Available online at www.sciencedirect.com
ScienceDirect
Ocean Engineering 35 (2008) 301–309
OCEAN ENGINEERING
www.elsevier.com/locate/oceaneng

Experimental study of vortex-induced vibrations of a pipeline near an erodible sandy seabed

Bing Yang[a], Fu-Ping Gao[a,*], Dong-Sheng Jeng[b], Ying-Xiang Wu[a]

[a]*Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China*
[b]*Division of Civil Engineering, University of Dundee, Dundee DD1 4HN, Scotland, UK*

Received 12 February 2007; accepted 12 November 2007
Available online 21 November 2007

Abstract

Based on similarity analyses, a series of experiments have been conducted with a newly established hydro-elastic facility to investigate the transverse vortex-induced vibrations (VIVs) of a submarine pipeline near an erodible sandy seabed under the influence of ocean currents. Typical characteristics of coupling processes between pipe vibration and soil scour in the currents have been summarized for Case I: pipe is laid above seabed and Case II: pipe is partially embedded in seabed on the basis of the experimental observations. Pipe vibration and the corresponding local scour are usually two coupled physical processes leading to an equilibrium state. The influence of initial gap-to-diameter ratio (e_0/D) on the interaction between pipe vibration and local scour has been studied. Experimental results show that the critical values of V_r for the initiation of VIVs of the pipe near an erodible sand bed get bigger with decreasing initial gap-to-diameter ratio within the examined range of e_0/D ($-0.25<e_0/D<0.75$). The comparison of the pipe vibrations near an erodible soil with those near a rigid boundary and under wall-free conditions indicates that the vibration amplitudes of the pipe near an erodible sand bed are close to the curve fit under wall-free conditions; nevertheless, for the same stability parameter, the maximum amplitudes for the VIV coupled with local scour increase with the increase of initial gap-to-diameter ratio.

Keywords: Submarine pipeline; Vortex-induced vibration; Ocean currents; Sandy seabed

1. Introduction

When a submarine pipeline is laid, pipeline spans may exist due to the unevenness of the seabed or be created by the local scour around the pipeline in hostile environmental conditions. Such pipeline spans, when exposed to currents, may undergo vortex-induced vibration (VIV), which has been widely recognized as one of the main causes of fatigue damage to pipelines (Blevins, 1977). Prediction of the behavior of vortex-induced vibration of pipelines in the proximity of a seabed is a major problem encountered in pipeline design.

The vortex-induced oscillation of a cylinder has attracted much attention from numerous researchers in the past few decades (Sarpkaya, 1979; Chakrabarti, 1994; Sumer and Fredsoe, 1995). In those studies, physical modeling is the primary approach due to the complexity of the phenomenon. Most existing experimental studies for the VIV of a cylinder focussed on either wall-free cylinders or cylinders in the proximity to a rigid boundary. For a wall-free cylinder, when Reynolds number is larger than a certain value (e.g. 40), vortex shedding occurs in the wake flow (Gerrard, 1966). The forces acting on the cylinder including lift and drag forces may experience periodic change due to the vortex shedding. Moreover, the frequency of the lift force is consistent with the vortex shedding frequency, and the frequency of the drag force is double that of vortex shedding (Drescher, 1956). Numerous experiments have shown that when the vortex shedding frequency brackets the natural frequency of an elastic or elastically mounted rigid cylinder with a suitable afterbody, the cylinder takes control of the shedding in apparent violation of Strouhal relationship. Then the frequencies of vortex shedding and the body oscillation collapse into a single frequency close to the natural frequency of the body,

*Corresponding author. Tel.: +86 10 82544189; fax: +86 10 62561284.
E-mail address: fpgao@imech.ac.cn (F.-P. Gao).

0029-8018/$ - see front matter
doi:10.1016/j.oceaneng.2007.11.001

which is known as the lock-in phenomenon (Sarpkaya and Isaacson, 1981). As observed by Jacobsen et al. (1984), when a cylinder gets closer to the rigid wall in a steady flow, regular vortices would not be shed behind the cylinder, but the vibration of cylinder still takes place. The close proximity of a pipeline to seabed boundary has been found to have much influence on the vortex shedding and the vortex-induced vibrations of pipelines (see, e.g., Tsahalis and Jones, 1981; Jacobsen et al., 1982; Fredsoe et al., 1985; Yang et al., 2006).

In the aforementioned studies, the cylinders or pipelines are in either wall-free conditions or close to rigid boundaries, i.e. soil scour was not involved. Quite a few researchers have investigated the current-induced local scour around fixed pipelines by means of physical modeling (e.g., Sumer et al., 2001; Bakhtiary et al., 2006; Mousavi et al., 2006) and numerical methods (e.g., Li and Cheng, 2000; Lu et al., 2005). The scour profiles and time scale for the local scour around fixed pipelines have been examined. When a pipeline is laid close to an erodible sandy seabed and under the action of currents, the local scour may be coupled with vortex-induced pipeline vibration. To date, only a few researchers have investigated the coupling between vortex-induced vibration and soil scour. In the most important work, Sumer et al. (1988b) allowed the pipe to move only in the transverse direction, whose experimental results showed that the vibrations of the pipes close to an erodible sand bed are ultimately dominated by vortex shedding due to the extra soil erosion, even though the pipe is placed very close to the original undisturbed bed. Shen et al. (2000) investigated the responses of the pipes moving in transverse and in-line directions. Recently, sand scour around a transversely vibrating pipeline has been investigated experimentally by Gao et al. (2006). For the complexity of dynamic interaction between pipe vibration and seabed scour, the physical mechanism of vortex-induced vibration of a pipeline close to an erodible sandy seabed has not yet been fully revealed until now.

In this study, dynamic responses of the pipe near a sandy seabed were simulated experimentally. The influences of the initial gap between the pipe and sandy seabed on the pipe vibration are investigated. Moreover, a comparison between the pipe vibrations in proximity to an erodible sandy bed and those near a rigid boundary is performed.

2. Similarity analysis and experimental setup

2.1. Similarity analysis

When a submarine pipeline is installed on a sandy seabed and exposed to ocean currents, dynamic interactions between pipeline, sandy seabed and ocean currents have been observed. Vortex-induced vibration of the pipeline and the scour of sand bed beneath the pipeline are two coupled physical processes, as illustrated in Fig. 1. The dynamic responses of the pipeline laid on a sand bed in ocean currents are mainly dependent on the following parameters of ocean currents, pipeline and sandy seabed, as listed in Table 1.

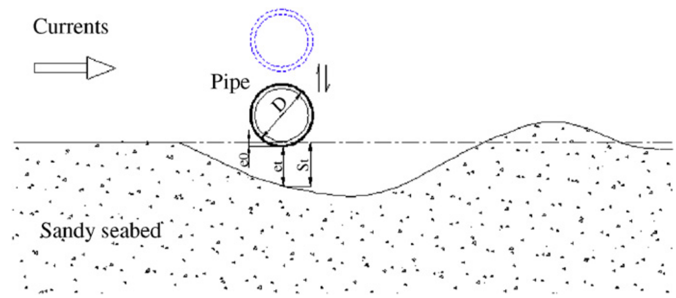

Fig. 1. Schematic diagram of dynamic coupling process between VIV of the pipeline and local scour.

Table 1
Physical quantities relative to dynamic responses of a pipeline near an erodible seabed

Physical quantities	Symbol	Dimension
Ocean current		
Mass density of fluid	ρ	ML^{-3}
Dynamic viscosity of fluid	μ	$ML^{-1}T^{-1}$
Undisturbed flow velocity	U	LT^{-1}
Duration of loading	t	T
Pipeline		
Pipe diameter	D	L
Relative roughness of the pipe surface	κ	1
Mass of the pipe per meter	m	M
Natural frequency of the pipe in still water	f_n	T^{-1}
Structural damping factor	ζ	1
Sandy seabed		
Mass density of sand grain	ρ_s	ML^{-3}
Mean diameter of sand grain	d_{50}	L
Relative density of sand	D_r	1
Gravitational acceleration	g	LT^{-2}
Initial gap between pipe bottom and seabed surface	e_0	L

The amplitude (A) and frequency (f) of the vortex-induced vibrations of a pipeline in the vicinity of the sandy seabed can be expressed as following, respectively:

$$A = \varphi(\rho, D, U, m, f_n, \kappa, \zeta, \mu, \rho_s, d_{50}, D_r, g, e_0, t), \tag{1a}$$

$$f = \phi(\rho, D, U, m, f_n, \kappa, \zeta, \mu, \rho_s, d_{50}, D_r, g, e_0, t). \tag{1b}$$

Based on the Buckingham Pi Theorem, the dimensionless expression of Eqs. (1a) and (1b) can be written as

$$\frac{A}{D} = \varphi'\left(m^*, V_{r_n}, \kappa, K_s, Re, G_s, \frac{d_{50}}{D}, Dr, \theta, \frac{e_0}{D}, \frac{tU}{D}\right), \tag{2a}$$

$$\frac{f}{f_n} = \phi'\left(m^*, V_{r_n}, \kappa, K_s, Re, G_s, \frac{d_{50}}{D}, Dr, \theta, \frac{e_0}{D}, \frac{tU}{D}\right), \tag{2b}$$

where m^* is mass ratio of the pipe:

$$m^* = \frac{4m}{\pi\rho D^2}, \tag{3}$$