# Numerical Investigation on the Onset of Tunnel Erosion Underneath a Submarine Pipeline in Currents

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A finite element model is proposed for coupling between the flow around a submarine pipeline and the seepage flow within the porous seabed underneath the pipeline, to investigate the onset of tunnel erosion underneath the pipeline with an initial embedment in steady currents. With the proposed FEM model, the flow-field around the pipe and the seepage-field in the soil can be obtained simultaneously. Numerical results indicate that the seepage flow is induced by the pressure drop along the water-soil interface. The effects of flow velocity, initial embedment on the pressure drop are also investigated numerically. It is indicated that the maximum hydraulic gradient in the soil at the downstream side of the pipe always locates at the intersection of the pipe with soil surface. The process of tunnel erosion can be initiated when the hydraulic gradient at the exit of seepage flow reaches the critical value for seepage failure.

***Key Words :*** *Submarine pipeline; Seepage failure; Scour; Steady currents; Numerical model*

## 1. INTRODUCTION

When a submarine pipeline is laid upon seabed, there always exists certain initial embedment into the soil. Under the influence of ocean environmental loads, the soil particles underneath the pipeline may be scoured, which could finally lead to the occurrence of pipeline spanning (Herbich, 1981). The pipeline spans may experience vortex-induced vibration (see, Gao et al., 2007), which has been widely recognized as one of the main causes for the fatigue damage to pipelines.

The mechanism for the onset of local scour underneath pipelines (also named as ‘tunnel erosion’) has received much attention in the past few decades, which has been reviewed and summarized by Sumer and Fredsoe (2002). The conditions under which the onset of tunnel erosion occurs underneath the shallowly embedded pipeline in steady currents have been investigated experimentally, such as the work by Mao (1988), Chiew (1990), etc. Their experiments showed that the pressure difference between the upstream and the downstream of the pipe induces seepage flow in the soil below the pipe, and the onset of tunnel erosion was linked with the soil piping failure. Based on the results of a series of tests, Sumer et al. (2001) further proposed a criterion for the onset of scour for the pipes with small embedment in non-cohesive soils.

Besides those physical experiments, numerical methods have also been adopted for simulating the aforementioned or related physical phenomena. Most of the previous numerical studies, e.g., Brors (1999), Liang et al. (2005), concentrated on the simulation of flow around the pipe, and sediment transport for predicting equilibrium scour-hole profiles around the pipe without embedment into the soil. The seepage flow in the soil below the pipe was not taken into account in their studies. Till now, the numerical investigations on the onset of tunnel erosion of pipelines are scarce. Liang and Cheng (2005) and Yang et al. (2005) proposed numerical models for simulating the seepage failure of soil induced by pressure drops to explain the mechanism of onset of tunnel erosions. However, in those numerical studies, the flow-field around the pipe was calculated firstly to get the pressure distribution along the rigid bed; the seepage flow in the underlying soil was then calculated with the obtained pressure distribution as the boundary conditions. By means of those numerical models, the flow-field and seepage-field could not be obtained simultaneously, which would bring much inconvenience for parametric studies.

In this study, a finite element model is proposed for coupling calculation between the flow around a submarine pipeline and the seepage flow within the porous soil underneath the pipeline. Parametric study is performed to further reveal the underlying physical mechanism of the tunnel erosion below pipelines in steady currents.

## 2. TWO-DIMENSIONAL NUMERICAL MODEL

As aforementioned, the process of scour underneath the shallowly embedded pipeline in currents involves the coupling of two flow-fields, i.e. the flow-field around the pipeline and the seepage field within the underlying soil. In this paper, the finite element method (FEM) was employed to simulate this two-dimensional quasi-static process.

The governing equations for the flow above seabed are the two-dimensional Reynolds-averaged Navier-Stokes and continuity equations for incompressible flow, which can be written in the Cartesian coordinate system:

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

$$\frac{\partial u_i}{\partial x_i}=0 \quad (2)$$

where $u_i$ is the mean velocity of fluid; $u_i^{'}$ and $u_j^{'}$ are the pulse velocities of fluid; $t$ is the time variable; $\rho$ is the density of fluid; $p$ is the pressure of fluid; $\nu$ 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. The term of turbulent fluxes can be approximated by Boussinesq assumption as

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

in which, $k$ is the turbulent kinetic energy, i.e. $k=\overline{u_i^{'}u_i^{'}}/2$, $\nu_t$ is turbulent viscosity. A turbulence model is necessary to provide a value for the turbulent viscosity $\nu_t$ throughout the flow field. The standard $k-\varepsilon$ model was employed for its credibility and insensitivity for the density of grid during numerical simulation, i.e.

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

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

where the turbulent viscosity $\nu_t$ is defined as $\nu_t=C_\mu\frac{k^2}{\varepsilon}$, with $\varepsilon$ denotes turbulent energy dissipation rate; $G_k$ is defined as $G_k=-\overline{u_i^{'}u_j^{'}}\frac{\partial u_i}{\partial x_j}$, the constants are $C_{1\varepsilon}=1.44$ $C_{2\varepsilon}=1.92$, $C_\mu=0.09$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$.

The two-dimensional seepage flow within seabed is governed by Laplace's equation:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0 \quad (6)$$

in which the pressure head $h=\frac{p}{\rho g}$, here $p$ is the seepage pressure.

In order to solve the above governing equations for the flows above and within the seabed in a whole procedure, the sequential coupling is implemented via imposing the NS-continuity derived pressure distribution along the bed surface (Bw4 and Bw5 in Fig.1) as a Dirichlet boundary for the seepage flow equation. Compared with the flow velocities around the pipe, the seepage velocities in the porous bed are generally minor in the magnitude. As such, it is reasonable to adopt the no-slip/no-flow conditions at the sediment-water interface. At the left-hand side inflow boundary (Bw1 in Fig.1), a constant free stream velocity $u_1=V$ is specified. The top of the flow (Bw2) is treated as a no-flow symmetry boundary. At the outflow boundary (Bw3), the pressure is given a reference value p = 0, whereas the other flow variables are allowed to adjust freely with zero x-gradient conditions. On the surface of seabed

(Bw4, 5) and pipeline (Bp6), the Logarithmic wall function is implemented. In the seepage domain, the pressure heads along the surface of sand (Bw4, 5) are expressed by the pressure of the flow field. The pipeline surface contacting with sediment (Bp10) and the other boundaries of the porous sand domain (Bs7, 8, 9) are treated as Neumann boundary condition, i.e. $n \cdot \nabla h = 0$.

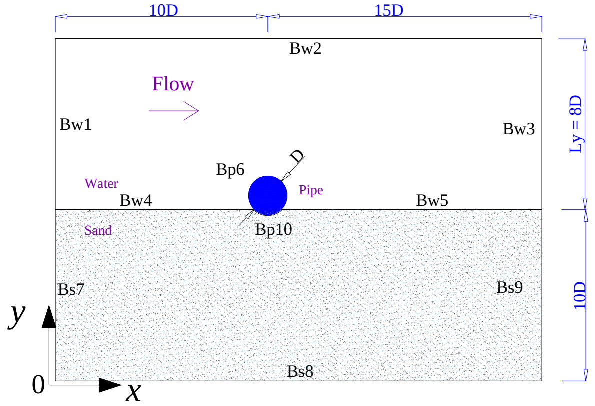


**Fig.1** Illustration of computational zone (not in scale)

## 3. NUMERICAL RESULTS AND DISCUSSIONS

### (1) Examination of Blockage Effects

In the numerical model, a prototype size pipe ($D$ = 0.6m) is chosen and it is located in $x$ = 6.0 with an embedment. The upstream boundary is in 10$D$ from the center of the pipe, and the downstream boundary in 15$D$. The soil depth is chosen as 10$D$. In the offshore fields, submarine pipelines are generally laid underwater with water depths much larger than their diameters. In the numerical simulations, the height of water domain ($L_y$) may bring blockage effects on the local pressure distributions in the proximity of the pipeline. As such, it is worthy of examining the influence of the height of water domain on the pressure distribution along the water-soil interface around the pipeline. For a parametric study, the height of water domain ($L_y$) are set as $L_y$ = 3$D$, 4$D$, 6$D$, and 8$D$, respectively, and other parameters are kept constant, i.e. $V$ = 1.0 m/s, $D$ = 0.6m, $e/D$ = 0.05, where $e/D$ is the initial embedment of the pipe.

Fig. 2 shows the pressure distributions at the water-soil interface near the pipe for various values of $L_y$. It is indicated that, the pressures at the water-soil interface ($P_s$) are greatly affected by $L_y$ in the examined range, i.e. $3D < L_y < 8D$. The magnitudes of $P_s$ are much bigger for small values of $L_y$, (e.g. $L_y = 2D$, see Fig. 2). With the increase of $L_y$, its effects on the local pressure distribution (i.e. the blockage effects) get less. The difference of local pressure distribution is minor between the cases of $L_y = 6D$ and $L_y = 8D$. That is, the blockage effects can be ignorable in the larger water depths conditions (e.g. $L_y > 6D$, see Fig. 2). In the following sections, the height of water domain is chosen as $L_y = 8D$ for large water depths, to avoid the aforementioned blockage effects.

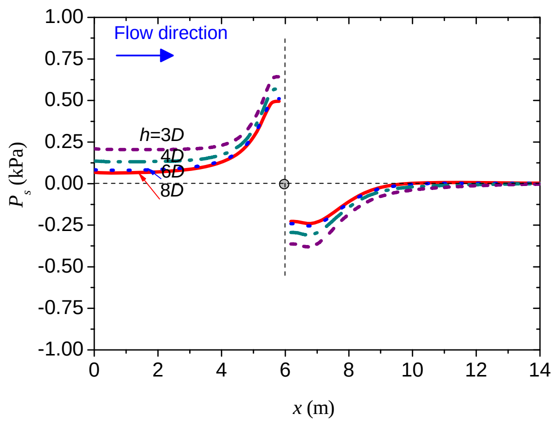


**Fig. 2** Pressure distributions at the water-soil interface near the pipe for various water depths ($D$ = 0.6m, $e/D$ = 0.05, $V$ = 1.0 m/s, the pipe is located at $x$=0.6m)

### (2) Flow-field and Seepage-field around the Pipe

By means of the proposed numerical model, the flow-field around the partially buried pipeline and the seepage-field below the pipe are obtained simultaneously. Fig. 3 illustrates the distributions of the flow pressure and seepage pressure around the pipe. It is indicated in the figure that the existence of the pipeline changes the flow-field around itself. The flow pressures in front of the pipeline are higher than those at the rear of it. This pressure drop further induces seepage flow within the soil underneath the pipe (see Fig. 3).

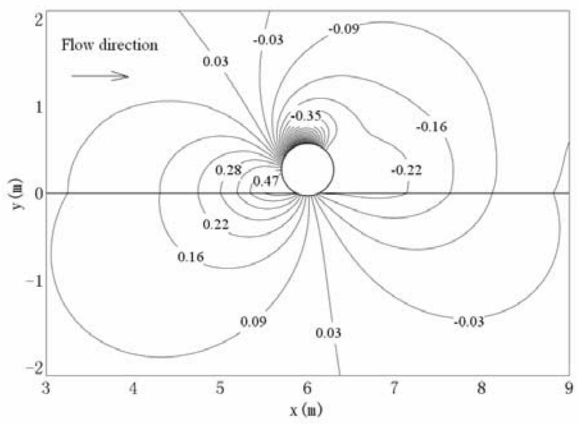


**Fig. 3** Contour of flow pressure and seepage pressure around the pipe (unit: kPa) ($D$ =0.6m, $e/D$ =0.05, $V$=1.0m/s)

### (3) Effects of Flow Velocity, Initial Embedment on the Pressure Drop

As shown in Fig. 3, there exists pressure difference between the upstream and downstream of the pipeline, which leads to seepage flow in the soil. The seepage-field may be influenced by various factors, such as the inflow velocity and initial embedment, etc. Thus, it is meaningful to make further efforts to study the effects of inflow velocity and initial embedment on the pressure drops.

Fig. 4 shows the pressure drops at the water-soil interface ( $P_s$ ) for various inflow velocities ($V$), i.e. $V$= 0.2, 0.5, and 1.0 m/s. It is indicated that, as the inflow velocity increases, the pressure drops increase dramatically, provided that the remaining parameters are kept unchanged. The pressure drops at the water-soil interface may also be affected by the initial embedment of the pipe ( $e/D$ ) due to its own submerged weight. Only the partially buried pipe with small embedment is considered in this study, e.g. $e/D$ =0.02, 0.05, and 0.1 (see Fig. 5). In the range of $e/D$ from 0.02 to 0.1, the pressure drops decrease slightly with increasing the embedment.

### (4) Discussion on Onset of Tunnel Erosion: Seepage Failure

Under the action of steady currents, seepage flow can be induced in the porous soil due to the pressure drops along the water-soil interface. It has been observed in the previous experiments that tunnel erosion is always initiated immediately behind the pipeline. When the current velocity is increased, the critical state for onset of tunnel erosion is reached and a mixture of sand and water break through the space just at the downstream of the pipe (Sumer & Fredeso, 2002). In those experiments, the detailed distribution of the hydraulic gradients in the soil adjacent to the embedded pipe was not provided due to the difficulties in the pore pressure measurements.

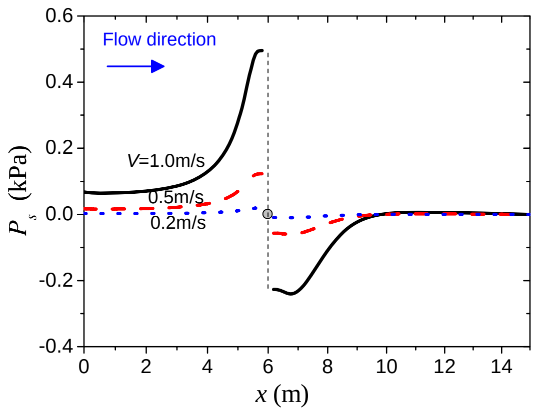


**Fig. 4** Pressure distributions at the water-soil interface near the pipe for various inflow velocities. ($D$ = 0.6m, $e/D$ = 0.05, the pipe is located at $x$ = 6m)

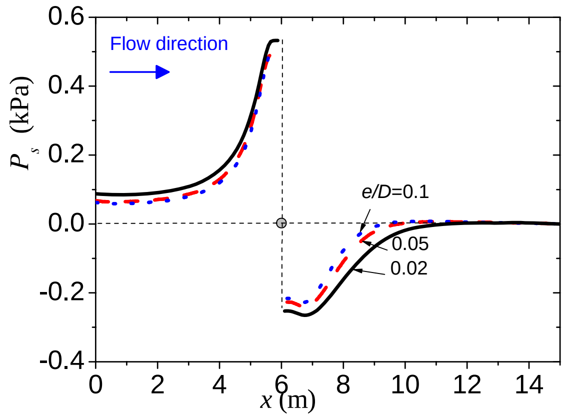


**Fig. 5** Pressure distributions at the water-soil interface near the pipe for various initial embedments ($D$ = 0.6m, $V$ = 1.0 m/s, the pipe is located at $x$ = 6m)

In this paper, the distribution of hydraulic gradients in the sand beneath the pipe is further investigated numerically. Fig. 6 shows the contour of hydraulic gradient ($i$) in the sand beneath the pipeline. It is illustrated in the figure that the maximum hydraulic gradients locate at the two corner points upstream and downstream of the pipe. Since the seepage forces at the upstream zone (see point-A in Fig. 6 and 7) are downwards, this would enhance the resistance to scouring. However, the seepage forces at the downstream zone (see, point-B in Fig. 6 and 7) are upwards in the direction tangential to the pipe surface, which may induce seepage failure. The local seepage failure as "piping" or "boiling" is most likely occur closely adjacent to the downward intersection between the pipe and the soil surface (the exit of the seepage flow).

The numerical results indicate that the hydraulic gradient at downstream pipe-soil surface intersection (see point-B in Fig. 6) reaches the maximum value. Terzaghi (1943) defined the concept of critical hydraulic gradient $i_c$ which controls the seepage failure as $i_c = (G_s - 1)(1 - n)$, where $G_s$ is the specific gravity of sand particles, $n$ is the soil porosity. The criterion for the onset of seepage failure can be written in the simple form: $i > i_c$, where $i$ denotes the actual hydraulic gradient at the exit of the seepage flow. It is noted that this criterion was derived from analyzing the balance between submerged weight and vertical seepage force exerted on a small volume of soil. For a loose sandy soil with $G_s$ =2.63, $n$=0.52, the critical hydraulic gradient can be determined as $i_c$ =0.78, according to the above definition of the critical hydraulic gradient. In the numerical simulations, a series of hydraulic gradients can be obtained for a certain initial embedment. When the calculated value of hydraulic gradient at the point-B equals the critical value (e.g. $i_c$ = 0.78), the process of tunnel erosion is initiated and the corresponding current velocity is regarded as the critical velocity for onset of tunnel erosion of the shallowly embedded pipeline (see Fig. 6 and Fig. 7).

## 4. CONCLUDING REMARKS

The onset of tunnel erosion underneath a pipeline shallowly embedded in a sandy seabed in ocean currents involves the coupling between the flow-field around the pipe and the seepage-field in the porous soil beneath the pipe. Unlike the previous numerical models in which the flow-field and seepage-field are obtained separately, this paper presents a finite element model using a sequentially coupled formulation, by means of which the flow-field and the seepage-field can be calculated simultaneously.

The effects of flow velocity, initial embedment on the pressure drop are investigated numerically. The pressure drop induced seepage flow in the soil underneath the pipe with small embedment is further discussed in detail. When the hydraulic gradient at the exit of seepage flow reaches the critical value for seepage failure, the process of tunnel erosion can be initiated and the corresponding current velocity is regarded as the critical value for onset of tunnel erosion of the shallowly embedded pipeline.

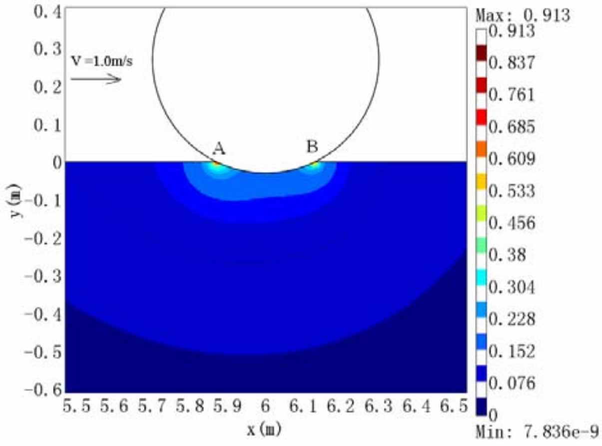


**Fig.6** Contour of hydraulic gradient underneath the pipe ($V$ = 1.0 m/s, $D$ = 0.6m, $e/D$ = 0.05, the pipe is located at $x$ = 6m)

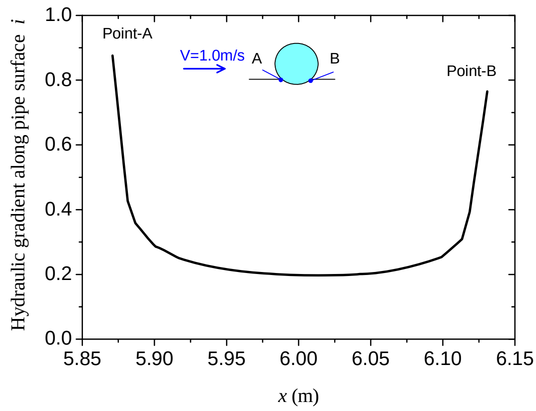


**Fig.7** Hydraulic gradients along the pipe-soil interface ($V$ = 1.0 m/s, $D$ = 0.6m, $e/D$ = 0.05, the pipe is located at $x$ = 6m)

**ACKNOWLEDGMENT:** This work is financially supported by National Natural Science Foundation of China (Grant No. 50509022), the Eleventh Five-Year Plan of Chinese Academy of Sciences (Grant No. KJCX2-YW-L02).

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