Computational Fluid Dynamics Modelling of Pipe-Soil Interaction in Current

I. Iyalla, K. Umah, and M. Hossain

Abstract—Subsea pipelines are subjected to wave and steady current loads which cause pipeline stability problems. Current knowledge and understanding on the pipeline on-bottom stability is based on the research programmes from the 1980’s such as the Pipeline Stability Design Project (PIPESTAB) and American Gas Association (AGA) in Joint Industry Project. These projects have mainly provided information regarding hydrodynamic loads on pipeline and soil resistance in isolation. In reality, the pipeline stability problem is much more complex involving the cyclic hydrodynamics loadings, pipeline response, soil resistance, embedding and pipe-soil-fluid interaction. In this work Computational Fluid Dynamics (CFD) modelling is used to determine the submerged weight necessary for pipeline lateral stability, and the effect of soil embedment and soil porosity on pipeline lateral stability. The results show that increase in pipeline submerged weight, soil embedment and soil porosity increases pipeline lateral stability. The use of CFD provided a better understanding of the complex physical processes of pipe-soil-fluid interaction, and also reduces the need for expensive test facilities and complex design complications.

Index Terms— Horizontal force, Pipeline, Stability, Total lateral soil resistance.

I. INTRODUCTION

Petroleum reserves located under the seabed have resulted in the development of offshore structures and facilities to support the activities of the oil and gas industry which include exploration, drilling, storage, and transportation of oil and gas. Offshore structures constructed on or above the continental shelve and on adjacent continental slopes take many forms and serve a multitude of purposes such as towers for microwave transmission, installation for power generation, pipeline system for transporting reservoir fluids from wells to tieback installations or onshore location, and platforms [1]. Producing oil and gas from offshore and deepwater wells by means of subsea pipelines has proven to be the most convenient, efficient, reliable and economic means of large scale continuous transportation to existing offshore installation or onshore location on a regular basis [2].

One of the major problems encountered with the use of subsea pipelines is the wave-induced instability of pipelines lying on the seabed. There is a complex interaction between pipeline, soil, and hydrodynamic loads when a subsea pipeline is installed on the seabed; under wave loading, to limit the lateral movement of the pipeline, a balance exists between wave loading, the submerged weight of pipeline and soil resistance. Without sufficient resistance from the soil, the pipeline will loose on-bottom stability which may result in the breaking of pipeline. Conventionally, to avoid the occurrence of such instability, the pipeline has to be given a heavy weight coating or alternatively be anchored or trenched into the soil to avoid the occurrence of pipeline instability. However, both methodologies are considered expensive and complicated from the aspects of design and construction. Thus a better understanding of on-bottom subsea pipeline stability is of utmost importance in pipeline ([3]; [4]; [5]).

The design for stability of subsea pipelines involves a consideration a multitude of complex design aspects such as hydrodynamic loads on the pipeline and soil, pipe-soil interaction, wave-pipe-soil interaction, and choosing an approach which ensures a final optimum design outcome. However many of these aspects are not yet fully understood by the pipeline community. When these aspects are over simplified to achieve a quick and easy solution, the result is a costly stabilization requirement. More importantly, if the various stability parameters have not been fully understood, over simplification could also lead to a non-conservative design solution [6].

Before the 1970’s, coulomb’s friction theory was applied in the estimation of the frictional force between submarine pipeline and the seabed under the influence of ocean waves. Lyons examined the soil resistance to lateral sliding of marine pipelines experimentally and concluded that the Coulomb friction theory is unsuitable for explaining the wave-induced interaction between pipeline and soil particularly when the soil is adhesive clay because the lateral friction between pipeline and soil is a function of pipe, wave and soil properties ([7]; [8]).

There has been a rapid change in recent times in the state-of-the-art in subsea pipeline on-bottom stability.

Manuscript received March 18, 2010.

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Current knowledge and understanding of subsea pipeline on-bottom stability is based on earlier research programmes carried out in the 1980's such as the Pipeline Research Committee of the American Gas Association (AGA) who developed an analytical model for both hydrodynamic forces on a subsea pipeline, as well as the pipe soil interaction process. This research resulted in the development of simulation software for design, and the preparation of design guidelines. The second research work carried out by the Pipeline Stability Design (PIPESTAB) Project also focussed on similar aspects as the AGA research, and aimed at developing a technically sound basis for on-bottom stability design of subsea pipelines ([9];[10];[11]). These projects indicated that the application of Coulomb's friction theory in the estimation of the frictional force between submarine pipeline and the seabed was too conservative. This has thus formed the basis for today's pipeline stability design criteria ([3]; [4]).

The AGA and PIPESTAB projects mainly provided information regarding hydrodynamic loads on subsea pipelines and soil resistance in isolation, thus the wave-induced sand scour around the pipeline was not considered. Gao, Gu and Jeng explored the mechanism of pipeline instability by adopting a unique U-shaped oscillatory water flow tunnel with hydrodynamic loading. Sand scouring which is an indication of wave-pipe-soil interaction was observed in the experiment [8].

Sometimes ocean current may be the principal environmental load on the seabed especially in deeper waters. Gao et al investigated the ocean current-induced pipeline lateral stability experimentally and it was observed that the process of pipeline losing lateral stability in waves is slightly different from that in current especially during pipeline breakout. They also observed that pipeline laid directly on a sandy seabed in currents remain more stable than in waves [5].

Experimental works are expensive to perform and is time consuming. Sometimes there are risks and environmental issues involved in designing these test facilities hence there is need to investigate the stability of submarine pipeline using a computer modelling technique. With the progress in the development of computational technology, Computational Fluid Dynamics (CFD) is becoming the most available and useful tool for simulating a wide range of flow, mass, momentum and energy problems. The model presents the opportunity to simulate different flow conditions and environment faster and without the difficulty and expenses required for real life experiments. These will benefit the industry in the understanding of the behaviour of subsea pipelines under various conditions.

2. MODEL DESCRIPTION

The model was created so that it will represent a typical pipeline installed on a seabed, with the inlet in the direction of the positive X-axis and the direction of flow perpendicular to the axis of the pipeline.

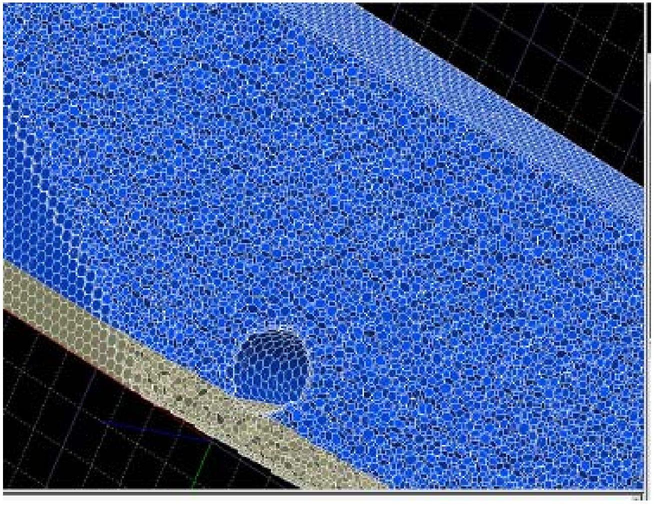

Fig 1: Cross section of the interior volume of the resulting Mesh

Fig. 1 shows the generated mesh near the pipe/seabed. The computational mesh comprises of 168201 polyhedral cells. The geometry of the imported mesh is considered to be a control volume of a 3-D section of a pipeline installed on the seabed (see fig. 2). The boundary names and types, and selected parameters were set as shown in table I and table 2 respectively.

An unsteady, incompressible and segregated flow model was chosen to solve the flow equations. The flow will indicate a fully turbulent flow if **Re** is calculated using the default dynamic viscosity of water, the density of seawater, the diameter of the pipeline and a low fluid velocity of 0.2m/s. Therefore, a turbulent flow regime was chosen.

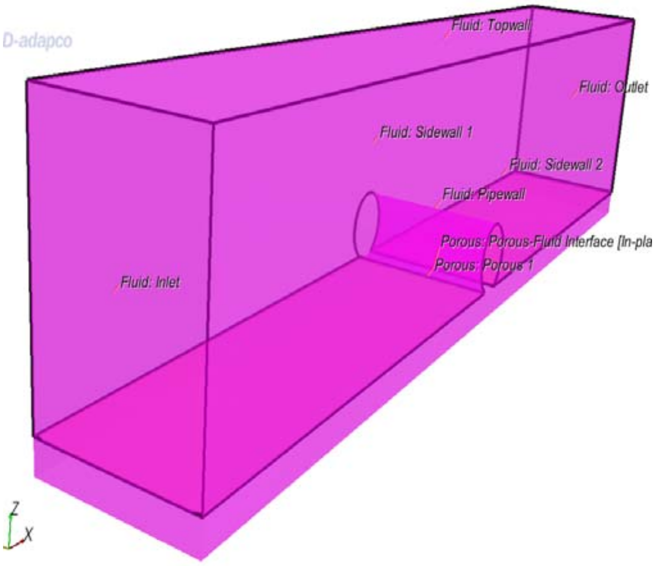

Fig. 2: 3-D view of the geometry and some boundaries.

Table I: Characterization of boundary types

REGION			
Fluid		**Porous**	
Boundary Name	***Boundary Type***	***Boundary Name***	***Boundary Type***
Fluid-Porous Interface	No-Slip Wall	Porous 1	No-Slip Wall
Inlet	Velocity Inlet	Porous 2	No-Slip Wall
Outlet	Pressure Outlet	Porous 3	No-Slip Wall
	No-Slip Wall	Porous-Fluid Interface	No-Slip Wall
Side wall 1	Symmetry Plane		
Side wall 2	Symmetry Plane		
Top wall	Symmetry Plane		

Considering that the flow is turbulent, the Reynolds-Averaged Navier Stokes (RANS) equation is generally used for solving turbulent flows. The K-Epsilon model was chosen for solving the unsteady incompressible Navier Stokes equation because it is very effective in flow regions with high $\mathbf{Re}$ and has a lesser computational requirement and a higher level of accuracy. The Realizable Two-Layer K-Epsilon model is a combination of the Realizable K-Epsilon and the Two–Layer approach and can be modified in All y + Wall Treatment. Buoyancy plays an important role when a pipeline is submerged in water and was selected alongside gravity.

The segregated fluid temperature model will calculate the energy equation with variant independent temperature.

Table 2: Selected parameters

Parameter	**Value**
Density of H_2O	1025 Kg/m^3
Viscosity of H2O	0.001002 Pa-s
Reference Gravity	0, 0, -9.81m/s
Reference Temperature	273K
Reference Pressure	101325 Pa
Static Temperature	280K
Turbulence Dissipation Rate	0.1 J/Kg-s
Turbulence Kinetic Energy	0.001 J/Kg
Inlet Velocity	0.2 to 1.5 m/s
Porous Inertial Resistance	50 Kg/m^4 in XX, YY and ZZ components
Porous Viscous Resistance	3000 Kg/m^3-sn in XX, YY and ZZ components
Time Step	0.05 seconds
Maximum Inner Iteration	5
Maximum Physical Time	90 seconds

Series of simulations were performed by varying flow velocity to determine the hydrodynamic coefficients and forces acting on the pipeline in current. The flow velocities were varied between 0.2m/s to 1.5m/s. The embedment of the pipeline and the porous resistance of the seabed were also varied in order to determine their various effects on the stability of pipelines.

3. RESULTS AND ANALYSES

3.1 Pipeline Stability Analysis in Currents

The lateral stability of the pipeline in currents can be achieved by maintaining a balance between the horizontal forces acting on the pipeline and the total lateral soil resistance. Fig. 3 shows the graph for stability criteria for 0.5m diameter pipeline with 5% embedment. The pipeline will be unstable if the horizontal force becomes greater than the total lateral soil resistance. At the point of intersection between the horizontal force and total lateral soil resistance, the critical velocity of the current U_C that will cause the pipeline to become unstable is determined (in this case 0.94m/s). This implies at any current velocity below U_C the pipe will be stable and any current velocity above U_C will result in lateral instability of the pipeline.

Reducing the diameter to thickness ratio of the pipeline will increase the thickness as well as the submerged weight of the pipeline thus increasing the total lateral soil resistance which will cause the pipeline to be more stable. Any small proportional increase in submerged weight results in a proportional increase in the total lateral soil resistance and the critical velocity that will cause pipeline instability. In fig. 4 any submerged weight above 415N will keep the pipeline stable in a sea state with current velocity U_{C1} or less.

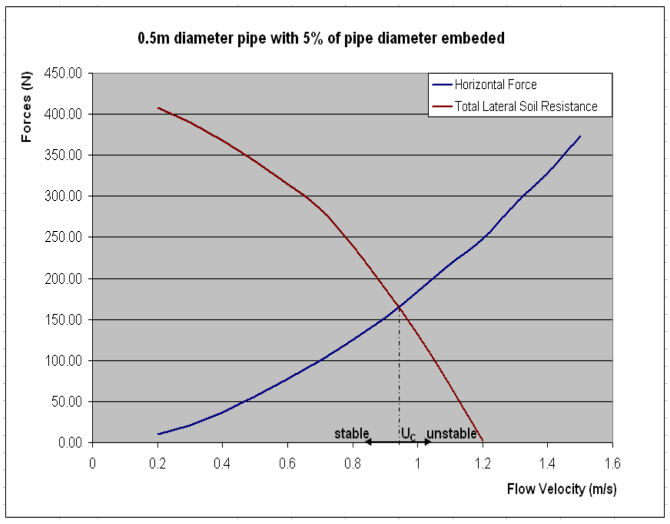

Fig. 3: Pipeline stability criteria for 0.5m diameter pipeline with 5% embedment

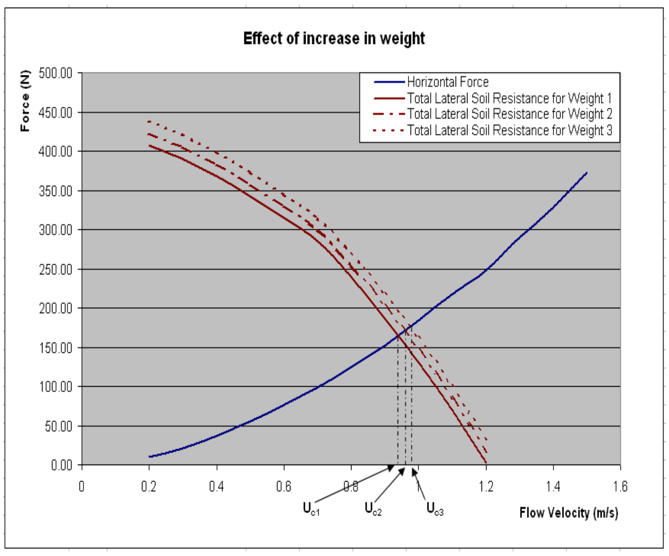

Fig. 4: Effect of weight increase on 0.5m diameter pipe (submerged weight 1 = $415N$, submerged weight 2 = $440N$ and submerged weight 3 = $465N$).

3.2 Effect of Soil Embedment on Pipeline Lateral Stability

The submerged weight of an installed pipeline induces some degree of embedment of the pipeline. The degree of embedment also depends on the properties of the seabed soil. Fig. 5 shows that a slight reduction (2%) in pipeline embedment reduces the total lateral soil resistance drastically (approximately 23%). This is due to the reduced pipe-soil contact. Its effect on the horizontal force was insignificant when compared with the effect on the total lateral soil resistance. This implies that the higher the degree of embedment the more stable the pipeline and vice versa.

3.3 Effect of Seabed Porosity on Pipeline Lateral Stability

Increasing the porous inertial resistance and porous viscous resistance by 100% and 67% respectively results in a corresponding reduction in the porosity of the seabed. Fig 6 shows that this reduction in porosity results in a slight reduction (5%) in the lateral stability of the pipeline. There is a higher rate of decrease in total lateral soil resistance of the less porous seabed with flow velocity when compared with the higher porous seabed.

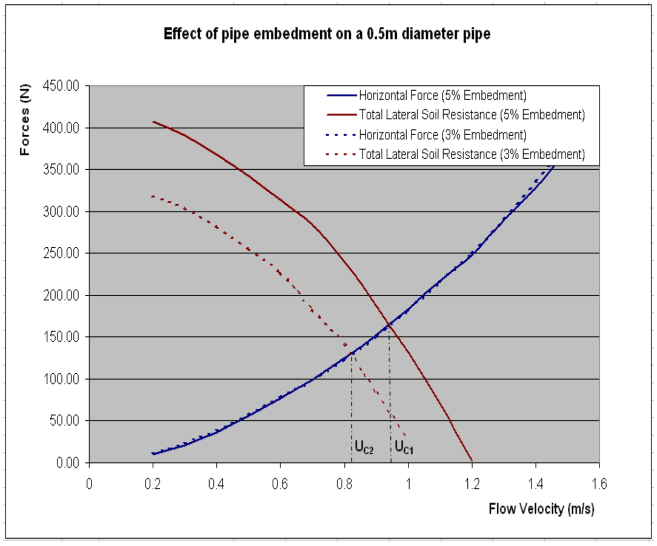

Fig. 5: Effect of soil embedment on pipeline lateral stability.

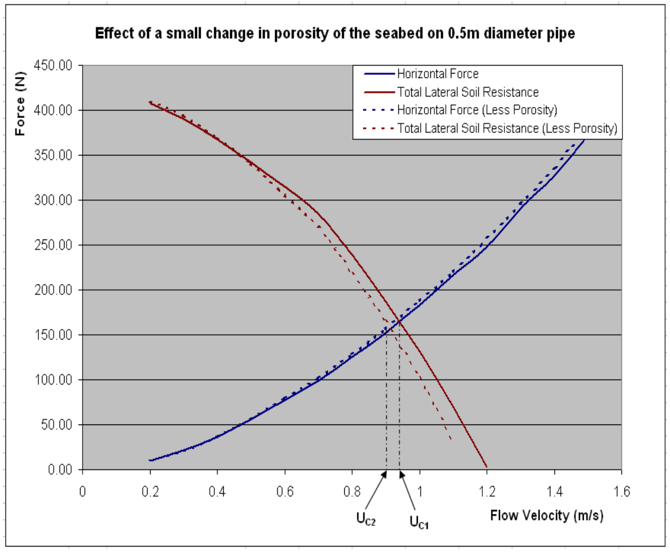

Fig. 6: Effect of porosity on the pipeline lateral stability

A very slight rate of increase in the horizontal force was observed with the less porous seabed as flow velocity increased. This is due to the reduced fluid-soil interaction; the less porous seabed reduces the ease with which the fluid flows through the soil, thus increasing the pressure acting on the pipeline.

4. CONCLUSION AND FURTHER WORK

The CFD model took into account the boundary layer effects, the wake flow effects, the vortex fields and the fluid interaction with the porous seabed. Its prediction in current is therefore accurate based on the current velocity and other chosen parameters.

The simulation results clearly validate the importance of pipeline embedment on the lateral stability of submarine pipeline in accordance with the PIPESTAB project and AGA project. This is a complement to the pipe-soil interaction model. It also confirms the effect of porosity of the seabed on the stability of submarine pipeline. Comparably, the porosity effect can be associated with porous seabed (sandy) and less porous seabed (clay) to determine how soil properties influences pipeline stability.

The simulation results illustrate how a proportional increase in the submerged weight of a pipeline will result to a proportional increase in its lateral stability. A small increase in pipeline embedment will increase its lateral stability considerably and a decrease in porosity of the seabed will reduce the total lateral soil resistance of submarine pipelines resulting to pipelines loosing lateral stability easier.

The use of CFD in the design of submarine pipeline stability will contribute to the growth and profitability of the industry in the future. It is recommended that new methods need to be developed to determine the most suitable method for determining the submerged weight required to keep the pipeline stable on the seabed.

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Appendix

Governing Equations

$$\boldsymbol{F_f = \mu(W_S - F_L)} \qquad (1)$$

where $\boldsymbol{F_f}$ is the frictional force between the pipeline and the soil, $\boldsymbol{\mu}$ is the coefficient of friction, $\boldsymbol{W_S}$ is the submerged weight of pipeline and $\boldsymbol{F_L}$ is the hydrodynamic lift force.

$$W_S = \rho_s \frac{\pi}{4}\left(D_o{}^2 - D_i{}^2\right)Lg - \rho_w \frac{\pi}{4} D_o{}^2 Lg$$

where ρ_s and ρ_w are densities of steel pipe and seawater respectively, D_o is outer diameter of pipe, D_i is internal diameter of pipe, L is length of pipeline and g is acceleration due to gravity

Traditionally, the frictional resistance must be greater than the total horizontal force ($\boldsymbol{F_T}$) for the pipeline to be stable ([2]; [12]). That is

$$\boldsymbol{\frac{\mu(W_S - F_L)}{F_T} > 1} \qquad (2)$$

$$\boldsymbol{F_H = F_F + F_R} \qquad (3)$$

where F_H is total lateral soil resistance, F_F is sliding resistance and F_R is lateral soil passive resistance

Equation (3) becomes

$$\boldsymbol{F_H = \mu(W_S - F_L) + \beta\gamma A} \text{ for sand}$$
(4)

$$\boldsymbol{F_H = \mu(W_S - F_L) + \frac{\beta c A}{D}} \text{ for clay} \qquad (5)$$

where β **is** empirical soil passive resistance coefficient, it is a function of the pipe displacement and the lateral loading history, γ **is** effective buoyant unit weight of sand, A **is** one half the area of a vertical cross section of the soil displaced by the pipe during the penetration and oscillations, c is remoulded undrained shear strength for clay and D is pipe diameter

$$\boldsymbol{F_H = \mu(W_S - F_L) + \frac{2}{3}\beta\gamma D^2\left(\frac{H_U}{D}\right)^{\frac{3}{2}}} \quad \text{for}$$
$$0 \le H_U \le D \text{ for sand} \qquad (6)$$

$$\boldsymbol{F_H = \mu(W_S - F_L) + \beta c D\left(\frac{H_U}{D}\right)} \text{ for } 0 \le H_U \le D$$
for clay (7)

where H_U height of soil ridge [13]