Development of ABAQUS User Subroutine for Advanced Pipe/Soil Modelling

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Abstract

Ample field observations of offshore pipelines indicate that extensive sediment transportation induced seabed deformation occurs in the vicinity of pipelines. Despite this, the existing pipeline design strategies fail to account for these effects. Very little research work has been undertaken to present the tripartite interaction between the pipeline, soil and fluid. Since 2008, Wood Group Kenny has been undertaking development of a novel 2D pipe-soil-fluid (PSF) model to deliver a more accurate prediction of the soil profile evolution around the pipe compared to conventional design models, at reduced computational cost compared with the current state-of-the-art continuum FEA methods. The aim of this project is to investigate the behavior of the existing 2D PSF model and improve the previous Visual Basic (VB) code into more simplification and generalization program with FORTRAN language. The implementation of the algorithm in ABAQUS as a User Element Subroutine can successfully present the 3D visualization of soil profile deformation in the vicinity of pipelines. This novel PSF model has the potential to be further developed as a reliable pipe-soil modelling package for offshore pipeline design capable of calculating the tripartite pipe-soil-fluid interaction in a computationally efficient manner.

1. Introduction

The stability and integrity design of offshore pipelines are of vital importance as they are the major infrastructure facilities to link up the offshore oil and gas industries and onshore hydrocarbon product users.

However, most of the existing conventional subsea pipeline stability design approaches failed to take into consideration the potential mobility of the non-cohesive seabed soil before the onset of the pipeline instability. In 1996, seminal work by Palmer and other researchers brought up these issues and attracted attentions of offshore industries (Griffiths 2012). Thus, the potential instability of the seabed caused by natural flow induced sediment transport becomes a major contributor to the instability of offshore pipelines and brings extreme pipeline design challenges to the offshore fields that are periodically exposed to extreme cyclonic weather conditions. Especially on the North West Shelf (NWS) of Australia, lots of significant energy resources projects are affected by the severe metocean conditions. Despite the traditional solutions currently utilised in the NWS, the economic cost required by these conventional approaches are significant due to costly secondary stabilisation requirements. Thus, considerable research has been undertaken to develop a practical and regionally applicable offshore stabilisation design model to achieve major cost saving and reliability improvement to the subsea operators in the NWS (Griffiths 2009).

In 2012, as one of the offshore pipeline design leaders, a novel 2D pipe-soil-fluid (PSF) interaction model has been developed by Wood Group Kenny, based on a large set of seabed shear stress databases generated from a series 2D computational fluid dynamics (CFD) models. This novel PSF model achieves a significant step change improvement in predicting the seabed profile evolution around the pipe than the conventional design approaches at a reduced computational cost by avoiding using the co-simulation of continuum soil FEA with the fluid/sediment CFD modelling (Griffiths, 2012). The major objective of the current project is undertaking improvements on the existing 2D PSF model and extending it to 3D using the ABAQUS User Element Subroutine to present the soil profile deformation in the vicinity of pipelines and calculate the vertical pipe-soil reaction force against pipe motion. This PSF model has the potential to be further developed into a reliable commercial pipe-soil modelling package for subsea operators, especially in the region of the NWS, to deliver major cost savings and stability improvements.

2. Modelling Process

2.1 Multiple Contact Cases for Extremely Long Pipelines

Current offshore pipeline design involves the analysis of pipelines with increasing length in order to improve the offshore oil and gas exploration and extraction activities (Zhang, 2002). For example, the NWS pipeline from North Rankin to Withnell Bay in 2008 has the length of more than 100 kilometers, which includes multiple different pipe-soil contact sections along the axial direction of the pipeline. A series of equally spaced pipe nodes are aligned on each pipe section, the number and the distance of the pipe nodes for each section are user defined depending on particular modelling requirements. In order to implement the multiple pipe and soil properties in each contact section, external PSF data files are utilized to contain the different contact information, such as the geometry and materials of pipeline, soil properties and initial soil profile depending on geographic conditions. Figure 1 illustrates that a pipeline sitting on the seabed has two different contact sections.

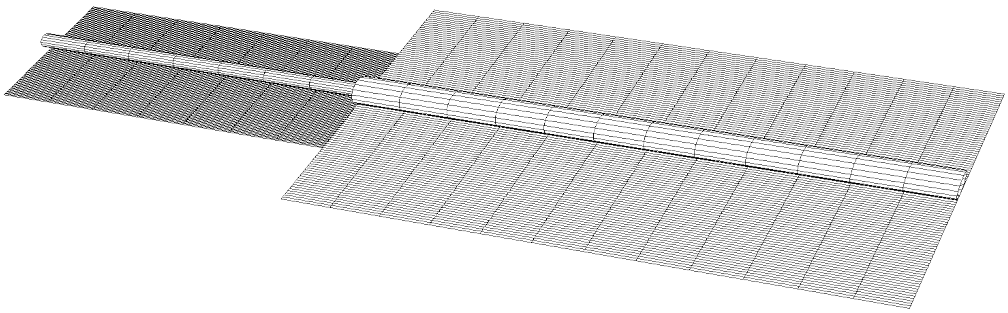

Figure 1 Multiple Contact Cases for Extremely Lone Pipelines

2.2 PSF Implementation

2.2.1 PSF Model Structure and Flow Chart

In the lateral direction of the pipeline, an arbitrary series of soil nodes are equally spaced on both sides of the pipe. The incremental displacement for each node of each time increment is passed to the PSF USER Subroutines. The subroutines update the soil elevation and calculate the soil reaction forces according to the PSF algorithms, which are then passed back to the ABAQUS FE solver. The dynamic equilibrium of the pipe-soil-fluid interaction is thus established using the conventional iterative time incrimination procedure.

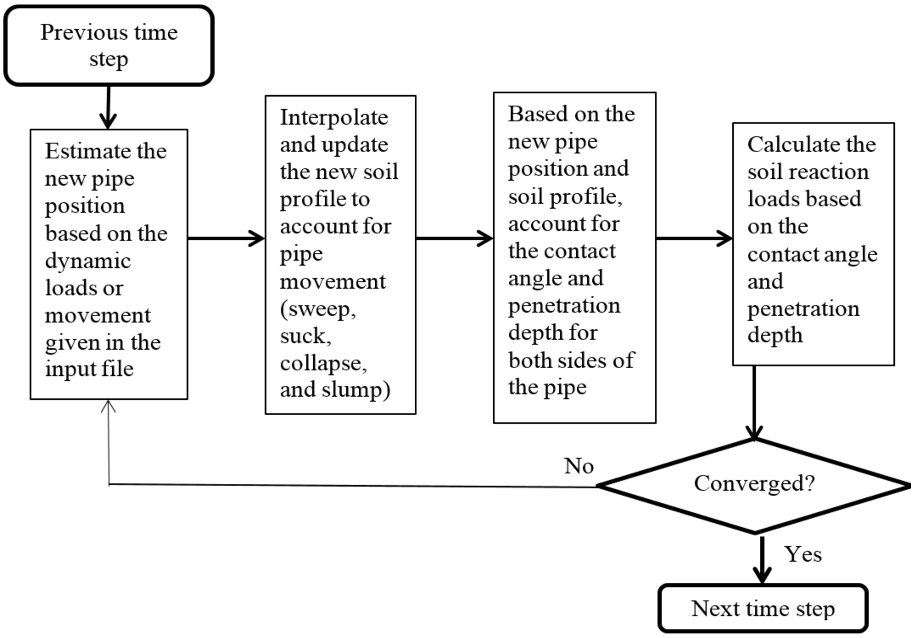

Figure 2 PSF Model Flow Chart

2.2.2 Pipe-Soil Interaction - Soil Deformation

- **Governing Rules:** Based on the existing 2D PSF model (Griffiths, 2012), the soil profile deformation is calculated with the following three governing rules:

  1. Soil cannot be created or destroyed.
  2. Soil cannot exist inside the pipe.
  3. Soil cannot maintain a profile exceeding its natural angle of repose (unless it is supported by the pipe).

- **Algorithm for Calculation:**

  1) **Sweep Algorithm**: soil area that is located in front of the old pipe in the motion direction and displaced by the new pipe is calculated as swept area. The swept soil will be placed on both sides of the new pipe depending on the direction of pipe motion as shown in Figure 3.

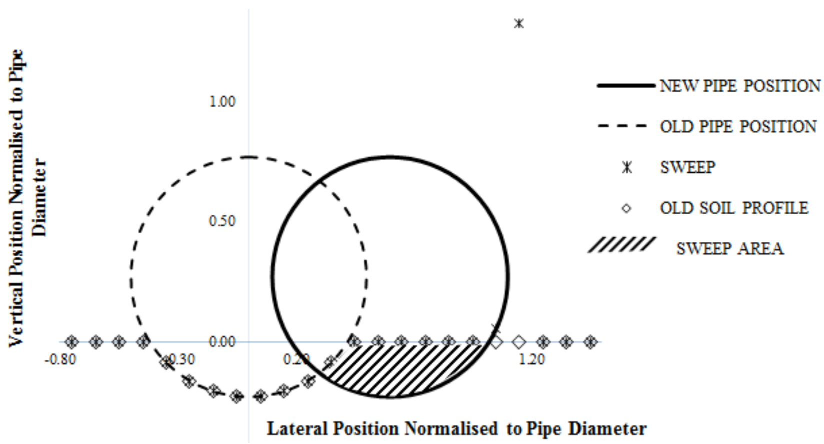

Figure 3 Soil Sweeping Algorithm

2) **Collapse Algorithm**: update the soil elevation of soil nodes within swept area after the pipe motion as shown in Figure 4. It should be noted that the collapse algorithm has been developed as a part of this CEED project to improve the efficiency and accuracy of the soil deformation response.

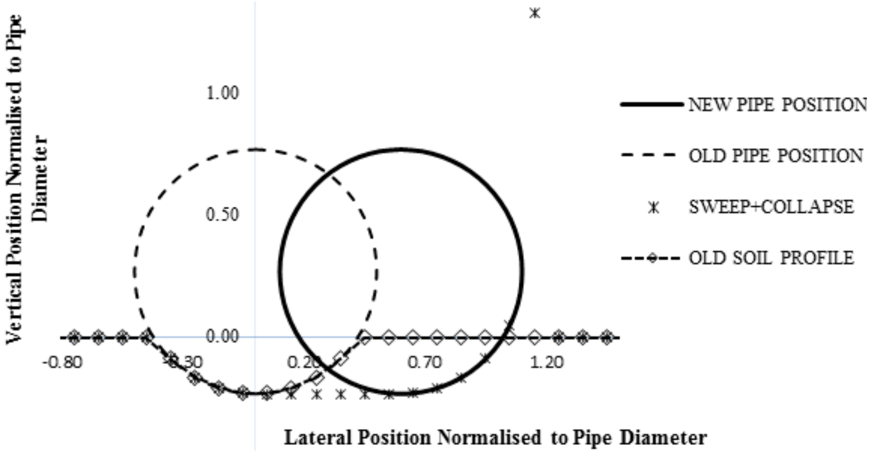

Figure 4 Soil Collapsing Algorithm

3) **Suck Algorithm**: void area generated behind the pipe in the motion direction is calculated as suck area. The suck area will be filled by sucking sediment from both sides of the new pipe depending on the direction of pipe motion.

4) **Slump Algorithm**: in order to achieve a stable position for each sediment, a series of sub-iterations are applied during the PSF USER Subroutine execution to allow the soil slump when the surfaces exceed the soil internal repose angle as shown in Figure 5.

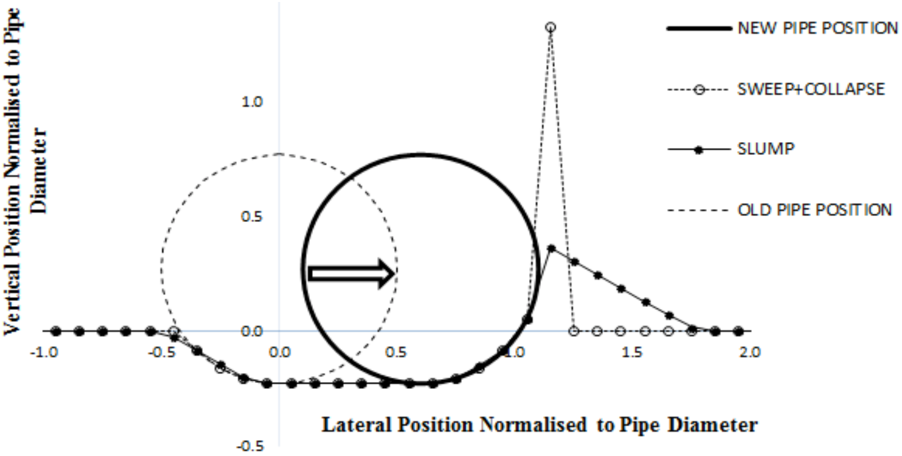

Figure 5 Soil Slumping Algorithm

2.2.3 Pipe-Soil Interaction – Soil Reaction Loads

Firstly, the PSF model considers the profile of the soil around the pipe and calculates contact angle, embedment depth and bearing width on both left and right sides of the pipe. However, during the pipe motion, the contact between pipe and soil will be discontinuous depend on the discrete soil nodes, thus in order to achieve a smooth and continuous function of the embedment, an interpolation algorithm has been generated. Based on the previous PSF model,

the interpolation algorithm has been developed to generally handle all situation, which leads to effectively code simplification and computational cost saving.
Furthermore, PSF model converts the relative penetration between pipe and the locally soil elevation into an equivalent "penetration" Z_{eff} to obtain the vertical soil reaction force F_v refer to Eq. (1) and Eq. (2), which are inverted from F109 (DNV, 2011). In addition, in order to improve the numerical convergence, the elastic mobilization distance is also taken into account (typically 1%).

$$\kappa_s = \left(\frac{0.037}{Z_{eff}}\right)^{\frac{1}{0.67}} \quad \text{--------(1)} \qquad\qquad F_V = \frac{D^2 * r_{sp}}{\kappa_s} \quad \text{--------(2)}$$

3. Verification and Validation

Work completed to date on this project has achieved very significant improvement in the efficiency and structure of the PSF algorithm, as well as resolution of a large number of undocumented features and exceptions. Work remaining to be completed includes accounting for the suck algorithm in the pipe-soil displacement module shown in Section 2.2.2, which only considers sweep/collapse/slump algorithms to date. The accuracy of the PSF algorithms can be examined by comparison to the rules listed in Section 2.2.2, which should indicate no soil deficit by comparing the total soil volume between the old and new soil profile.

Additionally, this PSF model effectively reduces the computational cost. The comparison of computer time and CUP usage of the above load-unload case between PSF model and the FEA method Coupled Euler-Lagrangian (CEL) are shown in Table 1.

Table 1. Comparison of computational cost between PSF model and CEL

Modelling Package	Computer Time (s)	CPU usage
PSF	60	1
CEL	72000	6

In order to verify the pipe-soil reaction force of this PSF mode, the typical results of contact angle and vertical reaction force from a load-unload test are reproduced by this PSF mode in Figure 6. The contact angle and vertical reaction force required for penetrating the pipe increased approximately linearly with normalized vertical displacement. The gradients of the unloading lines are much higher than those of the loading lines and they are closed to 0.01, which is the user defined elastic mobilization distance normalized to pipe diameter.

Figure 6. Contact Angle under Load-unload Test

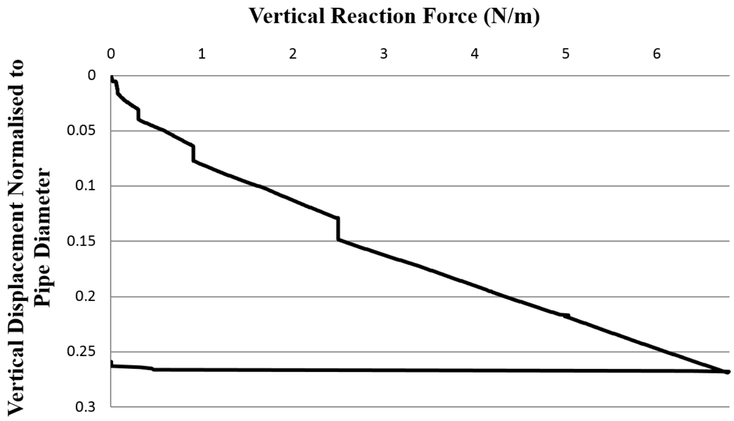

Figure 7. Vertical Reaction Force under Load-unload Test

Further to the algorithm refinement and implementation, a series of validation and verification tests continue to be performed by comparing the results from numbers of benchmark tests with the predictions by conventional models.

4. Conclusions and Future Work

Compared with the previous 2D PSF model, this project has successfully achieved a much more efficient and applicable approach to capture the soil deformation and soil reaction force, which are important elements in subsea pipeline stability design. Despite further development and refinement still required, such as pipe-fluid interaction and fluid-soil interaction, it is clear that this project has taken a significant and crucial step towards implementation in 3D and realization of the idea to promote the PSF model to the offshore pipeline industry.

5. Acknowledgements

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6. References

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