Formulation of 3D Soil Springs for Pipe Stress Analyses

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ABSTRACT
A conventional pipe stress analyses often idealizes the pipe soil interaction with a beam-spring finite element model where independence is assumed between reactions in axial, lateral and vertical directions. There is however interdependence between these springs as recognized in recent PRCI guidelines. This paper highlights the development of a 3D soil-spring interaction model based on a continuum finite element analysis approach. For the constructed landslide scenarios considered in application of the model, the directional dependency is shown to change the accumulated plastic strain profile in the pipe.

RÉSUMÉ
Les analyses conventionnelles de contrainte de conduite idéalisent souvent l'interaction sol-conduite avec un modèle d'éléments finis poutre et ressort où l'indépendance est supposée pour un mouvement dans les directions axiale, latérale et verticale. Il existe cependant une interdépendance entre ces sources et est reconnu dans les récentes directives du PRCI. Cet article met en évidence le développement d'un modèle 3D d'interaction sol-printemps basé sur une approche d'analyse par éléments finis en continu. Pour les scénarios de glissement de terrain considérés dans l'application du modèle, il est montré que la dépendance directionnelle change le profil de déformation plastique accumulé dans la conduite.

1 INTRODUCTION

Buried pipe stress analyses often assume independence between each soil spring set in the axial, lateral and vertical direction. There is however interdependence between these springs, as shown for axial-lateral interaction by Phillips et al., (2004), and this dependency in two-dimensions (2D) is recognized in the PRCI (2009) guidelines. This paper demonstrates the initial development of a 3D soil-spring interaction model for clay using finite element analyses. This numerical modeling approach, combined with field testing and physical experimentation, will prove to advance pipe-soil interaction guidelines and pipeline design in the future.

1.1 Background

Figure 1 illustrates how independent springs are used to analyze continuous pipeline response to changes in operational conditions or externally imposed ground deformation. The pipe is modeled as a deformable beam with non-linear material and geometric properties, with non-linear springs modeling both transverse (i.e. vertical and horizontal) and parallel (i.e. axial or longitudinal to the pipe) soil–pipe interactions.

The pipe resistance may be considered in terms of a Von Mises stress criteria, which combines the normal and shear stresses in the pipe. Similarly, soil has finite shear strength. There should therefore be interdependence between the soil springs.

Significant work has been done on the 2D interaction between either the two orthogonal springs or say the axial-lateral springs. For examples, Jung et al., (2016) recently developed the vertical-lateral springs for sand which provided the analytical results for pipeline response to strike-slip fault rupture shown to compare favorably with the results of large-scale tests.

Phillips et al., (2004) developed relationships for the axial-lateral spring interaction in clays. These relationships were developed further for sand, e.g., Daiyan et al., (2011) and are now included in the PRCI guidelines, PRCI (2009). Accounting for this interaction can reduce buried pipe strains to ground movement as shown by Phillips et al., (2012). This axial-lateral interaction in sand has been further developed by Kenny et al., (2015) and Marcotte et al., (2017). Adding the third direction of movement adds an additional level of complexity to the model development and physical testing.

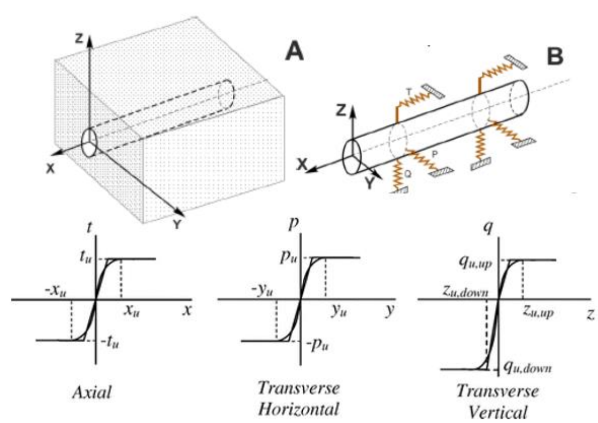

Figure 1. Structural model of pipe-soil system, after PRCI (2009)

Some initial work has been done on the 3D spring interaction using macro-elements for surface laid offshore pipelines (Tian & Cassidy (2009), for example). Further research is however required to develop such 3D spring interaction models for buried pipelines, as demonstrated by Cocchetti et al. (2009) for sand, hence the motivation behind publishing this paper work on clay.

1.2 Approach

A 3D pipe-soil interaction model for clay was developed using the finite element analyses (FEA) software, Abaqus. A rigid pipe section was modelled in a clay soil continuum, such as shown in Figure 2. The pipe section was displaced monotonically to failure in a succession of directions in a number of separate analyses to produce a series of load deflection curves.

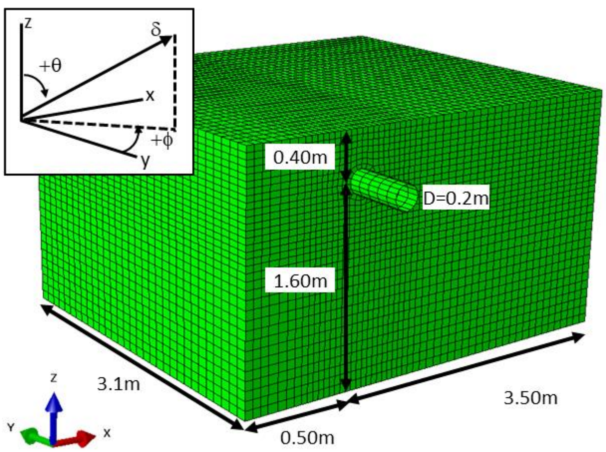

Figure 2. Finite element mesh for 3D pipe-soil analysis

The series of resistance curves constructs a 3D interaction envelope. The envelope is then used to demonstrate the change in pipe response considering fully interdependent, rather than dependent, soil springs using structural FEA modelling of a pipeline section subject to ground movement.

2 DEVELOPMENT OF 3D INTERACTION ENVELOPE

The geometry in Figure 2 considers a 0.2 m diameter rigid pipe at a burial depth of 0.40 m (H/D ratio of 2.0). The pipe is shown to extend 0.5 m outside the soil domain to facilitate continuous interaction with axial movement. The pipe is modeled as a discrete rigid body associated with a rigid reference point. A spherical coordinates system is used to define the pipe displacement vector. "ϕ" defines the direction in the x-y plane ranging from 0, pure axial movement, to 90 degrees, pure lateral movement. "θ" defines the direction from the vertical axis projected to the x-y plane. "θ" ranges from 0 to 180 degrees pure upward to downward movement, respectively.

A soil strength, s_u, of 45 kPa was selected and since Von Mises failure criteria is used to model the soil, the yield strength of the material, σ_y, is equal to $\sqrt{3}S_u$ in order to make the strength definitions consistent. The elastic modulus, Poisson ratio and unit weight of the material was assumed to be 18MPa, 0.33 and 17.5 kN/m^3, respectively. Coulomb friction is assigned to the pipe-soil interface considering a friction coefficient, μ, of 0.364 (tan 20º).

The dynamic, explicit solver Abaqus/Explicit is much more robust and computationally efficient for analyzing large models in comparison to Abaqus/Standard. With many analyses needed to define a 3D failure surface, the Explicit solver was used. A number of analyses were carried out to define the 3D envelope using combinations of parameters listed in Table 1. A total displacement of 0.2 m (one diameter) was found to be sufficiently large enough to capture peak resistances. Small angles of phi (ϕ), in the axial-lateral plane, were needed to capture the transition from shear to bearing failure further discussed later in this paper. The angle theta (θ), measured from vertically upward to axial-lateral plane, was arbitrarily selected to fill the 3D space.

Table 1. 3D analysis parameters

Parameter	Values
Displacement, δ (m)	0.2
Theta, θ (degrees)	0, 15, 30, 45, 60, 75, 80, 90, 100, 115, 135, 150, 165, 175, 180
Phi, ϕ (degrees)	0, 1, 5, 15, 30, 45, 60, 75, 90

Representative force-displacement results for movement in the upward direction are shown in Figure 3 for θ = 45 degrees. The initial force-displacement curve is typically hyperbolic. Forces typically begin to plateau after a total displacement of approximately 10mm, with maximum total force selected at varying total displacement depending on angle ϕ as indicated in the figure. Components of the maximum total force in axial, lateral and vertical directions are then noted to construct the 3D failure surface.

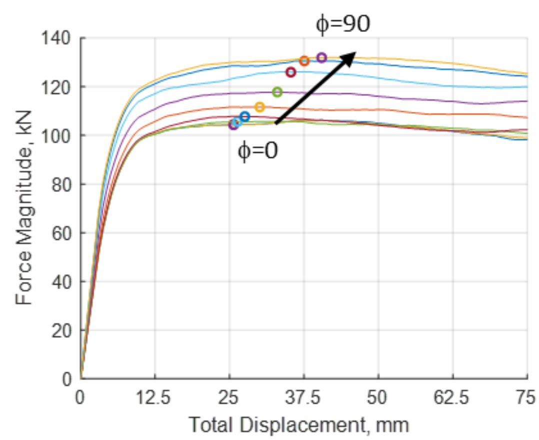

Figure 3. Force-Displacement results for theta (θ) = 45 degrees (upward movement)

Representative force-displacement results for movement in the downward direction are shown in Figure 4 for θ = 135 degrees. The total force does not "peak" in the downward direction but continues to increase as displaced material is lifted upward surcharging the buried pipe region. For the parameters used in this analysis, the slope of the force displacement curve become reasonably constant after a total displacement of 50 mm. Thus, components of the maximum total force in the three directions are then noted at 50mm total displacement to construct the 3D failure surface.

Pipe displacement near the axial-lateral plane, θ = 90 degrees, indicate a different response compared to pipe movement with a relatively large component of upward or downward movement (Figure 5). As ϕ increases, the soil behavior shifts from a shear to bearing-type behavior causing a transition in the 3D failure envelope between these modes of failure. The value of "peak" force was selected at a total displacement of 50 mm consistent with the typical downward movement criteria. It should be noted that for ϕ = 1 and 5 degrees (small angles in axial direction), the resistance value highlighted is not a peak resistance. The lateral bearing pressure is still growing. The pipe needs to move to a considerable total displacement to fully mobilize potential resistance. Resistance loci plotted in the lateral-axial plane at select vertical angles, Figure 6 show how the shape of the envelope changes from elliptic, to a blended linear-elliptic, back to elliptic as the vertical angle sweeps from upward to downward movement.

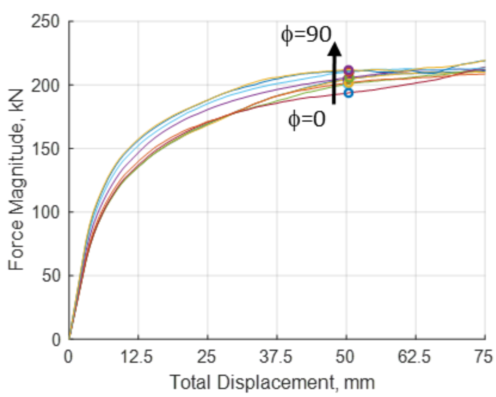

Figure 4. Force-Displacement results for theta (θ) = 135 degrees (downward movement)

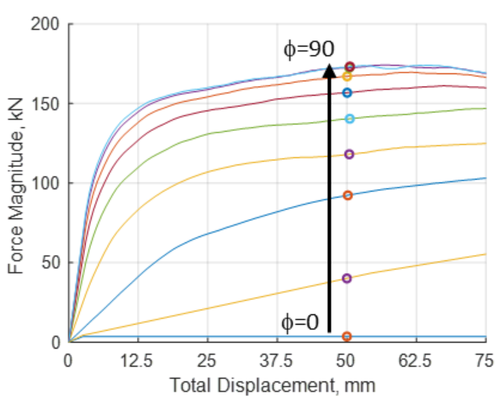

Figure 5. Force-Displacement results for theta (θ) = 90 degrees (lateral-axial plane)

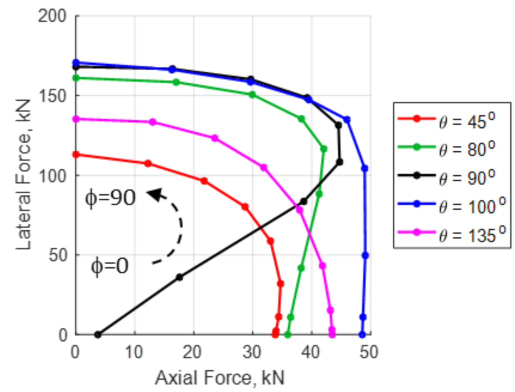

Figure 6. Lateral-axial resistance loci

The remaining analyses were processed with the maximum force and corresponding force components selected using criteria described above. A surface was then fitted to each force component with respect to θ and ϕ using 3D natural neighbor interpolation in Matlab. Axial, lateral and vertical force surfaces are shown in Figure 7 through Figure 9 in terms of kN/m so they can now be used in a structural pipe-soil analysis using the "p-y" soil spring method. Plotting the three force components together, parametrically with θ and ϕ, produces a comprehensive 3D soil failure envelope (Figure 10).

The x-y-z components of the total displacement to reach the total peak force are not equivalent to x-y-z displacements to reach the maximum of each force component. In other words, maximum forces in each direction do not generally occur at the same total displacement. With respect to the component displacement to realize maximum directional forces, this study found that component displacements are consistent those presented in ALA (2001) and PRCI (2009) for the clay material modeled. This analysis found that the:

- maximum axial force, t_u occurs at an axial displacement, x_u of around 10 mm;
- maximum lateral force, p_u occurs at a lateral displacement, y_u of around 0.15D;
- maximum vertical force, q_u occurs at a vertical displacement, z_u of around 0.10H; and,
- maximum downward force, q_d occurs at a vertical displacement, z_d of around 0.25D (slightly greater than 0.2D recommended in guidelines).

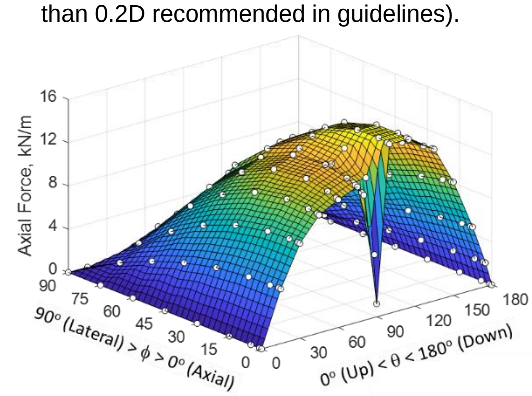

Figure 7. Axial force surface as function of θ and ϕ

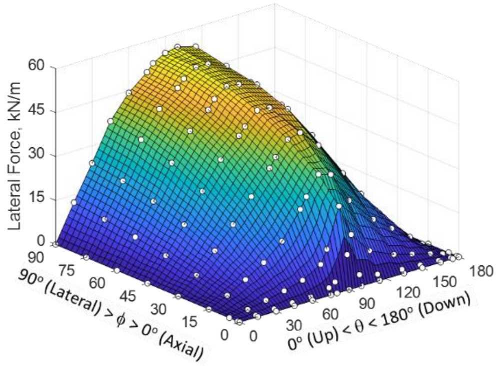

Figure 8. Lateral force surface as function of θ and ϕ

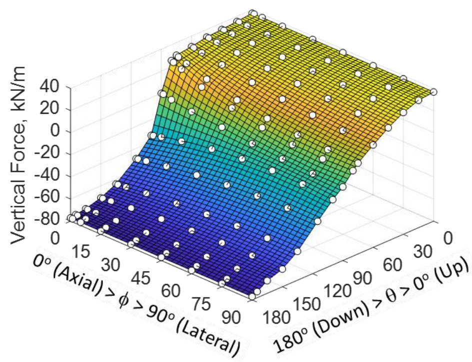

Figure 9. Vertical force surface as function of θ and ϕ

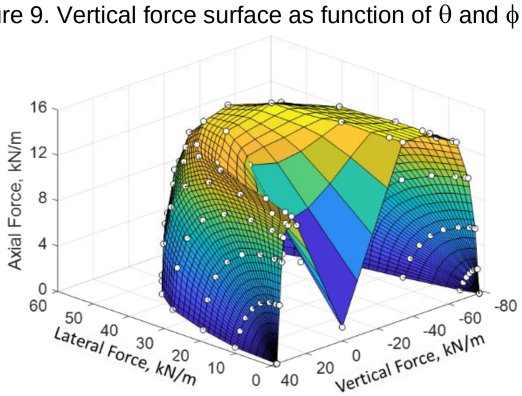

Figure 10. 3D soil failure envelope

3 APPLICATION OF 3D INTERACTION ENVELOPE

Two pipe-soil interaction scenarios were constructed to highlight the difference between independent and dependent soil springs in applying the 3D soil failure envelope presented considering bi-linear soil springs.

3.1 Simple Landslide Scenario

The geometry of a pipeline running orthogonally down an 11 degree slope is represented in Figure 11. A 250m section of soil is prescribed to move 0.5 m obliquely, at a 30° angle, across the slope and pipe as might be the case in a landslide or slope subsidence scenario. The 0.2m diameter pipe was assigned a wall thickness of 5 mm and yield strength of 293 MPa. The pipe was also subjected to an internal pressure of 10.5 MPa. The independent, bi-linear, soil springs were given the properties highlighted in Table 2.

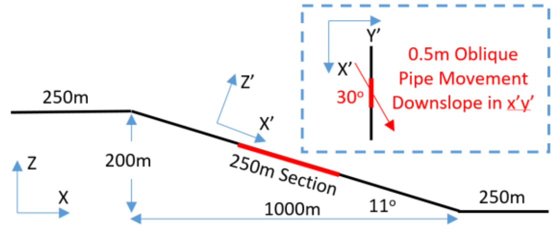

Figure 11. Pipeline geometry in landslide scenario

Table 2. 3D analysis parameters

Direction	Ultimate Resistance for (θ & ϕ) (kN/m)	Displacement at Ultimate Resistance (m)
Axial	t_u = 1.2 (90° & 0°)	x_u = 0.01
Lateral	p_u = 54.3 (90° & 90°)	y_u = 0.03
Vertically Upward	q_u = 36.8 (0° & 0°)	z_u = 0.04
Vertically Downward	q_d = 77.1 (180° & 0°)	z_d = 0.05

The pipe displacement from the independent springs analysis was used to update the soil springs the subsequent analysis to incorporate directional dependency (Figure 12). Nodal pipe translation angles (Figure 13) were projected onto the 3D failure envelope to predict ultimate resistances in each direction for each pipe. Vertical pipe displacements were small and thus the vertical dependency on soil springs was minimal.

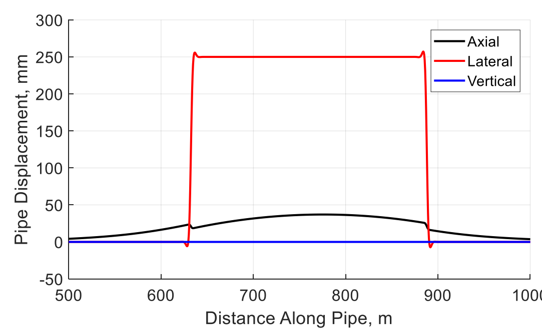

Figure 12. Pipe displacement from independent spring analysis

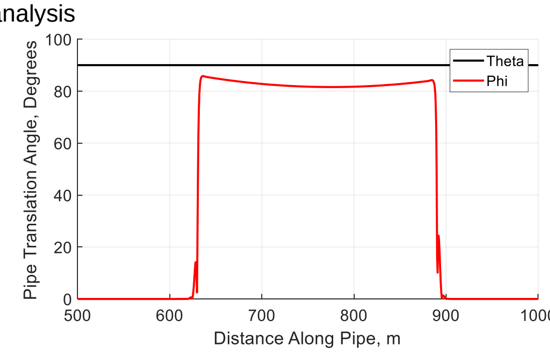

Figure 13. Pipe translation angles from independent spring analysis

The axial soil resistance increases most significantly at the transitions in and out of the prescribed soil displacement zone (at 630 and 890m along pipe, Figure 14). Accounting for increased lateral soil pressure from the pipe moving through the soil, higher axial shear loads are imposed on the pipe and this translates into increased axial pipe displacement. With the "relative" pipe movement remaining predominantly in the lateral direction across the pipe, lateral pipe displacement and resistance is relative unchanged (Figure 15). The result of applying dependent springs in this analysis results in doubling the plastic strain at the downstream transition, as compared to the independent analysis (Figure 16).

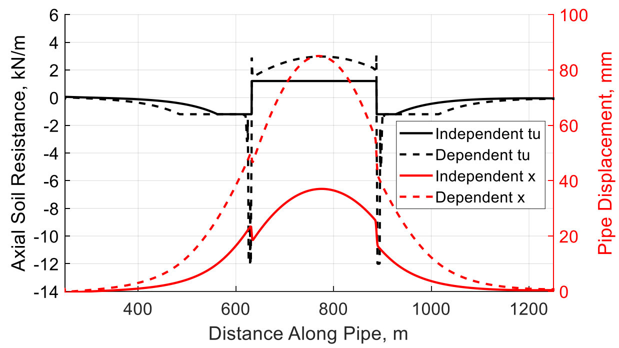

Figure 14. Comparison of axial soil resistance and displacement

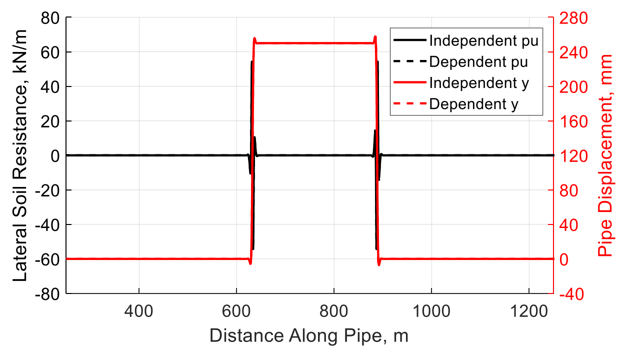

Figure 15. Comparison of lateral soil resistance and displacement

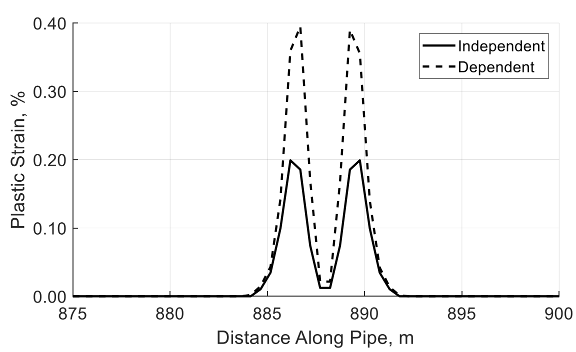

Figure 16. Comparison of plastic strain developed for independent and dependent soil spring analysis

3.2 3D Landslide Scenario

A more complex landslide case was modeled considering a section of pipe, oriented obliquely down a slope, such that the soil movement in the Y-Z plane and creates significant pipe-soil displacement in all three directions (Figure 17). A 40m section of soil is displaced 0.75 m laterally and 0.20 m downward which, in turn, creates considerable axial feed in. The same pipe geometry, internal pressure and material properties were applied as described in the previous case. Displacements to reach ultimate resistances are as described in Table 2 with ultimate resistances obtained from 3D failure envelope after an independent spring analysis was carried out.

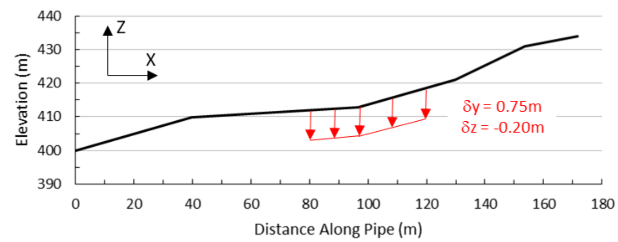

Figure 17. 3D landslide scenario geometry

The pipe displacement from an independent spring analysis are shown in Figure 18. With significant downward movement, "relative" pipe displacement needs to be considered. Since it is the soil mass that is prescribed to move downward, the pipe moves relatively upward and the pipe-soil interaction has the associated upward resistance. At the transitions of prescribed movement (78m and 118m), a sudden change in relative displacement is noted as the pipe-soil interaction changes from active to passive. Relative axial displacements, omitted from Figure 18 for clarity, are equal and opposite of axial pipe displacements. The associated soil translation angles are shown in Figure 19.

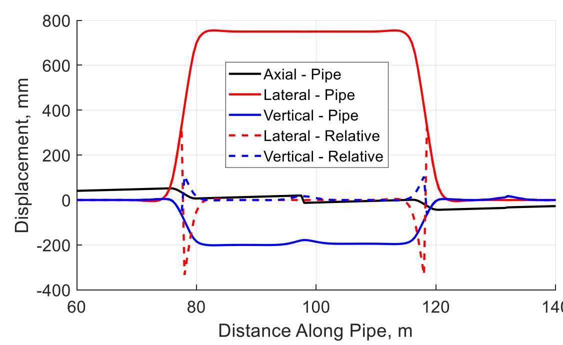

Figure 18. Pipe and relative soil displacements for 3D landslide for independent springs

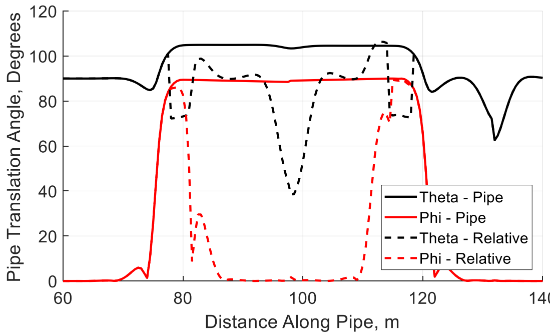

Figure 19. Pipe and relative soil translation angles for 3D landslide for independent springs

The axial soil resistance and shear transfer increases significantly as the pipe mobilizes increased bearing pressure with lateral and vertical movement (Figure 20). The axial resistance profile is irregular and variable due to the nature of the pipe translation angles (θ and ϕ). Lateral and vertical resistances, shown in Figure 21 and Figure 22, are predicted to be reduced as a higher portion of the soils ultimate strength is accounted for in shear in the axial direction. As a consequence of a softer soil condition considering soil spring dependency, the plastic strain developed in the pipe is shown to be reduced (Figure 23).

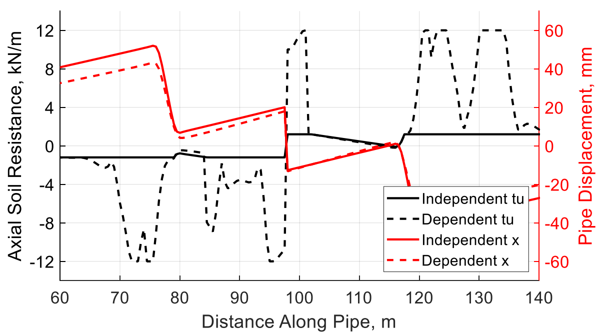

Figure 20. Comparison of axial soil resistance and displacement for 3D landslide

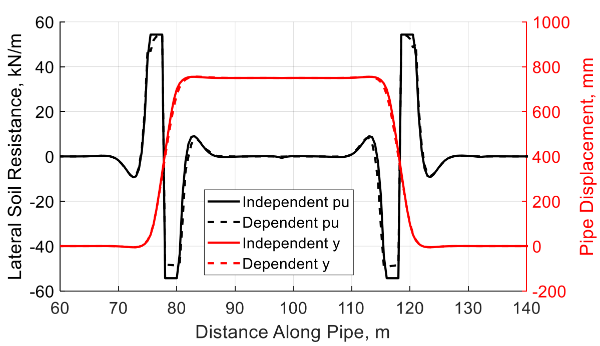

Figure 21. Comparison of lateral soil resistance and displacement for 3D landslide

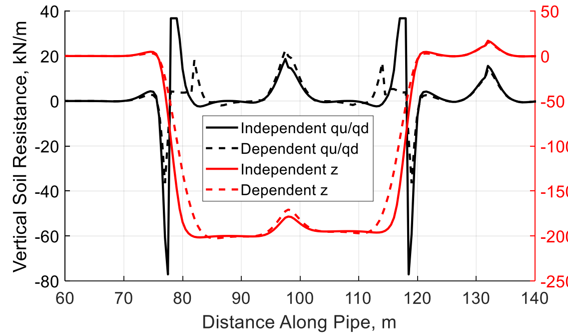

Figure 22. Comparison of vertical soil resistance and displacement for 3D landslide

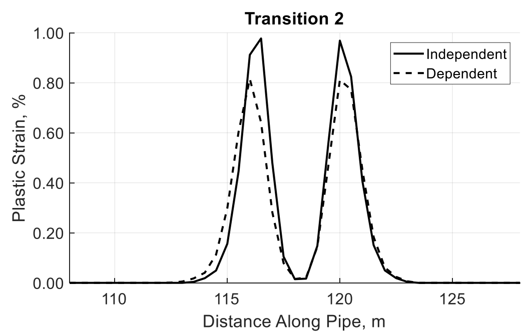

Figure 23. Comparison of plastic strain developed for independent and dependent soil spring analysis

4 CONCLUSIONS

This project has highlighted the importance of considering interdependence between pipe-soil interaction springs in a pipe stress analysis. By developing a soil capacity envelope based on 3D continuum modeling, updated soil springs can reflect modified capacities depending on the direction of pipe movement. For a frictional interface, axial resistance can be much higher than indicated by PRCI guidelines when accounting for increased lateral and vertical bearing pressure. At the same time, lateral and vertical capacities are shown to be reduced in comparison to pure vertical and lateral loading directions. For the landslide scenarios considered in application of the model, the directional dependency is shown to change the accumulated plastic strain profile in the pipe.

This work focused on a single pipe configuration "wished" in place in a clay soil. Future work should be done under various pipe and soil conditions in order to develop a generalized soil failure envelope without requiring complex 3D modeling for each specific pipe stress analysis. Bi-linear soil springs were assumed for simplicity in the analysis presented. Future work should incorporate the influence of the hyperbolic formulation presented in PRCI (2009) and assess the goodness of fit for the proposed coefficients in the PRCI guideline.

5 ACKNOWLEDGMENT

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