Modeling the process of river bed bottom erosion in the area of the underwater pipelines location

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Abstract. This paper deals with the modeling of flows and transport of sand particles during erosion of pipelines. The results of an experimental study of velocity fields and numerical CFD modeling in a three-dimensional transient formulation on the basis of Reynolds averaged Navier-Stokes equations in the ANSYS software package are presented. Modeling was carried out with different arrangement of pipelines, simulating cylinders, on a sandy bottom. The influence of the number of cylinders on the process of bottom soil reformation is analyzed.

1. Introduction
Underwater pipelines are complex engineering facilities. On the one hand, subsea oil and gas pipelines and sewer dukes when crossings navigable rivers are affected by the flow, waves and ice; on the other hand, they themselves change the speed structure of the stream, which affects the intensity and direction of channel deformations during the construction and operation of underwater facilities. Bottom erosion occurs as a result of bottom currents of various nature depending on the magnitude of the current velocity and direction, as well as the characteristics of the bottom soil. Sagging of the pipeline occurs on the diffuse part of the bottom; it leads to the generation of its free oscillations and development of resonant phenomena with a complex oscillation diagram. The task of identifying potentially dangerous, susceptible to erosion areas and their development over time is of great importance at the design and operation stages of underwater pipelines.

Due to the desire to prevent the negative consequences leading to accidents, the deformation of the channels under the pipelines has been the subject of research for many decades by both domestic [1-3] and foreign [4-6] scientists.

The classical problem of flowing around a cylinder with a fluid flow has been the subject of a large number of scientific papers. We mention here only the fundamental works [7-9]. A great amount of theoretical and experimental information has been obtained, which is crucial for solving a number of important problems, such as, for example, resistance to the movement of bodies in a liquid and the structure of the hydrodynamic wake behind a body moving in a liquid.

Until recently, the velocity field in the vicinity of the cylinder was the least studied. In theoretical papers, the case of relatively small values of the free stream Reynolds numbers was mainly considered. As a result, the development of computer technology and numerical methods made it possible to carry out direct numerical simulation of turbulent flows at high Reynolds numbers, and the
PIV-method for measuring velocity (Particle Image Velocimetry), free from the indicated drawback of the hot-wire anemometric method, became available to experimenters.

2. Experimental facility and methods

This paper presents experimental data on the horizontal and vertical components of the averaged velocity in a transverse flow around a horizontal cylinder with a turbulent incident flow with a free surface. The study is conducted in the laboratory of experimental applied hydrodynamics of the Lavrentyev Institute of Hydrodynamics of Siberian Branch of Russian Academy of Sciences.

The experimental design is shown in Figure 1. A cylinder with a diameter of $D = 0.028$ m was located perpendicular to the side walls of a rectangular channel of width $B = 0.2$ m at various distances from its axis to the bottom $z_0$. A photograph of the experimental setup and PIV equipment is shown in Figure 2. Here 1 is the mirror for a shadow under the cylinder; 2 is the working channel; 3 is the flow damper; 4 is an optical system forming a light knife; 5 is the flexible mirror system; 6 is the laser and 7 is digital video camera.

![Figure 1. Experiment design.](image1)

![Figure 2. Photograph of the experimental setup.](image2)

In the experiments, the volume flow rate $Q$ and the distance $z_0$ are changed. The values of the given parameters vary in the ranges: $0 \leq z_0 \leq 0.042$ m; $0.00336 \leq Q \leq 0.00576$ m$^3$/s. With the help of the free surface level controller located at the channel exit, the oncoming flow depth $h$ is kept constant and equal to 0.12 m. The average rate $U$ is calculated from the volume flow rate $Q$, channel width $B$ and water depth $h$ as $U = Q (B \cdot h)^{1/3}$. Depth $h$ is determined using measuring needles with a standard error of no more than 1%. Using the PIV method, implemented using Dantec Dynamics equipment, in the longitudinal plane of channel symmetry, instantaneous values of the longitudinal $u$ and vertical $w$ velocity components as functions of spatial variables $x$, $z$ and time $t$ are measured.

Four series of experiments are performed. In the first series, which corresponds to a completely buried pipeline, the cylinder is absent. In the second series, the cylinder is placed half of its diameter above the bottom ($z_0 = 0$). In the third series, the cylinder lays at the bottom of the channel ($z_0 = 0.5D$). In the fourth series, there is a gap between the bottom of the channel and the cylinder equal to the diameter of the cylinder ($z_0 = 1.5D$). Photographs of the cylinder in the last three series are shown in Figure 3.

![Figure 3. Photos of the cylinder at various position: cylinder rises above the bottom of the channel by half its diameter, $z_0 = 0$ (a); the cylinder lies at the bottom of the channel $z_0 = 0.5D$ (b) and a gap under the cylinder is equal to its diameter $z_0 = 1.5D$ (c).](image3)
In each series, four values of the average rate are set as $U = 0.14; 0.17; 0.21$ and $0.24$ m/s. Speed field data are obtained in the following ranges: $-0.7 \leq x^0 \leq 0.5; \delta^0 \leq z^0 \leq 0.87$

3. Experimental results and discussions

Figure 4 shows the profiles of the longitudinal velocity component $u^0(z^0)$ in the cross section of the channel $x^0 = 0$ in the absence of a cylinder, and with the above three positions of its axis. For these profiles, the values of the Reynolds and Froude criteria are $2.04 \cdot 10^4$ and $0.025$, respectively. In the absence of a cylinder, the indicated Re value the velocity has turbulent profile. In the presence of a cylinder, the no-slip condition takes place on its surface, and immediately behind the cylinder a stagnant zone is formed, outside of which the speed increases significantly.

\[
\begin{align*}
\text{Figure 4.} & \quad \text{Longitudinal velocity profiles } u^0: \\
& \quad h = 0.12 \text{ m}; U = 0.17 \text{ m/s}; x^0 = 0; \text{no cylinder (1)}; \\
& \quad z_0 = 0 \text{ (2)}; z_0 = 0.5D \text{ (3)} \text{ and } z_0 = 1.5D \text{ (4)}. \\
\end{align*}
\]

\[
\begin{align*}
\text{Figure 5.} & \quad \text{Longitudinal velocity profiles } u_0: \\
& \quad h = 0.12 \text{ m}; U = 0.17 \text{ m/s}; 1 - \text{no cylinder,} \\
& \quad x^0 = 0 \text{ (1)}; z_0 = 1.5D, x_0^0 = -0.23 \text{ (2)}; \\
& \quad z_0 = 1.5D, x_0^0 = 0.35 \text{ (3)}.
\end{align*}
\]

In terms of sediment transport, speed near the bottom is of greatest interest. The data given in Figure 4 show that in the case of a cylinder with a gap equal to D (profile 4 in Figure 4), the velocity at $z^0 = \delta^0$ increased by 1.7 times compared to the case when there is no cylinder in the flow (profile 1 in Figure 4). In the case of a washable bottom, an increase in speed near the bottom leads to a more intensive sediment removal. When the cylinder rises above the bottom, a stationary vortex and a stagnant zone are formed behind the cylinder, in which sediment deposition can occur. When the gap exists under the cylinder, the vortices are shedding from either one or other sides of the cylinder. Similar picture known as the Kármán vortex street is observed in a free flow [9].

At a certain distance behind the cylinder, a turbulent hydrodynamic wake forms, the averaged speed of which is less than the speed of the incoming flow. A decrease in the averaged local velocity also occurs in front of the cylinder. The corresponding illustrations for the case of the arrangement of the cylinder with a gap equal to D are shown in Figure 6 to compare the velocity profiles at $x_1^0 = -0.23$ and at $x_2^0 = 0.35$ with a velocity profile in the case without a cylinder.

As in cross section $x^0 = 0$ (see profile 4 in Figure 4), the velocities and their gradients near the bottom are greater than those in the absence of a cylinder. At a distance from the bottom $z^0 = \delta^0$, the velocity magnitude increased by 1.28 times in front of the cylinder, and by 1.74 times behind the cylinder.

The hydrodynamic pressure on the bottom and sediment transport are substantially dependent on the presence of a vertical velocity component in the flow. In the absence of a cylinder, the vertical component of the averaged velocity in a uniform flow is zero. With a cylinder in its vicinity, there are significant vertical components of the averaged velocity. The results of measuring the profiles of the longitudinal $u^0(z^0)$ and vertical $w^0(z^0)$ components of the averaged velocity for various combinations of the given parameters are presented in Figure 6. Positive values of $x^0$ correspond to cross sections located behind the cylinder, negative values of $x^0$ correspond to cross sections in front of the cylinder. The value $x^0 = 0$ corresponds to the cross section of the flow passing through the axis of the cylinder.

The data given in Figure 7 show that in the presence of a cylinder, the absolute value of the horizontal component of the averaged velocity exceeds 1.6 times the average consumption speed at
individual points of the flow, and the vertical component reaches 50% of the average consumption speed. Noteworthy is the fact that at short distances in the wake of a cylinder \( \nu^0 \) may be negative (see profiles 1, 2, 3 in Figure 6 and 7). Since measurements by a hot-wire anemometer are carried out only at a sufficiently large distance behind the cylinder, the presence of negative velocities in the wake of the cylinder was not detected earlier. This flow feature in the near wake, detected by the PIV method, is due to the influence of large eddies shedding from the cylinder.

![Figure 6](image-url)

**Figure 6.** Profiles of the longitudinal \( u^0 \) (a) and vertical \( w^0 \) (b) velocity components: \( z = 0; h = 0.12 \text{ m}; 1 - x^0 = 0.35; 2 - x^0 = 0.23; 3 - x^0 = 0.175; 4 - x^0 = 0; 5 - x^0 = 0.175; 6 - x^0 = -0.23; 7 - x^0 = -0.35 \)

\[ x^0 = x/h; U = 0.14 \text{ m/s}. \]

![Figure 7](image-url)

**Figure 7.** Profiles of the longitudinal \( u0 \) (a) and vertical \( w0 \) (b) velocity components \( U = 0.17 \text{ m/s}. \)

Designations are the same as in Figure 6.

In the presence of a sufficiently large gap between the cylinder and the bottom of the channel, as well as between the cylinder and the free surface, the structure of the vortex motion in the near wake of the cylinder is qualitatively similar to that observed in a free flow around the cylinder [10]. In the case of free flow, instead of the Re criterion introduced above, the criterion \( \text{Re}_1 = U \cdot D/\nu = D \cdot \text{Re} \) is used, in which the cylinder diameter is used as a characteristic linear dimension. In a free flow, at low Re values (\( \text{Re}_1 < 1 \)), the flow is attached to the cylinder surface. When \( \text{Re}_1 > 5 \), the flow separates, and a structure with two stable vortices with the opposite direction is formed behind the cylinder. Such a structure is retained in the range \( 5 < \text{Re}_1 < 50 \).

In the range \( \text{Re}_1 > 60 \), the vortices behind the cylinder are no longer stable, but they are alternately shedding from the one or the other side of the cylinder. In the range \( 60 < \text{Re}_1 < 5000 \), at some distance behind the cylinder, there is the Karman vortex street [8]. With an increase in \( \text{Re}_1 \), starting from the lower boundary of the range of existence of the vortex street, Strouhal number \( St = nD/U \), where \( n \) is the vortex shedding frequency (Hz), increases. At \( \text{Re}_1 > 600 \) \( St \) becomes constant and equal to 0.212.

Even in the indicated range of values of \( \text{Re}_1 \), the classical vortex strees is stable only at a limited distance behind the cylinder. With the growth of \( \text{Re}_1 \) beyond this range, destructive tendencies intensify, and the hydrodynamic wake becomes turbulent already at a small distance behind the cylinder. In our experiments, the values of \( \text{Re}_1 \) were set from the range \( 3900 \leq \text{Re}_1 \leq 6700 \), i.e. either corresponded to the region of existence of the Karman classical vortex path, or only slightly exceeded the upper boundary of this region.
4. Computational problem setup and numerical methods
The process of reforming the bottom soil in the tray is considered numerically. The tray of 130 cm length has a rectangular cross-section with a width of 10 cm, and a height of 19 cm. Sand is evenly distributed at the bottom of the tray. The particle diameter \((d = 0.05 \text{ mm})\) is chosen so as to exclude the occurrence of particle removal in the absence of a cylinder. On the sandy bottom the cylinder of diameter \(D = 2.5 \text{ cm}\) is placed fixed rigidly to the side walls of the tray. This allows to simulate real conditions when the cylinder is stationary along the underwater transition path and rests on a surface formed by sand.

Two cylinder arrangements on the sand surface are considered named as Experiment 1 and Experiment 2 (Figure 8). Numerical modeling is implemented in the ANSYS Fluent software based on the Reynolds averaged Navier-Stokes equations, supplemented by the standard \(k-\varepsilon\) turbulence model and the equations of the Euler model of multiphase media taking into account the granularity of the particle phase. Details of model calculations in ANSYS are described in [11].

The identical boundary conditions are prescribed for the Experiments 1 and 2, namely, water mass flow rate at the inlet is set as \(Q = 1.2 \text{ kg/s}\) and pressure is set as \(P=1 \text{ atm}\) at the outlet.

![Figure 8](image)

**Figure 8.** Schemes of the experiments performed: Experiment 1 (a) and Experiment 2 (b).

5. Numerical simulation results and discussions
As a result of the calculation, the following fields were obtained: fields of velocities, pressures, and phase concentrations. Volumetric concentration iso-surfaces \(\alpha = 0.01\) are constructed for a visual representation of bottom soil reorganization at different points in time for the Experiment 1 (Figure 9) and Experiment 2 (Figure 10).

After 0.3 seconds from the beginning of the Experiment 1, the process of sand washing under the cylinder and formation of the bottom ridges are observed (Figure 9). After a few seconds, the ridge reaches the cylinder, and it is completely covered with sand. The process is very intense. Further, the ridge continues to move along the tray, the cylinder is again exposed and a cavity is formed under it.

![Figure 9](image)

**Figure 9.** Volumetric concentration \(\alpha = 0.01\) iso-surface for Experiment 1, \(t = 0.3 \text{ s}\).

![Figure 10](image)

**Figure 10.** Volumetric concentration \(\alpha = 0.01\) iso-surface for Experiment 2, \(t = 0.1 \text{ s}\).

Sand erosion under the first cylinder in the Experiment 2 was recorded already after 0.1 seconds from the start of the study (Figure 10). At the tenth second, the size of the bottom ridge increases from the rear of the cylinders. The pronounced heterogeneous structure of the surface of the bottom relief confirms the general thesis that the generation of individual erosions under the cylinder is not synchronous and along the entire length of the cylinder, but locally under the influence of local small-scale disturbances. After 30 seconds from the start of the Experiment 2, the second cylinder was exposed, and under the first one, the depth of the washout funnel increased.

The following series of figures shows the formation of vortices shown by streamlines. Vortices that form in front of the pipe (Figure 11a) and between two pipelines (Figure 11b) contribute to the erosion process.
6. Conclusions

Experimental studies of velocity fields and numerical modelling of hydro-physical processes in the area of the location of the cylinders that imitate underwater pipelines are carried out.

In the course of experimental studies using PIV equipment, it is found that the presence of a cylinder substantially changes the velocity field in a flow with a free surface. In the vicinity of the cylinder, an increase in the averaged horizontal velocity component and the appearance of an averaged vertical velocity component are recorded. Such changes should be taken into account, in particular, when analyzing the deformation of the eroded bottom. From this point of view, the most interesting experimental results are those in which there is a gap between the bottom and the cylinder. With a gap equal to the diameter of the cylinder, the longitudinal component of the averaged velocity near the bottom can 1.8 times exceed its value in the absence of a cylinder. At the same time, the tangential stresses at the bottom increase.

Numerical experiments using ANSYS Fluent 18.2 on the basis of Reynolds averaged Navier-Stokes equations are performed. The erosion of the sandy bottom is studied at a given mass flow rate \( Q = 1.2 \text{ kg/s} \). It is found that the intensity of the reformation of the moving bottom depends on the number of cylinders located on the surface of the sand. It is revealed that when two cylinders are located on the bottom surface, the process of bottom soil reformation is accelerated.

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