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# The Uplift Resistance of an Offshore Pipeline and the Effect of Soil Homogeneity

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**Abstract.** Offshore pipelines are often considered one of the most reliable fluidized fuel transportation systems. However, the transporting fuel with enhanced temperature induces thermal stress in the pipeline, which further threatens to buckle and rupture the offshore pipelines. In the current study, the buckling resistance behaviour of an offshore pipeline is studied using a finite element package (PLAXIS 2D). Furthermore, a comparison of uplift resistances for the homogeneous and normally consolidated (NC) soil beds is performed to understand the effect of soil homogeneity. The numerical model is validated with the past studies, and a good match is obtained. Moreover, different soil and installation parameters are varied to perform a parametric study and investigate the pipeline uplift resistance behaviour. Two different buckling resistance ($P_u$) behaviours of the pipeline are obtained in pre-peak and post-peak conditions for both homogeneous and NC soil-bed conditions. The magnitudes of $P_u$ for homogeneous and NC soil conditions are compared, and the changes in $P_u$ are reported and justified. The variation of the $P_u$ with different parameters (soil unit weight and embedment depth ratio) is also described using the failure mechanism of the soil around the pipeline.

**Keywords:** Homogeneous Soil, Normally Consolidated Soil, Pipeline, Upheaval Displacement, Finite Element Analysis, Undrained Shear Strength.

## 1 Introduction

The shear strength within the backfill soil can vary depending on the pipe installation method and the degree of consolidation of the soil above the pipeline at the post-installation stage. However, to reduce the computation cost and simplify the analyses, the shear strength ($S_u$) is often considered uniform throughout the depth of the soil bed. Again, it is also a common practice to consider linearly increasing [1] the shear strength profile of the normally consolidated or over-consolidated offshore clay beds. The consideration of the shear strength profile along the soil-bed depth plays an essential role in the study of the offshore pipeline upheaval displacement behaviour.

Several studies have explored the upheaval displacement behaviour of pipelines embedded within soft-clay. The load-displacement behaviour of the pipeline during upheaval displacement is experimentally studied by [2] and [3] under 1-g conditions. While several researchers [4] also performed multiple scaled-model tests under enhanced gravity to study the parameters mentioned above. Moreover, the soil-pipe interaction during pipe uplift was also studied by several authors [5,6]. The load-displacement relation and interaction between the pipelines and the soil are also estimated in different analytical studies [7,8]. In these studies, different soil parameters such as soil unit weight ($\gamma'$), pipe embedment depth (*H/D*) and pipe parameters such as pipe weight, pipe-soil interface shear and tensile capacities, pipe diameter (*D*) are varied and their effect on the resistance of soil against pipe uplift ($P_u$) is observed. However, the shear strength profile [$S_u$-profile ] within the clay-bed is critical in deciding the pipeline uplift displacement behaviour, and it is crucial to explore the effect of variations of $S_u$-profile along the depth on pipeline upheaval resistance ($P_u$).

Thus, in the current study, the variation of the $P_u$ with different soil and installation parameters (*H/D*, $\gamma'$) are explored for homogeneous and normally consolidated (NC) soil beds. Here homogeneous soil bed implies that the undrained shear strength ($S_u$) is constant throughout the soil depth. In contrast, in the case of NC soil, the $S_u$ varied linearly with increasing depth of soil bed. A schematic diagram is given in Figure 1. to describe the shear strength and unit weight distribution considered for the study. The diameter of the pipe is represented as *D* and the embedment depth is given by *H*, while $Z_c$ represents the depth of the centre of the pipeline. Moreover, $S_{u,ref}$ implied the shear strength at the top of the soil bed, and the $S_{u,eff}$ represented the undrained shear strength at a depth *Z*.

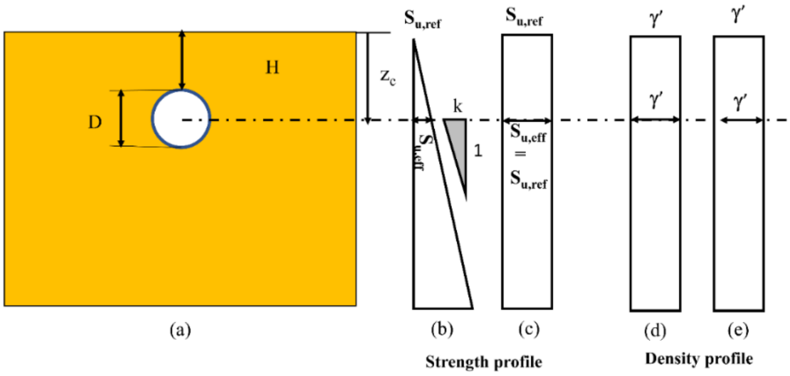


Figure 1. A visualization of the (a) schematic diagram of the pipe soil system; (b) and (c) strength profile for NC and homogeneous soil, respectively; and (d) and (e) density profile for NC and homogeneous soil, respectively.

## 2 Methodology

In the current study, a numerical analysis is performed using a finite element package (PLAXIS 2D) to study the effect of several soil and installation parameters on the resistance against the pipeline uplift. Furthermore, the effect of soil homogeneity on those parameters is also studied. Moreover, it is considered that the soil is homogeneous along the pipe length, and the interaction between soil and pipe is similar throughout the pipe length. Thus, the pipe-soil system is modelled as a 2D plane strain problem in the current study. The further details of the analysis are discussed below.

### 2.1 Boundary Dimensions and Boundary Conditions

The boundary dimension and condition significantly affect the analysis and must be considered carefully. The criterion of boundary dimension is such that there should not be any additional stress at the boundary during the movement of the pipeline. At the same time, the boundary condition should be chosen in such a way that the movement of the soil at the model boundary simulates the movement of the soil in the actual condition. Thus, a boundary optimization study was performed to finalize the dimension of the boundary, and a boundary dimension of 7 diameters from the bottom and side of the pipeline was chosen for bottom and side boundaries, respectively. The side boundaries are considered free to move in the vertical direction and fixed in the horizontal direction. In comparison, the bottom boundary is fixed and restrained from moving in any direction.

### 2.2 Elements

In finite element studies, the whole structure is discretized into several elements. The discretized soil volume is often called a 'mesh'. In PLAXIS 2D, triangular elements of 15 and 6 nodes are available to model a soil volume. Thus, in the current study, the soil volume is discretized into several 15-node triangular elements, and the pipeline cross-section is discretized into multiple 5-node beam elements.
Moreover, the size of the elements decides the accuracy and the duration of the analysis. For smaller size elements, both accuracy and duration of the analysis are higher. While for larger element sizes, both analysis accuracy and duration decrease. Thus, a convergence study similar to [9] is performed to decide the element size, and a relative element size of 0.33 is considered [10,11]. A similar element size is used for both homogeneous and normally consolidated soil. A typical 15-node triangular element and a 5-node beam element are shown in Figure 2.

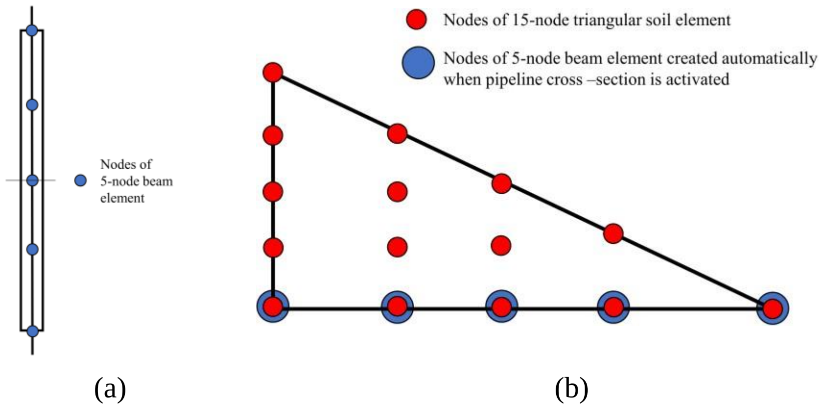


Figure 2: A typical diagram of a (a) 5-node beam element constituting the pipe cross-section and a (b) 15-node triangular element constituting the soil volume.

### 2.3 Constitutive Modelling and Model Parameters

For homogeneous and normally consolidated soil conditions, the soil volume is modelled as an elastic perfectly plastic material with Mohr-Coulomb failure criteria. Furthermore, almost similar parameters are used to represent the soil volume, except for the undrained shear strength of the soil. Some parameters are constant throughout the analysis; while others are varied to perform a parametric study. The elastic modulus to shear strength ratio ($E/S_u$), Poisson's ratio ( $\mu$), interface reduction factor ($R_{inter}$) and interface tensile capacity are kept constant throughout the analysis for both homogeneous and normally consolidated soil conditions. Moreover, for both cases, the shear strength of the soil can be represented as:

$$S_{u,eff} = S_{u,ref} + k \cdot z \tag{1}$$

Where,

$S_{u,eff}$ = effective undrained shear strength at z depth.

$S_{u,ref}$ = effective undrained shear strength at the surface of the soil bed.

$k$ = incremental shear strength of the soil.

On the other hand, the unit weight ($\gamma'$) of the soil and the embedment depth ratio (H/D) are varied to study the dependency of the pipeline uplift resistance on these parameters. The pipe is modelled as an elastic material with a rough outer surface. The roughness of the pipe is represented by the interface reduction factor ($R_{inter}$). Moreover, the buckling of the pipeline is simulated by applying nodal displacements. The details of the parameters are given in Table 1.

**Table 1.** Parameters used to model the soil and pipe volume.

| Parameter | Magnitude | |
|---|---|---|
| | Homogeneous soil | NC soil |
| Undrained shear strength at the soil surface ($S_{u,ref}$) (kN/m$^2$) | 0.01 | 10 |
| Incremental shear strength with depth (k) | 2 | 0 |
| Soil unit weight ($\gamma'$) (kN/m$^3$) | 2,5,10,20 | |
| Soil Cover Depth Ratio (*H*/*D*) | 0, 1, 2, 4, 6, 8, 10, 15, 20 | |
| Elastic modulus to shear strength ratio ($E/S_u$) | 500 | |
| Poisson's ratio ($\mu$) | 0.495 | |
| Strength reduction at the interface ($R_{inter}$) | 1.0 (Fully rough pipe case) | |
| Interface Tensile Capacity | 0 (No-tension condition) | |
| Pipe diameter (m) | 1 | |
| Pipe in-plane axial stiffness (kN/m) | 7.8 x 106 | |
| Pipe out of the plane axial stiffness (kN/m) | 6.225 × 106 | |
| Pipe flexural Rigidity (kN m$^2$/m) | 5265 | |

### 2.4 Phases of Analysis

The analysis is done in three phases: the initial, construction, and uplift. In the initial phase, the self-weight of the soil volume is calculated. While in the construction phase, the pipe element is activated, which implies the installation of the pipeline. Moreover, in the uplift phase, the nodal displacements are activated to simulate the pipe uplift.

### 2.5 Validation

The results from the current study are validated with the results obtained by [7] from their finite element analysis. The comparison between the results from the literature and the current study is given in Figure 3. The validation is done for weightless soil. The tests are performed for smooth and perfectly rough outer surfaces of pipeline. Moreover, an immediate breakaway of soil from the pipeline during pipe uplift or no tension (NT) condition is considered. It can be observed that the results obtained from the current study match well with the results predicted by the numerical model in the previous studies with a 10% or lesser deviation.

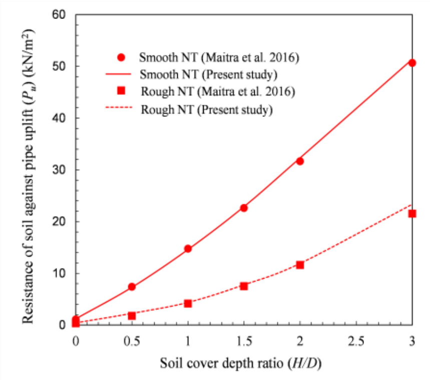


Figure 3. Comparison between the $P_u$ predicted by the current model and the $P_u$ obtained from the previous studies in the case of the weightless soil ($\gamma' = 0$)

## 3 Result and Discussion

The observation obtained from the current study and the possible explanations is discussed in this section. Initially, the effect of several soil and installation parameters on the resistance against pipe uplift ($P_u$) is discussed. Later, the effect of homogeneity is also explored. For all the cases, the no-tension interface condition is considered, implying that the soil below the pipeline was immediately separated when the upheaval buckling started.

### 3.1 Upheaval Buckling of the Pipeline Embedded in Homogeneous Soil-Bed

A homogeneous soil bed refers to a soil bed where the shear strength of the soil does not vary with the depth of the soil bed. Moreover, for a pipeline buried in a homogeneous soil bed, $P_u$ depends on the pipeline's embedment depth ratio (H/D) and the soil unit weight (γ').

**Effect of embedment depth ratio (H/D).** The variation of the $P_u$ with $H/D$ is shown in Figure 4. In Figure 4., the vertical axis represents the resistance against pipe uplift ($P_u$), and the horizontal axis represents the pipeline embedment depth ratio ($H/D$).

An increasing trend of the $P_u$ is observed with $H/D$. However, $P_u$ attained a constant magnitude after reaching a peak value, and no variation of $P_u$ is observed for further increase in $H/D$. The whole section of the plot represented two mechanisms of failure. A global failure of soil above the pipeline by the wedge failure mechanism is represented by the increasing part of the plot. At the same time, a local failure of the soil around the pipeline by flow around mechanism is represented by the stabilized portion of the graph. Moreover, the global failure depends on the weight of the failure block and the shear strength at the failure boundary, which further depends on the pipe embedment depth [12]. Thus, $P_u$ increased with increasing $H/D$ initially.

However, after the $P_u$ reached the peak magnitude, a transition of the failure mechanism from global failure to local failure occurred. Unlike global failure, local failure is independent of the pipeline embedment depth [10,12]. Thus, no variation of $P_u$ is observed with a further increase in the $H/D$ after $P_u$ reaches the maximum value.

It can also be observed from the figure that the $H/D$ corresponding to which the $P_u$ reached a peak value is dependent on the unit weight (γ) of the soil. With increasing γ', $P_u$ attained the peak value for lower embedment depth ratio ($H/D$).

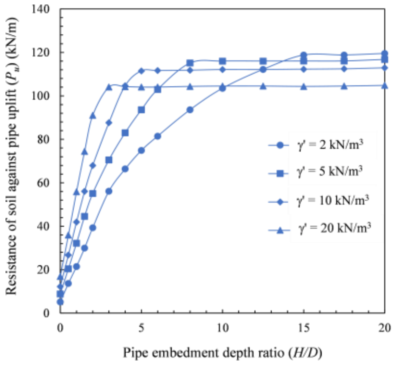


Figure 4. Variation of resistance against pipe uplift with pipe embedment depth ratio for homogeneous soil bed.

**Effect of unit weight of soil (γ').** The variation of the $P_u$ with γ' is shown in Figure 5. In Figure 5., the vertical axis represents the resistance against pipe uplift ($P_u$), and the horizontal axis represents the pipeline unit weight of soil (γ').

It can be observed that the resistance against the pipe uplift ($P_u$) increased with an increasing unit weight of soil (γ'). However, after reaching a peak value, $P_u$ decreased with increasing γ'. It can also be observed that the $P_u$ attained a similar magnitude at the post-peak condition irrespective of the pipe embedment depth ratio ($H/D$).

However, the unit weight of soil corresponding to which $P_u$ attained peak decreased with increasing *H*/*D*. From the Figure 5. it can be observed that $P_u$ reached peak value only for *H*/*D* greater than or equal to 4. For *H*/*D* lesser than 4, the resistance against the ($P_u$) did not even reach the peak value for the selected range of soil unit weight.

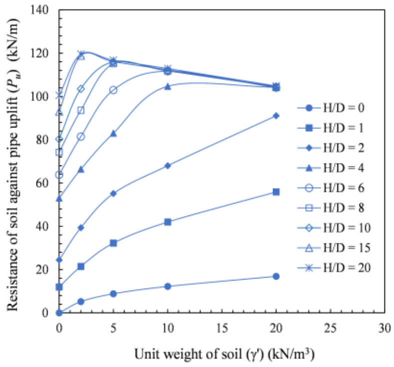


Figure 5. Variation of resistance against pipe uplift with a unit weight of soil for homogeneous soil bed.

### 3.2 Upheaval buckling of the pipeline embedded in normally consolidated soil-bed

In the case of normally consolidated (NC) soil, the shear strength of the soil is considered to be increasing linearly with increasing soil depth. Similar to the previous case, in case of NC soil also, the resistance of soil against pipeline uplift is dependent on the embedment depth ratio of pipeline (*H*/*D*) and the soil unit weight ($\gamma'$).

**Effect of embedment depth ratio (*H*/*D*).** The variation of the $P_u$ with *H*/*D* is shown in Figure 6. for different magnitudes of the soil unit weight. It can be observed that the Pu increased with increasing pipe embedment depth ratio irrespective of the soil unit weight, similar to the homogeneous soil-bed condition. However, $P_u$ never reached the peak value for the chosen combination of the soil unit weight and the pipeline embedment depth. Thus, the post-peak behaviour is not observed in the NC condition. Moreover, only global shear failure occurred within the soil above the pipeline for the considered range of the $\gamma'$ and *H*/*D*. The transition of failure mechanism from global to local failure is not observed in case of pipelines embedded in normally consolidated soil.

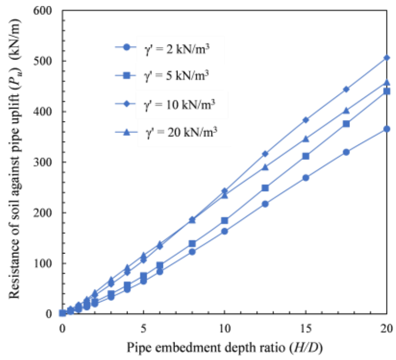


Figure 6. Variation of resistance against pipe uplift with pipe embedment depth ratio for normally consolidated soil bed.

**Effect of unit weight of soil (γ').** The effect of soil unit weight (γ') on the resistance of soil against pipe uplift ($P_u$) is presented in Figure 7. It can be observed from the figure that $P_u$ increased with increasing γ' up to a peak value. At the post-peak stage, the uplift resistance is observed to be decreasing with further increase in γ', similar to the case of homogeneous soil bed. However, $P_u$ reached the peak value for the embedment depth ratio higher than or equal to 8. For *H*/*D* lesser than 8, $P_u$ is yet to reach the peak value for the considered range of soil unit weight.

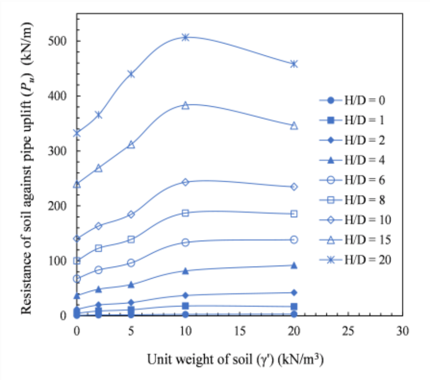


Figure 7. Variation of resistance against pipe uplift with a unit weight of soil for normally consolidated soil bed.

### 3.3 Effect of soil homogeneity on the upheaval buckling resistance of the pipeline

A comparison between $P_u$ in homogeneous soil and normally consolidated soil is given in this section. The variation of the $P_u$ with H/D is given in Figure 8 for both the homogeneous and normally consolidated soil conditions. From Figure 8, it can be observed that the resistance against the pipe uplift ($P_u$) for homogeneous soil and the normally consolidated soil are at the same range up to the embedment depth ratio of 5. However, $P_u$ for NC soil increased phenomenally beyond $H/D$ of 5.

For the particular case considered in the study, the shear strength for the homogeneous soil bed is 10 kN/m$^2$ throughout the soil bed. However, for the normally consolidated soil bed, the shear strength varied with an increment of 2 kN/m$^2$ per m depth. Hence, the $P_u$ for homogeneous and NC soil is observed to be in the same range up to 5 m of depth. However, for higher embedment depth the shear strength of the NC soil increased manifold, and the $P_u$ also increased extensively.

The behaviour of failure mechanisms for homogeneous and NC soil are also different. Initially, for both the homogeneous and normally consolidated cases global failure mechanism occurred, indicating a linearly increasing $P_u$ with increasing pipe embedment depth. However, the $P_u$ reached a peak value, and the transition of failure from global to local mode occurred for a $H/D$ value well below 5 for homogeneous soil bed. While for the pipeline embedded in a normally consolidated soil, $P_u$ did not achieve the peak value, and the transition of failure mode did not occur even for a $H/D$ value as high as 20.

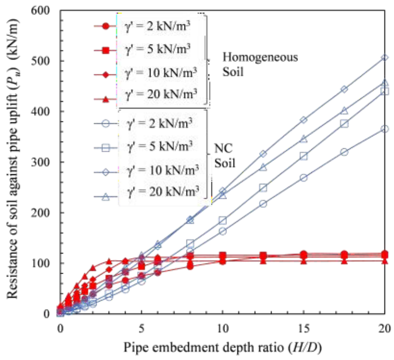


Figure 8. Comparison between resistance against pipe uplift within a homogeneous soil bed and a normally consolidated soil bed.

## 4 Conclusion

In the current study, the soil homogeneity along the depth of the soil bed and its effect on the $P_u$ is explored numerically using a finite element package called PLAXIS 2D. Two different soil conditions are considered: homogeneous and normally consolidated (NC) soil. The outer surface of the pipeline is considered to be perfectly rough, and no tension condition is assumed at the pipe-soil interface. The pipe embedment depth and the soil unit weight are varied systematically within a practical range, and the variation of the $P_u$ is studied for both conditions. Moreover, the variation of $P_u$ for the two conditions is compared with each other. The behaviour of the $P_u$ is further described from the failure mechanism of the soil around the pipeline. The significant observations from the current study are discussed below.

- The current model is validated by the model proposed by Maitra et al. [7]., and they showed a good match.
- The $P_u$ increased with increasing embedment depth for both the homogeneous and NC soil conditions. However, $P_u$ for homogeneous soil conditions attained a peak value for a particular value of *H*/*D*. While for NC soil, the Pu did not achieve the peak value even for the considered range of the *H*/*D*.
- The $P_u$ increased with increasing soil unit weight ($\gamma'$) until reaching the peak for homogeneous and NC soil conditions. However, for further increase in $\gamma'$, the $P_u$ is observed to be decreasing.
- The $P_u$ for homogeneous and NC soil conditions are compared. It can be observed that up to an embedment depth ratio of 5, both the $P_u$ are in a similar range. However, for further increase in *H*/*D*, the $P_u$ increased significantly.

The current analysis is performed using the Mohr-coulomb model, a simplified model. Such analyses are essential for the initial understanding of the soil-pipe interaction and study of the failure mechanism of the soil. However, more advanced models should be used to understand the pipe uplift behaviour better.

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