

3D CFD Investigation of Seabed Shear Stresses around Subsea Pipelines

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Abstract

Field observations on offshore pipelines indicate that local scour due to sediment transport around subsea pipelines laid on erodible seabed is almost inevitable. Conventional offshore design strategies usually assume that the pipelines are stably placed on a relatively stationary seabed, which fails to take into consideration the potential instability of the seabed profile. As a major forcing mechanism for sediment transport, seabed shear stresses may dominate seabed deformation. Nevertheless, little work has been undertaken to research shear-stress-induced seabed deformation in the vicinity of pipelines and thence the consequences for subsea pipeline design. This project seeks to provide a 3D view of seabed shear stresses for different seabed topographies under various flow situations. With a view of modifying the existing two-dimensional PSF model, computational fluid dynamics modelling in FLUENT with DES $k\omega$ -SST turbulence model and user defined velocity boundary conditions have been performed to achieve the objectives. Based on the results, some valuable conclusions about variation seabed shear stresses and sediment transport due to flow inclination and variation in scour hole geometry can be drawn.

1. Introduction

Offshore pipelines are major infrastructure facilities in the oil and gas industry. Their stability and integrity is of the highest importance as failure will result in both serious environmental disaster and heavy economic loss. However, the current offshore design codes assume that the pipelines rest on a relatively stationary seabed throughout their life time (Xu 2010), which fails to take into consideration the potential instability of the seabed. As a major forcing mechanism for sediment transport, seabed shear stresses may dominate seabed deformation. However, little work has been undertaken to investigate shear stress induced seabed deformation in the vicinity of pipelines. Given the fact that most offshore fields in the northern part of Australia are periodically exposed to extreme cyclonic weather conditions which can induce significant seabed shear stresses (Kalkhoven 2012), as one of the offshore pipeline design leaders, it is necessary for the Client to undertake comprehensive investigation into seabed shear stresses generated by various marine flow situations and the impact on seabed deformation and pipeline stability.

This series of CEED projects established by the Client have developed a systematic database of seabed shear stresses as a parametric function of pipeline spanning/embedment, trench configuration and current and wave attack angle. Two-dimensional modelling dealing with planar seabed topographies has previously been undertaken, from which pipe-soil-fluid (PSF)

interaction models have been built (Xu 2010, Shen 2011, Kalkhoven 2012). By assuming that the seabed geometry is two-dimensional the pipe and fluid flow is perpendicular relative to the pipeline, these models can provide a good estimation of shear stresses in the center of a long scour hole. However, as shown by Shen (2011) for steady currents, high shear stresses at the edges of a scour hole, where the 3D seabed profile is extremely complex, can produce significant effects on local sediment transport and scour propagation along the pipeline. Hence by continuing to undertake 3D investigations into different seabed topographies in typical scouring stages under both perpendicular and inclined current or wave flows, we are able to take into account the variation of seabed shear stresses in the dimension along the pipe and thereby extend those existing two-dimensional PSF models.

Scour below a pipeline in real life always takes place in a 3D fashion. When an incoming flow hits a pipeline sitting on a non-cohesive porous seabed, the pressure on the upstream face of the pipe is increased significantly due to the stagnated flow. The downstream face pressure is relatively small under the concurrent effect of flow separation and wake vortex generation. This pressure difference drives a seepage flow underneath the pipe. When the seepage flow becomes excessive, piping occurs, a mixture of water and sediment breaks through underneath the pipe, resulting in the onset of scour below the pipeline (Sumer et al. 2001). Once the scour is initiated, it spreads along the pipeline in two opposite directions and forms an increasing span length. Both the free span length and rate of scour development depend on flow characteristics, sediment properties and pipeline parameters (Cheng et al. 2009). Initially, the combination of small span length and large pressure gradient induces a complex 3D flow field, especially around two span shoulders, with substantial amounts of sediment travelling through the trench underneath the pipe. As the span shoulders get further apart, pipe weight is increasingly exerted on the soil (Sumer et al. 2001) until the bearing capacity of the marine soil is exceeded, thus a general shear failure occurs by sliding soil wedges in an outward direction. As soon as the pipe touches the bed, no more flow or sediment can pass underneath the pipe. Instead, suspended sediment carried by the flow will accumulate beside the pipeline until partial self-burial occurs, and an equilibrium state of sediment transport is reached. This self-burial process may increase the pipe lateral resistance significantly and save the cost of artificial pipe trenching or burial.

Shen (2011) has finished running nine 3D cases under steady current conditions and summarised some important conclusions for perpendicular and inclined steady current flow situations. To advance this 3D modelling, geometries with longer span scour holes under flows comprising perpendicular or inclined wave components are planned to be performed in this project.

2. Modelling Process

2.1 Overview

The project employs a computational fluid dynamics modelling method to realise the objectives and applies a major commercial CFD software package FLUENT that is commonly used across the industry. Different aspects of the project task are finished by different components as illustrated below:

- Geometry models are generated by DESIGNMODELER
- Geometry models are meshed by MESHING
- Numerical CFD modellings are implemented by FLUENT
- Post process of the results are finished by CFD-POST

2.2 Description of Geometry Domains

In order to achieve the project objectives, the computational domain must describe the geometric seabed conditions. The geometric domain size and seabed profile parameters are shown in Figure 1 and Figure 2. By varying L_{berm} , Z_{soil} , Z_{pipe} and L_{span} , different seabed topographies in typical scouring stages can be achieved.

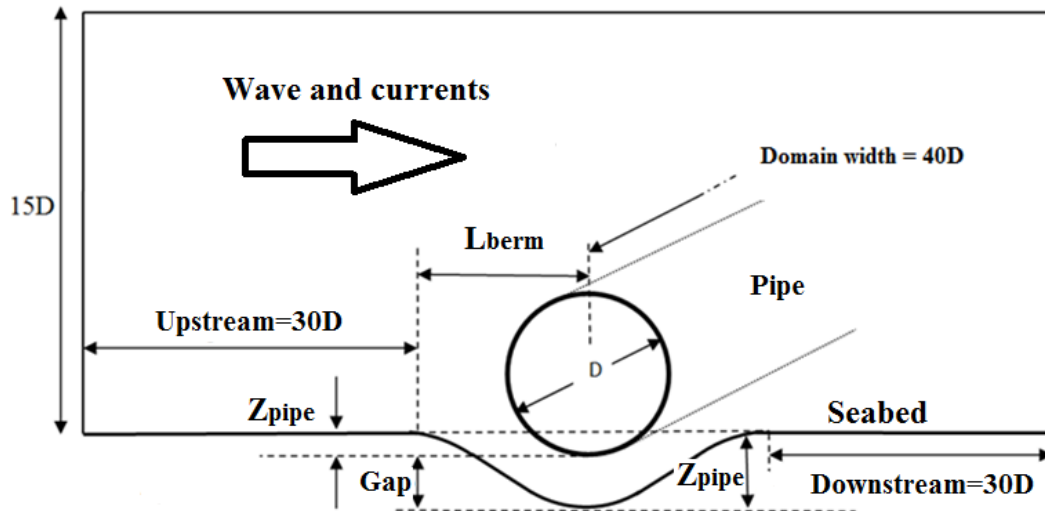


Figure 1 Elevation view of computational domain size

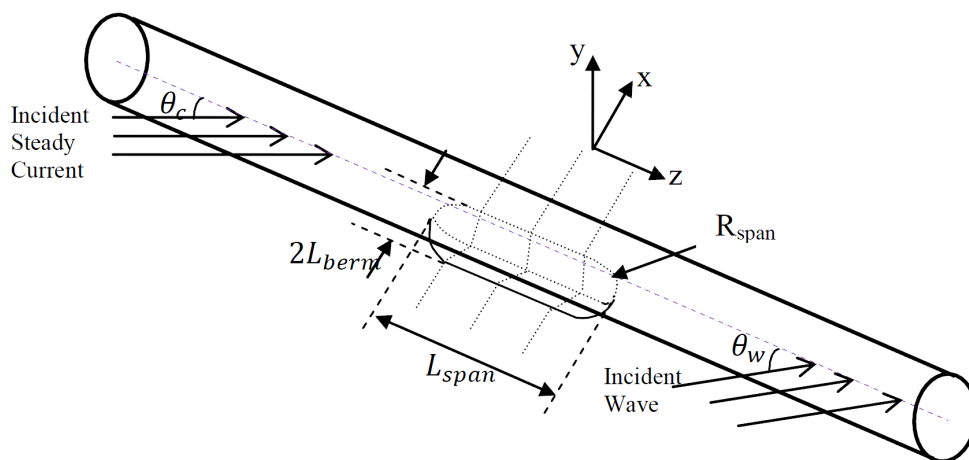


Figure 2 Perspective view of detailed pipeline with a free scour span initiated in the middle

2.3 Computational Meshing

Mesh quality is of the highest importance in computational fluid dynamics modelling. In this 3D modelling project, firstly, the hexahedron dominant mesh strategy is required in order to both reduce the total number of elements used and increase the accuracy of result. Secondly, mesh refinement around areas of interest must be taken into account. Considering the flow characteristics within the solution domain, finer meshing is applied where velocity boundary layers develop and highly 3D flows can be expected. Thirdly, particular attention is paid to the scour span shoulders, since failing to keep finite computing element skewness low enough and meshing direction aligned with the expected flow paths could cause convergence problems in the FLUENT solver. Therefore, to achieve a high-quality mesh, the whole

domain is divided into more than 200 sub-structured bodies and multiple mesh methods are employed. The Figure 3 below show the mesh profiles of core region (around pipe) for both mid-domain and side-domain sections.

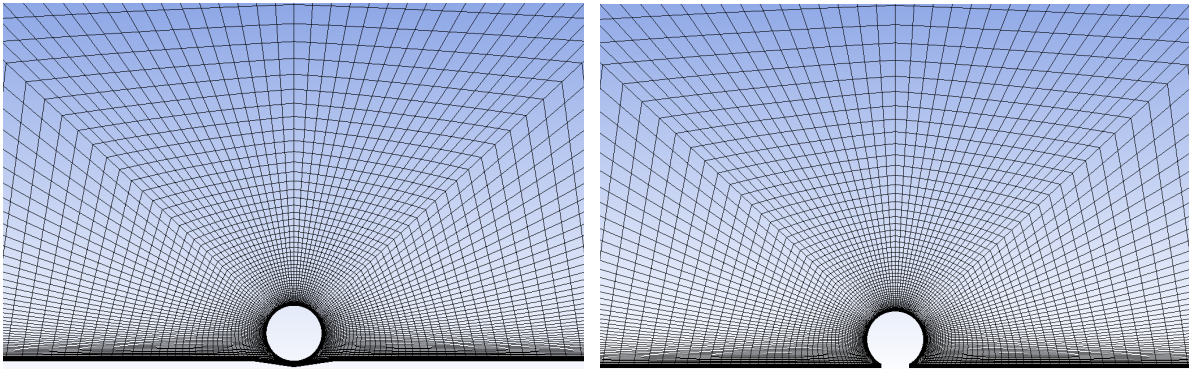


Figure 3 Mesh profile of mid-domain and side-domain section

Mesh problems mainly exist in the connections between these two sections, where highly distorted bodies are generated. For this geometric case, more than 5 million cells are created with the finest element height of 0.001m along the seabed and pipe surface.

2.4 Computational Modelling

2.4.1 Boundary conditions

In order to best describe the flow condition within the computational domain, particular attention is paid to the boundary conditions for each face. For inlet and top boundaries, a velocity inlet boundary condition is employed by specifying user defined function (UDF) of velocity, turbulence kinetic energy and specific dissipation rate, in which metocean condition can be described as current only, wave only and combined current and wave cases. For seabed and pipe boundaries, a non-slip wall boundary condition is applied with a specified wall roughness height of 0.0025m. For side boundaries, a periodic boundary conditions as used by Shen (2011) have been applied, which has been proved to successfully describe the complex wake flow right after the pipe, even for wave cases where in this project the domain has been extended to match the periodicity of wave phase. For the outlet boundary, pressure outlet and velocity inlet boundary conditions are used for steady current cases and wave cases respectively.

2.4.2 Turbulence Model

The turbulence model was selected by Shen (2011) based on benchmarking against the particle image velocimetry (PIV) data describing the velocity field in the vicinity of the pipe from Akoz and Kirkgoz (2009) experimental work in large-scale open water channel. Eventually, DES $k-\omega$ SST turbulence model was selected, which can accurately predict the boundary velocity profile and wake recirculating flow estimation to PIV results (Shen 2011).

3. Results and Discussion

The major concern of this project is to investigate the variation of seabed shear stresses induced by 3D flows due to scour propagation under both perpendicular and inclined current or wave headings. Modelling cases are defined by input parameters of seabed profile and inlet flow, and options for the 6 input variables are suggested by the client mentor listed in Table 3.1. By varying these parameters, a 3D case matrix was developed containing 66 cases in total.

As DES turbulence model for 3D modelling requires significant CPU and RAM resources, to date only 24 cases have been finished (9 were finished by Shen).

Variables	Possible values		
Current velocity U_c (m/s)	1	0.5	
Current attack angle θ_c (deg)	90	45	15
Wave velocity U_w (m/s)	1	0.5	
Wave attack angle θ_w (deg)	90	45	15
Seabed elevation Z_{soil} (m)	-0.1	-0.25	-0.5
Berm length L_{berm} (m)	0.75	3	5
Span length L_{span} (m)	1	5	10

Table 1 Options for 3D case matrix input parameters

Figure 4 shows plots of normalised shear stress (NSS) verses normalised seabed location along 3 typical X axis-parallel seabed lines passing through the span center ($Z=0$), span shoulder ($Z=0.5 \times L_{span}$) and domain side boundary ($Z=0.5 \times \text{domain width}$) respectively for cases with varying span geometry and a constant steady current acting perpendicular to the pipe axis. The NSS is defined as the ratio of local shear stress to the ambient (near domain inlet) shear stress, and the normalised seabed X location is defined as the ratio of the seabed X coordinate value to the pipe diameter. Results from 3D Case19 (10m span), Case8 (5m span) and Case7 (1m span) are illustrated in the diagram, which have identical scour hole planar dimensions in XY plane ($Z_{soil}=0m$, $L_{berm}=0.75m$) and identical flow situation ($U_c=1m/s$, $\theta_c=90deg$, $U_w=0$) but different span lengths along Z axis.

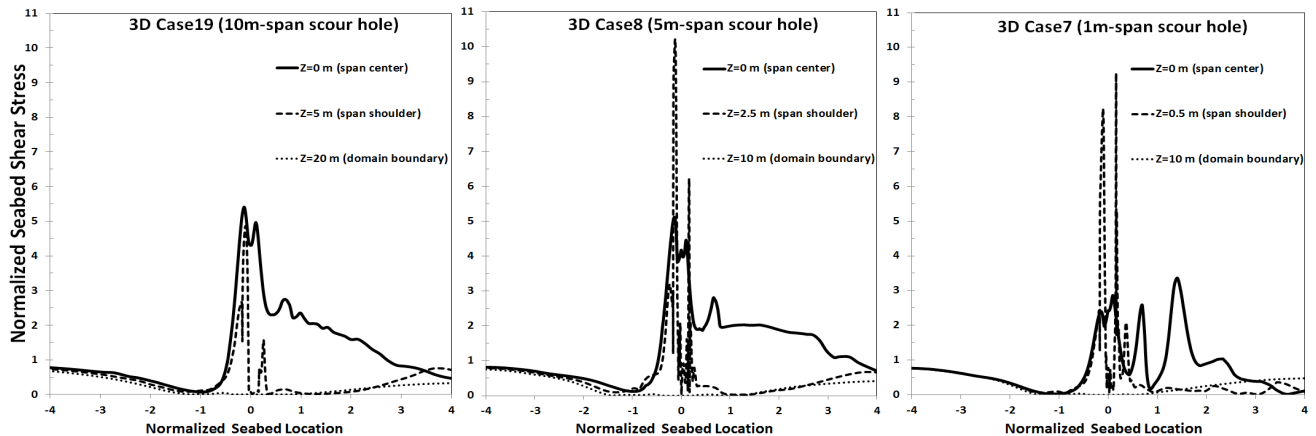


Figure 4 Normalised seabed shear stress $\frac{\tau_{local}}{\tau_{ambient}}$ vs. Normalised X location $\frac{X}{D}$

It is clearly shown that NSS values around the scour hole region (span center and span shoulder) are much higher than those at ambient locations (far field in both X and Z directions). For relatively shorter spans (5m and 1m), the maximum NSS values occur at the region of span shoulders, and are more than 10 times the NSS values at ambient location. However, when it comes to the 10m span case, NSS value at span shoulders is comparable to that at the span center. Furthermore, for 1m, 5m, and 10m long spans, their maximum shoulder NSS values can be roughly taken as triple, twice and equal to their maximum span center values respectively. This implies the extreme NSS values at span shoulders reduce progressively as the scour hole gets longer.

As mentioned before, a 2D case can be treated as a domain with an infinitely long scour hole along the pipe. By comparing it with the series of 3D cases with identical planar scour hole dimension but different span lengths as shown below in Figure 5, it can be observed that the NSS plots for 5m and 10m span match closely to the 2D plots, while 1m span plot deviates.

This suggests that for pipelines above L_{span}/D between about 5 and 10, the hydrodynamics in the middle of the span starts to approach that of the infinite 2D case.

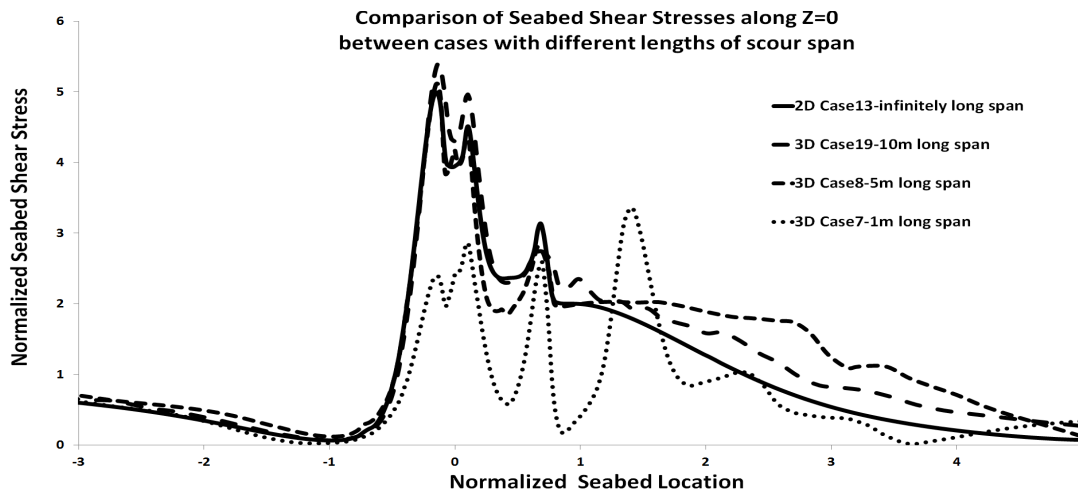


Figure 5 Comparison of NSS plots between cases with different span length

4. Conclusions and Future Work

As can be concluded from the results, once scour is initiated, the resulting complex 3D flow can generate much higher NSS values and hence much more significant local sediment transport than those at ambient locations, especially around the span shoulders. Therefore, in the initial short-span stage, the scour hole can spread along the pipeline in two opposite directions very fast and form a larger and larger span. As the scour hole grows longer, the flow passing through it becomes less extreme and the shoulder NSS values decline near the span center value, hence the scour propagation rate along the pipe decreases as well. In addition, it can be deduced that no more edge effects appear on the span center NSS value profile when the span length exceeds 5m long.

Given the fact that only 15 3D cases have been finished at this point, more 3D cases are in progress and hence more comprehensive analyses can be conducted. Another valuable topic to investigate is the lift and drag force variation profile along the pipe axis direction as scour is proceeds.

5. References

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