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Occurrence of Spanning of a Submarine Pipeline with Initial Embedment

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ABSTRACT

For better understanding the mechanism of the occurrence of pipeline span for a pipeline with initial embedment, physical and numerical methods are adopted in this study. Experimental observations show that there often exist three characteristic phases in the process of the partially embedded pipeline being suspended: (a) local scour around pipe; (b) onset of soil erosion beneath pipe; and (c) complete suspension of pipe. The effects of local scour on the onset of soil erosion beneath the pipe are much less than those of soil seepage failure induced by the pressure drop. Based on the above observations and analyses, the mechanism of the occurrence of pipeline spanning is analyzed numerically in view of soil seepage failure. In the numerical analyses, the current-induced pressure along the soil surface in the vicinity of the pipe (i.e. the pressure drop) is firstly obtained by solving the N-S equations, thereafter the seepage flow in the soil is calculated with the obtained pressure drop as the boundary conditions along the soil surface. Numerical results indicate that the seepage failure (or piping) may occur at the exit of the seepage path when the pressure gradient gets larger than the critical value. The numerical treatment provides a practical tool for evaluating the potentials for the occurrence of pipe span due to the soil seepage failure.

KEY WORDS: Submarine Pipeline; Pipe span; Currents; Sands; Seepage failure

INTRODUCTION

When a submarine pipeline is laid upon seafloor, there always exists some embedment into the soil. In severe ocean environments, the soil beneath the pipeline may be scoured, and the pipeline will thereby be suspended above the seafloor. The occurrence of pipeline span is proven to bring much potential for vortex-induced vibrations of pipelines. Therefore, to efficiently avoid the occurrence of pipeline span is highly desired in the pipeline engineering.

As illustrated in Fig.1, for an initially partially embedded pipeline under the influence of ocean currents, vortices may be induced in both upstream side and downstream side of the pipeline, and the resulting pressure drop would further induce seepage flow within the seabed. The soil scouring beneath the pipe is a coupling process between vortices around the pipeline and seepage within the soil.

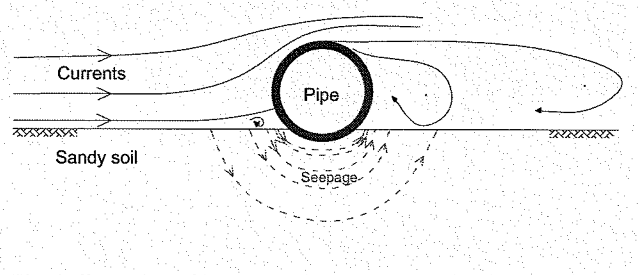

Fig. 1 Illustration of currents induced seepage flow beneath a partially embedded pipe (not in scale)

The mechanism for the occurrence of the spanning of a submarine pipeline with some initial embedment into the seafloor has attracted much attention from numerous researchers. Mao (1986) has described the vortexes formed at front and at the rear of the pipe, and discussed the correlations of seepage flow with the onset of scour beneath the pipe. Based on the further experiments, Chiew (1990) concluded that piping is the dominant cause of the initiation of scour beneath the pipeline in currents. Sumer and Fredsoe (1991) conducted experiments to determine the critical condition in the case of wave loading, and expressed it in terms of Keulegan-Carpenter number (*KC*) and the initial embedment-to-diameter ratio (e_0/D). Sumer et al. (2001) studied the onset of scour below pipelines and the self-burial in both waves and currents. Their experimental results indicated that the excessive seepage flow and the resulting piping are the major factor for the onset of scour below the pipeline. The criterion for onset of scour was given in Sumer and Fredsoe (2002). Besides the aforementioned experiments, numerical method was recently also adopted for simulation of this physical phenomenon, such as the work by Liang and Cheng (2005), Yang et al. (2005) etc.

In this paper, for a better understanding of the mechanism of scour beneath a submarine pipeline, the whole process of the occurrence of pipeline spanning was simulated physically in a flume. Furthermore, the seepage failure is studied numerically to reveal the mechanism of onset of scour beneath the pipeline in ocean currents.

PHYSICAL MODELLING

Experimental Setup

The tests were conducted in a flume (0.5m wide, 0.6m deep and 19m long), which is capable of generating steady currents with velocity up to approximately 0.6m/s. A type of fine silica sand was adopted for simulating a sandy seabed, whose physical characteristics are listed in Table 1. In the table, d_{50} is the mean particle diameter of sands; C_u is the uniformity coefficient of sands; G_s is the specific gravity of soil grains; e is the void ratio of sands; γ' is the buoyant unit weight of sands; D_r is the relative density of sands. A model pipe was attached to the frame of the flume with two connecting screw poles, which can be easily adjusted to obtain the desired initial pipe embedment (see Fig.2).

For simulating the whole process of the occurrence of pipe spanning, the flow speed was increased continuously. In the meanwhile, the local scour around the pipe was recorded with a digital video camera.

Table 1. The main physical characteristics of test sand

d_{50} (mm)	C_u	G_s	e	γ' (kN/m^3)	D_r
0.12	1.41	2.66	0.86	8.7	0.6

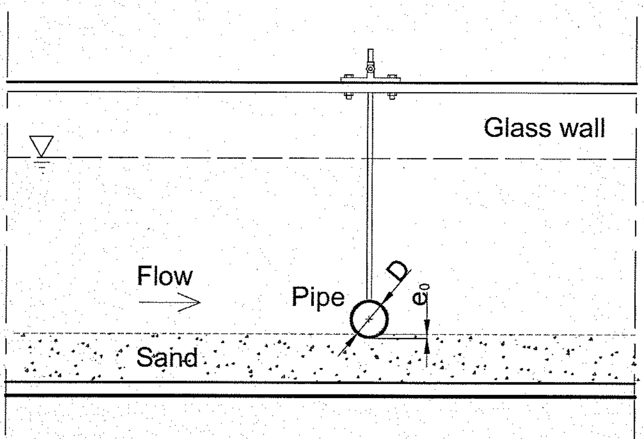

Fig.2 Experimental setup

Characteristic Phases

In the process of the partially embedded pipeline being suspended (i.e. the occurrence of pipe span) under the influence of currents, there usually exist three characteristic phases as follows (see Fig.3):

(1) Local scour around pipe:
Experimental observations have indicated that three types of vortices are formed around the test pipe, which was also reported by Mao (1988). As illustrated in Fig.1, one of the vortices may be formed at the upstream of the pipe, the other two vortices formed downstream of the partially embedded pipe (e.g. D=50mm, e_0/D=-0.05 in our tests) at a certain flow velocity (e.g. U=0.13m/s). The vortices would thereby increase the shear stress upon the surface of the sandy bed. As shown in Fig. 3(a), local scour was induced at both upstream and downstream sides of the pipe when the critical Shields number for the onset of scour is reached.

(2) Onset of soil erosion beneath pipe:
The pressure drop was caused due to the presence of the pipe structure, which further induced the seepage flow within the sands beneath the pipe (see Fig.1). When the flow velocity got high enough (e.g. U=0.17m/s in our tests), the seepage failure (or piping) was observed taking place sporadically just beneath the partially embedded pipe at its downstream side, as shown in Fig.3(b).

(3) Complete suspension of pipe:
After the seepage failure occurred at several sporadic spots along the pipe, the perforation zones would spread rapidly and finally result in the complete suspension of the pipe in the two-dimensional modeling (see Fig.3(c)).

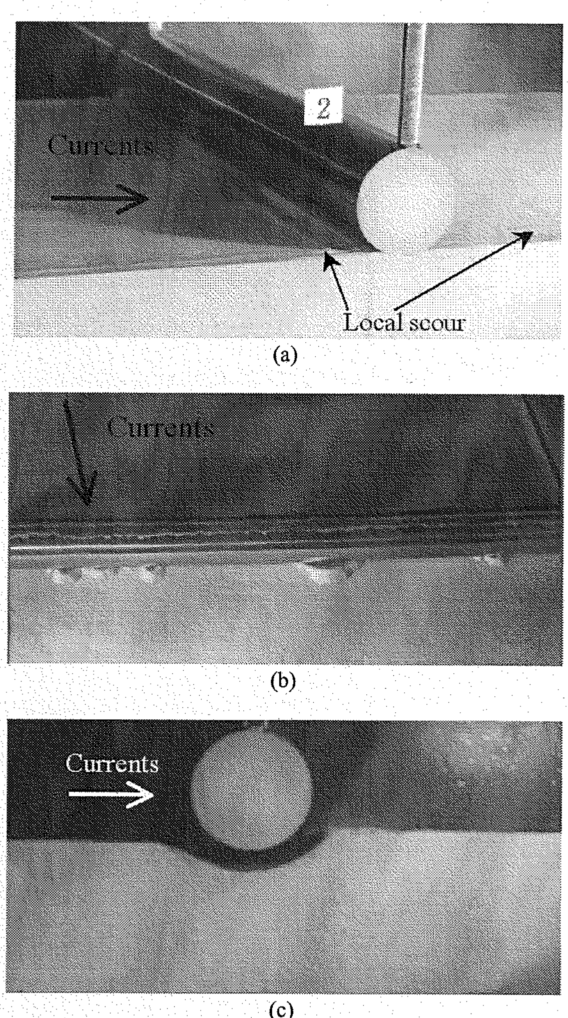

Fig.3 Process of a partially embedded pipe being suspended in currents (D=50mm, e_0/D=-0.05):(a) Local scour around pipe (U=0.13m/s); (b) Onset of soil erosion beneath pipe (U=0.17m/s); (c) Complete suspension of pipe (U=0.17m/s)

The sequence of piping process has also been described in detail by Sumer et al.(2001).The existing experimental observations have shown that in the process of pipeline being suspended, the onset of soil erosion beneath the pipe is not the inevitable consequence of the local scour around the pipe, for the positions of the onset of soil erosion are just beneath the pipe at the downstream side (see Fig.3 (b)), which are different from those of the local scour around the pipe (see Fig. 3(a)). This indicates that although the local scour around the pipe due to the lee wake always emerges in the course of the pipe being suspended, its effect on the onset of soil erosion beneath the pipe is not significant. The pressure drop induced seepage failure beneath the pipe is the main cause for the onset of soil erosion beneath the pipe, which would eventually have the pipe being complete suspended.

TWO-DIMENSIONAL NUMERICAL SIMULATION

Based on the above experimental observations and analyses, it will be reasonable for assuming that the local scour around the pipe is ignored in the numerical modelling of onset of soil erosion beneath the pipe due to soil seepage failure. This would make the analysis conservative to some extent. In numerical simulations, the flow around the pipe and the seepage flow beneath the pipe could be modelled separately. Firstly, the flow around the pipe will be modelled numerically. The current-induced pressure along the soil surface in the vicinity of the pipe (i.e. the pressure drop) can be obtained. Secondly, seepage flow within the soil beneath the pipe will thereafter be modeled with the obtained pressure drop as the boundary conditions along the soil surface.

Governing Equations

The current induced seepage flow beneath a partially embedded pipeline is considered as a two-dimensional problem, as depicted in Fig.4.

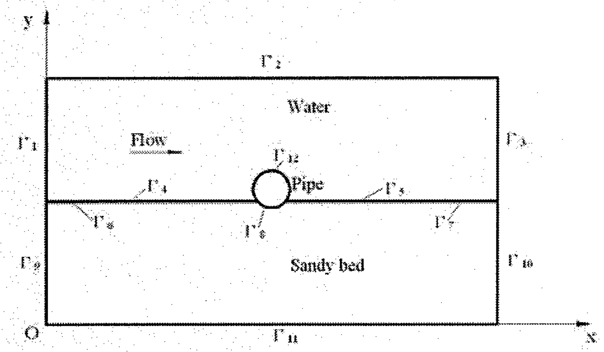

Fig.4 Definition of the boundaries of the computational zone

The Reynolds-averaged continuity and momentum equations of the incompressible fluid are as follows:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\nu\frac{\partial^2 u_i}{\partial x_j \partial x_j}-\frac{\partial}{\partial x_j}(\overline{u_i' u_j'}) \tag{2}$$

in which u_i is the mean velocity of fluid; u_i', u_j' are the pulse velocities of fluid; t is the time variable; ρ is the density of fluid; p is the pressure of fluid; ν is the kinematic viscosity of fluid; x_i (or x_j) is the variable of coordinate, whose subscripts i, j (=1,2) refer to the x and y direction respectively. According to the Boussinesq approximation of vortex viscosity, the unclosed term $-\overline{u_i' u_j'}$ in Eq.(2) can be expressed as:

$$-\overline{u_i' u_j'}=\nu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}k\delta_{ij} \tag{3}$$

in which $k(=\overline{u_i' u_i'}/2)$ is the turbulent kinetic energy; ν_t is the turbulent viscosity. The standard $k-\varepsilon$ turbulence model is adopted:

$$\frac{\partial k}{\partial t}+\frac{\partial}{\partial x_i}(u_i k)=\frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\varepsilon \tag{4}$$

$$\frac{\partial \varepsilon}{\partial t}+\frac{\partial}{\partial x_i}(u_i \varepsilon)=\frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{5}$$

where the turbulent viscosity is defined as $\nu_t=C_\mu k^2/\varepsilon$, in which C_μ is a constant, ε is the dissipation rate of turbulent energy; $G_k=-\overline{u_i' u_j'}\frac{\partial u_i}{\partial x_j}$; In the calculations, $C_{1\varepsilon}$=1.44, $C_{2\varepsilon}$=1.92, C_μ=0.09, σ_k=1.0, σ_ε=1.3.

Under the assumption that the sandy seabed is an incompressible homogeneous medium and that it is isotropic with respect to permeability, the continuity equation for the two-dimensional seepage flow through the soil can be described with Laplace's equation:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0 \tag{6}$$

in which h $(=p/\rho g)$ is the hydraulic head within soil, g is the gravitational acceleration.

Boundary Conditions and Input Data

The boundaries of the computational zone (from Γ_1 to Γ_{12}) are shown in Fig.4. The length of the computational zone is chosen as 15.0m, the height of water as 4.8m and soil depth as 6.0m. A prototype size pipe (D=0.6m) is chosen, and its initial embedment-to-diameter ratio e_0/D=0.05. The incoming flow velocity u_0=1.5 m/s (Re≈9.0×10^5). The soil parameters are same as listed in Table 1.

For modelling of the flow around the pipe, the following boundary conditions should be satisfied:

$u_1=u_0$, $u_2=0$, $(u_i' u_i')^{1/2}/(u_i u_i)^{1/2}=1.5\%$, $l=0.04$ m (at the inflow boundary Γ_1) (7a)

$\frac{\partial u_1}{\partial x}=0, \frac{\partial u_2}{\partial x}=0, \frac{\partial p}{\partial x}=0$ (at outflow boundary Γ_3) (7b)

$\frac{\partial u_1}{\partial y}=0,\ u_2=0, \frac{\partial p}{\partial y}=0$ (at top boundary Γ_3) (7c)

$u_1=0, u_2=0$ (at the surface of sand bed and pipe Γ_4, Γ_5, Γ_{12}) (7d)

where u_1, u_2 are flow velocities in the x and y directions respectively; l is the characteristic length of turbulence.

For modeling of the seepage flow within the sandy bed, the following boundary conditions should be satisfied:

$h=h_1(x)$ (at sand surface of the upstream side of the pipe Γ_6) (8a)

$h=h_2(x)$ (at sand surface of downstream side of the pipe Γ_7) (8b)

$\frac{\partial h}{\partial n}=0$ (at the interface of pipe and sand bed Γ_8) (8c)

$\frac{\partial h}{\partial x}=0$ (at the lateral side of sand bed Γ_9, Γ_{10}) (8d)

$\frac{\partial h}{\partial y}=0$ (at the bottom of sand bed Γ_{11}) (8e) where n denotes the normal direction of the pipe circumference.

Computational Method and Analysis of Numerical Results

The Navier-Stokes equation and the seepage equation are solved separately. The flow equations (1) and (2) are solved by finite volume method, and the SIMPLE algorithm is used to deal with the pressure-velocity coupling. The finite element method is adopted to solve the seepage flow equation (6) with quadratic triangle element. As aforementioned, the flow field around the pipe is calculated by solving the N-S equation firstly. The pressure distribution along the sand bed, i.e. the pressure drop, is thereby obtained, which will be used for the boundary pressure conditions at soil surface for solving the seepage flow beneath the pipe.

The numerical results of pressure distribution around the pipe in the currents are given in Fig.5. As shown in the figure, there exist a high-pressure zone in front of the pipe and a low-pressure zone at the rear of the pipe. The pressure along the soil surface in the vicinity of the pipe is plotted in Fig.6. The figure indicates that an obvious pressure drop can be induced in the steady flow with high velocity, which would further induce seepage through the soil mass beneath the pipe.

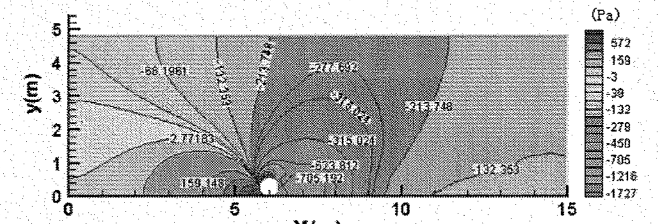

Fig.5 Contour of the pressure around the pipe in a steady current (e_0/D= -0.05, D=0.6m, U=1.5m/s)

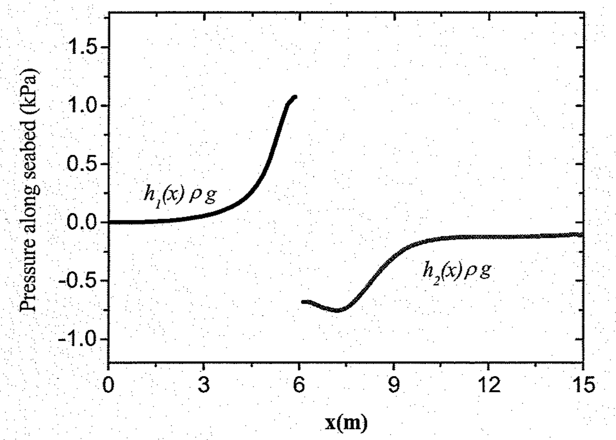

Fig.6 Current-induced pressure along the soil surface in the vicinity of the pipe (pipe is located at x=6m; e_0/D= -0.05, D=0.6m, U=1.5m/s)

In many practical cases, the nature of the flow through soil is such that the velocity and pressure gradient vary throughout the soil medium. Flow of water through the soil mass results in seepage force being exerted on the soil itself. When the upward seepage occurs and the hydraulic gradient is equal to a critical value i_{cr}, soil piping or heaving originates in the soil mass (Terzaghi, 1948). The critical hydraulic gradient can be expressed as follows (see Das (1983)):

$$i_{cr} = \frac{G_s - 1}{1+e} \tag{9}$$

In this example, submitting G_s=2.66, e=0.86 into Eq.(9), we get i_{cr} = 0.89.

Fig. 7 gives the contour of pressure gradient within the sands. The local amplification of the contour just beneath the pipe is also plotted in Fig. 8. As indicated in the figures, at the noses of the pipe, the pressure gradients get larger than the critical value for the piping seepage failure of the sand. For the seepage flow at the upstream side of the pipe is downward, the seepage there would increase the stability of soil particle. However, at the exit of the seepage path (i.e. the downstream side of the pipe), the upward seepage force would make the soil particles beneath the pipe lose stability. This will finally bring the occurrence of the spanning of the pipeline.

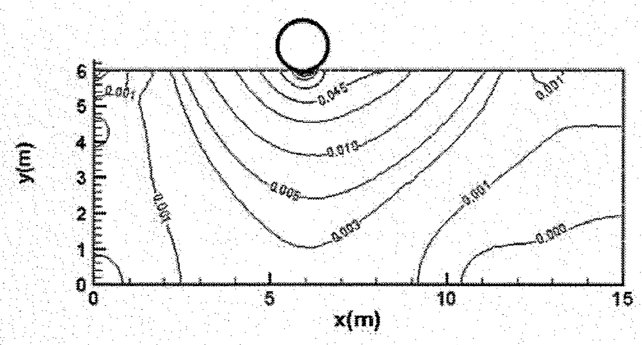

Fig.7 The contour of pressure gradient within the sandy bed (the coordinate of the center of the pipe is x=6m, y=6.27m)

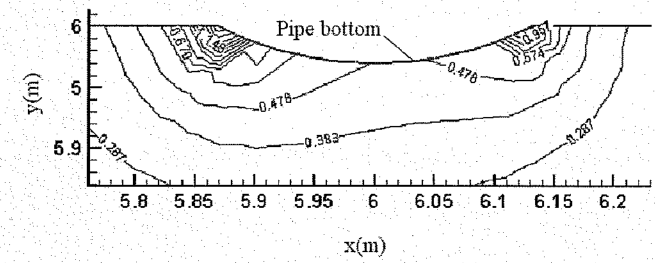

Fig. 8 The contour of pressure gradient in the sands beneath the pipe (local amplification)

CONCLUDING REMARKS

In order to have a better understanding of the mechanism of the occurrence of pipeline span for a pipeline with small initial embedment, physical and numerical methods are employed in this study. Experimental observations show that there often exist three characteristic phases in the process of the partially embedded pipeline being suspended: (1) local scour around pipe; (2) onset of soil erosion beneath pipe; and (3) complete suspension of pipe. Although the local scour around the pipe due to the lee wake always emerges in the course of the pipe being suspended, its effect on the onset of soil erosion beneath the pipe is much less compared with the pressure drop induced seepage failure of soil. Based on the above observations and analyses, the current induced seepage failure of soil beneath the pipe is analyzed numerically. In the numerical models, the flow around the pipe and the seepage flow in the sand are calculated separately. Numerical analysis indicates that the seepage failure (or piping) may occur at the exit of the seepage path when the pressure gradient gets larger than the critical value. The numerical treatment provides a practical tool for evaluating the possibility of the occurrence of pipe span due to the soil seepage failure.

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