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

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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,

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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.

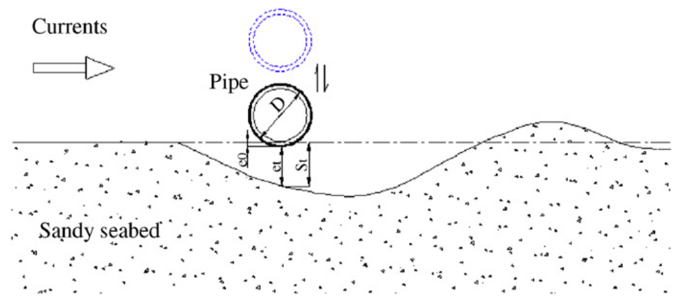

Fig. 1. Schematic diagram of dynamic coupling process between VIV of the pipeline and local scour.

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:

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

which represents the ratio of pipe inertia and fluid inertia; the nominal reduced velocity (V_r) is defined as

$$V_r = \frac{U}{f_n D}, \tag{4}$$

where f_n is the natural frequency of the pipe in the water; K_s is the stability parameter indicating pipeline's ability to dissipate energy:

$$K_s = \frac{4(m + m_a)\zeta}{\pi \rho D^2} \tag{5}$$

in which $m_a = C_A m_d$ is the added mass, C_A is the coefficient of added mass, $C_A \approx 1.0$ and $m_d = \pi\rho D^2/4$ for a cylinder; the normalized damping (ζ) is defined as $\zeta = c_{sys}/c_{cr}$, where c_{sys} is the system damping, and c_{cr} is the critical damping; $Re = \rho UD/\mu$ is the Reynolds number indicating the ratio of fluid inertia force and fluid viscosity force; the specific gravity of sand grain $G_s = \rho_s/\rho$, which is approximately 2.65 for standard quartz sand; d_{50}/D is the dimensionless diameter of sand grain; the Shields parameter (θ) is defined as

$$\theta = \frac{U_f^2}{(G_s - 1) g d_{50}}, \tag{6}$$

which governs the sediment transport, where U_f is the bed shear velocity and can be calculated with the Colebrook–White formula, i.e. $U/U_f = 8.6 + 2.5\ln(D/2k_b)$, in which k_b is the roughness of bed and is usually taken as $2.5d_{50}$ (Sumer and Fredsoe, 2002); e_0/D is the dimensionless initial gap between pipeline and seabed; tU/D is the dimensionless loading time.

For the proper physical modeling of the complex interaction between pipe vibration and soil scour, the derived scaling laws that accurately describe the similarity between small-scale models and the prototypes should be satisfied. The equality of non-dimensional parameters (Pi terms) for the model and the prototype systems yields the scaling laws to be satisfied. According to the theory of vortex-induced vibration (see Blevins, 1977; Sarpkaya and Isaacson, 1981), m^*, V_r, K_s are of major importance in determining the VIV of structures, so they are followed in these small-scale experiments. Re is of the order of 10^3–10^4 in our tests, being in the subcritical flow range, whereas in the fields, Re is of the order of 10^5 or more. In the subcritical Re range (approximately $300 < Re < 3 \times 10^5$), the vortex shedding occurs at a well-defined frequency (see Blevins, 1977). It has been found that the effects of Reynolds number on the vortex shedding are negligible, when high Reynolds number and marine-roughened real-life pipelines are considered (Achenbach and Heinecke, 1981; Sumer et al., 1988a).

As for the initiation of sediment motion at the bed surface, there usually exists a critical value of the Shields number (θ_{cr}), which is a function of the grain Reynolds number (Yalin and Karahan, 1979). For the medium sand ($d_{50} = 0.38$ mm) in this study, θ_{cr} is approximately 0.045. The local scour around structures (e.g. pipelines) may thereby be classified into two categories: the clear-water scour ($\theta < \theta_{cr}$) and the live-bed scour ($\theta > \theta_{cr}$). In the case of clear-water scour around fixed pipes, the variation of scour depth with θ was found pronounced. However, when the live-bed scour is reached, very small variation of the scour depth with θ has been observed (see Sumer and Fredsoe, 2002).

2.2. Experimental setup

A new hydro-elastic facility in conjunction with a flume has been constructed for the present experiments on the interaction between the transverse vibration of the pipeline and the soil scour (see Fig. 2). The flume is 0.5 m wide, 0.6 m deep and 19 m long, capable of generating steady currents with velocity up to approximately 0.6 m/s. The test pipes are made of duralumin, therefore can be regarded as rigid. The pipe was attached to the supporting frame by two connecting struts, two sliding struts and a set of springs. The sliding struts can move along the four runners, which were connected to the two localizers by four bearings. The gap between the pipe bottom and the soil surface can be adjusted easily by changing the height of the supporting frame. Two model pipes were used, one having a diameter of $D = 0.032$ m and the other $D = 0.050$ m. The pipe surface is smooth, i.e. $\kappa \approx 0$.

The natural frequency of the spring supported test pipe (f_n) was obtained by spectral analyses of free-decay tests of the pipe in wall-free conditions. The structural damping factor (ζ) was determined with free-decay testing method, i.e. applying a given excitation to the pipe in still water, then recording the vertical responses of the pipe. A laser displacement transducer was employed for the non-contact measurement of the vertical displacements of the pipe (see Fig. 2). For slightly damped structures, the structural damping factor can be estimated with $\zeta = \ln(A_i/A_{i+n})/(2\pi n)$, where A_i is the initial amplitude of pipe vibrations, A_{i+n} is the amplitude after n cycles (see Blevins, 1977). In the experiments, the water depth was maintained at 0.3 m. The flow velocity was measured by a micro-propeller current-meter. Sands of 15 cm depth were used to simulate a sandy seabed. The mean grain diameter was $d_{50} = 0.38$ mm and relative density was $D_r = 0.66$, indicating the soil is a medium-dense one.

3. Experimental results and discussions

3.1. Typical characteristics of the coupling between soil scour and pipe vibration in currents

3.1.1. Case I: $e_0/D \geqslant 0$ (pipe is laid above seabed)

Pipeline spans usually exist due to the unevenness of the seabed. The dynamic response of the pipe near an erodible sandy seabed with positive e_0/D was simulated physically.

Fig. 3 gives the variation of pipe amplitude of vibration and scour beneath the pipe with time for the case of $e_0/D = 0.75$. It is indicated from Fig. 3 that the vortex-induced vibration of the pipe and the scour beneath

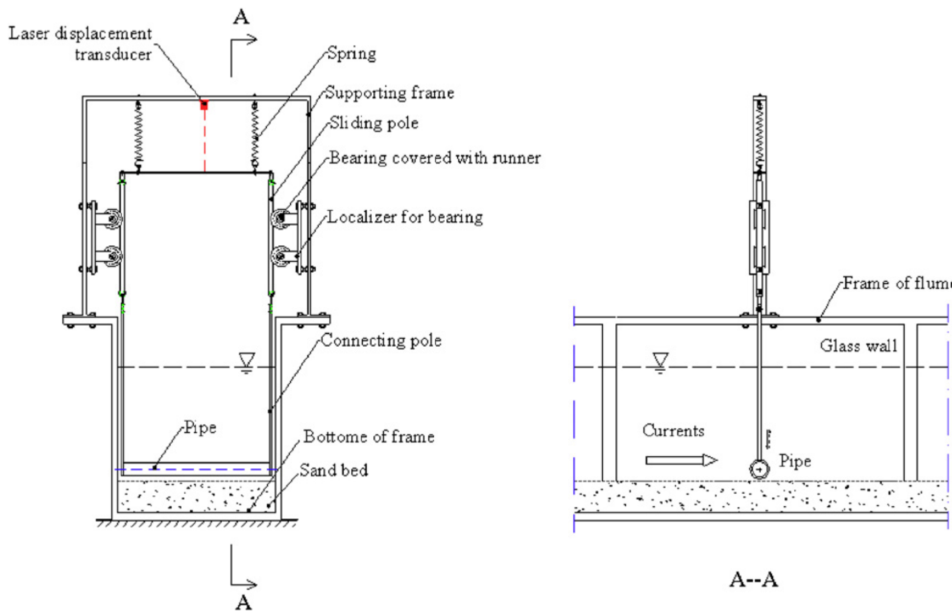

Fig. 2. Experimental set-up.

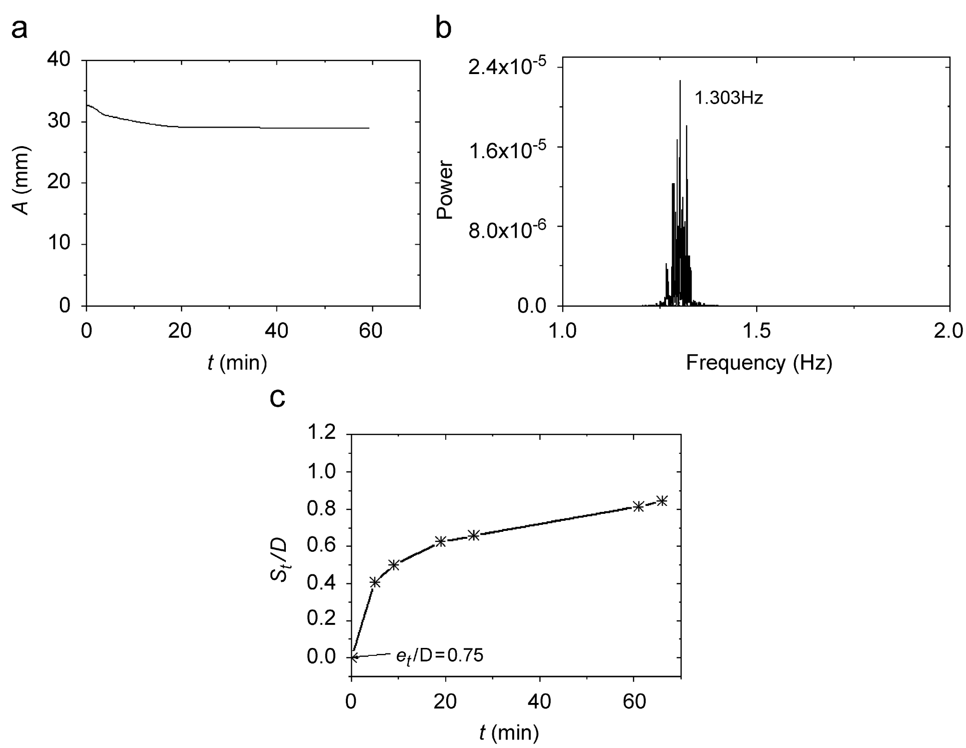

Fig. 3. Dynamic coupling between pipe vibration and sand scour for a pipe initially with a gap to seabed: (a) amplitude of pipe vibration versus time; (b) power spectrum of pipe vibration; (c) scour depth versus time ($e_0/D = 0.75$, $D = 0.032\,\mathrm{m}$, $U = 0.255\,\mathrm{m/s}$, $V_r = 6.53$, $m^* = 3.87$, $K_s = 0.0749$, $\theta = 0.039$, $d_{50} = 0.38\,\mathrm{mm}$, $D_r = 0.66$) (adapted from Gao et al., 2006).

the pipe may occur simultaneously with an initial positive gap-to-diameter ratio (e_0/D) at a certain flow velocity. Fig. 3 also shows that the amplitude of pipe vibration quickly reaches a constant value, meanwhile its frequency changes within a narrow frequency band. Concurrently, the local scour depth beneath the pipe (S_t) increases with time. It was observed that pipe vibration and soil scour were coupled with each other, and finally they reached an equilibrium state.

3.1.2. Case II: $e_0/D<0$ (pipe is partially embedded in seabed)

In the fields, most pipelines are installed on the seabed with some initial embedment (i.e. e_0/D is negative). In our experiments, the whole process of the vortex-induced vibration of a partially embedded pipe ($e_0/D = -0.25$), and the corresponding soil scour in steady currents was also simulated.

When the flow velocity was not high enough (e.g. $U = 0.235$ m/s, $V_r = 6.02$), the test pipe kept stationary while the soil beneath the pipe was being scoured until an equilibrium state was reached. The time development of scour depth is plotted in Fig. 4.

When flow velocity is increased to certain values (e.g. $U = 0.255$ m/s, $V_r = 6.53$; see Fig. 5), the scour beneath the pipe continues to develop with time and the vibration amplitude of the pipe is almost imperceptible at the initial stage, as shown in Fig. 5. However, when the gap between pipe bottom and the scoured sand surface (termed as e_t) gets larger (e.g. $e_t = 0.14D$; see Fig. 5(c)), the pipe suddenly began to vibrate (see Fig. 5(a)). Within several minutes after the initiation of the VIV of the pipe (e.g. $t > 8$ min; see Fig. 5(a) and (c), the local scour around the pipe develops rapidly due to the vibrations of the pipe. In the process of soil scouring, the amplitude of the pipe vibration increases rapidly to a maximum value at the initial stage, then decreases to some extent until an equilibrium state is reached (see Fig. 5(a)). It was found that the vibration frequency decrease slightly with increasing scour depth (Gao et al., 2006), and the frequency width of VIV in the process of sand scouring is small (see Fig. 5(b)).

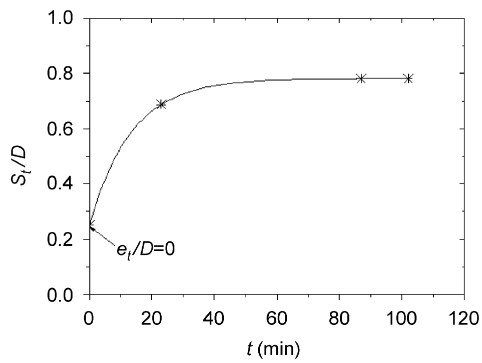

Fig. 4. Time development of scour depth without occurrence of the VIV of pipe ($e_0/D = -0.25$, $D = 0.032$ m, $U = 0.235$ m/s, $V_r = 6.02$, $m^* = 3.87$, $K_s = 0.0749$, $\theta = 0.036$, $d_{50} = 0.38$ mm, $D_r = 0.66$).

3.2. Influences of initial gap-to-diameter ratio on pipe vibration and soil scour

The initial gap between pipeline and seabed surface is an important factor for the interaction between VIV of the pipeline and the local scour. Fig. 6 shows the effects of initial gap-to-diameter ratio on pipe vibrations and sand scour at the equilibrium state. The vibrations did not occur at small values of V_r when the pipes were laid close to the seabed (e.g. $e_0/D = 0$, -0.25; see Fig. 6(a)) while the soil scour could be induced (see Fig. 6(c). It was observed that the vortex shedding was suppressed when pipe is in the proximity of the boundary (Grass et al., 1984). The critical values of V_r for the occurrence of pipe vibration get bigger with decreasing the initial gap-to-diameter ratio from 0.44 to -0.25. The vibration amplitude and scour depth at equilibrium states affect each other, and both of them are

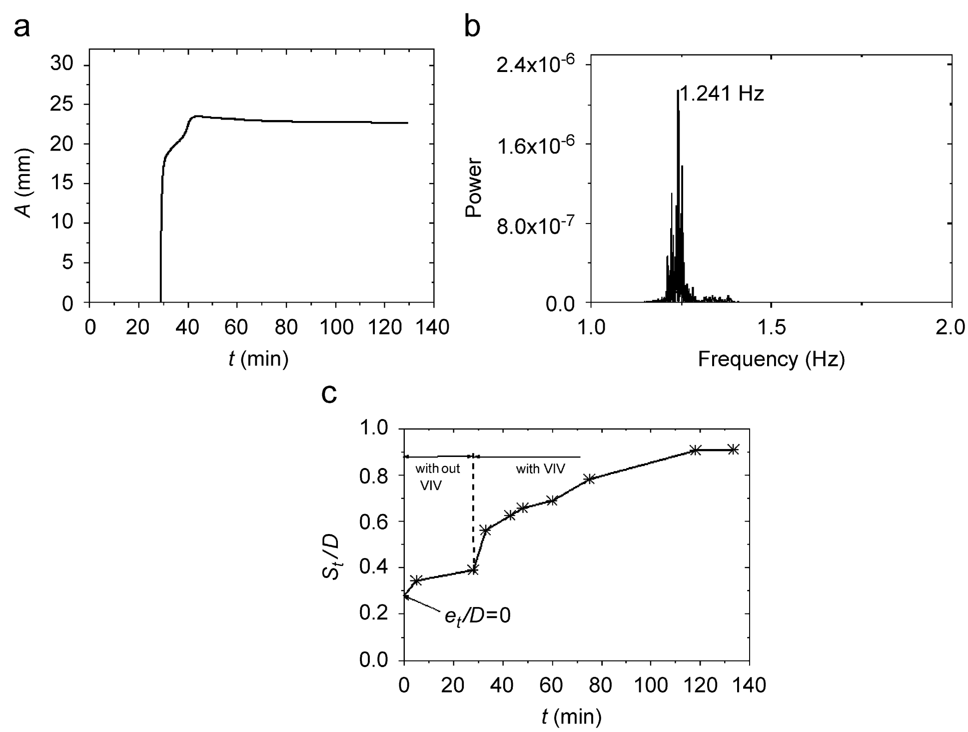

Fig. 5. Dynamic coupling between pipe vibration and sand scour for an initially partially embedded pipe: (a) amplitude of pipe vibration versus time; (b) power spectrum of pipe vibration; (c) scour depth versus time ($e_0/D = -0.25$, $D = 0.032$ m, $U = 0.255$ m/s, $V_r = 6.53$, $m^* = 3.87$, $K_s = 0.0749$, $\theta = 0.039$, $d_{50} = 0.38$ mm, $D_r = 0.66$) (adapted from Gao et al., 2006).

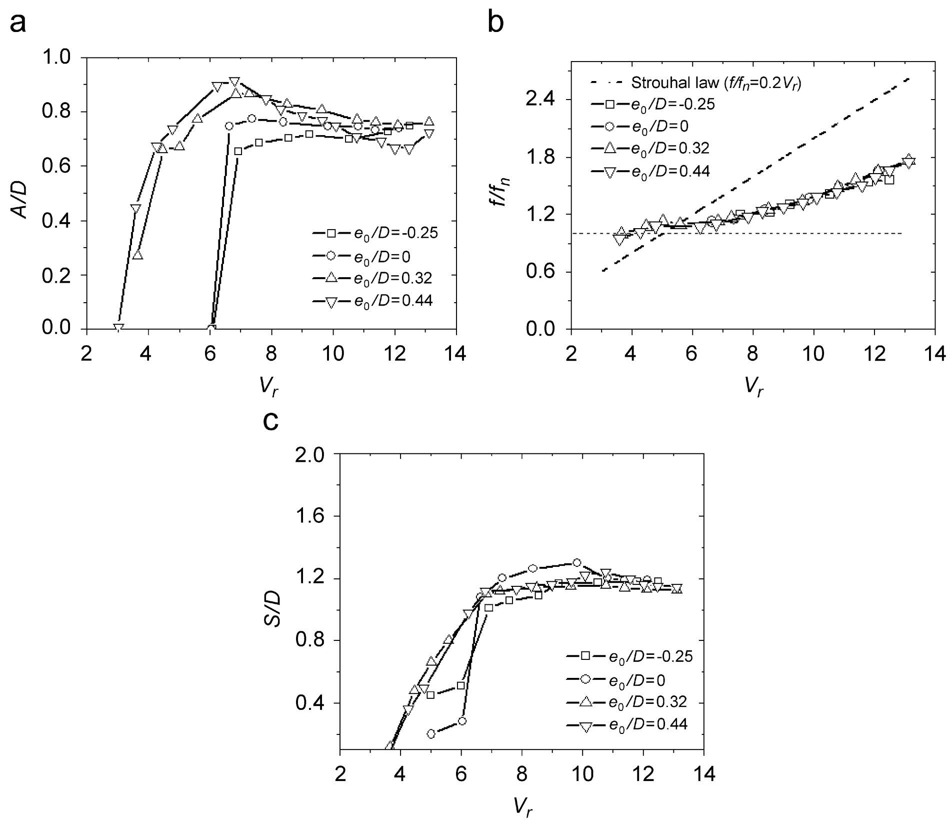

Fig. 6. Effects of initial gap-to-diameter ratio on pipe vibration and sand scour at equilibrium state: (a) A/D versus V_r; (b) f/f_n versus V_r; (c) S/D versus V_r ($D = 0.05$m, $m^* = 1.35$, $K_s = 0.127$, $d_{50} = 0.38$ mm, $D_r = 0.66$).

influenced by the initial gap-to-diameter ratio. The maximum amplitude of pipe vibration (A_{max}/D) increases with increasing the initial gap-to-diameter ratio. Nevertheless, as illustrated in Fig. 6(b), the values of the frequency ratio (f/f_n) for four initial gap-to-diameter ratios (i.e. $e_0/D = -0.25$, 0, 0.32, 0.44) collapse nearly along the same curve indicating that the influence of initial gap ratio upon the vibration frequency at equilibrium states was weak.

A comparison is made between the vibrations of the pipe laid above an erodible sand bed and those above a rigid boundary for the case with $e_0/D = 0.31$ under the condition of same mass ratio ($m^* = 3.87$) and stability parameter ($K_s = 0.0638$), as shown in Fig. 7. It can be seen from Fig. 7(a) that the maximum amplitude of the pipe vibration near the scoured sand is obviously larger than that near the rigid boundaries under the same test conditions. Besides the vibration amplitude, the vibration frequency may also be influenced by the sand scouring. Experimental results show that the vibration frequency of the pipe laid above a rigid bed is slightly higher than that of the pipe close to the scoured sands at the same V_r number (see Fig. 7(b)). The equilibrium scour depth increases with increasing V_r number (see Fig. 7(c)).

3.3. Comparison with previous work

To better understand the dynamic responses of the elastically mounted pipe in the vicinity of an erodible sand bed, a comparison is made with the previous work on the VIVs under various boundary conditions (see Fig. 8). Note that in the experiments conducted by Govardhan and Williamson (2000), the test pipe was in the wall-free conditions (i.e. $e_0/D \gg 1$), $m^* = 10.3$, $K_s = 0.0110$; in the experiments by Fredsoe et al. (1985), the boundary is rigid, $e_0/D = 0.7$, $m^* = 2.0$; in present experiments, the pipe is located near an erodible sand bed with $e_0/D = 0.75$, $m^* = 3.87$, $K_s = 0.0682$ (see Fig. 8). Unlike the VIV of a structure in air (typically $m^* = O(100)$), the case of an oscillating pipeline in water is associated with relatively small mass ratios, i.e. $m^* = O(10)$.

The experiments conducted by Govardhan and Williamson (2000) showed that the amplitude response of the pipeline under wall-free conditions includes three principal branches, namely the initial, upper and lower branches for the low stability parameter (K_s). Nevertheless, the aforementioned three branches do not exist when the pipeline is in close proximity to the rigid boundary (Fredsoe et al., 1985) or to the scoured seabed in the present tests, as shown in Fig. 8(a). The maximum vibration amplitude is closer to that of Govardhan and Williamson (2000) than that of Fredsoe et al. (1985), which might be due to their difference in mass-damping parameters. It is indicated in Fig. 8(b) that the trends of the frequency ratio (f/f_n) versus the reduced velocity (V_r) in the present experiments agree well with those by Govardhan and Williamson (2000); however, the lower

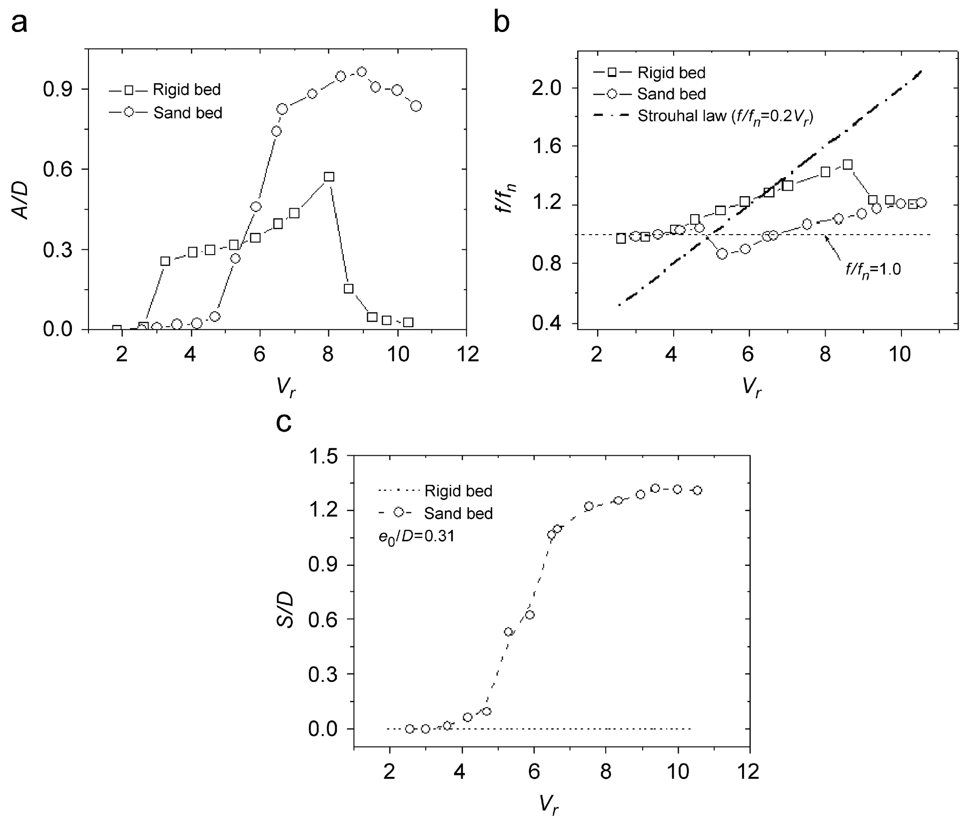

Fig. 7. Comparison of pipe vibrations near an erodible soil with those near a rigid boundary: (a) A/D versus V_r; (b) f/f_n versus V_r; (c) S/D versus V_r ($e_0/D = 0.31$, $D = 0.032\,m$, $m^* = 3.87$, $K_s = 0.0638$, $d_{50} = 0.38\,mm$, $D_r = 0.66$).

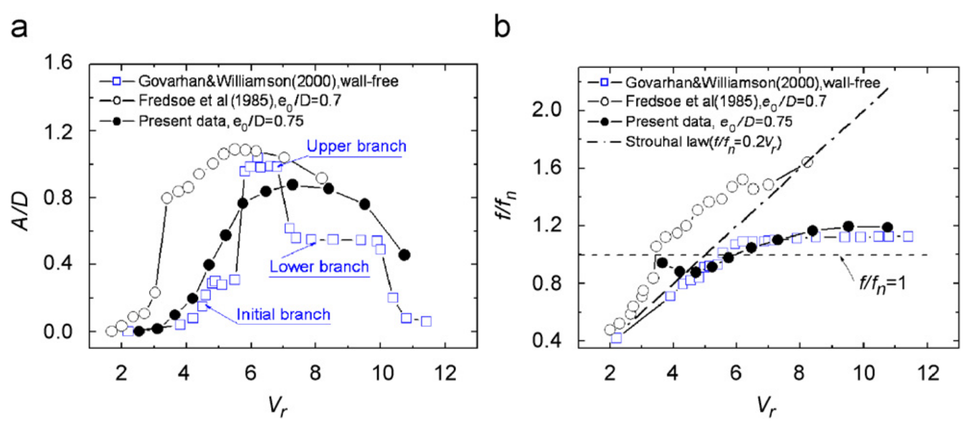

Fig. 8. The comparison of the pipe vibrations for pipes under various boundary conditions: (a) A/D versus V_r; (b) f/f_n versus V_r (Govardhan and Williamson (2000): wall-free, $m^* = 10.3$, $K_s = 0.0110$; Fredsoe et al. (1985): rigid bed, $e_0/D = 0.7$, $m^* = 2$; present data: erodible sand bed, $e_0/D = 0.75$, $m^* = 3.87$, $K_s = 0.0682$, $d_{50} = 0.38\,mm$, $D_r = 0.66$).

mass ratio may lead to an increase of the vibration frequency (see the data from Fredsoe et al. (1985) in Fig. 8(b)).

Maximum vibration amplitude (A_{max}/D) versus stability parameter (K_s) for various boundary conditions is plotted in Fig. 9. The solid line in the figure is a curve fit to the experimental data on VIVs of the elastically mounted cylinder under wall-free conditions by a large number of investigators, which was updated by Skop and Balasubramanians (1997) (also see Govardhan and Williamson, 2000). It is indicated in the figure that the present data on VIVs of the pipe near erodible sand bed are close to the curve fit under wall-free conditions; nevertheless, for the same stability parameter (e.g., $K_s = 0.127$), the maximum amplitudes for the present VIV coupled with local scour at equilibrium states (A_{max}/D) increase when increasing the initial gap-to-diameter ratio (e_0/D) from -0.25 to 0.44. The values of A_{max}/D near the rigid

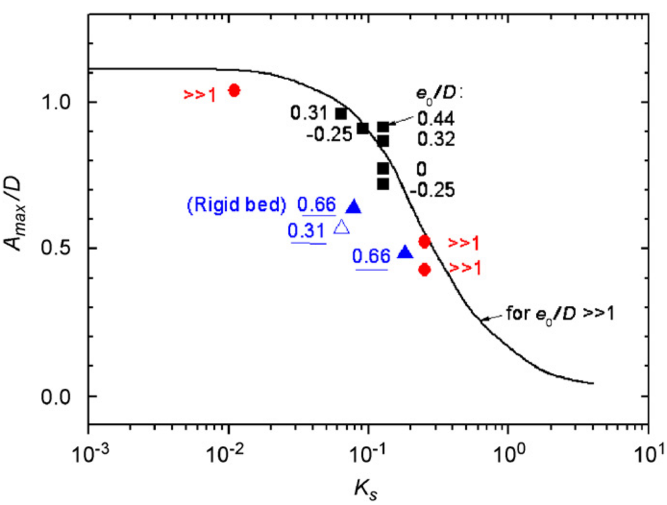

Fig. 9. Maximum vibration amplitude (A_{max}/D) versus stability parameter (as K_s). (●) Govardhan and Williamson (2000): wall-free conditions; (▲) Yang et al.(2006): rigid bed; (□) present data: rigid bed; (■) present data, erodible sand bed; (—) Skop and Balasubramanians (1997).

boundary are obviously smaller than those near the scoured sand bed and under wall-free conditions, for the same stability parameters and initial gap-to-diameter ratios (e.g., $e_0/D = 0.31$, $K_s = 0.127$, in Fig. 9). Note that the very close proximity of the pipe to the rigid boundary (e.g. $e_0/D < 0.3$) may induce remarkable increase of vibration amplitudes due to the periodical collision between the test pipe and the rigid boundary, as observed by Yang et al. (2006).

4. Concluding remarks

Unlike most previous studies focusing on the vortex-induced vibration of a cylinder either under the wall-free conditions or in the proximity to a rigid plane boundary, this paper investigates experimentally the vortex-induced vibration of a pipeline close to an erodible sandy seabed. Experimental observation shows that vortex-induced vibrations of a pipe in the currents are significantly influenced by the sand scour beneath the pipe. Pipe vibrations and the corresponding local scour are usually two coupled physical processes leading to an equilibrium state.

The critical V_r number for the initiation of pipe vibration gets larger with decreasing initial gap-to-diameter ratios (e_0/D) within the examined range of e_0/D ($-0.25 < e_0/D < 0.75$). For the pipeline with an initial small embedment in the sand, the pipe vibration is initiated only when the scour depth reach a certain value.

A comparison of the pipe vibrations near an erodible soil with those near a rigid boundary and under wall-free conditions is made, which indicates that the maximum 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.

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