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NON-LINEAR CLAY SOIL MODEL FOR LATERAL PIPE-SOIL INTERACTION

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ABSTRACT

This paper describes implementation and application of non-linear lateral soil models for pipeline lateral buckling analysis. Several lateral soil models have been developed in the past and the model developed by Verley is often referenced in pipeline on-bottom hydrodynamic stability analyses (see [11], [13]). The Verley's model includes the build up of soil passive resistance as a function of small cyclic lateral motions and it is implemented in the PONDUS software (developed by MARINTEK) for on-bottom stability analysis as well as the DNV-RP-F109. However, the Verley model does not include the build up of additional soil berm resistance due to large cyclic in-place lateral motions applicable for lateral thermal buckling behaviors. The effect of additional soil berm resistance from large cyclic motions has been investigated by other research projects, such as the SAFEBUCK JIP [5]. In this paper, a complete non-linear lateral soil models with inherent soil berm resistance including both effects are formulated. The soil model combines the Verley model, the models described in DNV-RP-F109, and the berm model from SAFEBUCK's results. The DNV and Verley's model are used to model soil resistance in small amplitude cycle continued by the berm model after breakout achieved during large amplitude cycle. The new model is compared with PONDUS to validate the results of Verley and DNV model. The soil model is implemented inside SIMLA software [15] to enable finite element analysis. An example application of the model to pipeline global buckling analysis is then presented.

Keywords: Pipe-soil interaction, On-bottom stability, Non-linear clay soil model, lateral buckling, PONDUS.

INTRODUCTION

The offshore oil and gas exploration now continue to progress into deep water areas where, soft clay soil conditions are frequently encountered and where interaction effects related to riser and pipeline behaviors are the focus in several research projects. Two main types of the pipe-soil interaction problem are typically studied: the first one is vertical riser/pipe-soil interaction, and the second one is lateral pipe-soil interaction. Exposed pipelines are often subjected to extreme temperatures and pressures during operation potentially causing large lateral displacements due to buckling behavior.

The cyclic thermal heating and cooling that pipelines experience during its lifetime may lead to build up of soil berms that will influence the buckling mode shape as well as the bending moment distribution. An example of such behaviour is seen in Figure 1. In design analyses, such behaviour is often modelled in a simplified way by only considering the friction between the pipe and the soil (also known as the Coulomb model). However, the Coulomb model fails to include important behaviours such as soil berm and breakout resistances. Several research projects have been conducted in the past with regard to refining the pipe-soil interaction modelling. This includes the models developed by Verley [12], [13] for on-bottom stability analysis and the models developed related to global buckling behaviour as part of the SAFEBUCK Joint Industry Program (JIP) [5] and [10]. The PONDUS software developed by MARINTEK for on-bottom stability analysis is one of the softwares that utilize the Verley's model. The focus in this model is the development of break-out resistance from small lateral oscillations related to hydrodynamic loads. On the other hand, the SAFEBUCK JIP program is primarily concentrated on the lateral soil model during in-place large displacement lateral buckling, including

the effect of the soil berm build up from large in-place lateral displacements.

The above non-linear interaction models are combined and implemented into the finite element (FE) software SIMLA [15] to perform non-linear finite element analysis and numerical studies including which results that can be expected.

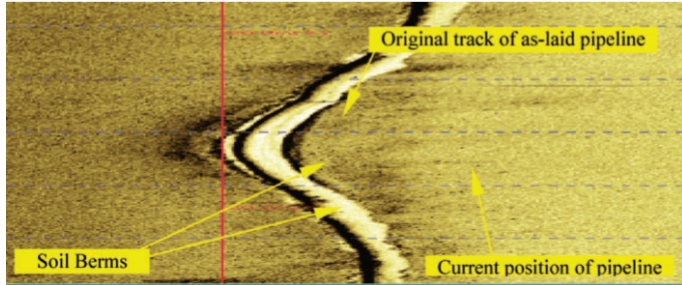


Figure 1 Example of soil berm build-up [6].

NON-LINEAR MODELS FOR CLAY SOIL

The proposed model combines the Verley’s model and the berm resistance model from the SAFEBUCK JIP program for cohesive soils. The model described by Verley et al [12] is often cited in industry and implemented in DNV guidelines [11] and software PONDUS [13]. However, there are slight differences between how the Verley model is implemented in the PONDUS program and how it is formulated in DNV-RP-109. Both versions have been investigated, respectively referred to as PONDUS-mode and DNV mode.

Verley’s model

Soil resistances in lateral pipe-soil interaction have two main components: friction (Coulomb) force and passive resistance force. The total soil force, F_s therefore can be expressed as follows [13]:

$$F_s = F_f + F_R \quad [1]$$

where F_f is friction force and F_R is soil passive resistance force.

The Coulomb force, F_f is simply expressed as follows [13]:

$$F_f = \mu(w_s - F_l) \quad [2]$$

where w_s is submerged weight per unit length, F_l is lift force acting on the pipe and μ is friction coefficient. The friction coefficient for clay is typically defined as 0.2 [13].

The passive soil resistance force F_R is a non-linear function and is described by a force-displacement relationship. Figure 2 shows the force-displacement relationship of soil passive

resistance force. There are four stages of passive force development:

1. An elastic region that typically have lateral displacement less than 0.02D. The upper limit of the soil force is denoted as F_{R1}
2. Plastic region where the soil started to build-up breakout resistance. The upper limit of the force is denoted as F_{R2}
3. After breakout region where the soil force decrease due to pipe breakout from the trench
4. Constant passive resistance during high lateral displacement. The soil force at this stage is denoted as F_{R3} .

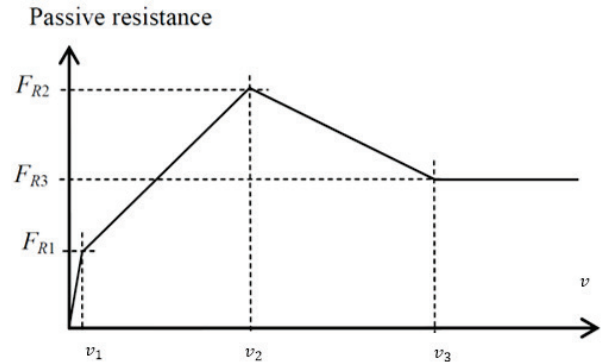


Figure 2 Typical load-displacement curve for lateral soil resistance [11].

• Elastic Regime

In elastic regime, soil passive force is linearly increasing until reaching F_{R1} and no work is done. The assumed pipe initial penetration z_i is due to self-weight and expressed as follows [11]:

$$\frac{z_i}{D} = 0.0071 \left(\frac{G^{0.3}}{K_0} \right)^{3.2} + 0.062 \left(\frac{G^{0.3}}{K_0} \right)^{0.7} \quad [3]$$

$$G = \frac{s_u}{D \cdot \gamma_s} \quad [4]$$

$$K_0 = \frac{s_u \cdot D}{w_s} \quad [5]$$

where s_u is undrained shear strength of the clay, D is pipe diameter, and γ_s is dry unit soil weight which can be taken as 18000N/m³ for clay [11].

The upper limit of the passive resistance force and lateral displacement in this stage is denoted as F_{R1} and Y_1 and defined as follows ([11] and [13]):

$$F_{R1} = \frac{4.13K_c(w_s - F_l)}{G^{0.392}} \left(\frac{z_l}{D} \right)^{1.31} \quad [6]$$

$$K_c = \frac{s_u \cdot D}{w_s - F_l} \quad [7]$$

The upper limit of the lateral displacement in elastic regime v_1 is defined as $0.02D$ by DNV [11] or $(F_f + F_{R1})/k_s$ by PONDUS [13] where k_s is soil stiffness.

Therefore, the soil stiffness and passive force in elastic regime can be expressed as follows:

$$K_s = \frac{F_{R1}}{Y_1} \quad [8]$$

• Plastic Regime

If the lateral motion increases further, the passive soil resistance will enter the plastic regime. The soil penetration will increase due to accumulated work (energy) by lateral motion. The work in the plastic regime is defined as follows [13]:

$$E = \int_0^t F_R ds \quad [9]$$

The total soil penetration, z_2 , due to lateral motion in the plastic regime can be found as follows [13]:

$$\frac{z_2}{D} = \left[0.12 \cdot S^{0.637} \xi^{0.32} \left(\frac{a}{D} \right)^{-0.25} \right], \left(\frac{a}{D} \right) \geq 0.05 \quad [10]$$

$$\xi = \frac{E}{s_u \cdot D^2} \quad [11]$$

where a is the pipe oscillation amplitude in the lateral direction. If (a/D) is less than 0.05, then $a/D=0.05$ [13].

The soil penetration in the plastic regime is limited by the following equations [12]:

$$\left(\frac{z_2}{D} \right)_{max} = 1.15 \cdot G^{0.54} \left(\frac{a}{D} \right)^{0.17}, \left(\frac{z_2}{D} \right) \leq 0.3, \left(\frac{a}{D} \right) \geq 0.05 \quad [12]$$

Based on the test data available in [3] and [4] the upper limit of the soil penetration is defined as follows [12]:

$$z_{2max} = 0.3 \cdot D, \left(\frac{z_2}{D} \right) > 0.3 \quad [13]$$

The peak of the soil resistance force in this stage (the breakout strength) is denoted as F_{R2} and can be found as follows ([11], [13]):

$$F_{R2} = \frac{4.13K_c(w_s - F_l)}{G^{0.392}} \left(\frac{z_2}{D} \right)^{1.31} \quad [14]$$

From Eqs. [10] and [14], it can be seen that the breakout strength will vary during the lateral motion increment. The maximum lateral motion, where the maximum breakout, v_2 , occurs is defined as $0.5D$ [11]. More results data has been made

available from the CARISIMA project [7] and [9], and in the latest version of PONDUS program, the v_2 was extended to $0.75D$.

The soil stiffness in the plastic regime can be found as a function of soil penetration, as shown below:

$$k_{z2} = \frac{(F_{R2} - F_{R1})}{v_2 - v_1} \quad [15]$$

From the equation, it easily can be seen that the soil stiffness in the plastic regime is not constant and varies with an increase in soil penetration.

By assuming the linear relation between F_{R1} and F_{R2} during plastic deformation, the passive soil resistance therefore can be found as:

$$F_R = F_{R1} + k_{z2} \cdot (v - v_1) \quad [16]$$

Even though a linear relation is assumed, the passive soil resistance may show a non-linear result due to changing breakout strength during lateral motion.

• After Breakout

If the pipe continues to move in the same direction after breakout, some horizontal resistance in addition to friction will present due to the soil mound being pushed ahead of the pipe [13]. The accumulated work is set to zero, and no work is considered in this stage. The soil penetration is reduced, accordingly, to the penetration associated with z_3 . DNV recommends the value of z_3 as half of the soil penetration at z_2 until $v=D$, as defined below [11]:

$$z_3 = 0.5z_2^* \quad [17]$$

where z_2^* is the soil penetration at breakout.

In PONDUS, after soil breakout the force-displacement curve moves with distance of $(v-v_2)$. The value of z_3 in PONDUS is also calculated with a different method by using Eq. [3].

The residual resistance, F_{R3} , is therefore defined as follows:

$$F_{R3} = \frac{4.13K_c(w_s - F_l)}{G^{0.392}} \left(\frac{z_3}{D} \right)^{1.31} \quad [18]$$

The calculation of the residual limit, v_3 , is different in DNV and PONDUS. In DNV, v_3 is set to be equal to $1D$, while in PONDUS the limit is calculated using the following expression:

$$v_3 = D \left(0.6 \left(\frac{5.5}{\kappa} + 1 \right) + \frac{v_2}{D} \right) \quad [19]$$

where $\kappa = \frac{\gamma_s D^2}{w_s - F_l}$.

The slope of the passive soil force after breakout is then defined as follows:

$$k_{z3} = \frac{(F_{R2} - F_{R3})}{v_3 - v_2} \quad [20]$$

The passive soil resistance for in-between therefore can be found by modifying Eq. [16] by the appropriate slope, as follows:

$$F_R = F_{R2} + k_{z3} \cdot (v - v_3) \quad [21]$$

If the pipe still moves in the same direction after reaching z_3 , the passive soil resistance is set equal to F_{R3} and soil penetration equal to z_3 .

- **Large Amplitude Cycle (Berm Model)**

During large lateral displacement (typically higher than 1D), part of the soil will be dragged by the pipe, causing added soil resistance. This effect had been captured inside Verley's model by means of residual soil resistance. However, Verley's model does not capture the effect of soil berm that builds up at the end of every large displacement sweep.

With soil berm, the lateral deformation is arrested. If the soil berm is ignored, the soil resistance remains constant (equal to residual and friction force). Numerical modelling shows that this will cause the buckle to grow in amplitude with each cycle, and will result in underestimating the fatigue damage [2].

Some research has been conducted to formulate the soil berm resistance (e.g. SAFEBUCK [6] and IPT [7]) in a simple and easily implemented way. Both SAFEBUCK and IPT proposed that the soil berm resistance can be formulated as friction load. The SAFEBUCK program proposed that the additional berm resistance, ΔF_{berm} , can be added on top of residual soil resistance during the berm build-up, F_{R3} . The proposed value of ΔF_{berm} is:

$$\Delta F_{berm} = 1.5F_v \quad [22]$$

where F_v is the vertical force acting on the force. The number of sweeps required to achieve this maximum berm resistance is five cycles (typically) [6].

The maximum soil berm resistance is therefore can be calculated as follows:

$$F_{berm,max} = \Delta F_{berm} + F_{R3} \quad [23]$$

Linear incrimination of soil resistance from F_{R3} to maximum berm resistance is assumed from half distance between previous know soil reversal point and residual limit, v_3 .

IMPLEMENTATION OF NON-LINEAR MODEL

The non-linear soil model referred to above has been implemented into a FORTRAN subroutine referred to as DNVMODEL-Y in the following. The subroutine was then integrated inside the SIMLA finite element software [15]. A specialized work array is created inside the subroutine containing the memory parameters needed for calculating soil force and stiffness. SIMLA is based on stepwise loading with equilibrium iterations at each load step. Therefore, in every iteration step, the last known work array from previous equilibrium configuration is copied during each iteration. The subroutine then calculates the updated soil force and stiffness. At the end of successful equilibrium iteration, the work array is finally updated with respect to the new values. Figure 3 shows the communication between SIMLA and the soil subroutine (DNVMODEL-Y). DNVMODEL-Y contains three (3) different soil models: PONDUS, DNV and Large Displacement Model (BERM Model).

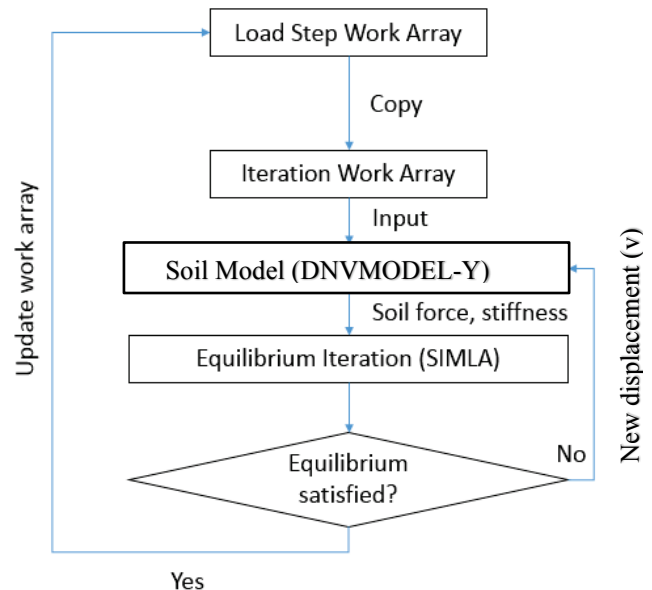


Figure 3 Communication flowchart between soil subroutines and SIMLA

VALIDATION OF MODEL

Two validation methods for Verley's and DNV models inside the program have been applied. Firstly, by comparing the results the model with the existing PONDUS program. Then secondly by giving an oscillating prescribed displacement history as input and validate the force-displacement curve. The input soil data for every analysis cases are according to Table 1. The pipe used in PONDUS and DNVMODEL-Y has an outer diameter of 0.2032m and thickness of 0.01m. The submerged weight of the pipe is 167.8 N/m.

- **PONDUS Comparison**

In order to compare the results between DNVMODEL-Y and PONDUS, it was necessary to first perform the analysis in PONDUS and then use the displacement outputs as a prescribed displacement history for DNAMODEL-Y. Two analysis cases were developed for the validation procedure. The first case includes small lateral displacements without breakthrough while for the second case, large displacements triggering breakout (larger than 0.75D) were applied.

Table 1 PONDUS Test Case Soil Parameters

Parameter	Value
Soil shear strength, S_u	800 Pa
Shear strength gradient, S_g	0
Soil elastic stiffness, K_s	65000 N/m ²
Soil friction factor, μ_s	0.2
Dry soil weight (clay), γ_s	18000 N/m ³

Figure 4 shows the results from Case 1. From the soil force history, it can be seen that the DNVMODEL-Y is able to replicate the soil force history from PONDUS.

The results for large displacement is seen in Figure 5 where very good correlation is demonstrated. The breakout resistances in both models are identical and the behavior is closely matched. After breakout, DNVMODEL-Y is observed to give slightly lower soil force compared to PONDUS. The reason for this is the difference in soil force and penetration calculation method after breakout in DNVMODEL-Y and PONDUS program. The observed maximum difference is around 10% for soil force after breakout between both models. Despite this differences, the results from DNVMODEL-Y show that the subroutine is able to produce correct soil behavior as compared to PONDUS.

There are some differences observed in both cases but these differences are quite small and unavoidable due to difference in calculation algorithms. Both models also produce identical peak force and maximum penetration which is the most important aspect for pipe-soil penetration.

- **DNV-PONDUS Comparison**

These test cases were developed to validate the analysis results of the PONDUS- and DNV-modes of the Verley model in DNVMODEL-Y routine by means of prescribed displacement loads. This was done to investigate the difference between the PONDUS implementation of the Verley model and the DNV-RP-F109 version of the same model

The result for Case 1 is shown in Figure 6. From the figure, it can be seen that the DNV-mode gives higher soil force compared to PONDUS-mode over time. The main reason for this difference is different assumptions of characteristic limit. DNV model does not have “elastic force extension” as seen in

the PONDUS model. In each reversal, the remaining soil force (D_s) directly enter plastic range after passing elastic limit. The DNV also use the penetration in reversal point as initial penetration therefore increasing the soil force further in each cycle. From penetration history, it can be seen that penetration develop much quicker in DNV-mode compared to PONDUS-mode. After few cycles, the soil force from DNV-mode can be twice of results from PONDUS-mode. If maximum allowed penetration is reached, the soil force stops increasing, forming a closed-loop in force-displacement curve.

The analysis results for Case 2 is seen in Figure 7. The results show key differences between both modes. In penetration development, it can be seen that DNV-mode gives a sharp decrease in penetration after the pipe breakout. On the other hand, the PONDUS-mode results show a very gradual decrease in penetration. Looking at the soil force history, the DNV-mode gives lower peak resistance and flat residual force compared to PONDUS-mode results. There are two reasons of these differences. The first regards the breakout limit. The DNV-mode uses 0.5D as the breakout limit instead of 0.75D used in PONDUS-mode. This lower limit in DNV-mode causes the DNV-mode to have lower peak soil force in each cycle due shorter plastic regime. The second reason is regarding the residual limit, v_3 . The DNV-mode is based on a fixed criterion for the start of the residual soil force of 1D. The PONDUS model residual limit depends on the submerged weight of the pipe and moves over time if the displacement is larger than 0.75D. This makes the DNV-mode reaching the residual limit faster than the PONDUS-mode. The third reason is due to difference in calculating the penetration after breakout between both modes. The DNV-mode uses linear interpolation between breakout penetration, z_2 and residual penetration, z_3 . This makes the penetration in DNV-mode decrease faster than in PONDUS-mode.

The results from DNV Case 1 and Case 2 show the differences between the DNV- and PONDUS-modes of DNVMODEL-Y. Even though there are some significant differences in both modes, the DNV-mode produces a soil force pattern and behavior as expected.

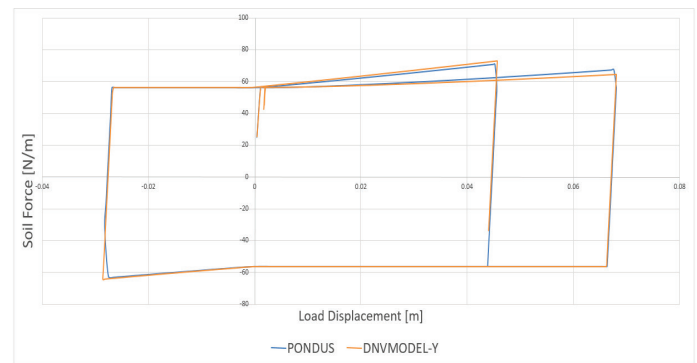


Figure 4 Force-displacement curve for PONDUS Case 1

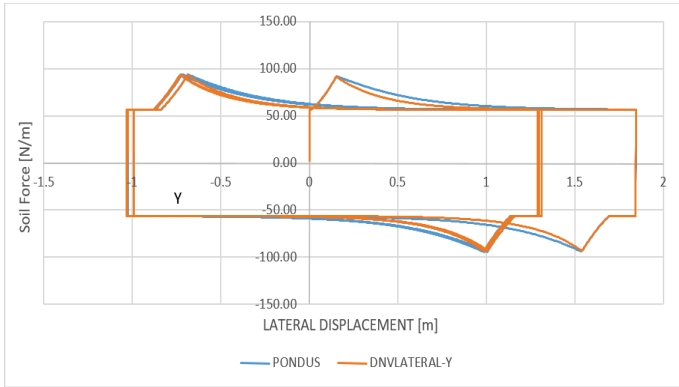


Figure 5 Force-displacement curve for PONDUS Case 2

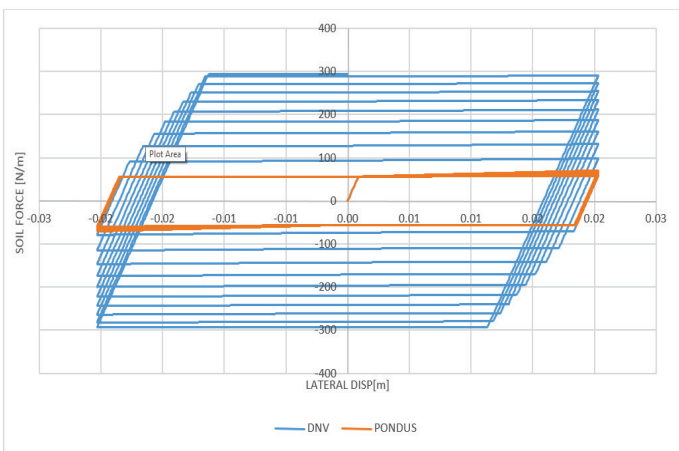


Figure 6 Force-displacement curve for DNV Case 1

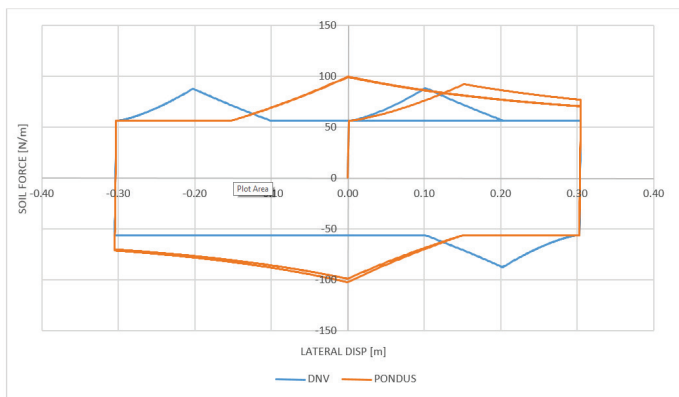


Figure 7 Force-displacement curve for DNV Case 2

• **BERM Model Validation**

This test case was developed to demonstrate the berm resistance model for large cyclic displacements as implemented in DNVMODEL-Y. The test case is consisting of large amplitude harmonic forced lateral transverse displacements, as shown in Figure 8. The berm resistance model was used in combination with the DNV-mode lateral model. The number of

cycles that needed to reach maximum berm resistance was defined as 5 cycles. The berm resistance at the end of every cycles is assumed to be linearly increasing until reaching the defined maximum berm resistance. The pipe used in the test case had an outer diameter of 0.2032m and with 0.01m thickness. The submerged weight of the pipe is 167.8 N/m.

The results of the analysis can be seen in Figure 9. The result show that the lateral model is capable of capturing the berm effect during large displacements. The berm resistance is linearly increasing starting from half distance between the start of residual force and next reversal point. The maximum berm resistance in each cycles is a fraction of the maximum possible berm resistance which is 307 N/m. In each successive cycles, this fraction is increased linearly until the defined number of cycles. It is worth mentioning that results show two distinct berm resistance cycles. However, the maximum possible berm resistance is not changed.

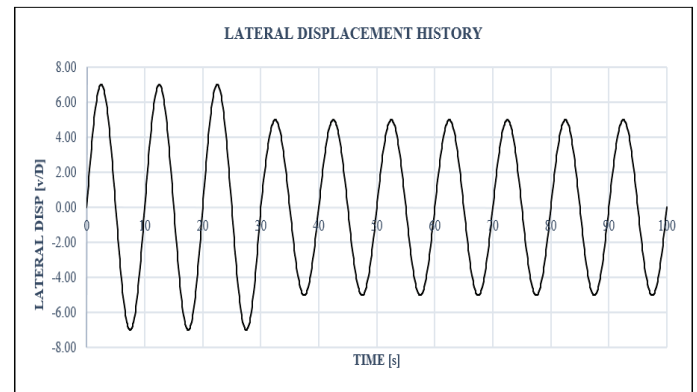


Figure 8 Lateral displacement history for berm resistance test case.

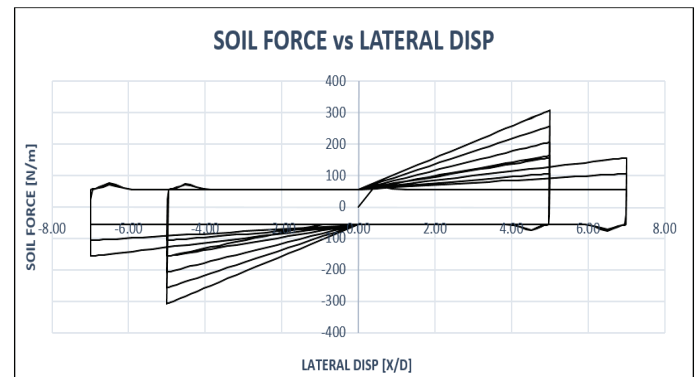


Figure 9 Results of berm resistance model for large amplitude lateral displacement

APPLICATION OF MODEL

This section is dedicated to show the application of the soil subroutines, DNVMODEL-Y, in conjunction with a SIMLA structural model to solve the pipe-soil interaction problem. Several sensitivity analyses were carried out. However, the

focus here is to demonstrate the difference that might be expected between using a Coulomb model versus the implemented berm model performance with regard to the buckling shape of the pipeline.

The Coulomb friction model is typically used to model pipe-soil interaction. In the following section, the implemented PONDUS and berm models will be compared to the Coulomb model to study the effect of each model in pipeline lateral buckling analysis.

• **Case Description**

A pipeline with 200m of length is considered in analysis presented in this section. The pipe has an outer diameter of 0.508m and 0.025m thickness. The pipe is modelled using the PIPE element type in SIMLA. Two PIPE element types are used in the analysis: PIPE31 element type is used to model purely elastic behavior, while PIPE 33 is used to model elastoplastic material [15]. Both of them assume constant axial strain and torsion. In the case of analyses using elastoplastic material, a stress-strain curve is defined as in Figure 10. To model pipe-soil interaction, a contact element is necessary to connect the pipe element with the soil element. The contact element type used in SIMLA, CONT126, is a 3D seabed contact element [15]. The lateral soil model subroutine, DNVMODEL-Y, is connected to this contact element to simulate lateral soil resistance and stiffness during pipe-soil interaction simulation. The pipe is divided into several elements, with every element having length of 1 m. The seabed element has a size of 1x4 m and is described in a separate input file. The sketch of the finite element model of the pipe and seabed is shown in Figure 11. The pipe is fixed at both ends, in all directions except vertical.

The model is subjected to both static and dynamic analysis. The static analysis is used primarily in the initialization stage. The initialization stage is used to create the pipe’s lateral imperfection and therefore to enable lateral buckling. The imperfection is created by loading the pipe laterally with artificial loads in the center of the pipe in the positive y-direction. The magnitude of the load is small (1 kN) to avoid entering the plastic range of the lateral soil model in the initialization stage accidentally. The dynamic analysis is used in the main part of the analysis after imperfection is created. The initial strain load is used in the dynamic analysis and is stepped over time in the form of a sine function. This is used to create a smooth expansion and contraction along the pipeline to simulate the thermal cycling. A period of 40 s is primarily used in the analysis to provide a smooth loading of the pipeline.

EPCURVE is a material model that is used to model elastoplastic material behaviour with kinematic/isotropic hardening. HYPERSURVE is used to model hyperelastic (non-linear elastic) material behavior [15]. The EPCURVE model is typically used to model Coulomb friction force, and therefore is

chosen to model the axial pipe-soil interaction. The HYCURVE is selected to model the pipe-soil interaction in the vertical direction.

The pipe is subjected to lateral transverse motions which are imposed in a simplified manner by means of a cyclic initial axial strain in the elements. The purpose of the initial strain is mainly to simulate expansion and contraction of the pipeline due to thermal cycling. The seabed is modelled as flat surface with uniform depth of 100m. No wave load is considered. Elastoplastic material is used for the pipe element to correctly model the pipe behavior.

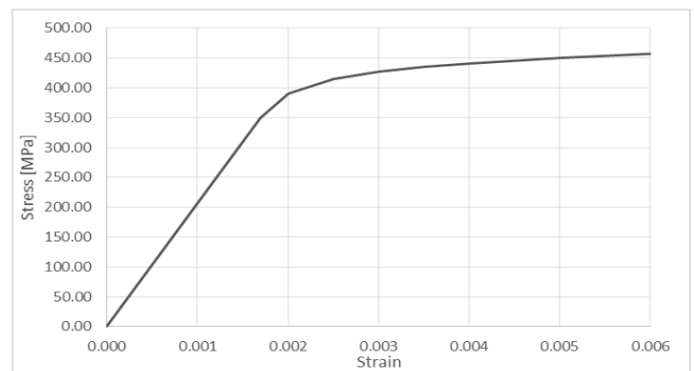


Figure 10 Stress-strain curve for elastoplastic material model

Several test cases with different strain load amplitudes were included to study the pipeline cyclic buckling phenomenon. Table 2 lists the analysis cases in terms of strain load. The soil models used in the analysis were the berm Model, the PONDUS model and the Coulomb friction model. Each model is subjected to the same strain load for each case therefore giving a total of 18 analysis cases. The Berm model is coupled with DNV the model and had been set to reach maximum in only one cycle to reduce analysis time. The Coulomb model is defined to have 0.45 friction coefficient.

Table 2 List of cases for pipeline walking analysis

Case Name	Strain Load
Case 2A	0.001 – 0.0005
Case 2B	0.0025 – 0.00125
Case 2C	0.005-0.0025
Case 2D	0.0075-0.00375
Case 2E	0.01-0.005
Case 2F	0.0125-0.0063

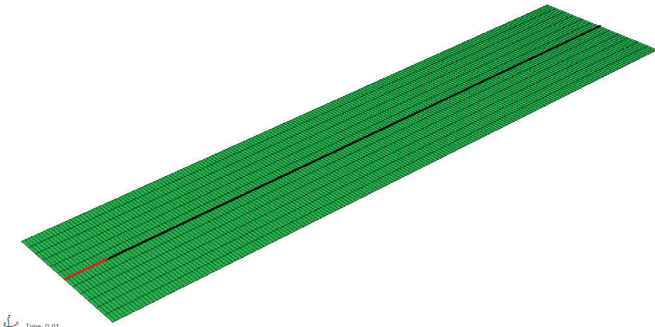


Figure 11 Sketch of finite element model of the pipe and the seabed

• **Results and Discussion**

Figure 12 shows the lateral displacement in the middle of the pipeline. The figures demonstrate that the largest irreversible lateral displacements occur for the Coulomb model, increasing for each cycle. The results from the Berm model shows the displacement is constrained by the soil berm. The PONDUS model result shows that the displacement growth is higher compared to the Berm model due to unaccounted soil berm effect. The growth, however, is still considerably lower compared to the result from the Coulomb friction model. It is worth mentioning that the PONDUS model has an inherent 0.2 Coulomb friction factor, giving the Coulomb model more than twice the friction force of PONDUS. Figure 12 shows that in this case the friction force has less effect in reducing the buckle growth.

Typical buckled pipeline configurations are shown in Figure 13. Regarding pipe-soil interaction, it is observed that the pipe behavior differs according to the soil models used in terms of lateral displacement growth. Figure 13 shows that the buckle grows very fast in Coulomb model compared to the results from Berm model. In the Berm model the lateral displacement growth is restricted by the soil berm due to high soil resistance. This results are in-line with results obtained by Bruton et al. [5] and confirm that the Berm model is working correctly.

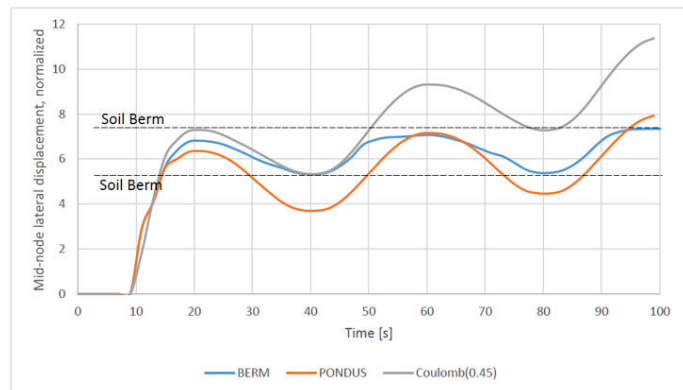


Figure 12 Mid-node displacement, normalized against diameter, for various soil models from Case 2C.

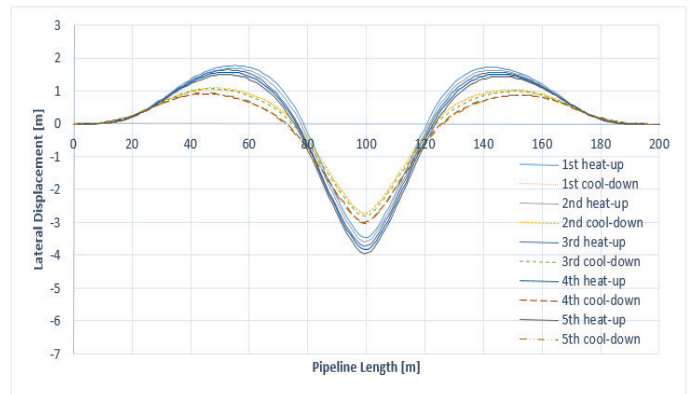
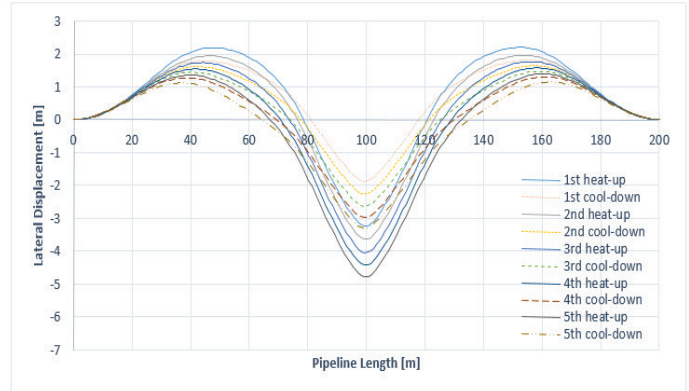


Figure 13 Buckled form of pipeline for Case 2C with Coulomb Model (top) and Berm Model (bottom)

CONCLUSION

In lateral non-linear pipe-soil interaction, two main components of soil resistance are encountered. The first component, friction force, is also known as the Coulomb model. The second component is called soil passive/remaining resistance. The soil passive resistance is shown to be time-dependent and a function of soil penetration and vertical force. The proposed soil model of soil passive resistance generally can be divided into three main paths. In the first path, known as the elastic regime, the soil force can be found from the soil elastic stiffness. In the second path, which is the plastic regime, the pipe started to dig into the soil and build up high soil resistance. In the third path, called the residual force path, the pipe breaks out of the soil trench and begins to drag soil along the way. The dragged soil provides resistance on top of the friction force, and if lateral displacement is quite large, it will build up the soil berm, which gives a very high lateral resistance. Three non-linear models are presented in this paper: DNV, PONDUS and SAFEPUCK Berm model. Each model has its own characteristics, which are explained in detail.

The presented soil models implemented in DNVMODEL-Y have been compared with PONDUS using forced lateral motion. The results show that DNVMODEL-Y can produce reasonable results and behaviors. The BERM model also has

been successfully implemented in conjunction with other two models.

The analysis results from pipeline walking analysis shows the importance of non-linear soil models especially in large displacement cycles. The Coulomb model show unrestricted buckling of the pipe, ignoring the presence of the berm buildup. This result indicates that use of the Coulomb model may cause underestimation of the fatigue damage of the pipeline. In addition, the Coulomb model also gave higher accumulated displacements per cycle compared to the other two models. These aspects can be circumvented by using a more accurate soil model as described above.

Ongoing work includes development of models for combining lateral and vertical pipe-soil interaction based on research projects tailored for different purposes.

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