Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2009
May 31 - June 5, 2009, Honolulu, Hawaii, USA

OMAE2009-79283

INVESTIGATING A NEAR-BED SUBMARINE PIPELINE IN A CURRENT

Mian Lin*
Department of Ocean Environment and Engineering

Yulong Cao
Department of Ocean Environment and Engineering

Lei Li
Department of Ocean Environment and Engineering

Guojun Huang
Department of Ocean Environment and Engineering

Laboratory of Environmental Mechanics,
Institute of Mechanics, Chinese Academy Sciences, Beijing 100190, China

ABSTRACT
This paper considers the lift forces acting on a pipeline with a small gap between the pipeline and the plane bottom or scoring bottom. A more reasonable fluid force on the pipeline has been obtained by applying the knowledge of modified potential theory (MPT), which includes the influences of the downstream wake. By finite element method, an iteration procedure is used to solve problems of the nonlinear fluid-structure interaction. Comparing the deflection and the stress distributions with the difference sea bottoms, the failure patterns of a spanning pipeline have been discussed. The results are essential for engineers to assess pipeline stability.

1 INTRODUCTION

In the offshore environment, the hydrodynamic force of a submarine pipeline would be varied with the distance from pipeline to seabed. Many experimental investigations have been concluded that the smaller of the gap ratio the more influence on flow field is. However many studies still have treated the pipeline as riser, in other words, the effect of seabed on flow field around pipe has been ignored. That is irrational because an asymmetry flow due to the seabed present will cause net force in the vertical direction.

Recently, some researchers have considered the problem by the well-know potential theory (PT), which ignores the effect of the water viscosity ([1], [2]). From the knowledge of PT, the velocity in the gap between the pipe and the seabed is higher than that above the pipe, resulting in negative lift coefficients ([3], [4], [5]). In reality, some experiments have shown that both velocities are very near and positive lift coefficients are induced and they are much smaller than that obtained by PT ([6], [7], [8], [9], [10]) (Fig.1). Fredsøe and Hansen [11] have developed the modified potential method (MPT) to overcome the problem. The MPT method has included the effect of vortex shedding on the downstream part of the pipe. In this paper we will use the method to analyze the pipeline hydrodynamic response.

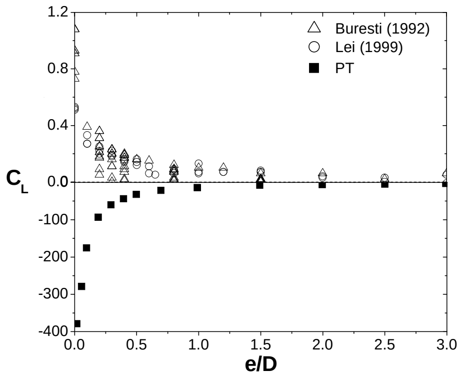


Fig.1 Comparing life coefficients by PT and experiments

The present work concerns the problem on a spanning pipeline at a plane bottom and a scouring bottom in current. Firstly the method of MPT is used to obtain the lift forces. And next the deflections and stresses with variation in the axis of a pipeline are calculated by the finite element method. Finally, useful information for the pipeline design and operation is discussed.

* Professor and author of correspondence

2 GOVERNING EQUATION

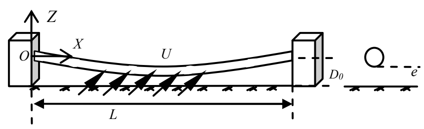
Consider a supported circular pipeline, the gap ratios *e/D* vary with *x* due to the pipeline's self-weight (Fig.2). The spanning length *L* is much greater than the pipe outer diameter *D*. The pipe consists of two layers: steel pipe covered with reinforced concrete and its center distance away from the seabed is D_0. The incoming current velocity is *U*. The coordinate system is shown in Fig.2a. For *L>>D*, the pipeline can be simplified as an Euler beam. The response of the pipeline is given by

$$EI\frac{\partial^4 w(x)}{\partial x^4} = \rho A g - mg + f(x) \qquad (1)$$

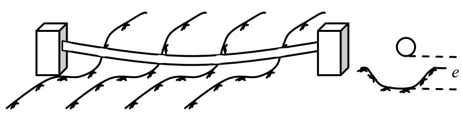
Boundary conditions are satisfied:

$$\begin{cases} w(0) = w(L) = 0 \\ \left.\dfrac{\partial w(x)}{\partial x}\right|_{x=0} = \left.\dfrac{\partial w(x)}{\partial x}\right|_{x=L} = 0 \end{cases} \qquad (2)$$

where *w(x)* is the deflection of the pipeline; $EI = E_c I_c + E_s I_s$ is equivalent bending stiffness for the two layers material and the subscripts *c, s* denote concrete and steel, respectively; ρ is the outer fluid density; *A* is the cross-section area of the pipe; *g* is the gravity acceleration; *m* is the mass per unit length; $f(x) = 0.5\rho C_L(x) A U^2$ is the fluid force per unit length, here $C_L(x)$ the lift force coefficient. Some former experimental research revealed the force state of a pipeline is changing with the gap ratio on a plane bottom [12]. Next section we will discuss the coefficient.



(a) plane bottom



(b) scouring bottom

Fig.2 The sketch of a supported pipeline at different bottoms (the right figure is shown the cross section)

3 LIFT FORCE COEFFICIENT

The present work regards the fluid field around a pipeline placed near a seabed as two dimension due to *L>>D*. And the stream function ψ is assumed to be consists of three parts:

$$\psi = \psi_c + \psi_b + \psi_v \qquad (3)$$

where ψ_c represents the current flow around a pipe without seabed, ψ_b the flow over the seabed without the pipe and ψ_v the flow induced by point unit vortex.

There are three boundary conditions: the surface of the cylinder and the seabed becomes streamlines, the maximum velocities U_{top} above the pipe equals to that U_{bottom} below the pipe, which images the wake on the lee side of the pipe. By setting suitable dipoles in cylinder and beneath the seabed, the velocity field can be obtained. The above description is the main structure of the MPT (detailed see [13], [14]).

From Bernoulli's equation, the flow pressure on the pipe surface can be given:

$$p + \frac{\rho v^2}{2} + \rho y g = C(\psi) \qquad (4)$$

The lift acting on the pipe is easily evaluated by integration of the vertical component of the pressure force in the interval $-\pi/2 \le \theta \le \pi/2$, as following:

$$C_L = \frac{1}{\rho U^2}\int_{-\pi/2}^{\pi/2}(-p)\sin\theta d\theta \qquad (5)$$

In fact, as the Reynolds number is over 105 orders, the flow field shows weak span wise relevance. Thus, assuming that the features of the flow field only depend on the gap ratio, the pipeline can be dealt with slices evenly along the *x* axis. The pipeline lift coefficient can be assessed by a two-dimensional method such as equation (5).

As the pipeline is placed on a plane bottom (Fig.2a), the lift force coefficient at every slice (x) can be calculated and then a fitting curve by the spline interpolation is plotted in Fig.3, which is satisfied the following equation:

$$C_L(x) = 1.1e^{-3.35\left[\frac{D_0}{D} - \frac{qx^2(l-x)^2}{24EID}\right]} \qquad (6)$$

where $q = g\left(A_c\rho_c + A_s\rho_s - A\rho\right)$, $a_{c,s}$ is the cirque area for concrete and steel, respectively, $\rho_{c,s}$ is the density for concrete and steel, respectively.

For convenience, some experimental results and calculation solution by pt are also marked in Fig.3. It is obviously that our results (solid line) are closer to experimental results.

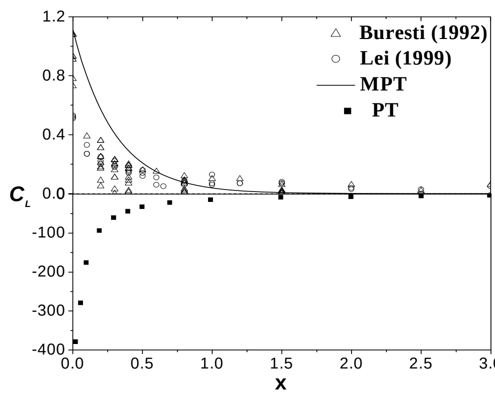


Fig.3 The variation in lift force coefficient with x at plane bottom

In reality, as a pipeline is located on a sand bed, the seabed sometimes presents a scouring hole below the pipe instead of a plane bottom (Fig.2b). Assuming that the profile is cosine-shaped (Fig.4), the maximum scouring depth is calculated and depends on incoming flow velocity, sand particle diameters and the gap ratio, et al [14].

Similarly with the plane bottom, on scouring bottom, we also obtain the fitting curve for scouring bottom (Fig.5), and the lift coefficient can be written as:

$$C_L = 0.6\left(0.003\right)^{\left[\frac{D_0}{D}-\frac{qx^2(l-x)^2}{24EID}\right]} + 0.4\left[\frac{D_0}{D}-\frac{qx^2\left(l-x\right)^2}{24EID}\right] - 0.7 \quad (7)$$

It is obvious that the coefficient curve for the plane bottom is positive and for the scouring bottom is negative. The reason is that the stagnation point s moves upward with the scouring hole deepening and finally the download pressure contribute to the lift force. This means that the influence of the presence of seabed is distinct.

The negative lift forces resulted from the scouring bottom may aggravate the deformation, even invalidation of a free-span. In next section, we will calculate the pipeline response.

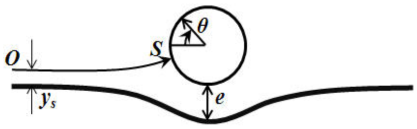


Fig.4 Flow around a pipe.
(S represents a stagnation point. OS is the stagnating streamline)

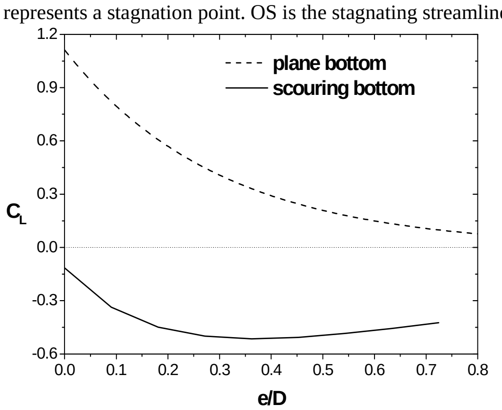


Fig.5 The variation of lift force coefficient with e/D

4 THE RESPONSE OF THE PIPELINE

In order to solve equation (1), the pipeline is discretized using equal length elements. The balance equation is written as:

$$[K]^e\ [\delta]=[f] \quad (8)$$

where $[K]^e$ is stiffness matrix of the element, is satisfied:

$$[K]^e = \begin{bmatrix} \frac{EA}{l} & 0 & 0 & -\frac{EA}{l} & 0 & 0 \\ & \frac{12EI}{l^2} & -\frac{6EI}{l^2} & 0 & -\frac{12EI}{l^2} & \frac{6EI}{l^2} \\ & & \frac{4EI}{l^2} & 0 & \frac{6EI}{l^2} & -\frac{4EI}{l^2} \\ & & & \frac{EA}{l} & 0 & 0 \\ & \text{symmetry} & & & \frac{12EI}{l^2} & -\frac{6EI}{l^2} \\ & & & & & \frac{4EI}{l^2} \end{bmatrix} \quad (9)$$

Here l is the element length; $[f]$ is the external force vector; $[\delta]^T = [u_i, w_i, \theta_i, u_j, w_j, \theta_j]^T$ is the displacement vector. Because equation (1) is nonlinear, it can not be solved directly. An iterative scheme is used to obtain the solution. The iterations stop when:

$$\sqrt{\sum_{i=1}^{N}\left[z(i)^{n+1} - z(i)^{n}\right]^2} \le \varepsilon \quad (10)$$

where N denotes the number of nodes; $z(i)^n$ is the deflection results of the ith iteration steps; $\varepsilon = 10^{-6}$ is a specified accuracy tolerance.

5 RESULTS AND DISCUSSION

Firstly, we consider the pipeline response with different methods. As mentioned previously, the direction of the lift force predicted by PT versus by MPT, so the response of the pipeline has significant distinction. In order to confirm it quantitatively, we consider an example. The calculated parameters are listed in Table 1.

Table 1. Calculated Parameters

Spanning Length	External Diameter	Internal Diameter	Steel Rigidity	Concrete Rigidity
20m	1m	0.8m	$2.11\times10^{11}\,Pa$	$2.5\times10^{10}\,Pa$

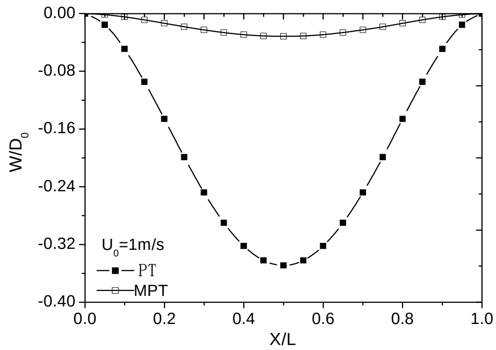


Fig.6 The deflection distribution along the pipeline (Plane bottom)

We use an iteration scheme to obtain the deflection distribution along the pipeline as plotted in Fig.6. To compare the maximum deflection occurring at the middle of the pipeline, the mid-span deflection by PT is about ten times of the solution by MPT. And the difference values are more distinct with increasing current velocity. As U>5.6m/s, according to the predicts by PT the pipeline would sticks to the seabed due to the downward force, but in real situation the pipeline is suffered upward lift force and the pipeline stabilizes at apposition above the original equilibrium position (Fig.7). In this figure we also plot the solution in the case of scouring bottom. It is seen that the pipeline always keeps stability position between seabed and original equilibrium position with increasing current velocity, though the pipeline endures downward forces.

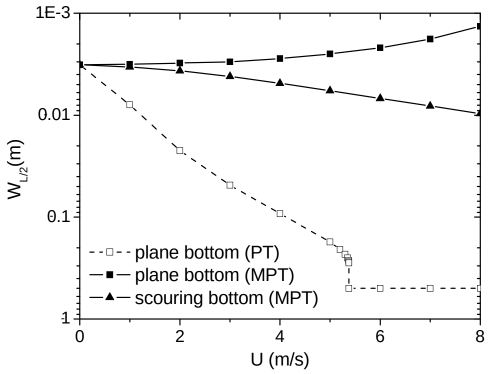


Fig.7 The variation of the pipeline deflection with current velocity

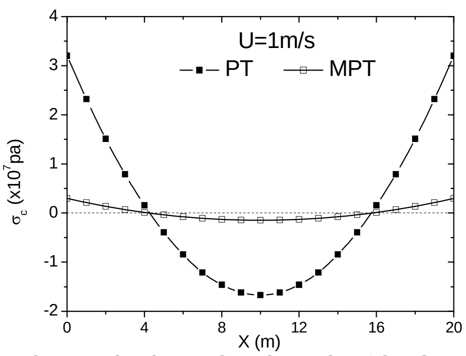


Fig.8 The stress distribution along the pipeline (Plane bottom)

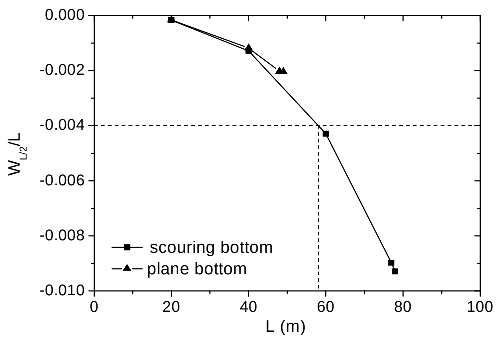


Fig.9 The maximum deflection of the pipeline

Otherwise we turn to the discussion of the stress distribution in the pipeline. Because the stresses of both steel and concrete pipelines increase monotonically and synchronously, so here we only discuss steel pipeline. The stress results for *U*=1m/s are plotted in Fig.8 by PT and MPT methods. Comparing the maximum stress occurred at both ends of the pipeline, the values by PT are almost ten times of that by MPT. In other words, the strength failure would not occur readily as expected by PT.

Secondly, we concern the pipeline failure problems. Two failure patterns are taken into account. One is deflection failure as the maximum deflection exceeds its allowable deflection/spanning length ratio $W_{L/2}/L$=0.004. The limiting value is given by DNV [15] for vertical deflections of offshore steel structures. The other is the strength failure, which induces yielding failure if the maximum stress exceeds yielding stress. The yielding stress in steel is about 10 times in concrete.

Setting incoming flow velocity *U*=1m/s, the initial gap ration $e_0 / D = 0.1$ and the pipeline fixed at the both ends, Fig.9 and Fig.10 show the variation of the maximum deflection and maximum stresses with spanning length *L*.

From Fig.9, the deflection failure curves depend on the spanning length. As the spanning length is short, there are no significant differences for the two bottoms. But as the spanning length enlarges, the results will be distinct. On the plane bottom, the pipelines are stability and as $L \geq 48m$ the pipeline sticks on the bottom. However, on the scouring bottom, the deflection failure occurs as the spanning length $L = 58.2m$.

Fig.10(a) and 10(b) show the maximum stresses in concrete and in steel, respectively. It is clear that, on a scouring bottom, the maximum stress in steel reaches the yielding stress as *L*=68.5m; the maximum stress in concrete reaches the value as *L*=57.1m. On plane bottom, the strength failures do not occur.

Comparing Fig.10(a) with Fig.9, the danger spanning lengths are very close, while the yielding stress in steel has not reached yet. It concludes that the value of the maximum deflection could be used to estimate whether a spanning pipeline is failure or not.

The above results are based on a certain value of incoming current velocity and initial gap. In reality which failure pattern is a priority should depend on many conditions, such as pipeline material properties, constraint conditions, environmental loadings. We will study in near future.

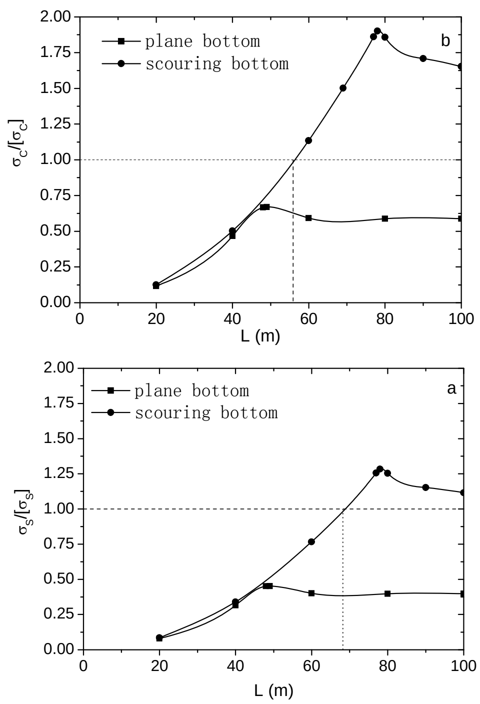


Fig.10 The maximum stress (a) in concrete; (b) in steel on the pipeline

ACKNOWLEDGMENTS

The financial support from NSFC (Grant No.40776057) and the project of CAS (KZCX2-YW-212-2) and the "863" programs (No. 2006AA09Z301) are gratefully acknowledged.

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