Modelling of Seabed Shear Stresses Around Subsea Pipelines

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Abstract

Conventional pipeline stability design methods usually consider a pipeline resting on a stationary seabed which fails to take into consideration the potential instability of the seabed profile, with significant implications for the pipeline's resistance to lateral movement. As a major forcing mechanism for sediment transport, seabed shear stresses may dominate the deformation of the bed. This paper describes a numerical model designed to calculate the seabed shear stresses at all locations near the pipe with planar and non-planar seabed topography and steady current and wave conditions. The seabed shear stresses distributions along the flow direction are identical for comparable seabed topography and flow conditions and can be well described by mathematical formulations.

1. Introduction

Pipelines are major infrastructure facilities in the oil and gas industry. They are widely used for transportation of hydrocarbon fluids. The integrity of pipelines is of the highest importance, as failure will both interrupt this major energy supply (having both social and political impacts), and the resultant leakage of hydrocarbons will cause considerable environmental harm.

A standard engineering task when designing subsea pipelines is to ensure that the pipeline is stable on the seabed under the action of hydrodynamic loads induced by waves and currents. The loads on pipeline consist of a horizontal force component $F_H$and a vertical force component F_V. In the vertical direction, the lift force component F_V is balanced by the subtraction of submerged pipe weight W_S and the bed vertical reaction $W_S - F_V$. In the horizontal direction, there must be a lateral force to balance the F_H component. For the case where the pipe is laying on the seabed surface (shown in Fig.1), the lateral resistance is provided by the seabed and can be modelled assuming Coulomb friction $f = \mu \cdot (W_S - F_V)$. However, this lateral resistance may not be sufficient to restrain the pipe under severe hydrodynamic loads. For example on the Australian North West Shelf (NWS), the case is much worse due to the combination of shallow water, severity of environmental loading during the passing of tropical cyclones and a seabed that over large areas comprises a thin veneer of sand overlaying calcarenite rock (Tørnes et al. 2009). In order to increase the lateral resistance, a few methods are available including increasing the self-weight of pipeline by applying concrete weight coating (primary stabilisation), or various methods of secondary stabilisation including lowering the pipeline into the seabed by trenching or using on-seabed restraints.

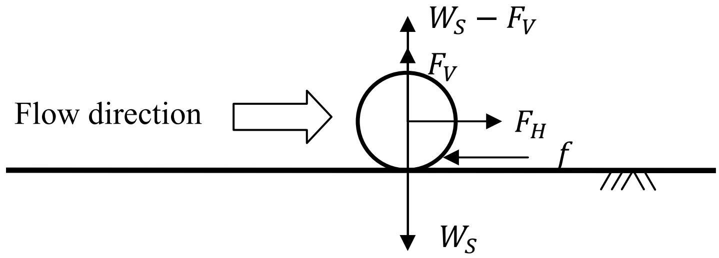

Figure 1 Forces acting on a pipe on the surface of a planar seabed

On the other hand, pipelines placed on an erodible seabed may bury themselves due to the effect of scour below the pipe. When the pipeline is placed on the seabed, the flow passes over the pipeline and separates. Behind the pipeline an area of recirculating flow is produced. There is also a pressure difference between the upstream and downstream of the pipeline and this pressure difference will cause seepage flows in the soil underneath the pipeline. As this seepage flow grows larger, it can move the soil particles in the flow channel and a scour hole between the bottom of the pipe and the deformed seabed will form and enlarge. The scour hole may also propagate three-dimensionally, along the length of the pipeline and form a free span below the pipe (Sumer et al. 2001). As the length of a free span reaches a certain value, the pipeline may sink into the scour holes as a result of self-weight and hydrodynamic forces (Li & Cheng 2001). After the pipe touches the bottom of the scour hole, the sediments carried by the flow will settle down at the upstream side of the pipe. Under oscillatory flow, alternating sides of the pipe will be upstream or downstream. So the pipe will be buried with the accumulation of sediment at both sides of the pipe. This self-burial process would increase the pipe lateral resistance significantly and may save the cost of artificial trenching or burial of the pipe. However, due to the present lack of understanding of the interactions among the pipe, soil and the flow, the self-burial processes have not been used in design. Traditional solutions tend to be conservative, which has led to high cost stabilisation solutions being utilised. A better understanding will improve reliability and remove uncertainty and conservatism in the stabilisation of pipeline systems.

This paper describes a numerical model designed to calculate the seabed shear stresses at all locations near the pipe with planar and non-planar seabed topography and control of inlet flow conditions. The seabed shear stresses distribution patterns along the flow direction are studied. Incorporating this analysis module into the pipeline design process, it is possible to predict the sediment transportation rate around the pipeline and hence increase the reliability of the estimated lateral resistance.

2. Model Description

The simulations are carried out using the commercial computational fluid dynamics (CFD) software FLUENT. It is a finite volume solver of the Reynolds Averaged Navier-Stokes equations.

2.1 Computational Domain and Boundary Conditions

Geometry was built using modelling software GAMBIT. A circular section representing the pipe was generated in/on/over the bottom of the domain. With upstream length of at least 50D and downstream length of 50D, the inlet flow can be fully developed before entering the pipeaffected zone and all the seabed shear stress changes due to the presence of the pipe can be captured. Four seabed profile parameters (L_{BERM}, Z_{SOIL}, Z_{PIPE} and Z_{BERM}) can be varied to prescribe seabed topography. The height of the domain is 15 times pipe diameter so the blockage effect can be neglected. Computational grids were also generated in GAMBIT with refined meshes placed near the seabed and around the pipe area.

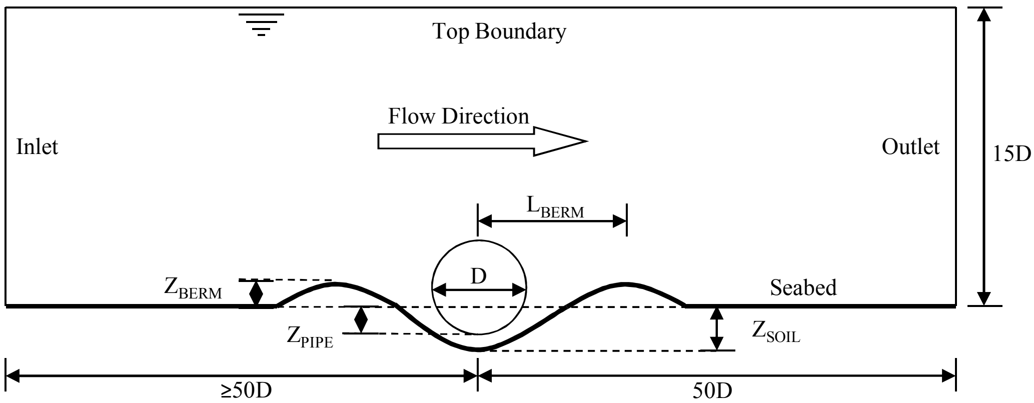

Figure 2 Sketch of computational domain (not to scale)

At the domain inlet, the boundary condition was set as velocity inlet. The velocity profile is specified by a user defined function (UDF) with 7 input parameters (wave height, wave length, wave period, water depth, reference current velocity, reference height and seabed roughness height). By changing these parameters, the UDF can generate velocity profiles of wave only, current only and combinations of wave and current. The UDF includes a wave velocity profile based on Airy Wave Theory, which gives both horizontal and vertical velocity components and a thin boundary layer close the seabed. The UDF also includes the logarithmic current velocity profile given in DNV-RP-E305. The top boundary is also set to be a velocity inlet using the same UDF. It works together with the inlet enabling the model to simulate the orbital movements of water particles experienced under sea waves. The outlet is set to be pressure outlet with p=0. A no-slip boundary condition with a given roughness height parameter is specified for the pipe surface and at the bottom wall (seabed).

2.2 Selection of Turbulence Model

FLUENT provides a range of turbulence models for different flow conditions and requirements. A number of relevant models have been used for preliminary simulations and the selection of turbulence model was finally between RNG k-ε and SST k-ω.

The RNG (renormalization group) k-ε model is an improved model based on the standard k-ε model which is widely used for industrial flow simulations but only valid for fully turbulent flows. It is similar in form to the standard k-ε model but provides an analytically-derived differential formula for effective viscosity that accounts for low-Reynolds-number effects. This, together with some other improvements, makes the RNG k-ε model more accurate and reliable for a wider range of flows. The SST (shear-stress transport) k-ω model was developed to combine the advantages of k-ω in near-wall region and standard k-ε in free-streaming region. A blending function was defined to ensure smooth transition between the two models. (Menter, 1994)

The post-process of preliminary simulation results were carried out using CFD visualization software Tecplot. The different forms of the lee-wake were compared with the physical experimental data presented in the work of Akoz and Kirkgoz (2009) (shown in Fig 3).

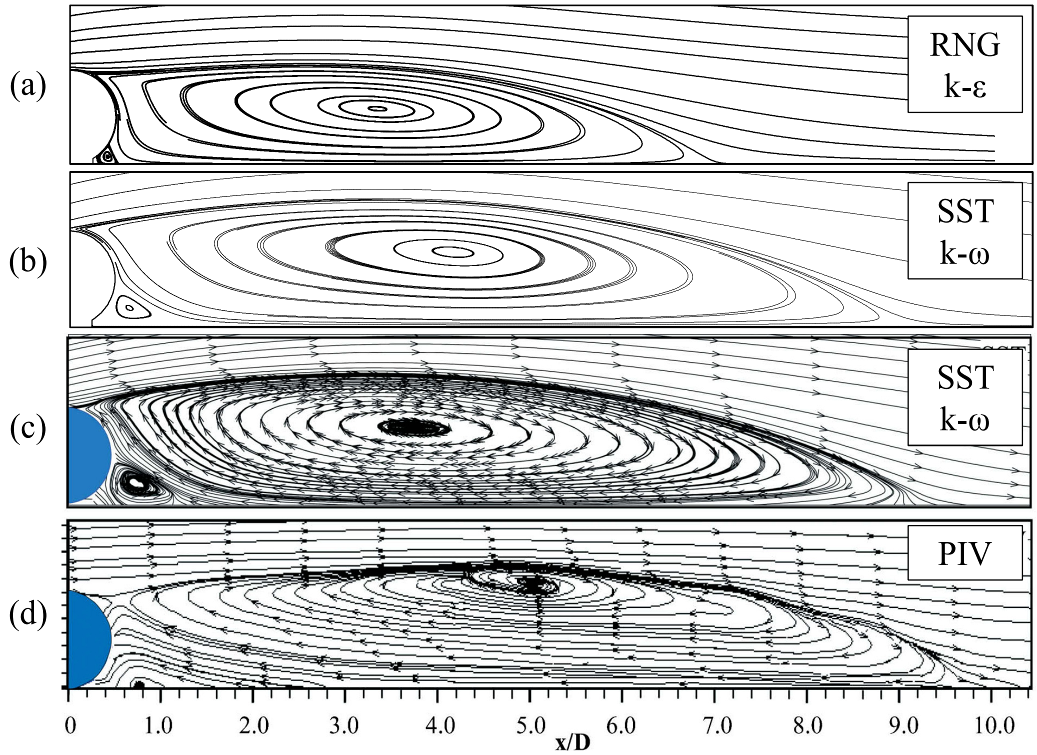

Figure 3 Computational time-averaged streamlines of lee-wake using RNG k-ε and SST k-ω turbulence models and experimental time-averaged streamlines for Re_D=5000. (a) &(b) Results from FLUENT; (c) Numerical results from Akoz and Kirkgoz (2009); (d) Experimental results from Akoz and Kirkgoz (2009).

Comparing (a) with (d), the RNG k- ε model underestimates both the length and the height of the lee-wake region. From (b) and (d), the results using SST k-ω show good agreement with experimental data in terms of the size of the lee-wake region. In addition, plot (b) is a good reproduction of plot (c) which is the result from Akoz and Kirkgoz (2009) using the same model. Therefore, the SST k-ω model was chosen.

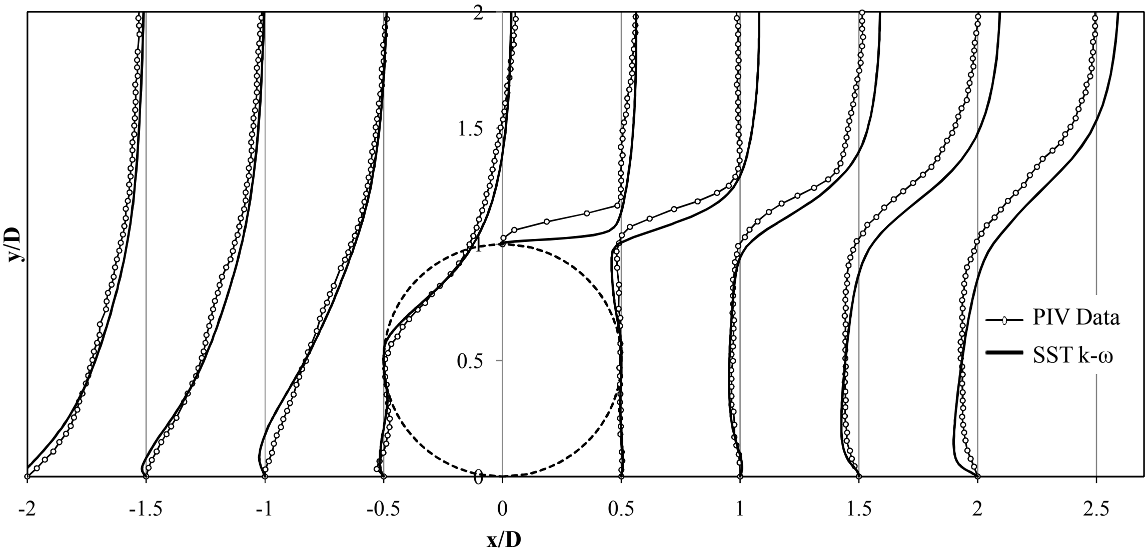

Figure 4 Numerical and experimental horizontal velocity profiles in the vicinity of the pipe for Re_D=5000.

2.3 Model Validation

Due to the lack of direct measurements data, it is not possible to validate the seabed shear stresses with physical experimental data. Instead, the horizontal velocity profiles in the vicinity of the pipe were compared with particle image velocimetry (PIV) data from Akoz and Kirkgoz (2009) for steady current flow with Re_D=5000. By varying the turbulence inlet intensity (ININ), a series of validation tests were conducted. Finally, for ININ=0.01, the numerical results fit reasonably well with the physical experiment (shown in Fig. 4).

3. Results and Discussion

In order to map out the seabed shear stress distribution pattern with seabed topography and inlet flow conditions, the following ranges of input parameters were determined based on engineering judgement (shown Table 1).

Parameter	Lower Bound	Upper Bound	Units
D	0.2	1.2	M
Z_{PIPE}/D	-1.5	1.5	-
Z_{SOIL}/D	-1.5	1.5	-
L_{BERM}/D	1	5	-
Z_{BERM}/D	0	1	-
Gap/D	0	0.1	-
U_C	0	1.5	m/s
U_W	0	2.5	m/s
T	8	16	s

Table 1 Parameters (illustrated in Fig.2) and testing ranges.

A large testing matrix based on engineering judgement has been generated to work out all the required combinations of these parameters. So far 57 cases have been simulated. Interpretations of the results are currently in progress.

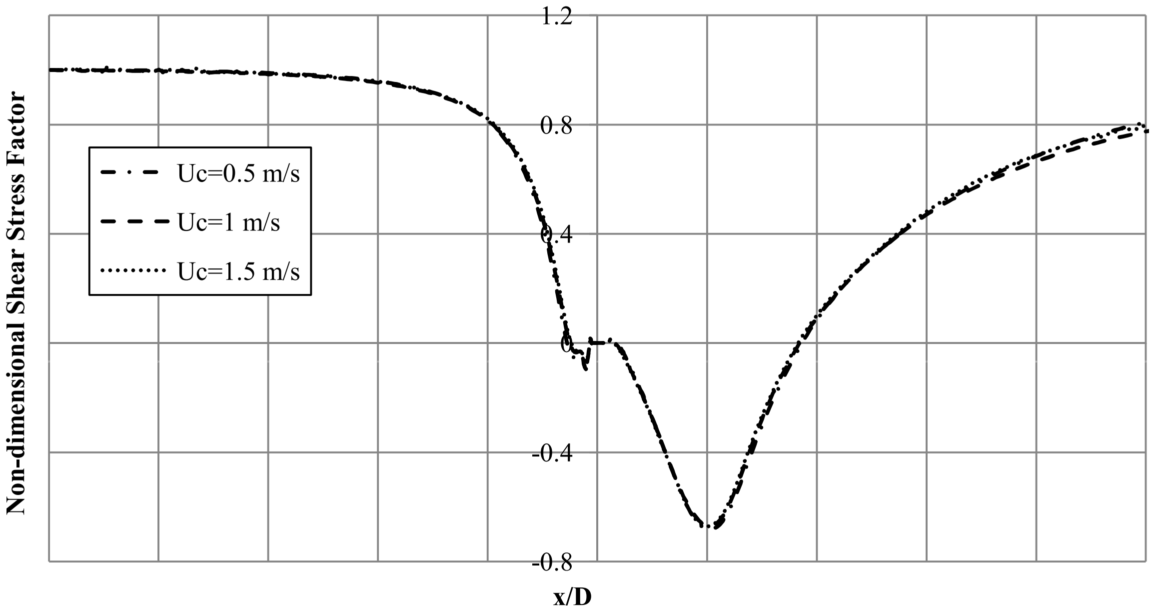

Figure 5 Shear stress factor vs. x/D for current velocity of 0.5m/s, 1m/s and 1.5m/s (Note - horizontal axis scale omitted due to confidentiality).

A non-dimensional shear stress factor (SSF) is defined as the ratio of shear stress at current location to the ambient (far field) shear stress. Plots of SSF versus non-dimensional horizontal distance x/D clearly show the variation of seabed shear stress due to the presence of the pipe. Fig.5 is such a plot showing distribution of three cases which have planer seabed shape with the pipe sitting on the seabed. Current velocities are 0.5 m/s, 1 m/s and 1.5 m/s respectively. The three curves are in good accordance with each other, suggesting that the flow fields are identical for current velocity range from 0.5m/s to 1.5m/s with this seabed topography.

4. Conclusions and Future Work

A large number of simulation results are being interpreted and studied. As shown in Fig.5, the seabed shear stresses variation due to the presence of the pipe is identical for certain velocity ranges and comparable seabed profiles. A series of formulae to predict seabed shear stresses and the variation pattern are being developed and supplemented as more combinations of parameters are simulated.

In future, efforts can be put in the following areas. Firstly, as the major outputs of this model are seabed shear stresses at different locations near the pipe, another model incorporating formulae of sediment transportation shall be developed to predict the rate of transport. Secondly, as the time history of seabed normal pressures are recorded during the simulation, these data can provide important reference to the investigation of seabed liquefaction. Thirdly, since the scouring effect is three-dimensional, it is worthwhile to follow up this research by developing 3D models to work out the shear stresses distribution in the pipe longitudinal direction due to wave and current flows other than perpendicular to the pipe.

5. Acknowledgements

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