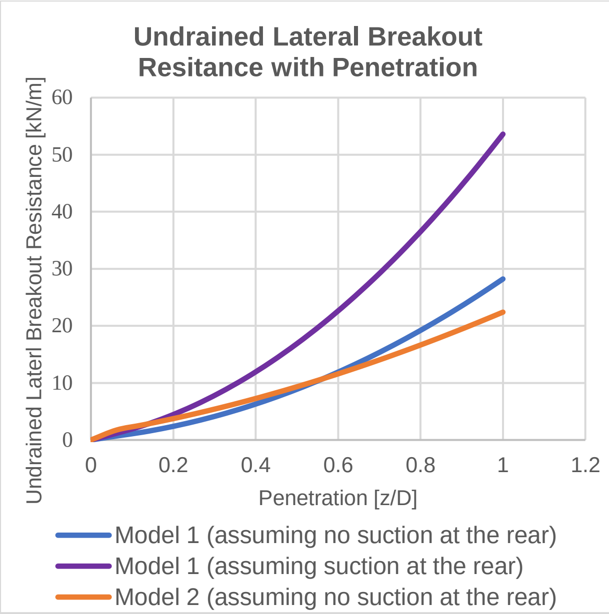

Figure 5. Undrained lateral breakout resistance with penetration

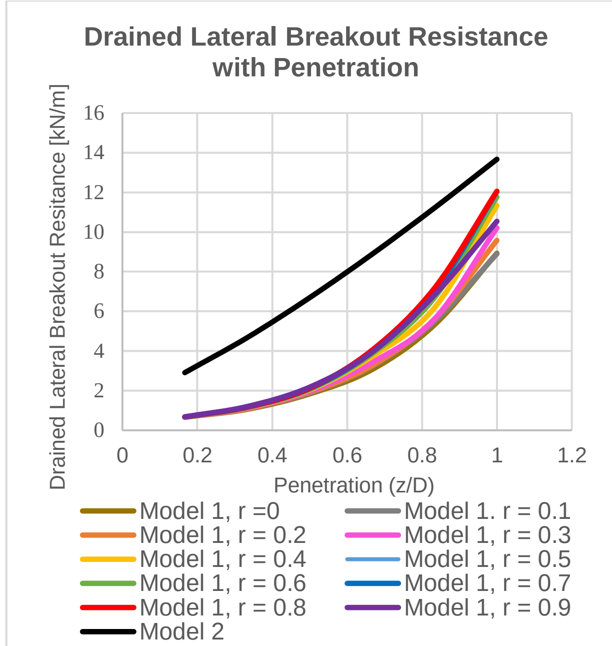

Figure 6. Drained lateral breakout resistance with penetration

Figure 5 above shows comparable results between model 1 and model 2 when suction is not present at the rear. When suction is present at the rear, the undrained lateral breakout resistance is increased at a more significant rate then when suction is not present as demonstrated by the purple line shown in Figure 5. A disadvantage of model 2 is that the frictional component is stress-dependent which does not account for pre-consolidation effects. According to DNVGL-RP-F114, “model 1 encourages the engineer to use a consistent frictional term both in the axial and lateral direction” (DNV GL, 2017). For model 2, the passive resistance is related to the shear strength of soil at the invert of the pipe. Therefore, model 2 does not reflect the shear strength variation between the seabed and the pipe invert. The variation in shear strength with depth below the seabed is given in equation 4.5 of DNVGL-RP-F114. This variation could be significant and is not reflected in the model.

5.2 Drained Breakout Resistance Results

Normalized penetration (z/D) was plotted against drained lateral passive resistance (kN/m) for varying values of the roughness parameter, r, using two different models, as shown in Figure 6. The results of this analytic parametric study show that although the drained lateral breakout resistance approximately increases with increasing penetration and increasing roughness parameter, this is not exclusively the case. As observed in Figure 6, a larger drained lateral breakout resistance was seen with r = 0.8 than r = 0.9 or r = 1 for certain depths using model 1. This implies that there is a point where roughness counteracts drained lateral breakout resistance at certain depths.

A limitation of model 2 is that it does not take into account the roughness parameter. This is observed by the approximately linear curve shown in Figure 6 for model 2, while model 1 showed a variation in drained lateral breakout resistance with roughness.

A simplification of model 1 (equation 5) is that the passive resistance is taken in accordance with classical earth pressure theory against a vertical surface in front of the pipe. As such, it does not fully capture the real failure surface being affected by the shape of the pipe (DNV GL, 2017). This set of equations could be improved to better account for the shape of the pipe.

6 SUMMARY AND CONCLUSION

As discussed in this paper, the lateral pipeline-soil interaction of partially embedded pipelines is an important to factor to consider in the design of subsea pipelines. Key parameters that influence the lateral breakout resistance of a pipeline include; pipeline weight, degree of embedment, pipe surface roughness and soil strength. To better understand the lateral pipeline-soil interaction in partially embedded pipelines, an analytic parametric study was conducted for both drained and undrained conditions. The magnitude of various key parameters that influence soil interaction were manipulated and plots relating lateral breakout resistance to penetration were produced for both conditions. For the undrained condition, the undrained shear strength was manipulated and three different models were plotted. Comparable results between model 1 and model 2, when suction is not present at the rear, were observed. When suction is present at the rear, the undrained lateral breakout resistance showed to increase at a more significant rate then when suction is not present. For the drained condition, the angle of internal friction was varied to show the change in drained lateral breakout resistance with penetration for each of the roughness parameters. Two different models were plotted. The results showed that although the drained lateral breakout resistance approximately increases with increasing penetration and increasing roughness parameter, this is not exclusively the case. There is a point where roughness counteracts drained lateral breakout resistance at certain depths.

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