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An analytical parametric study of uplifting resistance in buried pipelines

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ABSTRACT

Offshore pipelines are frequently used to transport hydrocarbons and gases to various areas in the world. Often, they are buried in trenches for a variety of reasons. Reasons include safety for the pipe from obstructions or to provide stability and to protect against accidental loads etc. The material in the pipes is often transported at high temperatures and pressures to facilitate the flow of the oil or gas. These conditions cause an increased amount of force on the interior of the pipeline, causing movement of the pipeline upward, which is called upheaval buckling. With buried pipelines, the predominant direction of motion will be in the path of least resistance, which would be a longitudinal profile imperfection triggering upheaval movement in a vertical direction. This movement of the pipeline could lead to the failures in the line, halting production, requiring repairs to the system, and dire environmental effects. The design of pipelines against upheaval buckling is a challenging aspect of their design. Accurate assessment of upheaval buckling needs advanced numerical simulations and/or experimental studies, which would be costly and time-consuming. The analytical solutions are fast and acceptably accurate, particularly for early stages of design. In this study, the effect of the key parameters contributing to the upheaval buckling of buried pipelines was analytically investigated. Key geomechanical soil parameters and rate effects were examined, and their effect on vertical pipeline-soil interaction during the upheaval buckling were investigated. Several invaluable trends were observed providing a good insight into the sufficiency of the analytical solutions.

RÉSUMÉ

Les pipelines en mer sont fréquemment utilisés pour transporter des hydrocarbures et des gaz dans diverses régions du monde. Souvent, ils sont enterrés dans des tranchées pour diverses raisons. Les raisons incluent la sécurité des tuyaux contre les obstructions ou pour assurer la stabilité et la protection contre les charges accidentelles, etc. Le matériau dans les tuyaux est souvent transporté à des températures et pressions élevées pour faciliter l'écoulement de l'huile ou du gaz. Ces conditions entraînent une augmentation de la force exercée sur l'intérieur du pipeline, entraînant son mouvement ascendant, appelé flambage de bouleversement. Avec les canalisations enterrées, la direction du mouvement prédominante sera la voie de la moindre résistance, qui serait une imperfection du profil longitudinal provoquant un mouvement de soulèvement dans la direction verticale. Ce mouvement du pipeline pourrait entraîner des défaillances dans la ligne, interrompre la production, nécessiter des réparations du système et avoir des effets environnementaux désastreux. La conception des pipelines contre le flambage par bouleversement est un aspect difficile de leur conception. Une évaluation précise du flambement de bouleversement nécessite des simulations numériques avancées et / ou des études expérimentales, qui seraient coûteuses et prennent du temps. Les solutions analytiques sont rapides et d'une précision acceptable, en particulier pour les premières étapes de la conception. Dans cette étude, l'effet des paramètres clés contribuant au flambage bouleversant des canalisations enterrées a fait l'objet d'une analyse. Les principaux paramètres géomécaniques du sol et les effets de taux ont été examinés, ainsi que leurs effets sur l'interaction verticale pipeline-sol pendant le flambement. Plusieurs tendances précieuses ont été observées, donnant une bonne idée de la suffisance des solutions analytiques.

1 INTRODUCTION

Exploring and improving existing methods of transporting hydrocarbons requires extensive analysis of a wide range of pipeline parameters and a theoretical application of subsea engineering principles. In recent years, there has been a steadfast increase in the usage of subsea pipelines to transport hydrocarbons, so understanding the full scope of various pipeline parameters is crucial.

In restrained subsea pipelines, large longitudinal compressive forces are generated by high hydrocarbon flow rates and temperatures. In some instances, this can create an overbend or even cause the pipeline to buckle, which compromises the pipeline. Generally speaking, there are two different types of failure modes with respect to buckling when dealing with subsea buried pipelines, local buckling, and global buckling. Local buckling implies gross deformation of the cross-sectional area of the pipe and can be defined by the situation whereby the soil above the pipe will displace around and below the pipe when the pipe begins to displace upwards [1]. The global buckling failure mode is characterized by an upward displacement of the soil above the pipeline when the pipeline begins to deflect upwards. A schematic of both of these failure modes can be seen in Figure 1: Buckling Failure Modes [1].

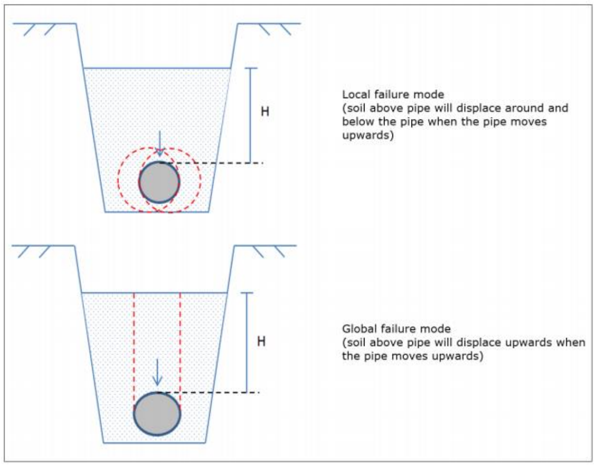

Figure 1: Buckling Failure Modes

These different buckling failures or overbend can be opposed, however, by the weight of the pipeline, and the uplifting resistance generated by the soil that the pipeline is buried beneath.

Conventional design guidelines and analytical models used for predicting the uplifting resistance in subsea pipelines are also based on the extent of saturation within the soil [2].

The material properties of the backfill material once the trenching of the pipeline has begun is also vital in subsea engineering design. Various parameters like soil density, soil compaction, and angle of internal friction are important properties in soil mechanics and will be investigated throughout the outlined report in order to analyze their respective impacts on the uplifting forces of subsea buried pipelines.

The following paper outlines the parametric studies conducted to examine the effects of soil moisture content, seabed soil cover, and soil density on the uplifting resistance of subsea pipelines.

2 LITERATURE REVIEW

Literature pertaining to parametric studies conducted on uplifting forces of subsea pipelines have been conducted on numerous accounts.

The uplift resistance of a pipeline buried in the seabed generally consists of four main components [3]: the submerged weight of the [pipeline], the submerged weight of the soil being lifted, the soils vertical shear resistance, and the vertical component of the suction force from varying excess pore pressures that exist above and below the [pipeline]. The resulting resistances are acting on the vertical slip planes shown in Figure 2: Vertical Shear Plane of Buried Pipeline.

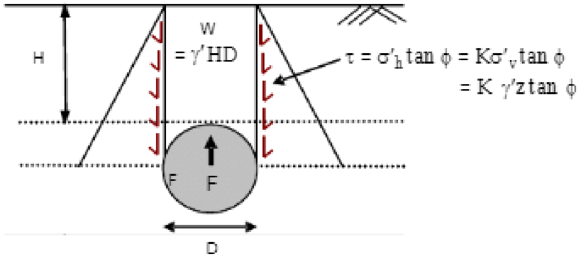

Figure 2: Vertical Shear Plane of Buried Pipeline

Finite element modeling was conducted by Koochekali et all [4], in order to determine the effect of pipe roughness on the theoretical plastic strain and soil displacement for pipelines by varying friction coefficients for the contact surface of the pipeline and soil. Their study showed that through increasing the pipe roughness (pipeline-soil contact surface friction), the soil uplifting resistance also increased.

A study conducted by Gudmund Eiksund in his research paper titled, “Modelling of Uplift and Lateral Resistance of Offshore Pipelines in Rock Berms” [5] examined the uplift resistance in cohesionless materials as a function of pipe embedment ratio, H/D. The uplift resistance measured at their aforementioned test site, showed a strong correlation with uplift tests conducted using FEM analysis, applying the same friction angles in a Mohr-Coulomb material model.

A study conducted by Zhenkui Wang et all [6], investigates the effect of soil cover depth and uplift soil resistance on the load-deflection behavior of a buried subsea pipeline. In their paper, they found that the mobilization distance of the uplift peak resistance has no considerable impact on the upheaval buckling behavior. They also suggest that in future research, “more attention should be paid to the decay rate from the uplift peak resistance to the residual resistance in nonlinear vertical soil resistance models” [6].

Finite element Analysis of upheaval buckling of submarine pipelines was conducted by Memorial University research team [7], which included a parametric study on the effects of burial depth, and the effect of post-peak reduction of uplifting soil resistance. They found that “For a given pipe diameter, as the soil cover (H) above the pipe increases with the H/D ratio, the uplift resistance of the pipe (Fv) also increased with H/D” [7]. H/D burial depth, pipe diameter ratios of 1.0, 2.0, and 3.0 were used throughout their study.

An experimental study conducted by K. Faizi et all, with physical modeling focusing on the effect of pipe burial depth, pipe diameter, and the length and number of geogrid layer on the uplift resistance was illustrated in their paper titled, “Uplift Resistance of Buried Pipelines Enhanced By Geogrid” [8]. Their findings suggest that peak uplift resistance of buried pipelines are directly related to its diameter and burial depth, however, they observed that the effect of burial depth is more significant when looking at the effects relating to uplifting resistance. Their analysis also showed that the finite-element analysis that they conducted was generally in a good agreement with respect to their experimental results that they obtained.

A study conducted by Nielsen et all (1990) [9], calculated an uplift resistance required to keep the upward movement of imperfect pipe sections below the critical values, preventing upheaval failure. For pipes buried in trenches with a natural backfill, they had determined that an initial upward mobilization of about 10-20 mm can be considered acceptable in most cases when determining a pipelines tendency to be subjected to upheaval buckling.

A study conducted by Chen et all (2012) [10], analyzing governing mechanisms of uplift resistance of plain seabed mudmats was done through centrifugal testing. In this study, uplifting resistance was assessed using conventional bearing capacity theory, and varied by changing the rate of uplift and the embedment depth of the mudmat.

Experimental analysis performed by Ivanovic et all (2014) [11], included examining mobilization displacements associated with uplift resistance of buried pipelines. In this analysis, a comparison between the Technip database and DNV recommendations was undertaken. Their results showed suitable DNV recommended values for higher H/D values, while some modifications were necessary for some smaller H/D values. Distinctions were made between very loose and loose sand to better represent the two cases.

3 METHODOLGY

An analytical parametric study was conducted for both the undrained and drained uplifting resistances on buried subsea pipelines. The equations outlined by DNVGL-RP-F114 [1], were used throughout the outlined parametric study. The effects of uplifting resistances on buried subsea pipelines, as discussed in section 5.5 in the DNVGL-RP-F114 [1], was the primary focus of this paper.

The forces acting on buried subsea pipelines can be modeled in the Freebody diagram depicting the shear planes shown in the figure below.

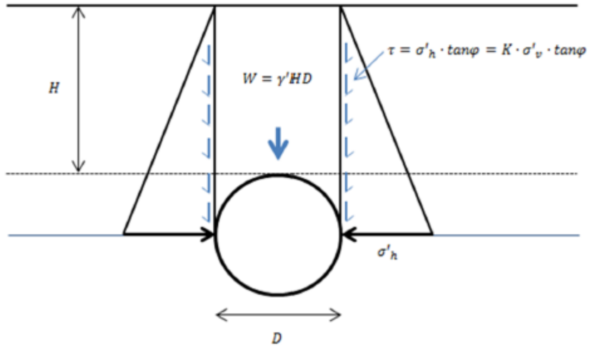

Figure 3: Freebody Diagram of Forces Acting on Subsea Buried Pipelines

Through altering the soil parameters, specifically the submerged weight of soil and angle of internal friction of backfilled material, and through altering the pipeline parameters, soil cover (H) and pipeline diameter (D), their corresponding effects on uplifting resistances in both drained and undrained conditions were analyzed.

The equation depicted below calculates the uplifting resistance of buried subsea pipelines in drained conditions.

$$F_{L,\ D} = \gamma' * H * D + \gamma' * D^2 * \left(\frac{1}{2} - \frac{\pi}{8}\right) + K * tan\varphi * \gamma' * \left(H + \frac{D}{2}\right)^2 \qquad (1)$$

Where,
γ’ is submerged weight of soil,
H is the cover height (above the pipe)
K is the lateral earth pressure coefficient also
Φ is angle of internal friction for backfilled material
D is the outer pipe diameter including pipe coating

The equation depicted below shows the uplifting resistance force of subsea buried pipelines in drained conditions as well but implements an empirical model for calculating an uplift resistance factor that gets substituted in place of the term K*tanφ shown in the equation above.

$$F_{L,\ D} = \gamma' * H * D + \gamma' * D^2 * \left(\frac{1}{2} - \frac{\pi}{8}\right) + f * \gamma' * \left(H + \frac{D}{2}\right)^2 \qquad (2)$$

The terms are the same as the variables depicted for the formula above, where f is derived from adding 0.19 and 0.38 respectively to the low estimate value of uplift resistance coefficients, $f_{LE.}$, as outlined in the DNVGL-RP-F114 [1]. The low estimate uplift resistance factor is calculated using the empirical model shown in the figure below.

$$f_{LE} = \begin{cases} 0.1 & \text{for} \quad \varphi \leq 30 \\ 0.1 + \dfrac{\varphi - 30}{30} & \text{for} \quad 30 < \varphi \leq 45 \\ 0.6 & \text{for} \quad \varphi > 45 \end{cases}$$

Figure 4: Low Estimate Uplift Resistance Factor [1].

As can be seen in figure 6 shown above, low estimate uplift resistance factors can be taken as 0.1 for sand with an internal friction angle of less than 30 degrees, 0.1 + (φ – 30)/(30) for sand with an internal friction angle between 30 and 45 degrees, and 0.6 for sand with an internal angle of friction of greater than 45 degrees. Sand that falls within each of these three categories can generally be classified as loose, medium, and dense sand, respectively. Once the uplift resistance factor is obtained, the total uplift resistance force can be obtained.

For undrained conditions, uplifting resistance can be equated for different vertical failure modes. For the local failure mode, the equation for uplifting resistance is shown below.

$$F_{uplift,\ local,\ u} = N_c * S_U * D - \gamma' * A_p \qquad (3)$$

Where,
N_c is a bearing capacity factor
S_u is undrained shear strength
D is the pipe diameter plus the pipe coating
$\gamma' * A_p$ represents the soil buoyancy effect

The uplifting resistance for a global failure mode is depicted in the equation below.

$$F_{uplift,\ global,\ u} = \gamma' * H * D + \gamma' * D^2 * \left(\frac{1}{2} - \frac{\pi}{8}\right) + 2 * S_u * (H + \frac{D}{2}) \qquad (4)$$

Where the variables are the same as the ones depicted in the formula above.

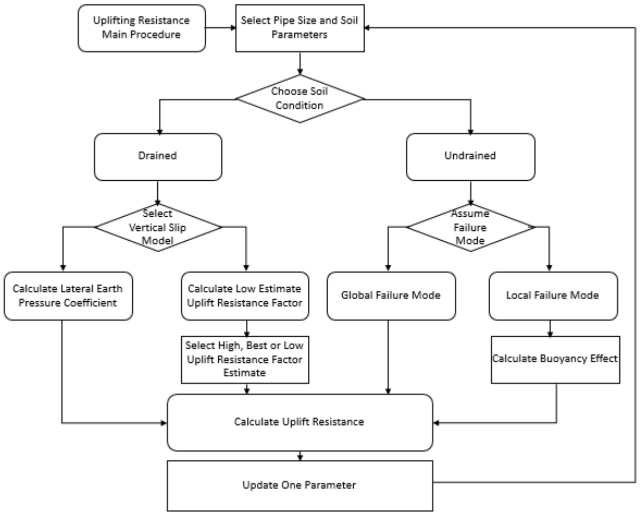

Figure 5: Methodology Flowchart

The flow chart depicted below, outlines the methodology followed for conducting the parametric study.

4 PARAMETRIC STUDY

An analytical parametric study of the uplifting force in buried subsea pipelines for both drained and undrained soil conditions was conducted. The default pipeline parameters used are given in Table *1*: Default Pipeline Parameters.

Table 1: Default Pipeline Parameters

Parameter	Symbol	Value	Unit
Pipe Diameter	D	0.4064	m
Cover Height	H	1.0	m
Surface Pipe Area	A_p	1.2767	m^2

The default soil parameters are depicted in Table *2*: Default Soil .

Table 2: Default Soil Parameters

Parameter	Symbol	Value	Unit
Submerged Weight of Soil	γ’	10.0	kN/m^3
Internal Angle of Friction	φ	30.0	degrees
Lateral Earth Pressure Coefficient	K	3.0	
Uplift Resistance Factor	f	0.29	
Undrained Shear Strength	S_u	50.0	kPa
Bearing Capacity Factor	N_c	10	

Various pipeline and soil parameters were examined to evaluate the impact of said parameters on the uplifting resistance behavior of buried subsea pipelines. Analysis of certain soil parameters were achieved by modifying their respective values within a reasonable range that was depicted within the DNVGL-RP-F114 [1], and the various studies cited within the literature review outlined above [4], [7].

Cover height, H, was modified within a range of values that matched the range that was analyzed in Arman et all [7] research paper on the Upheaval Buckling Analysis of Submarine Pipelines. This range initially had an H/D ratio ranging from 1.0 to 3.0, but for the purposes of this analysis, the cover height was extended to an end range of 3.0 meters in order to obtain a bigger data set. In doing this, more conclusive evidence pertaining to the individual impact on the different conditions for uplifting resistance was obtained.

Pipe diameter, D, was modified within a range of values that fall within the pipe sizes depicted in the Standard Pipe Schedule & Inner Diameter Dimensions for pipelines. The diameter ranged from 13.7mm to 1219mm as depicted by the max and min pipe sizes in Standard Pipe Schedule Charts for pipelines.

Submerged weight of soil, γ’, was modified within a range of values depicted in the DNVGL-RP-F109 titled, “On-Bottom Stability Design of Submarine Pipelines” [12]. DNVGL-RP-F109 states that submerged unit weights for very loose soil, to very dense soil, can range anywhere between 7000 N/m^3 to 13,500 N/m^3, respectively.

The angle of internal friction, φ, was modified within a range of values that was depicted within the DNVGL-RP-F114 [1]. Peak friction angles were modified within 25 degrees to 50 degrees. As a result of the internal friction angle changing, the low estimate for the uplift friction factor also changes, yielding a different uplift friction factor.

Undrained shear strength, S_u, was modified to fall within a range of reasonable values that was depicted in the “Basic Mechanics of Solids” University of West England webpage [13]. The undrained shear strength values ranged from 20 kPa for very soft soil, to 150 kPa for very hard soil.

5 RESULTS

A direct view of the effects of parameter manipulation on the various uplift resistance forces, drained and undrained soil conditions will be plotted separately and analyzed against the range of reasonable values for the parameter.

Figure 6: Drained Uplift Resistance vs. Cover Height

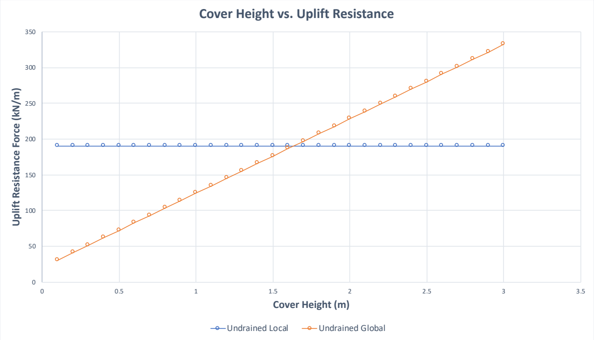

Figure 7: Undrained Uplift Resistance vs. Cover Height

As shown in Figure *6*: Drained Uplift Resistance vs. Cover Height and Figure *7*: Undrained Uplift Resistance vs. Cover Height, increasing the cover height directly relates in an increase in all uplift resistances other than the undrained soil condition with the local failure mode. As seen in Figure *6*: Drained Uplift Resistance vs. Cover Height, the uplift resistance using the lateral earth pressure coefficient increased at a rate which was higher than when using the uplift resistance factor.

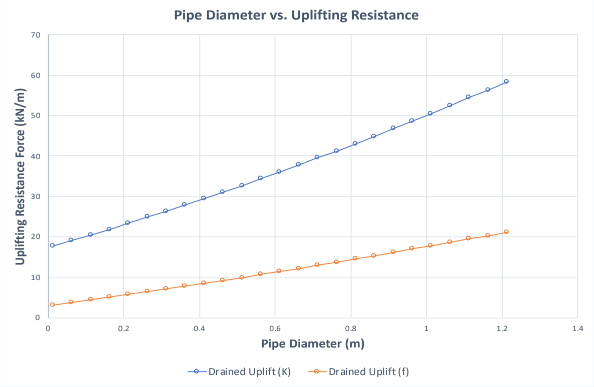

Figure 8: Drained Uplift Resistance vs. Pipe Diameter

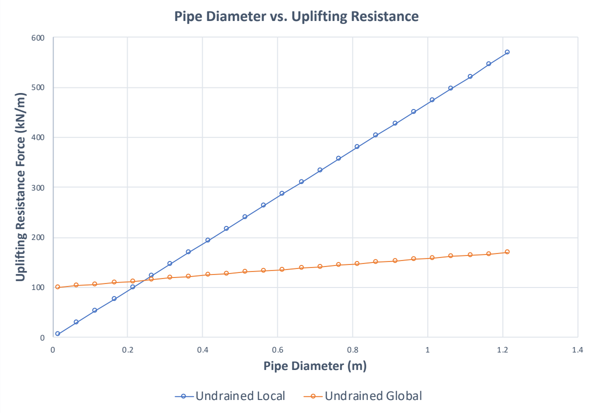

Figure 9: Undrained Uplift Resistance vs. Pipe Diameter

Both undrained and drained soil conditions experience increase in all uplifting resistance as the diameter of the buried pipeline is increased. The direct relationships can be seen in Figure *8*: Drained Uplift Resistance vs. Pipe Diameter and Figure *9*: Undrained Uplift Resistance vs. Pipe Diameter.

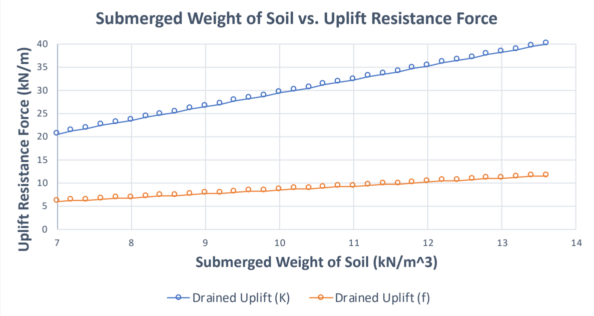

Figure 10: Drained Uplift Resistance vs. Submerged Weight of Soil

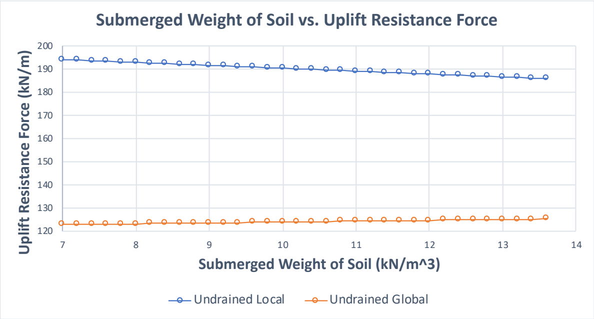

Figure 11: Undrained Uplift Resistance vs. Submerged Weight of Soil

The relationship between the submerged weight of soil and the uplift resistance varies depending on the soil condition and the failure mode. As shown in Figure *10*: Drained Uplift Resistance vs. Submerged Weight of Soil, for drained soil, the uplifting resistance increases as the submerged weight of soil. In Figure *11*: Undrained Uplift Resistance vs. Submerged Weight of Soil, this slight gradual increase is evident for the global failure mode. However, the local uplift resistance decreases in value as the submerged weight of soil increases.

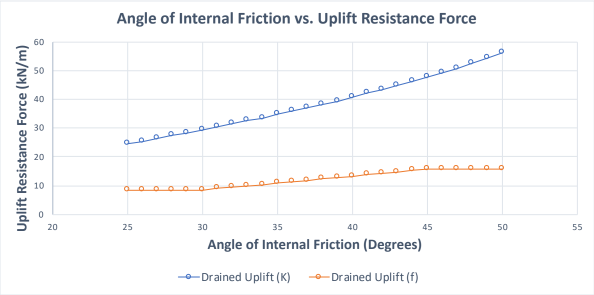

Figure 12: Drained Uplift Resistance vs. Angle of Internal Friction

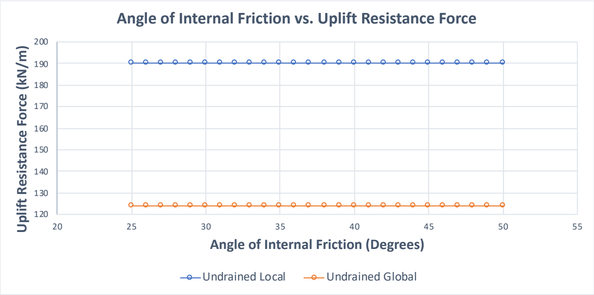

Figure 13: Undrained Uplift Resistance vs. Angle of Internal Friction

For drained soil conditions, an increase in the angle of internal friction, directly and indirectly, leads to an increase in the uplift resistance. Shown in Figure *12*: Drained Uplift Resistance vs. Angle of Internal Friction, the drained uplift resistance when considering the lateral earth pressure coefficient experiences with each increase in the angle of internal friction. When considering the uplift resistance factor, the uplift resistance force remains at a constant level for angles less than 30 degrees and greater than 45 degrees. In between this range, the uplift resistance increases as the angle increases. For undrained soil conditions, the angle of internal friction of the soil has no direct effect on in uplift resistance, as shown in Figure *13*: Undrained Uplift Resistance vs. Angle of Internal Friction.

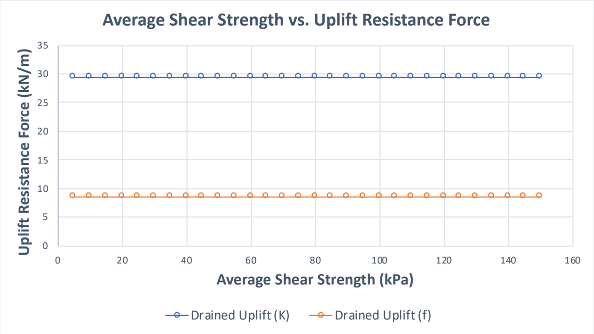

Figure 14: Drained Uplift Resistance vs. Average Shear Strength

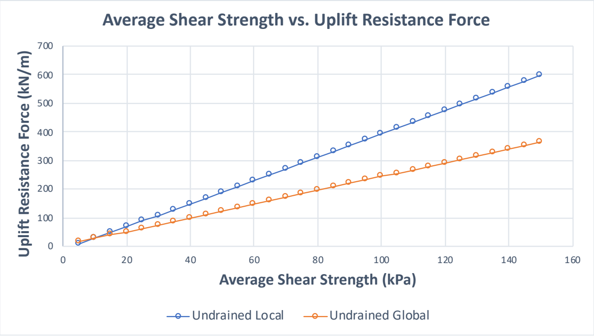

Figure 15: Undrained Uplift Resistance vs. Average Shear Strength

As can be seen in Figure *14*: Drained Uplift Resistance vs. Average Shear Strength, the average shear strength has no direct effect on the uplift resistance in drained soil conditions. In Figure *15*: Undrained Uplift Resistance vs. Average Shear Strength, an increase in the average shear strength from 1 to 150kPa is shown to result in an increase in the uplift resistance force for undrained soil conditions in both the local and global failure modes.

6 SUMMARY AND CONCLUSION

A numerical model was developed to test the various parameters of multiple uplifting resistance forces. The process went in a sequential order of maintaining variables as constant values within their acceptable range. The values were then graphically plotted to visually observe the change in value of each uplifting resistance force against the potential reasonable range for the variable. The variables that were altered included; the cover height above the pipe, the outer pipe diameter including coating, the submerged weight of soil, the angle of internal friction of the backfill material, and average shear strength. A summary of the key conclusions can be listed as follows:

- The increase of cover height from 0.1 meters to 3 meters will result in an increase of uplifting resistance force in undrained global, and drained conditions, however it has no effect on undrained local uplift resistance. The change in the drained uplift resistance was the most significant by increasing by a factor of over 8700% within the selected range.
- The change in uplifting resistance for all forces was increased near linearly with an increase in the outer diameter of the pipe within the standard pipe size range. The slope of each curve varied. However all curves resulted in a positive, upwards trend as the diameter increased. Proportionally, the undrained local uplifting resistance force experienced the most significant change through the increase in the pipe’s diameter.
- The effects of increasing the submerged weight of soil were varied depending on the uplifting resistance force. Drained uplift resistance was steadily increased and nearly doubled as the submerges weight of soil increased from 7 to 13.6 kN/m^3. Whereas, the undrained global uplift resistance experienced only slight increase and undrained local uplift resistance will decrease within this range. The negative trend for the local undrained resistance is contributed to the additional soil buoyancy effect on the pipeline as the submerged weight of the soil increases.
- Increasing the angle of internal friction of the backfill material will result in an increase for drained uplifting resistance. Altering the angle will result in a change to the uplift resistance factor between the ranges of 30-45 degrees, creating more significant change to the drained uplift resistance. Both undrained local and global uplift resistances were directly unaffected by increasing the angle of internal friction.
- Altering the average shear strength of the soil resulted in a similar effect as increasing the angle of internal friction, but to undrained soil conditions and had no effect on drained soil. Both undrained local and global failure modes experienced linear increases to the uplifting resistance forces as the average shear strength was increased from 1-150 kPa. Drained conditions were unaffected.

7 ACKNOWLEDGMENTS

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