Solutions for downslope pipeline walking on a seabed with a peaky tri-linear soil resistance model

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ABSTRACT

Offshore pipelines used for transporting hydrocarbons are cyclically loaded by great variations of pressure and temperature. These variations can induce axial instability in such pipelines. This instability may cause the pipelines to migrate globally along their length; an effect known as pipeline walking. Traditional models of pipeline walking have considered the axial soil response as rigid-plastic (RP); however, such behaviour does not match observations from physical soil tests. It leads to inaccurate estimates of walking rate (WR) per cycle and over design. In this paper, a tri-linear (3L) soil resistance model is used to represent seabed resistance to investigate the behaviour of pipeline walking. Different parameters, i.e. shapes and properties of tri-linearity (within the peaky soil model type) have been considered leading to a closed-form solution. This solution improves understanding of the main properties involved in the peaky tri-linear soil behaviour by providing a set of analytical expressions for pipe walking, which were benchmarked and validated against a set of finite element analyses.

KEYWORDS

axial resistance; pipe-soil interaction; pipeline walking; finite-element modelling; offshore engineering

1 INTRODUCTION

As offshore oil and gas industry increasingly explores deep water reservoirs, offshore pipelines become progressively important. Under operational load cycles, they expand and contract in response to temperature and pressure changes. However, these expansion and contraction cycles may have an asymmetric behaviour due to seabed slopes or other factors, such as multiphasic flow (Bruton *et al.*, 2010), and thermal transients (Carr *et al.*, 2006). The asymmetric expansion and contraction directly impacts the stability of these pipelines causing them to migrate in one direction, which generates the phenomenon known as pipeline walking (Carr *et al.*, 2003). Pipeline walking increases cost and risk and may severely impact the subsea system (Tornes *et al.*, 2000). It may overstress connections, alter loads and strains in any engineered lateral buckle and may also present the need for anchoring. Hence, accurately identifying and estimating pipeline walking is necessary to decrease the risk of production loss and environmental impact, and it can significantly decrease project development costs.

Presently, the common practice in the industry is to evaluate pipeline walking during the design phase using a set of analytical formulations as per Bruton *et al.* (2010). These calculations consider various aspects, such as operational (temperature, pressure, etc.), environmental (seabed overall slope angle, soil friction coefficient, etc.) and physical pipeline properties (length, steel wall thickness, etc.); but still imply some limitations such as the idealised rigid-plastic pipe-soil interaction, and the single seabed slope. Accurately evaluating high-temperature and high-pressure pipelines for downslope pipeline walking is of paramount importance to the industry because these conditions are commonly found in fully operational areas, such as the Gulf of Mexico, North Sea and Northwest Australia, as well as in frontier locations, which are still in early stages of exploration, such as the Brazilian Pre-Salt and the Arctic Region. The analytical formulation is based on an idealised soil resistance model and can provide inaccurate walking rates. Then, the assessment requires further improvement of the soil resistance model to overcome this limitation.

Costly and time demanding finite element analyses are used to confirm walking behaviour and to generate a reliable walking rate. However, emerging academic research (Castelo *et al.*, 2019; Castelo *et al.*, in press b) demonstrates that, if more realistic soil behaviour is considered in the analytical formulae, the requirement for time demanding and expensive finite element analyses can be reduced.

Although the formulation developed by Castelo *et al.* (2019) and Castelo *et al.* (in press b) generate significant cost-savings and improve efficiency, they are limited to a single soil model type, i.e. elastic-plastic (elastic-perfectly-plastic and non-linear elastic-plastic, respectively). Therefore, further improvement is needed to capture the walking behaviour with soils that develop a peak breakout resistance before reaching a plastic plateau, as commonly seen in the operational areas mentioned above, and thus the accuracy of pipeline walking results for analytical formulae is increased.

It has been found that there is a significant lack of knowledge about the influence of pipe-soil interaction models on pipeline walking. Rong *et al.* (2009) acknowledge that there is such an influence by stating: "*The axial mobilization distances may have significant effects on the axial walking. Unfortunately, limited literature is available* *about this topic.*" The latest joint industry project (JIP) research program, the SAFEBUCK JIP (Bruton *et al.*, 2007; Bruton and Carr, 2011a; Bruton and Carr, 2011b) has not clarified what should be the treatment for axial pipe-soil interaction, when pipeline walking is assessed. The SAFEBUCK JIP solely focused on the ideal rigid-plastic pipe-soil interaction model.

In addition, the pipe-soil interaction standard, DNVGL-RP-F114 (DNVGL, 2017) mentions: "*In assessments of pipe walking, a low value of mobilisation distance creates a higher rate of axial walking. To be conservative, a bi-linear fit to the non-linear response should be a tangent fit to the initial part of the axial force-displacement response, which represents the elastic recoverable part*". Hence, no guidance has yet been given on how to treat non-rigid-plastic soil models on pipeline walking assessments.

This paper investigates the impact on pipeline walking of a tri-linear soil resistance model accounting for a peak break-out behaviour. It starts by a brief literature review of the present methodology used to estimate the walking rate for elastic-plastic soils (Castelo *et al.*, 2019; Castelo *et al.*, in press b). It then builds on the previous knowledge to generate theoretical expressions for pipeline walking on peaky tri-linear soils. Next, finite element analyses are performed to provide confirmation on the theoretical framework. Finally, this paper generates a solution that allows an adjustment for the original rigid-plastic analytical formulation (Bruton *et al.*, 2010), so that the requirement for finite element analyses can be avoided.

2 BACKGROUND TO PIPELINE WALKING

2.1 Downslope mechanism

The seabed slope generates an asymmetry between the start-up (SUp) and shutdown (SDown) phases in the effective axial force (EAF) profile for a fully mobilised pipeline, as illustrated in Figure 1, where the rigid-plastic soil condition is considered. This asymmetry causes the virtual anchor sections (VAS) to be separated by a given distance, X_{ab}. For rigid-plastic soil representations, the virtual anchor sections correspond to the maximum absolute effective axial force along the pipeline length, L. Then, the distance X_{ab} can be associated to the axial displacement, δ_x, from a particular load phase (start-up and shutdown phases), as presented by Figure 2. Because it tends to create unbalanced displacements during different loading stages, the asymmetry in the effective axial force profile is presently understood to be root cause of pipeline walking.

Accounting for more realistic soil conditions, the distance X_{ab} cannot be associated with maximum effective axial force. Therefore, X_{ab} must be associated with the stationary points (SP), as thoroughly explained in Castelo *et al.* (2019).

2.2 Pipe-soil response

Previous research on pipeline walking has treated soils as rigid-plastic (Carr *et al.*, 2003; Carr *et al.*, 2006; Bruton *et al.*, 2010) or as elastic-plastic (Castelo *et al.*, 2019; Castelo *et al.*, in press b). However, it is known that some soils behave much more complex, usually producing first a breakout peak resistance and then decreasing their resistance to a residual plastic level.

Although many other studies, such as White *et al.* (2011), have already investigated peaky soils in general terms, none has gone through the specific impact on pipeline walking. This paper focuses on a soil representation that accounts for breakout soil resistance using a peaky tri-linear (3L) soil representation and how pipeline walking may change due to this different soil condition.

3 PROBLEM DEFINITION

Downslope pipeline walking is dependent on three types of properties: environmental, operational and those of the pipeline. This paper's parametric study uses typical parameter ranges for these three properties.

The environmental parameters include seabed slope angle, β, and residual friction coefficient, μ, taken to be 2 ° and 0.25, respectively. The operational parameters include temperature variation, ΔT, and pipe submerged weight, W, assumed to be 100 °C and 0.4 kN/m, respectively. The physical pipeline properties include steel outside diameter, *OD*, steel wall thickness, t, and length, taken to be 0.3239 m, 0.0206 m and 5000 m, respectively. Some additional environmental properties were taken as variables for the parametric study, and they are related to the pipe-soil response (cases i - iv). The full list of properties and parameters used in this study are provided in Table 1 and Table 2.

Figure 3 presents a schematic axial force-displacement response for an ideal set of peaky tri-linear soil cases. As investigated in White *et al.* (2011), it is known that various aspects affect the cyclic behaviour of peaky soils. These aspects may be related, but not limited, to the time interval between distinct movements, the varying pipeline embedment, etc. As a result, this paper takes into account two different extreme conditions for the cyclic load phases:

- “EqualPeaks”;
- “NoSUpPeak”.

As the conditions’ names suggest, the first condition, “EqualPeaks”, behaves with equal peaks for both loading and unloading phases – start-up and shutdown. Alternatively, the second condition, “NoSUpPeak”, behaves with no peak for start-up phases, while peaky for shutdown phases. There is no clear understanding in the literature of why the peak may exist for one load phase, while it may not occur for another load phase, but this may be due to the differing waiting periods causing different levels of consolidation or thixotropy (White et al. 2011). For example, shutdowns are generally shorter duration than operating periods.

Consequently, the axial force-displacement responses, shown in Figure 3, need to be updated to account for cyclic movements. Figure 4 shows the update to Figure 3, presenting three hypothetical load phases for “EqualPeaks” and “NoSUpPeak” conditions. The small numbered arrows indicate the loading path for each of the conditions (“EqualPeaks” on top, and “NoSUpPeak” at the bottom of Figure 4).

According to previous experience (Castelo *et al.*, 2019; Castelo *et al.*, in press b), the first load phase is not representative for the cyclic walking behaviour. At the initial state, the nodes will displace a shorter distance to reach the relevant (either peak or residual) force levels. Therefore, for simplicity, it is assumed that the first load phase does not peak; while for the cyclic load phases it will peak as prescribed by the "EqualPeaks" or "NoSUpPeak" conditions.

In addition, although the authors acknowledge that intermediate peak cases may occur in between "EqualPeaks" and "NoSUpPeak" conditions, these intermediate conditions would be enveloped by these two extreme conditions. For this reason, the intermediate cases are disregarded in this paper.

4 ELASTIC-PERFECTLY-PLASTIC SOLUTION FOR PIPELINE WALKING

From Castelo *et al.* (in press b) it is known that the walking rate for an elastic-plastic pipe-soil response, WR_{EP}, can be obtained simply by subtracting twice the equivalent mobilisation displacement, δ_{mobEQ}, from the walking rate for rigid-plastic soil, WR_{RP}, as shown by equation (1):

$$WR_{EP} = WR_{RP} - 2 * \delta_{mobEQ} \quad \textbf{(1)}$$

where the walking rate for rigid-plastic soil can be estimated from Carr *et al.* (2006) and the equivalent mobilisation displacement for a non-linear elastic-plastic pipe-soil response can be obtained from Castelo *et al.* (in press b).

As another option, reorganizing equation (1), as also explained by Castelo *et al.* (in press b), the walking rate for an elastic-plastic pipe-soil response, can be established by multiplying the walking rate for rigid-plastic soil by a reduction factor based on the equivalent mobilisation displacement and the non-walking mobilisation displacement, δ_{null}, as presented by equation (2):

$$WR_{EP} = WR_{RP} * \left(1 - \frac{\delta_{mobEQ}}{\delta_{null}}\right) \quad \textbf{(2)}$$

where the non-walking mobilisation displacement, δ_{null}, can be achieved using equation (3) – (Castelo *et al.*, 2019):

$$\delta_{null} = \frac{WR_{RP}}{2} \quad \textbf{(3)}$$

As confirmed by Castelo *et al.* (in press b), the same reduction factor can be applied to the distance between stationary points for an elastic-plastic pipe-soil response, $X_{ab,EP}$, as presented below by equation (4):

$$X_{ab,EP} = X_{ab,RP} * \left(1 - \frac{\delta_{mobEQ}}{\delta_{null}}\right) \quad \textbf{(4)}$$

where the distance between stationary points for rigid-plastic soil, $X_{ab,RP}$, can be estimated from Bruton *et al.* (2010).

A parametric study has been performed using finite element analyses, to investigate the peaky tri-linear pipe-soil responses seen in Figure 4, aiming on building on equation (1) to create an accurate, simple and fast methodology to estimate pipeline walking for this pipe-soil response type.

5 FINITE ELEMENT METHODOLOGY

The finite element model used in this paper is based on a straight pipeline laid on a uniformly sloping seabed. The properties of this model are presented in Table 1 and Table 2 (soil case ii). Table 2 also presents data used for the parametric study developed later in this paper.

The 5000 m pipeline was represented by 5001 nodes connected by 5000 equal Euler Bernoulli beam elements (B33 – 3 dimensional 3 noded elements in Abaqus – DASSAULT SYSTÈMES, 2014), creating a 1 metre “mesh” size. An overall sketch of the finite element model used is presented by Figure 5.

To represent the peaky tri-linear pipe-soil interaction, the soil was modelled as a set of macro elements connected to each pipeline node, which were described as user elements in user subroutine UEL coded in FORTRAN computer language.

5.1 Peaky tri-linear pipe-soil interaction models

Two different soil conditions were modelled for this paper: the “EqualPeaks” and “NoSUpPeak” extreme conditions as shown in Figure 4.

For the “EqualPeaks” condition, the user element interface followed a constant (positive) stiffness until a predefined peak elastic force, F_P, was attained. At this peak force a constant (negative) stiffness was followed, so that the reaction force reduced up to a residual plateau (residual plastic force, F_R). If the displacement was reversed, the same behaviour could be observed for the spring-slider in the opposite direction.

For the “NoSUpPeak” condition, the user element interface applied the same forces during loading as applied in the “EqualPeaks” condition. However, for start-up phases, the forces did not present the peak, because once the reaction force achieved the residual plateau, no further reaction was provided and the followed stiffness at this point was zero, where the forces remained in the residual plateau.

5.2 Loads

In the analysis, the pipeline was heated up uniformly with temperature increasing to 100 °C. This value represents a combined equivalent effect of temperature and pipe internal pressure (Hobbs, 1984).

The self-weight of the pipeline, W, and seabed slope angle, β, generate a sliding component, W_{comp}, to the weight:

$$W_{comp} = W \sin \beta \tag{5}$$

Operational cycling was modelled by alternating the pipeline temperature between the steady operational profile (start-up) and the rest condition (shutdown).

5.3 Analysis description

The geometry of the model was defined by a set of nodes created in a straight line as previously mentioned (Section 5 and illustrated by Figure 5). Then, the analyses were performed by running a sequence of load phases as follows:

1. Applying boundary conditions and UEL properties;
2. Applying gravity to pipeline;
3. Applying temperature heating-up (start-up temperature);
4. Applying temperature cooling-down (shutdown temperature);
5. Iterating phases 3 and 4 (9 times);
6. Extracting results from simulations' outputs.

6 FINITE ELEMENT ANALYSIS RESULTS AND COMPARISON WITH RIGID-PLASTIC SOLUTION

Figure 6 and Figure 7 show the effective axial force and the axial displacement distribution, respectively, for the "EqualPeaks" condition applied to ideal case ii.

Figure 8 and Figure 9 show the effective axial force and the axial displacement distribution for "NoSUpPeak" condition applied to ideal case ii.

Although, these two finite element analyses ("EqualPeaks" and "NoSUpPeak") provided similar results when compared to each other, as shown in Table 3, when compared to the analytical calculations from Bruton *et al.* (2010), as shown in Table 4, the deviation presented a remarkable margin.

The deviation between rigid-plastic calculations and finite element results (61 m for the distance between stationary points and 0.066m/cycle for the walking rate) is justified by the fact that the finite element analyses considered a more realistic soil. Instead of using a basic soil approximation, rigid-plastic, the analyses considered a more realistic soil response, peaky tri-linear pipe-soil interaction.

To estimate the realistic results for the distance between stationary points and for the walking rate, a closed-form solution is outlined for the peaky tri-linear pipe-soil response, as was done in Castelo *et al.* (2019) and Castelo *et al.* (in press b).

7 REVISED CLOSED-FORM SOLUTION FOR THE DISTANCE BETWEEN STATIONARY POINTS FOR PEAKY TRI-LINEAR SOILS – $X_{ab,3L}$

From Castelo *et al.* (in press b) where the soil is treated as a non-linear elastic-plastic spring, it is known that the distance between stationary points, $X_{ab,EP}$, is equal to the distance between stationary points for rigid-plastic soils, $X_{ab,RP}$, multiplied by a reduction factor, which is based on the equivalent mobilisation displacement, δ_{mobEQ}, and the non-walking mobilisation displacement, δ_{null}, as shown by equation (4).

Alternatively, for a peaky tri-linear pipe-soil behaviour, the equivalent mobilisation displacement, δ_{mobEQ}, might be substituted by an ideal mobilisation displacement, δ_{mob}'.

$$X_{ab,3L} = X_{ab,RP} * \left(1 - \frac{\delta_{mob}'}{\delta_{null}}\right) \quad \textbf{(6)}$$

8 REVISED ANALYTICAL SOLUTION FOR THE WALKING RATE FOR PEAKY TRI-LINEAR SOILS – WR_{3L}

From Castelo *et al.* (in press b), which treated the soil as a non-linear elastic-plastic spring, it is known that the walking rate, WR_{3L}, is equal to the walking rate for rigid-plastic soils, WR_{RP}, multiplied by a reduction factor based on the equivalent mobilisation displacement, δ_{mobEQ}, and the non-walking mobilisation displacement, δ_{null}, as previously shown by equation (2).

Analogously to $X_{ab,3L}$, for a peaky tri-linear pipe-soil behaviour, the equivalent mobilisation displacement, δ_{mobEQ}, might be substituted by an ideal mobilisation displacement, δ_{mob}'.

$$WR_{3L} = WR_{RP} * \left(1 - \frac{\delta_{mob}'}{\delta_{null}}\right) \quad \textbf{(7)}$$

9 IDEAL MOBILISATION DISTANCE – δ_{mob}'

As firstly developed by Castelo *et al.* (2019) and further expanded by Castelo *et al.* (in press b) for the elastic correction, the tri-linear correction, $Corr_{3L}$, for the walking rate predictions can be obtained by doubling the division of the unload-reload area, $A_{Unload\text{-}Reload}$, by the variation of residual plastic force, ΔF_R. However, differently to elastic-plastic soils, peaky tri-linear pipe-soil interactions have an additional area, created by the peak resistance, but the influence of the peak resistance is so small, that this additional area can be safely ignored resulting in:

$$Corr_{3L} = 2\left(\frac{A_{Unload-Reload}}{\Delta F_R}\right) \quad \textbf{(8)}$$

Then, following the same principles, the ideal mobilisation displacement, δ_{mob}', can be described with a similar procedure from Castelo *et al.* (2019) and Castelo *et al.* (in press b), as outlined by equation (9):

$$\delta_{mob}' = \frac{Corr_{3L}}{2} = \left(\frac{A_{Unload-Reload}}{\Delta F_R}\right) \quad \textbf{(9)}$$

As another option, since the soil behaves linearly, δ_{mob}' can also be written as:

$$\delta_{mob}' = \frac{F_R * \delta_{mobP}}{F_P} \quad \textbf{(10)}$$

where F_R is the residual plastic force, F_P is the peak elastic force, and δ_{mobP} is the mobilisation displacement where the peak elastic force is achieved.

Now, using the values provided in Table 2, δ_{mob}' was calculated for cases i - iv to be 0.065, 0.032, 0.043 and 0.052 m, respectively; while, equations (6) and (7) were rewritten, accounting for equation (10), as:

$$X_{ab,3L} = X_{ab,RP}\left(1 - \frac{F_R}{F_P}\frac{\delta_{mobP}}{\delta_{null}}\right) \quad \textbf{(11)}$$

$$WR_{3L} = WR_{RP} * \left(1 - \frac{F_R}{F_P}\frac{\delta_{mobP}}{\delta_{null}}\right) \quad \textbf{(12)}$$

Hence, using equations (11) and (12) in association to the values provided by Table 1, Table 2 and Table 4, the distance between stationary points and the walking rate were obtained, as presented by Table 5[*].

10 FINITE ELEMENT ANALYSES PARAMETRIC STUDY FOR PEAKY TRI-LINEAR PIPE-SOIL INTERACTION

The following parametric study validates the above solutions for the distance between stationary points' and walking rate for peaky tri-linear soils.

[*] The authors understand that 1 m lies inside the acceptable deviation given that this is the mesh spacing.

The parametric study uses the values provided in Table 1 and Table 2 as previously explained in section 3. For simplicity, pipeline length, pipeline submerged operational weight (accounting for content), residual friction coefficient and the overall route slope were kept constant, although the soil resistance was varied, as shown, for the ideal cases i - iv, in Table 2, Figure 3 and Figure 4.

10.1 Ideal mobilisation displacement – δ_{mob}'

Each of the parametric study cases tested had their own ideal mobilisation displacement, δ_{mob}', value according to equation (10) as shown in section 9.

Figure 10 presents the tri-linear correction results from the numerical solutions (finite element models) plotted against the values calculated using equation (8). The "EqualPeaks" and the "NoSUpPeak" soil conditions are represented by square and circular markers, respectively. The triangles represent elastic-perfectly-plastic conditions, accounting for the ideal mobilisation displacement – these were used to prove the applicability of the ideal mobilisation displacement methodology. Cases i, ii, iii and iv are indicated in the figure.

Figure 10 shows a very strong agreement between the tri-linear correction obtained from the finite element analysis and the results calculated using the proposed equation.

For elastic-plastic soil conditions, when the equivalent mobilisation displacement, δ_{mobEQ}, nears the value of the non-walking mobilisation displacement, δ_{null}, the walking rate tends to diminish up to zero and the walking phenomenon ceases (Castelo *et al.*, 2019; Castelo *et al.*, in press b). Analogously, to peaky tri-linear soils, when the ideal mobilisation displacement, δ_{mob}', nears δ_{null} the walking rate also tends to diminish up to zero and the walking phenomenon ceases.

10.2 Distance between stationary points for peaky tri-linear soil – $X_{ab,3L}$

Equation (10) is applicable to finding the ideal mobilisation displacement. Consequently, equation (11) must be applicable to finding the distance between the stationary points. To confirm, the finite element model outputs were compared with the calculated values from equation (11).

Figure 11 presents the results for the distance between stationary points using numerical solutions (finite element models) plotted against the values calculated using equation (11). The “EqualPeaks” and the “NoSUpPeak” soil conditions are represented by square and circular markers, respectively. The triangles represent elastic-perfectly-plastic conditions, accounting for the ideal mobilisation displacement. Cases i, ii, iii and iv are indicated in the figure.

Figure 11 shows a very strong agreement for the distance between stationary points obtained from the finite element analysis and the results calculated using the proposed equation.

10.3 Walking rate for peaky tri-linear soil – WR_{3L}

Figure 12 presents the walking rate results from the numerical solutions (finite element models) plotted against the values calculated using equation (12). The “EqualPeaks” and the “NoSUpPeak” soil conditions are represented by square and circular markers, respectively. The triangles represent elastic-perfectly-plastic conditions, accounting for the ideal mobilisation displacement. Cases i, ii, iii and iv are indicated in the figure.

Figure 12 shows a very strong agreement between the walking rates obtained from the finite element analysis and the results calculated using the proposed equation.

Overall, the results show that equation (12) – as presented by Table 6 – gives a true representation of the effects of peaky tri-linear soil springs on pipeline walking.

Finally, equation (1) can be translated for peaky tri-linear soils as equation (13):

$$WR_{3L} = WR_{RP} - 2\delta_{mob}' \qquad \textbf{(13)}$$

where the walking rate for peaky tri-linear soils, WR_{3L}, may be directly obtained by subtracting twice the ideal mobilisation displacement, δ_{mob}', from the walking rate for rigid-plastic soils, WR_{RP}.

11 OBSERVATIONS ABOUT THE EFFECTIVE AXIAL FORCE VARIATION OVER THE DISTANCE BETWEEN STATIONARY POINTS FOR PEAKY TRI-LINEAR SOILS – $\Delta S_{S,3L}$

For Castelo *et al.* (2019) and Castelo *et al.* (in press b), the effective axial force variation over the distance between stationary points, ΔS_S, solution was mathematically revised by making adjustments for the effective axial force physical boundaries, the axial displacement, δ_x, boundary conditions and the effective axial force boundary conditions. These factors directly impact the differential equation used to obtain the effective axial force values and ultimately change the ΔS_S expression.

While obtaining the effective axial force variation over the distance between stationary points is important, previous experience (Castelo *et al.*, 2019; Castelo *et al.*, in press b), shows that ΔS_S revision will not have a significant impact on finding the walking rate for peaky tri-linear soils. Furthermore, confidence in the numerical solutions obtained in previous research, and the use of similar approaches (Castelo *et al.*, 2019; Castelo *et al.*, in press b), suggest that the numerical results will be sufficient to prove the applicability of equations (10), (11), (12) and (13).

12 LIMITATIONS & FUTURE WORK

The emerging methodology has not been tested for implications on lateral buckling (also referred to as Euler buckling). It has been tested in previous stages of research for various pipeline lengths, which has been proved to have no influence over the overall findings (Castelo *et al.*, 2019; Castelo *et al.*, in press b). For variable slopes, the authors foresee further research to be published in the near future (Castelo *et al.*, in press a).

In general terms, there are no limitations for the applicability of this methodology as long as the pipeline route respect a uniformly sloped seabed with no lateral buckles.

13 CONCLUSIONS & FINAL REMARK

This paper provides a strategy to solve downslope pipeline walking problems considering peaky tri-linear soils. Different properties of tri-linearity (within the peaky soil model type) have been considered, leading to an innovative analytical solution.

The innovation is summarised as the multiplying factor introduced in equation (12) and highlighted below:

$$\left(1-\frac{F_R}{F_P}\frac{\delta_{mobP}}{\delta_{null}}\right) \quad \textbf{(14)}$$

This multiplying factor accounts for the pipe-soil interaction model properties to adjust the original rigid-plastic solution in a way to make the walking assessment results more accurate.

The new solution , based on the factor highlighted in equation (14), was benchmarked and validated against a set of finite element analyses.

Currently applied analytical solutions do not consider the soil model type with a peak, and it is known that they can provide inaccurate walking patterns.

Therefore, this paper resolves how the fundamental closed-form solution for rigid-plastic soils must be adjusted to allow for peaky tri-linear soils reducing the requirement for numerical modelling which can be time- and resource-consuming in early stages of design activities, such as preliminary estimates for downslope pipeline walking.

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NOMENCLATURE

3L	Tri-Linear
E	Steel Young's Modulus
EAF	effective axial force
F_P	peak elastic force
F_R	residual plastic force
JIP	joint industry project
L	pipeline length
OD	steel outside diameter
RP	rigid-plastic
SDown	shutdown phase
SUp	start-up phase
SP	stationary point
t	steel wall thickness
VAS	virtual anchor section
W	pipeline submerged weight
W_{comp}	pipeline weight component
WR	walking rate
x	axial coordinate along pipe length

X_{ab}	distance between stationary points
α	steel thermal expansion coefficient
β	seabed slope angle
ΔS_S	effective axial force variation over the distance between stationary points
ΔT	temperature variation
δ_{mob}'	ideal mobilisation distance
δ_{mobP}	peak elastic force mobilisation displacement
δ_{mobR}	residual plastic force mobilisation displacement
δ_{null}	non-walking mobilisation distance
δ_x	axial displacement
μ	residual friction coefficient
ν	steel Poisson coefficient

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Figure Captions List

Figure 1 Effective axial force diagrams for start-up and shutdown phases

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FIGURES

Figure 1 Effective axial force diagrams for start-up and shutdown phases

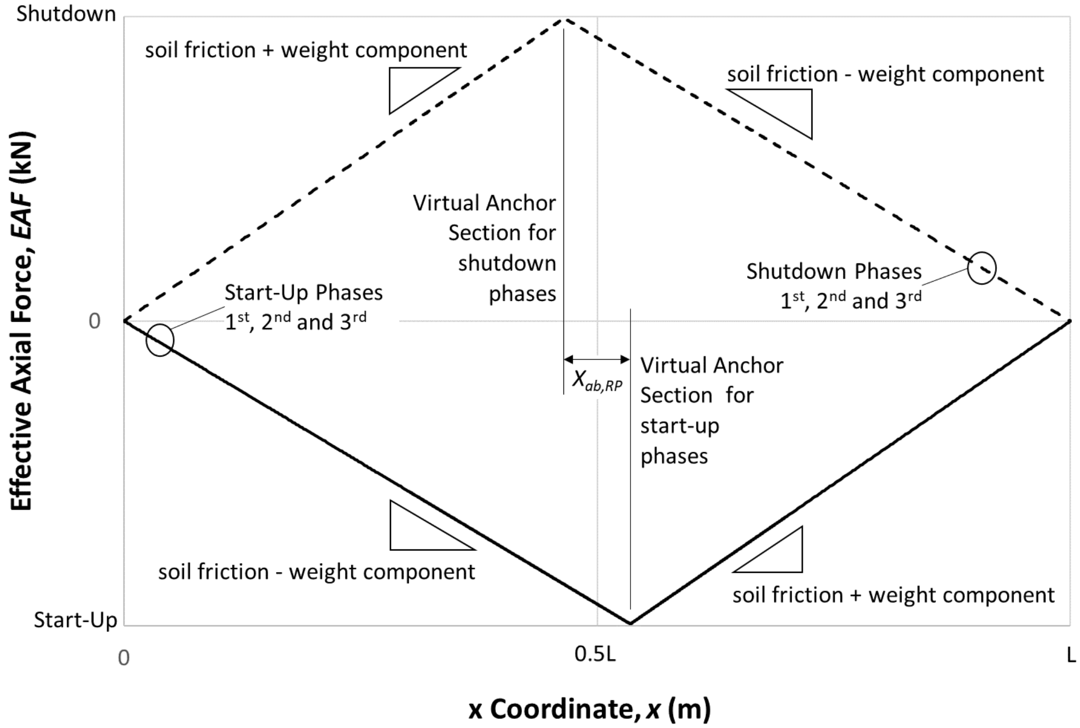


Figure 2 Axial displacement diagrams for start-up and shutdown phases

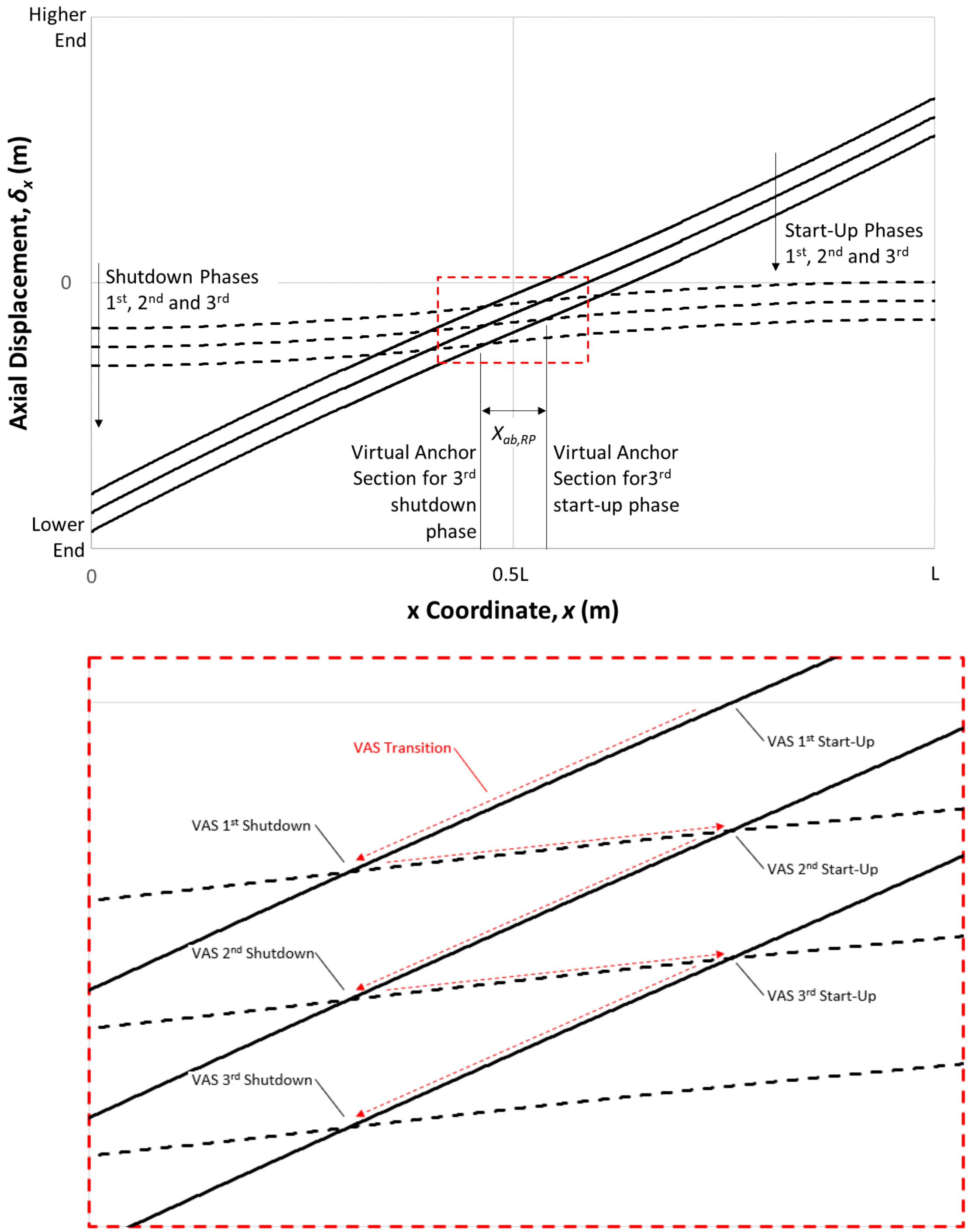


Figure 3 Tri-linear soil responses

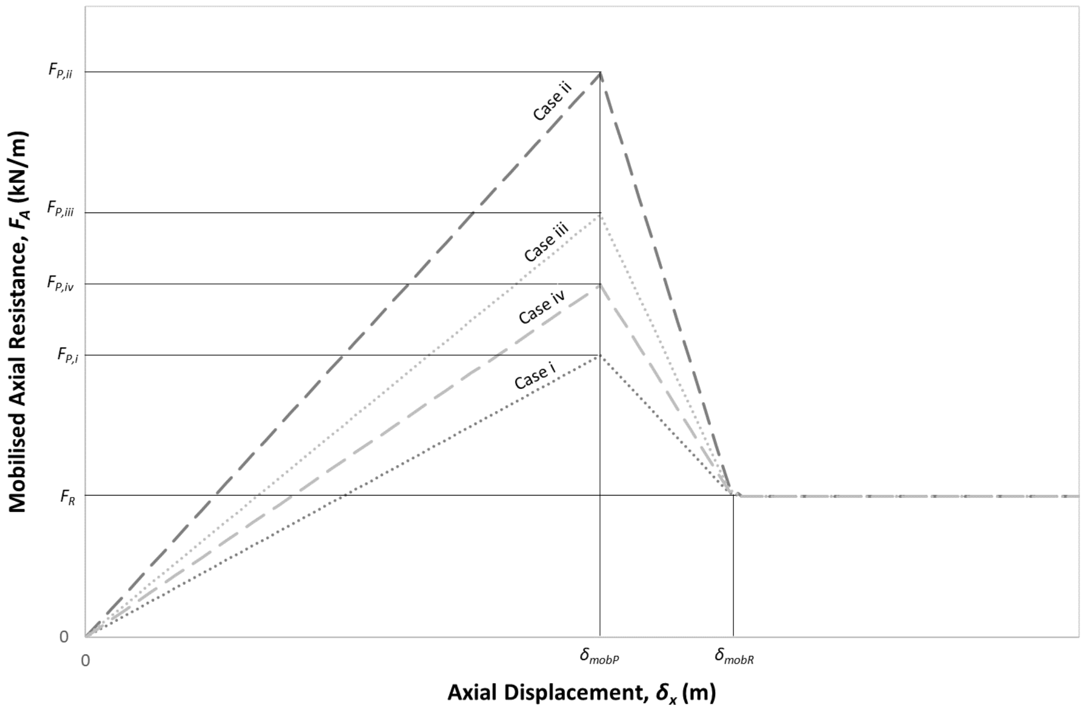
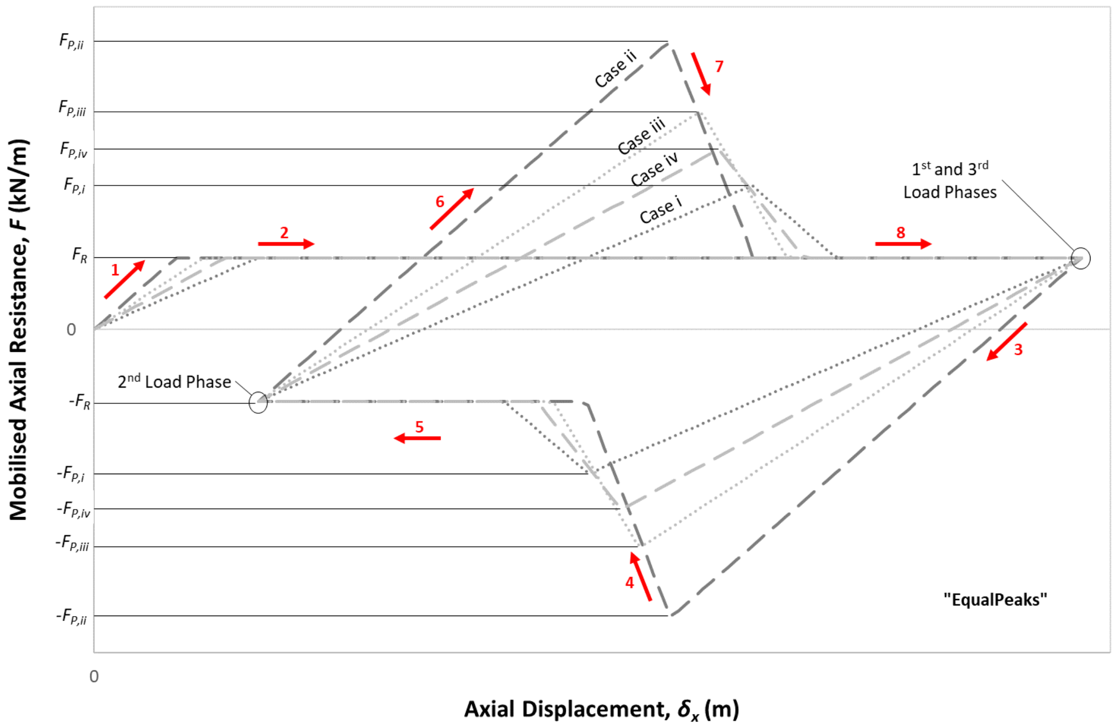


Figure 4 Tri-linear soil responses for cyclic movements



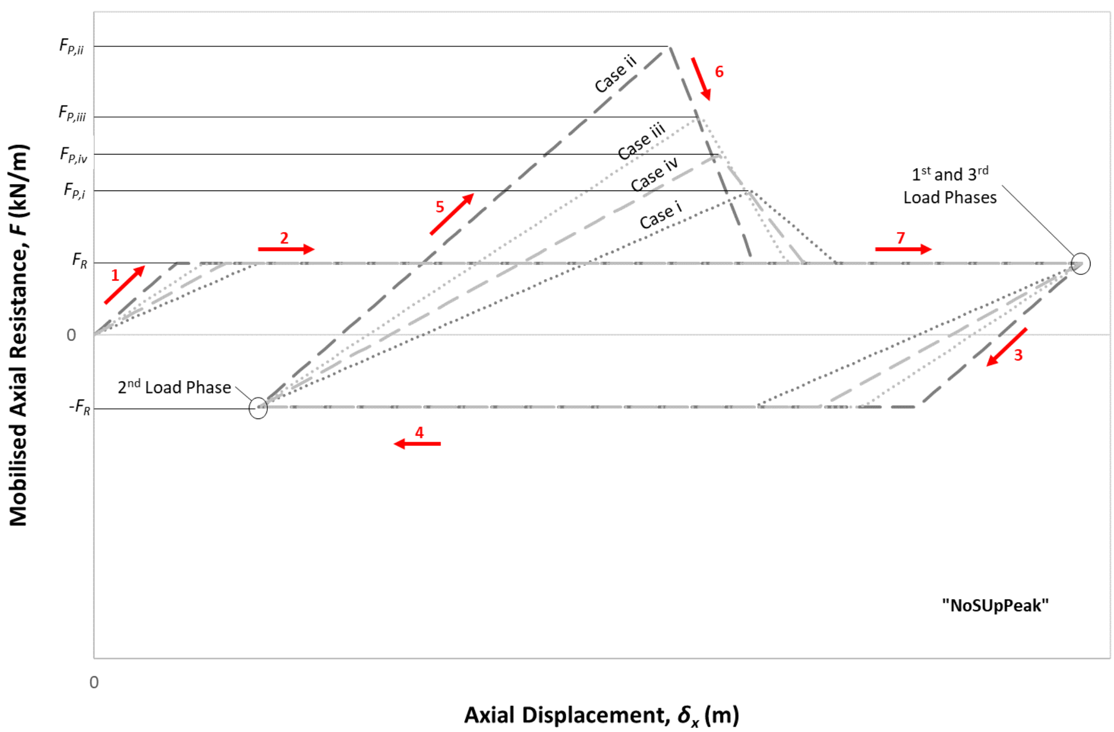


Figure 5 Finite element model sketch

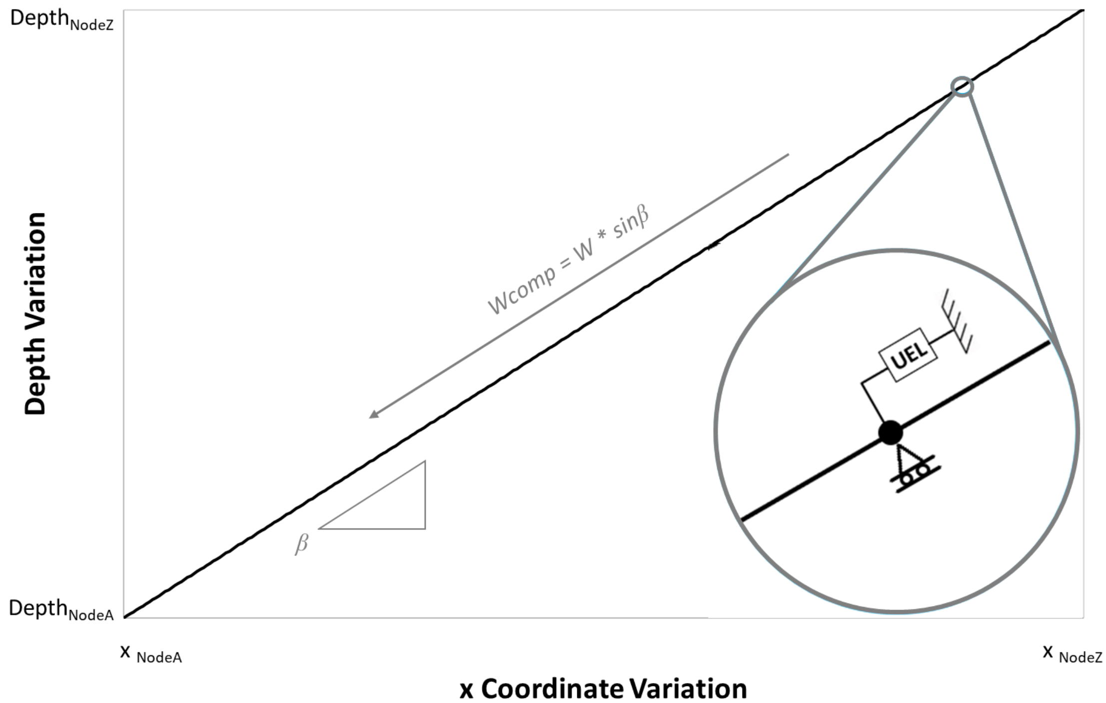


Figure 6 Effective axial force for tri-linear strategy case ii – EqualPeaks (Zoom)

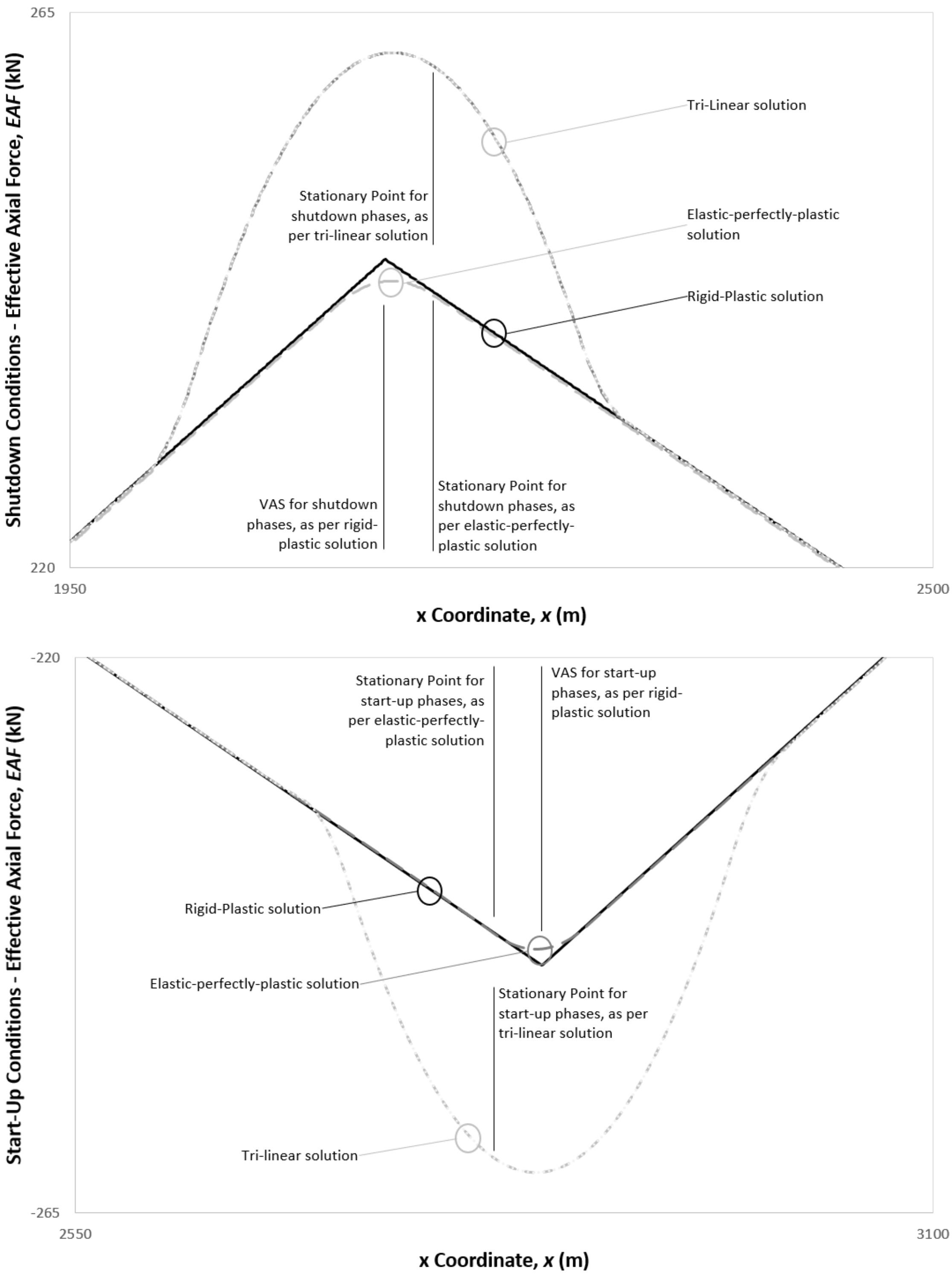


Figure 7 Axial displacement for tri-linear strategy case ii – EqualPeaks (Zoom)

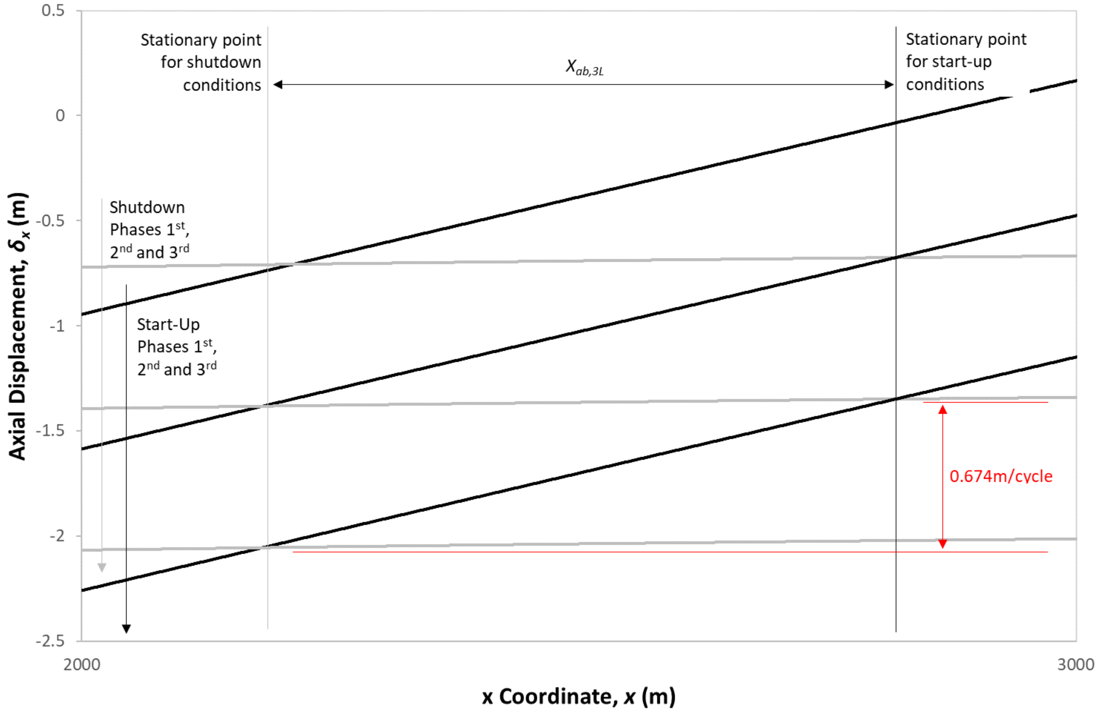


Figure 8 Effective axial force for tri-linear strategy case ii – NoSUpPeak (Zoom)

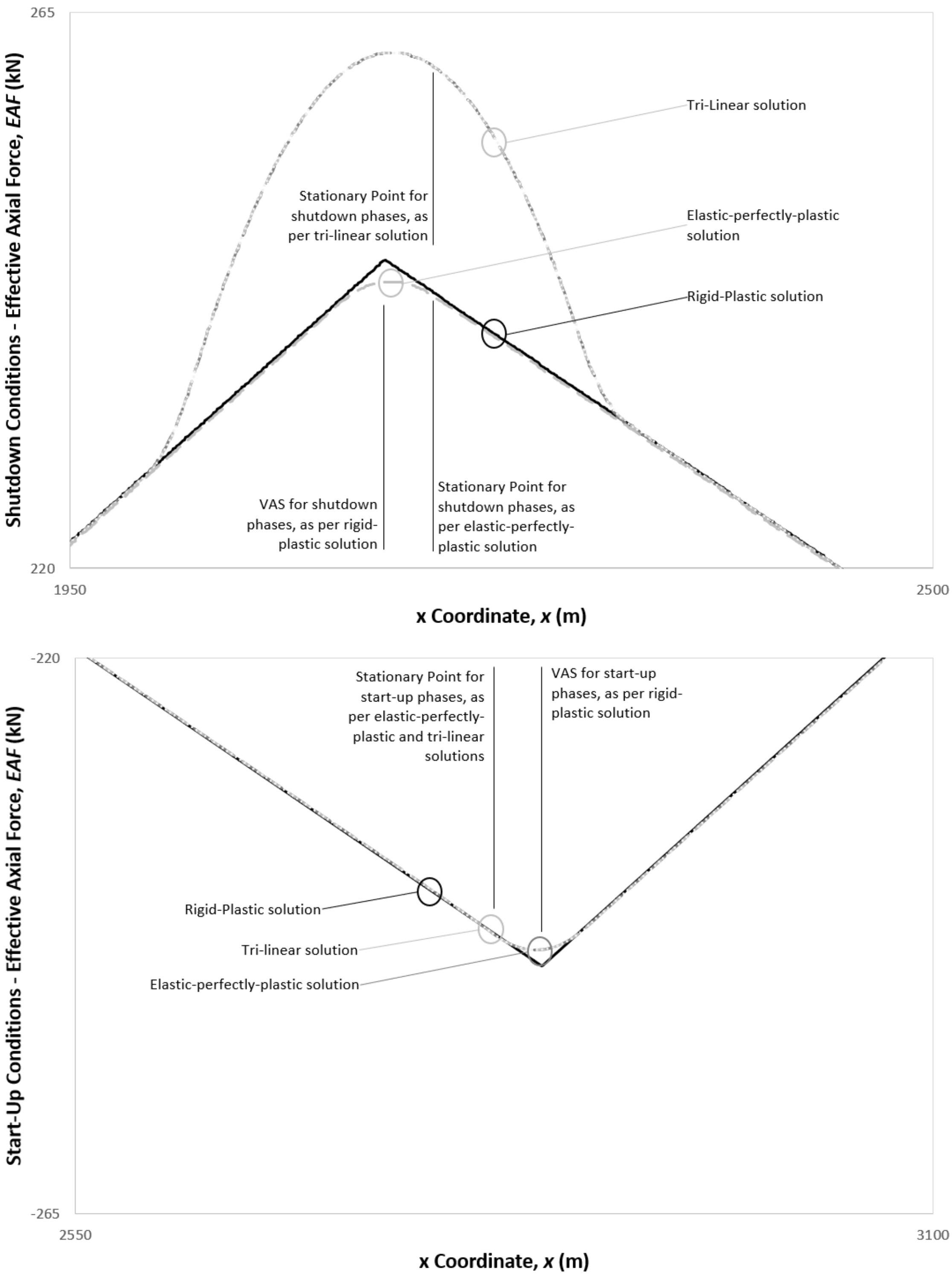


Figure 9 Axial displacement for tri-linear strategy case ii– NoSUpPeak (Zoom)

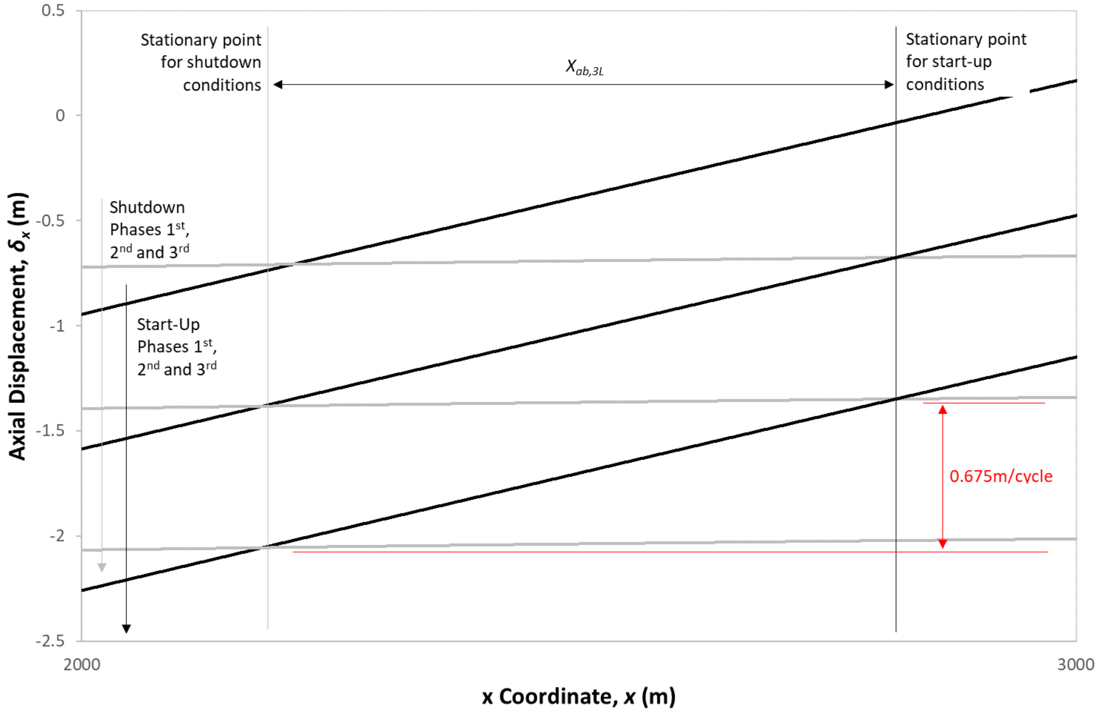


Figure 10 Tri-linear correction results

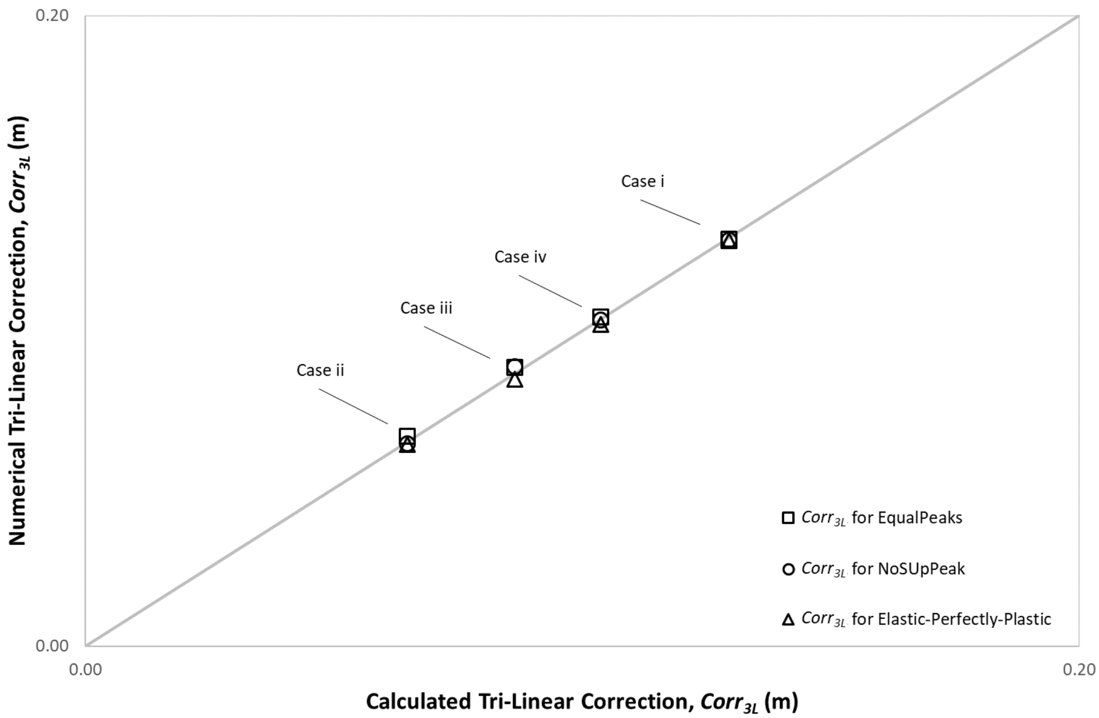


Figure 11 Distance between stationary points results

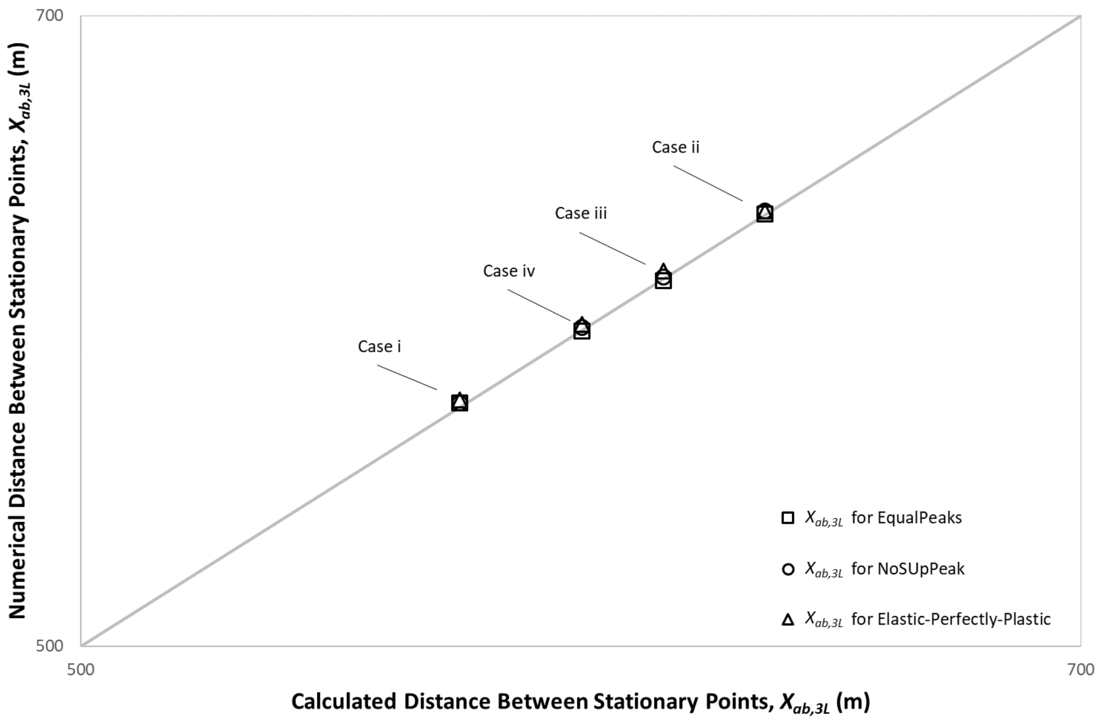


Figure 12 Walking rate results

TABLES

Table 1 General properties

Parameter	Value
Steel outside diameter, *OD*	0.3239 m
Steel wall thickness, *t*	0.0206 m
Length, *L*	5000 m
Seabed slope angle, *β*	2.0 °
Temperature variation, *ΔT*	100 °C
Pipe submerged weight, *W*	0.4 kN/m
Residual friction coefficient, *μ*	0.25
Steel Young's modulus, *E*	2.07×10^{11} Pa
Steel Poisson coefficient, *v*	0.3
Steel thermal expansion coefficient, *α*	1.165×10^{-5} °C^{-1}

Table 2 Case properties

Property	Cases			
	i	ii	iii	iv
Peak Elastic Force, F_P (kN)	0.200	0.400	0.300	0.250
Peak Elastic Force Mobilisation Displacement, δ_{mobP} (m)	0.129	0.129	0.129	0.129
Residual Plastic Force, F_R (kN)	0.100	0.100	0.100	0.100
Residual Plastic Force Mobilisation Displacement, δ_{mobR} (m)	0.162	0.162	0.162	0.162
Ideal Mobilisation Displacement, δ_{mob}' (m)	0.065	0.032	0.043	0.052

Table 3 Tri-linear finite element analysis results for soil case ii

Case		Distance Between Stationary Points	Walking Rate
ii	EqualPeaks	637 m	0.674 m/cycle
	NoSUpPeak	638 m	0.675 m/cycle

Table 4 Rigid-plastic calculation results

Case	Distance Between Stationary Points	Walking Rate
Rigid-plastic (Carr *et al.,* 2006)	698 m	0.740 m/cycle

Table 5 Analytical results

Case	Distance Between Stationary Points	Walking Rate
i	576 m	0.610 m/cycle
ii	637 m	0.675 m/cycle
iii	617 m	0.653 m/cycle
iv	600 m	0.636 m/cycle

Table 6 Tri-linear finite element analyses results

Case		Distance Between Stationary Points	Walking Rate
i	EqualPeaks	577 m	0.611 m/cycle
	NoSUpPeak	577 m	0.611 m/cycle
ii	EqualPeaks	637 m	0.674 m/cycle
	NoSUpPeak	638 m	0.675 m/cycle
iii	EqualPeaks	616 m	0.652 m/cycle
	NoSUpPeak	617 m	0.653 m/cycle
iv	EqualPeaks	600 m	0.635 m/cycle
	NoSUpPeak	601 m	0.636 m/cycle