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Dimensional Analysis and Experimental Apparatus on Interaction between Ocean Current-Pipeline and Seabed

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Abstract: Vortex-induced vibrations of a submarine pipeline and the concomitant scour around the pipeline with close proximity to an erodible seabed are a complex dynamic interaction between current, pipeline and seabed. In this paper, the method of dimensional analysis is used to analyze the interaction between ocean current,pipeline and seabed,and the similarity laws that should be followed in the small-scale laboratory experiments are established. An experimental apparatus for simulating the interaction between current,pipeline and seabed is thereby designed and constructed. Primary experimental results indicate that the apparatus is capable of modeling the vortex-induced vibrations of pipeline and the sand scour around the pipeline in typical ocean environments.

Key words: ocean currents; seabed; submarine pipeline; dimensional analysis; experimental apparatus; dynamic interaction

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1 Introduction

Submarine pipeline is a useful tool for transport of oil and gas during the course of oil and gas exploitation in the oceans. So far, the length of the submarine pipeline has been more than one hundred thousand kilometers in the world, and it is extending at the speed of several thousand kilometers every year.It is obvious that submarine pipeline has become an important part among the facilities of mining oil and gas in the ocean.However,when submarine pipelines are placed on the sandy seabed, local scour around the pipeline may occur under ocean current action.Sometimes,suspended span of the pipeline induced by local scour may form[1,2,3].Furthermore,suspended spans of pipeline may also exist because of uneven seabed or pipeline crossing. Under some condition vortex-induced vibration of pipe span may take place[4,13,14]. The status of outer force acting on the pipe will change because of vortex-induced vibration, which results in highly inner stress within the pipeline. Therefore, it is very important that analyzing the mechanism of local scour properly and predicting the behavior of vortex-induced vibration of the pipeline precisely.

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The interaction between current, submarine pipeline and seabed is a fluid- structure- soil coupling problem.Physical modeling is one of the most efficient methods for solving such problem[5-14]. In order to properly simulate the local scour around pipeline and vortex- induced vibration of pipeline in the laboratory,it is indispensable to develop a reliable experimental apparatus. In this paper, the dimensional analysis is employed for deriving the similarity laws in the coupling problem.Based on the similarity laws,a novel experimental facility was designed and constructed.Furthermore,some experiments on vortex - induced vibrations of pipeline and the local scour was simulated and analyzed.

2 Theoretical analysis

2.1 Dimensional analysis

The interaction between current,submarine pipeline and seabed mainly depends on the following quantities: the pipe diameter D, the pipe's mass of unit length M, the natural frequency of pipe span f_n, the surface relative roughness of the pipe κ, the gap between the pipe and the seabed e_0, the structural damping ratio of pipe span ζ, fluid density ρ, fluid dynamic viscosity coefficient μ, the undisturbed flow velocity U, the time t, the acceleration of gravity g, the sand grain density ρ_s, the mean grain diameter d_{50} ,the porosity of sandy soil n, and the non- uniform coefficient of sand grain Cu. The critical condition for the occurrence of pipeline spanning induced by local scour can be expressed as

$$h(\rho, U, \mu, D, e_0, \kappa, \rho_s, d_{50}, Cu, n, g, \cdots\cdots)=0 \quad (1)$$

Choosing ρ,D,U as fundamental quantities and employing π theorem,the Eq.1 can be rewritten as

$$h\left(\frac{\rho UD}{\mu}, \frac{\rho_s}{\rho}, \frac{d_{50}}{D}, \kappa, \frac{e_0}{D}, \frac{u_*}{\sqrt{(s-1)gd_{50}}}, n, Cu, \cdots\cdots\right)=0 \quad (2)$$

where s is the ratio of sand grain density and water density, $u_*=f(U)$ is the bed shear velocity.

The vibration frequency f, the vibration amplitude of pipeline A, the scour depth S, may be expressed as:

$$f=H_1(t, \rho, U, \mu, D, e_0, M, f_n, \kappa, \zeta, \rho_s, d_{50}, n, Cu, g, \cdots\cdots) \quad (3a)$$

$$A=H_2(t, \rho, U, \mu, D, e_0, M, f_n, \kappa, \zeta, \rho_s, d_{50}, n, Cu, g, \cdots\cdots) \quad (3b)$$

$$S=H_3(t, \rho, U, \mu, D, e_0, M, f_n, \kappa, \zeta, \rho_s, d_{50}, n, Cu, g, \cdots\cdots) \quad (3c)$$

Similarly, the Eq.3 can be rewritten as:

$$\frac{f}{f_n}=H_1\left(\frac{tU}{D}, \frac{\rho UD}{\mu}, \frac{\rho_s}{\rho}, \frac{d_{50}}{D}, \kappa, \frac{U}{f_n D}, \frac{M}{\rho D^2}, \frac{e_0}{D}, \zeta, \frac{u_*}{\sqrt{(s-1)gd_{50}}}, n, Cu, \cdots\right) \quad (4a)$$

$$\frac{A}{D}=H_2\left(\frac{tU}{D}, \frac{\rho UD}{\mu}, \frac{\rho_s}{\rho}, \frac{d_{50}}{D}, \kappa, \frac{U}{f_n D}, \frac{M}{\rho D^2}, \frac{e_0}{D}, \zeta, \frac{u_*}{\sqrt{(s-1)gd_{50}}}, n, Cu, \cdots\right) \quad (4b)$$

$$\frac{S}{D}=H_3\left(\frac{tU}{D},\frac{\rho UD}{\mu},\frac{\rho_s}{\rho},\frac{d_{50}}{D},\kappa,\frac{U}{f_nD},\frac{M}{\rho D^2},\frac{e_0}{D},\zeta,\frac{u_*}{\sqrt{(s-1)gd_{50}}},n,Cu,\cdots\right) \quad (4c)$$

The physical meaning of the above dimensionless quantities can be explained as follows:

$\frac{\rho UD}{\mu}$ (Re number) is the ratio of fluid inertia force and viscosity force; $\frac{\rho_s}{\rho}$ is the ratio of sand grain density and fluid density; $\frac{d_{50}}{D}$ is the ratio of sand grain mean diameter and pipe diameter, $\frac{U}{f_nD}$ (Vr number) is the ratio of fluid inertia and elastic restoring force of the pipe, $\frac{M}{\rho D^2}$ is the ratio of pipe inertia and fluid inertia, $\frac{e_0}{D}$ is the ratio of the initial embedment to pipe diameter, $\frac{u_*}{\sqrt{(s-1)gd_{50}}}$ (Shields number θ) is the ratio of bed shear stress and sand grain's weight in the water, n is the ratio of void volume to the whole volume of soil, Cu indicates the non-uniformity of sandy soil.

2.2 Similarity analysis

The above dimensionless quantities in the small-scale laboratory experiments should be kept same with that in the prototype according to similarity theory so that the physical phenomenon in the prototype can be simulated correctly.

If water, natural sand and smooth pipe are used in model test, the value of ρ_s/ρ and κ will keep constant and the similarity of ρ_s/ρ and κ can also be achieved. In general, Re is about $O(10^4\sim10^5)$ in the prototype and $O(10^3)$ in model test. Research shows that flow pattern around the pipeline changes little for Re around $1.0\times10^3<Re<2\times10^5$, so the flow property around the pipeline in the prototype is similar to that in small-scale laboratory experiments. Thus, it is reasonable to release the requirement of similarity for Re number.

As for $\frac{d_{50}}{D}$, it is not appropriate to change d_{50} in terms of length scale. For the mean grain diameter is smaller than a certain value, sand soil will become clay soil whose property is completely different from that of sand soil. So the similarity of $\frac{d_{50}}{D}$ cannot be achieved. The influence of disobeying $\frac{d_{50}}{D}$ similarity on the results will be studied in the future.

Only when the structural damping ratio (ζ) is less than 1.0, may the vibration of pipeline occur. The damping ratio mainly influences the maximum amplitude of vibration. When other parameters are constant, the maximum amplitude of vibration increases with damping ratio (ζ) decreases. The natural frequency of a spanned pipeline (mainly first order) is in the range of low frequency and the length of pipe span considered is more than fifteen meters [15]. Thus, as can be seen from the above, the structural damping ratio is small. Therefore, the similarity can be achieved so long as the value of structural damping ratio is kept low (e.g. less than 0.5).

Some previous researches have indicated that the Shields parameter influences scour weakly for the live-bed case ($\theta > \theta_c$)[16], in which θ_c is critical Shields parameter. In such cases, the similarity of Shields number is not important. Scour is influenced pronouncedly by Shields parameter for the clear-water case.The similarity of θ can not be achieved because of the natural sand used in model test.The experimental results for the clear-water case should be corrected when they are extrapolated to real-life situations.

Besides the above dimensionless quantities,the similarity of other quantities can be achieved in model test.To sum up,the dimensionless quantities whose similarities can be achieved are listed as

$$\frac{tU}{D}, \frac{\rho_s}{\rho}, \kappa, \frac{U}{f_n D}, \frac{M}{\rho D^2}, \frac{e_0}{D}, \zeta, n, Cu$$

3 Experimental apparatus

3.1 Fundamental characteristics of apparatus

The experimental apparatus comprises supporting system,displacement limiting system and pipe system (see Fig.1). Combined with a flume, the apparatus can be used for simulating the following phenomena: (1)local scour around the pipeline: observation of the local scour around the pipeline for studying the mechanism of scour can be performed in the laboratory; (2)vortex-induced in-line vibrations of a spanned pipeline above a rigid seabed; (3)vortex-induced transverse vibrations of a spanned pipeline above a rigid seabed; (4)vortex-induced vibrations of a spanned pipeline with two-degree freedoms above a rigid seabed;(5)the interaction between local scour around the pipeline and vortex-induced vibrations of spanned pipeline.

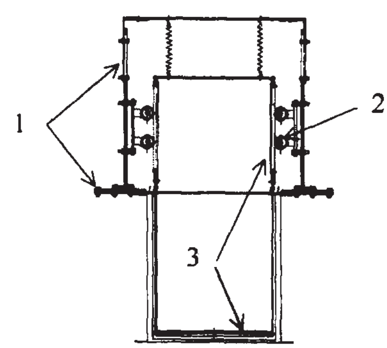


Fig.1 Experimental apparatus
(1- supporting system;
2- lateral displacement limiting system;
3- pipe system)

In addition, the apparatus can decompose the motion of two directions when the swaying angles of vertical rocker and that of horizontal springs are small (e.g.<5°). Accordingly, vibration displacement of two directions can be measured independently.It also has good flexibility and can be adapted to several flumes.The natural frequency of the apparatus,pipe diameter and the mass of the pipe can be changed in a wide range.

3.2 Determination of main parameters

3.2.1 Determination of the diameter of model pipe

The diameter of the model pipe is one of the most important parameters in the design of model pipe when the dimensions of a flume are given.Actually,it is not appropriate for the pipe diameter to be designed deviating from a certain range. Designing a model pipe with too large diameter could result in many problems: for example, if the length-to-diameter ratio is too small, there may exist obvious three-dimensional effects of sand scour; if the ratio of water depth to pipe diameter is too small, the choke effects may occur. On the contrary, if the pipe diameter is designed too small,the mass of the pipe should be also scaled down according to the similarity of mass ratio ($M/\rho D^2$).However,it is sometimes difficult to design the model pipe with too low mass and with high enough rigidity concurrently.Moreover,it would be difficult to observe the vortex shedding around the pipe if pipe diameter is very small. In the experiments, it is feasible for the pipe diameter to be around 0.03~0.06m. That is, the geometric scale is around 10~30[17~19].

3.2.2 Determination of the mass of model pipe

The mass of the model pipe is determined according to mass ratio ($M/\rho D^2$) and the length of the pipe. In general, the mass ratio in the prototype is around 0.85~3 [15~17],so the mass of the model pipe per meter (M)should be around 0.765~10.8kg/m.

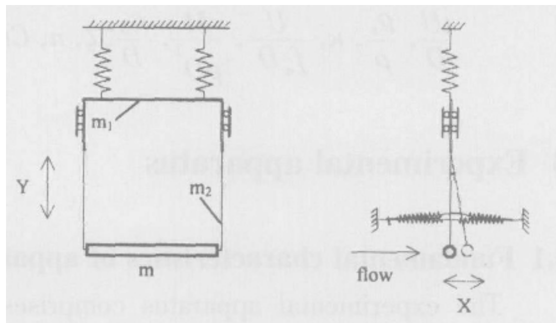


Fig.2 Schematic diagram of experimental apparatus

3.3 Determination of the spring constant

According to Hamilton's principle, applying the energy equation along vertical direction, we have (see Fig.2)

$$\int_{t_1}^{t_2}\delta\left(\left(\frac{1}{2}m_1v_1^2+\frac{1}{2}m_2v_2^2+\frac{1}{2}mv^2\right)-\left(m_1gy+m_2gy+mgy+\frac{1}{2}k_vy^2\right)\right)=0 \tag{5}$$

in which t_1, t_2 are time; m_1, m_2, m are the mass of pipe support, rockers and the pipe respectively; v_1, v_2, v_3 are the velocity of pipe support (m_1), rockers (m_2) and the pipe (m) respectively; y is the vertical displacement of the apparatus; k_v is the constant of vertical spring; g is the gravitational acceleration and δ is the variation operator.Arranging and simplifying Eq.5, the differential equation of displacement in y direction can be written as

$$(m_1+m_2+m)\frac{d^2y}{dt^2}+k_vy=m_1g+m_2g+mg \tag{6}$$

From Eq.6, the angle frequency of the pipe in vertical direction will be

$$\omega_v=\sqrt{\frac{k_v}{m_1+m_2+m}} \tag{7}$$

Thus, the spring constant in vertical direction is

$$k_v=(m_1+m_2+m)4\pi^2f_v^2 \tag{8}$$

Similarly, the spring constant in horizontal direction will be

$$k_h = \frac{\left(m + \frac{m_2}{3}\right) 4\pi^2 f_h^2 - \frac{m_2 g}{2l} - \frac{mg}{l}}{b^2/l^2} \tag{9}$$

in which f_v, f_h are natural frequency of the pipe in vertical direction and horizontal direction respectively.b is the distance between the horizontal spring's hanging point on the rocker and the anchor point of the rocker, l is the length of the rocker.

4 Primary experimental results

4.1 The damping property of the apparatus in still fluid

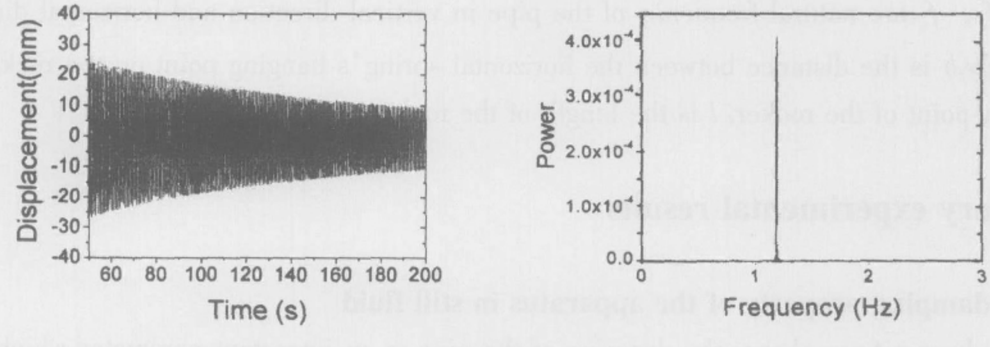
As is known from above, the damping of the pipe is an important parameter which influencing the response of the vortex- induced vibrations of the pipe. The damping property of the apparatus is measured in the still air and water.

Tab.1 Test conditions for damping property of the apparatus

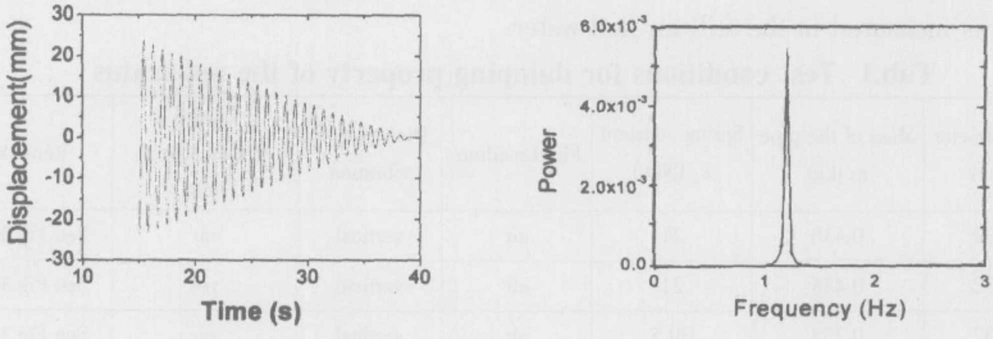
Pipe diameter D (m)	Mass of the pipe m (kg)	Spring constant k_v (N/m)	Fluid medium	Direction of vibration	Lateral displacement limit	Remark
0.032	0.438	21	air	vertical	no	See Fig.3(a)
0.032	0.438	21	air	vertical	yes	See Fig.3(b)
0.032	0.753	39.5	air	vertical	no	See Fig.3(c)
0.032	0.753	39.5	air	vertical	yes	See Fig.3(d)
0.032	0.753	39.5	water	vertical	no	See Fig.3(e)
0.032	0.753	21	water	vertical	no	See Fig.3(f)
0.032	0.753	21	water	vertical	yes	See Fig.3(g)

Fig.3(b) shows the response of the pipe with lateral displacement limit in the air. The mean damping coefficient in Fig.3(b) is 0.0071.Fig.3(a) shows the response of the pipe without lateral displacement limit in the air.The mean damping coefficient in Fig.3(a) is 0.00083. The only difference between the experimental conditions in Figs.3(a) and 3(b) is the lateral displacement limit. The case is the same between the experimental conditions in Figs.3(c) and 3(d). Figs.3(a), 3(b), 3(c) and 3(d) indicate that the damping of the pipe with lateral displacement limit is one order larger than that of the pipe without lateral displacement limit. It is also can be seen from Figs.3(a)~3(d) that lateral displacement limit has little influence on natural frequency of the pipe.

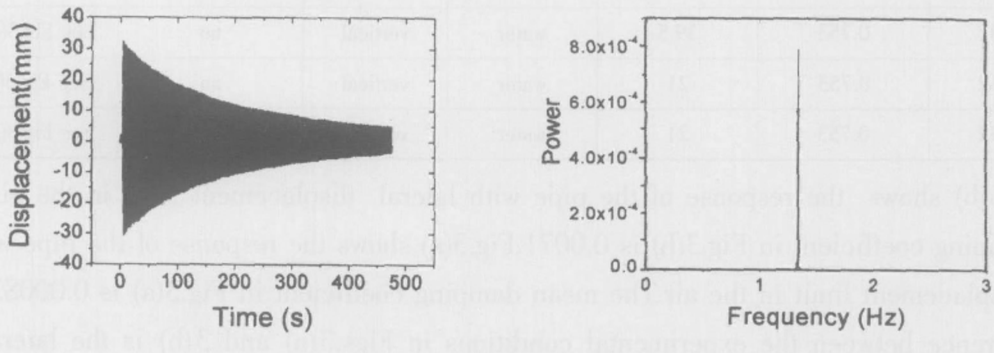
The fluid medium is air in Fig.3(c) and water in Fig.3(e). The only difference is the fluid medium between the experimental conditions in Figs.3(c) and 3(e). The mean damping coefficient is 0.0013 in Fig.3(c) and 0.0351 in Fig.3(e). Namely, the damping of the pipe in the water is one order larger than that in the air. Because the added mass in the water is larger than that in the air,the natural frequency of the pipe in the water will be smaller than that in the air under the same condition.The above conclusion is testified by the frequency spectrum in Figs.3(c) and 3(e).



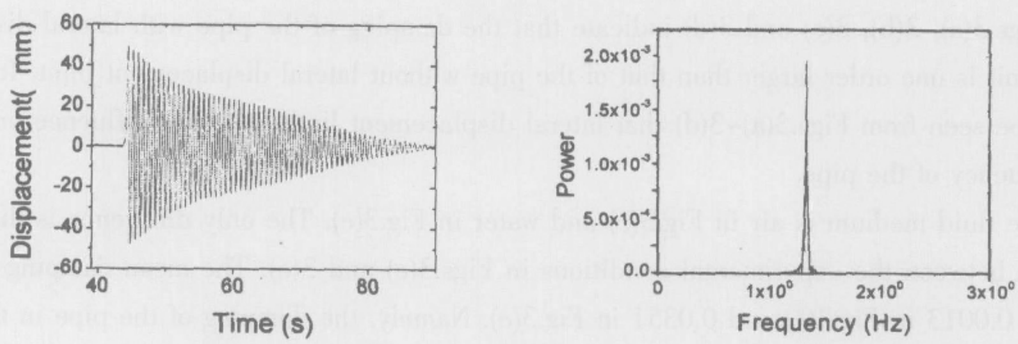
(a) case 1



(b) case 2



(c) case 3



(d) case 4

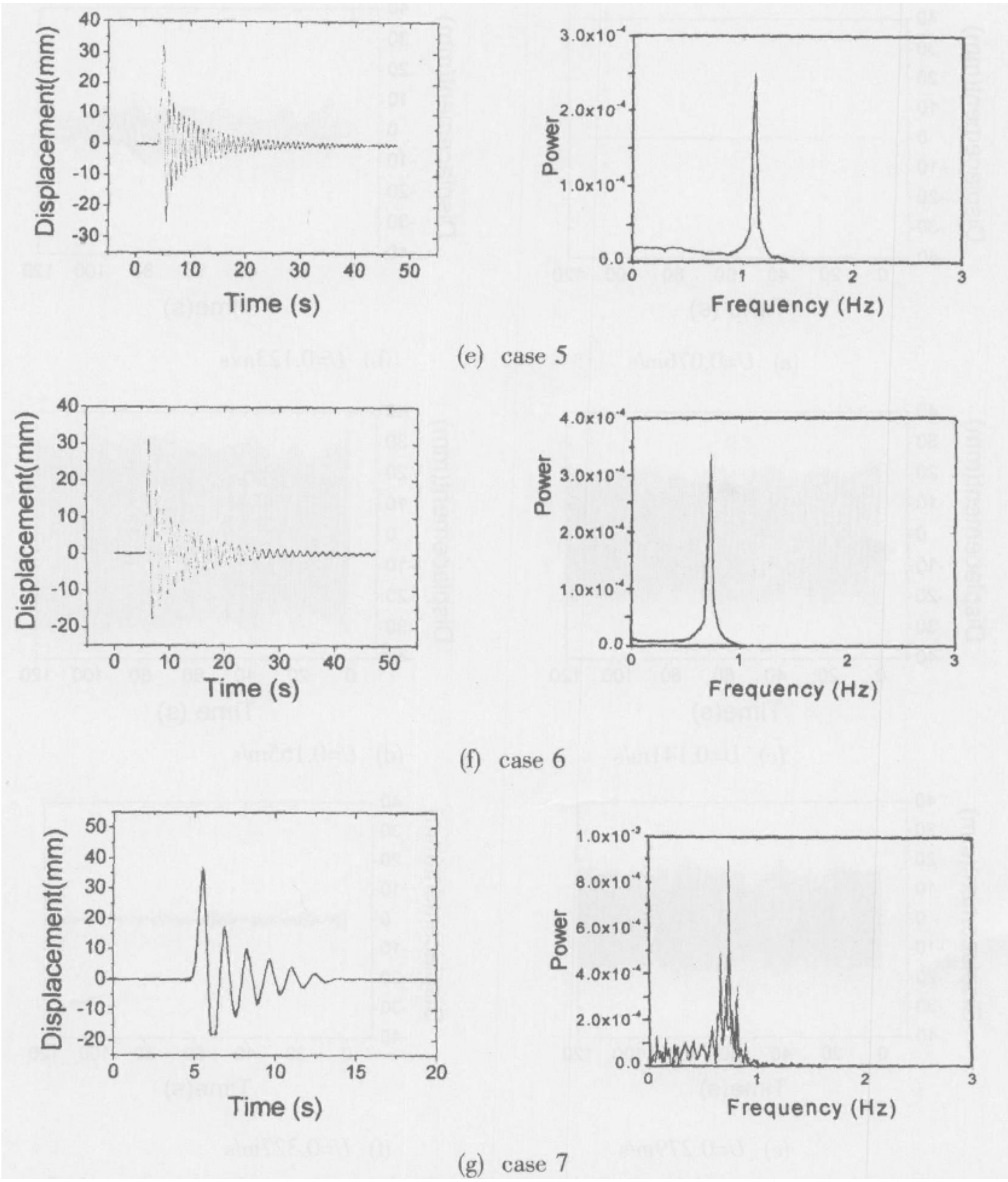
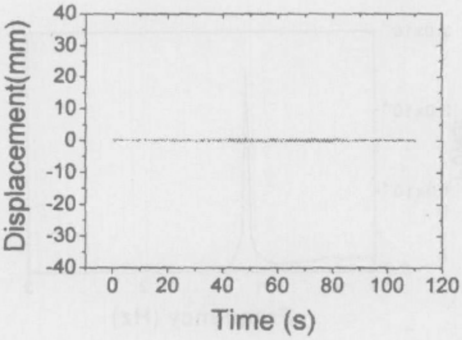


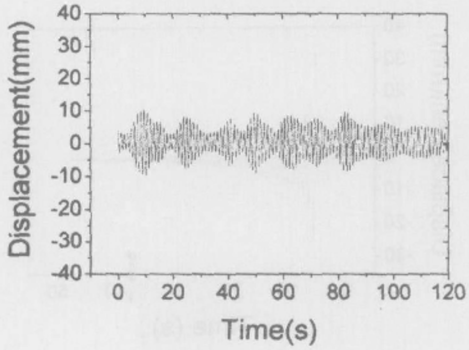
Fig.3 Typical time traces of the displacement and corresponding natural frequency of the pipe in the free- decay test (left: pipe displacement history; right: the corresponding power spectrum)

4.2 Vortex- induced vibrations of pipe

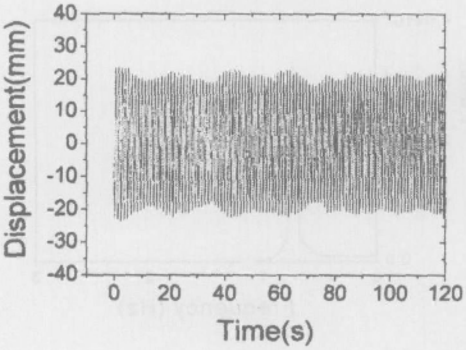
The tests on cross- flow vortex- induced vibration of the pipe near a rigid bed were conducted in a 0.5m wide water flume.The length of the model pipe with a diameter of 0.032m is 0.47m.The pipe is hydraulically smooth.The mass of the pipe is 1.4605kg.The natural frequency of the pipe in still water is 0.91Hz.The ratio of structural damping in water is 0.0198. The distance between the pipe and the rigid bed is 0.064m.The mean flow velocity is measured using a type of propeller current- meter.The laser- optical displacement sensor is used to measure the displacement of the pipe. The results are shown in Figs.4~6.



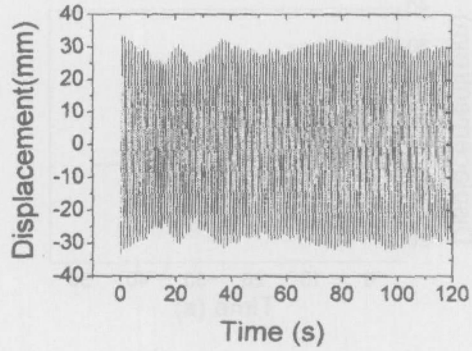
(a) U=0.076m/s



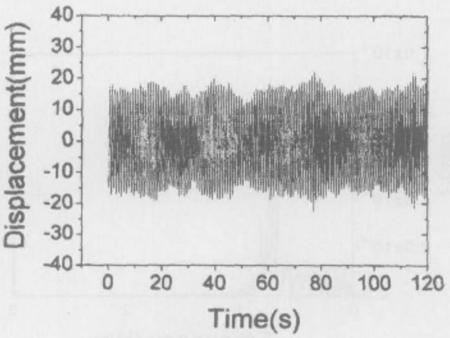
(b) U=0.123m/s



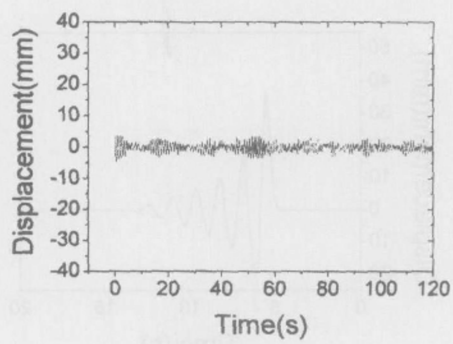
(c) U=0.141m/s



(d) U=0.165m/s



(e) U=0.279m/s



(f) U=0.327m/s

Fig.4 Typical time traces of the displacement of the pipe at various velocities of steady flow

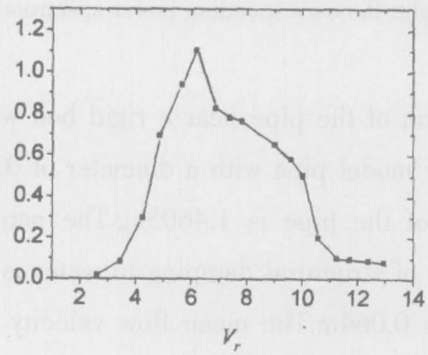


Fig.5 Variation of vibration amplitudes of pipe with reduced velocity

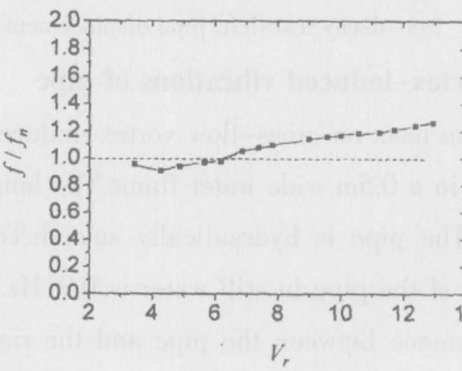


Fig.6 Variation of vibration frequencies of pipe with reduced velocity

It can be seen from Figs.4~5 that with the flow velocity is increased,the vibrating amplitude of the pipe increases at initial stage and decreases at final stage.When $M/(\rho D^2)$=3.04, ζ= 0.0198 and e_0/D=2, it can be seen from Fig.5 that the excitation range of cross- flow vibration in terms of V_r is about $2.5<V_r<11$ with maximum amplitude occurring at V_r=6.2.The maximum vibration amplitude is about 1.1D.Fig.6 shows that the vibration frequency is not equal to the natural frequency of the pipe in the lock- in range, but it increases slowly with V_r.

4.3 Local scour around the pipe

In this section, the experiments on local scour around the fixed pipe are conducted. The mean grain diameter d_{50} of the sand soil with n=0.41 is 0.4mm.The non- uniform coefficient of sand grain is 1.35.The smooth pipe with a diameter of D=32mm is used.The gap between the pipe and the seabed e_0 is 0. The mean flow velocity is 0.255m/s.

Fig.7 shows the scour depth varies with time.It is can be seen from Fig.7 that scour depth develops quickly at initial stage and change slowly after approximately 80 minutes. Fig.8 presents the scour profile at time t=120min.As shown in this figure, the position of maximum scour depth is not just beneath the center of the pipe,but located at about 0.5D distance horizontally from the center of the pipe.

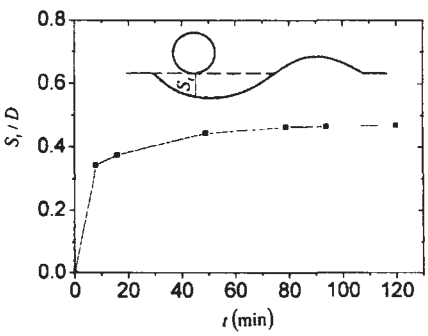


Fig.7 Time development of scour depth (u=0.255m/s)

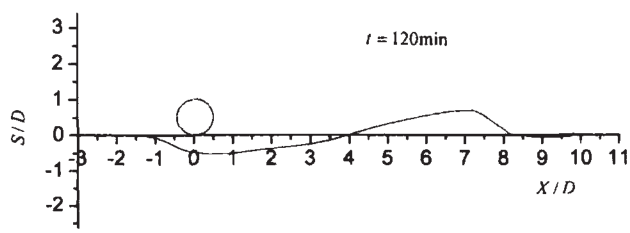


Fig.8 Scour profile at time t=120 min (u=0.255m/s)

5 Concluding remarks

The method of dimensional analysis is employed for analyzing the dynamic interaction between ocean currents,pipeline and seabed in the phenomena of vortex- induced vibrations of a submarine pipeline and the scour around the pipeline with close proximity to an erodible seabed.The similarity laws are established for physical modeling of the interaction between ocean currents, pipeline and seabed. Based on the similarity analysis, a novel experimental apparatus has been designed and constructed.The results of a series of primary tests show that the apparatus is capable of simulating scour around pipeline or/and the vortex- induced vibrations of pipeline in typical ocean environments.

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海流—管道—海床之间动力相互作用的量纲分析及实验模拟装置研制

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摘要：海底管道涡激振动和管道周围海床冲刷是海流—管道—海床之间复杂的动力耦合问题。文章应用量纲分析方法对海流、管道与海床之间的动力耦合作用进行了分析，确定了在实验模拟中应遵循的相似准则。在此基础上,研制了一套能模拟海流、海床与海底管道之间相互作用的实验模拟装置。初步实验结果表明文中研制的实验模拟装置能够模拟典型海洋环境下海底管道的涡激振动和管道周围海床冲刷等问题。

关键词：海流；海床；海底管道；量纲分析；实验装置；动力耦合
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