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SALTATION OF SAND IN VICINITY OF CYLINDRICAL COLUMN

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Abstract: *The paper presents a model of sand sediment transport in water stream in vicinity of a high cylindrical column. It is assumed that an averaged turbulent flow is horizontally layered in vicinity of the cylinder. In each layer the flow around the cylinder is modelled as a potential flow generated by a vertical dipole line. Flow in viscous sub-layer on the surface of the cylinder is neglected. The presented flow model is approximate; however it is simple for use. Trajectories of saltating particles near the cylinder were calculated. Further investigation of such flow will allow a determination of zones where solid particles will collide with the column. That might be useful for prevention of its damage or destruction.*

Keywords: ***Saltation of sand, flow around cylinder, logarithmic profile, dipole line, averaged turbulent flow.***

1. Introduction

The effect of sand movement in vicinity of obstacles is very important for stability of various constructions. Often the constructions or their parts have a form of vertical cylinder. In water, for example, sand movement around cylindrical obstacles occurs in channels, rivers, lakes, sea, around various columns, building pillars, bridge legs, stands of pipes for boring, and breakwaters. For example, in desert when cylindrical column stands on a sand surface, blowing wind undermines the construction and as a result the column might decline or even fall.

Knowledge of flow of viscous fluid with particles around a cylinder is important for some engineering works both on land and in water. For instance, investigations of a sand movement around a cylindrical column are a subject of many up-to-day works (Euler & Herget, 2012; Kawamura et al., 1999; Mochizuki et al., 2012).

In Kawamura et al. (1999) work the laminar flow of air around a circular cylinder standing on the sand is computed numerically and the movement of the sand is investigated. They used the MAC method for calculation of the flow field around the cylinder and for estimation of the sand transfer caused by the flow. In results they determined the shape of the ground near the cylinder, accumulation and dented regions, and the conditions at which the cylinder falls down.

Euler & Herget (2012) presented an extensive investigation of sand movement around spherical and cylindrical obstacles. A novel approach was applied by conducting experiments in laboratory flume and validating against other laboratory and field data. The results of this work have shown a significant relationship between the morphometry of fluvial obstacle marks and obstacle Reynolds number.

Mochizuki et al. (2012) experimentally studied sand movement in air around cylindrical obstacle standing on the sand. As a result they found zones of accumulation and erosion of sand bed.

Since experimental investigation of a flow is labour-consuming, its numerical simulation by solving the Navies-Stokes equations is time-consuming, we propose a simple model for fast calculation of averaged turbulent flow around a cylinder with possibility of its application to sand saltation in vicinity of that cylinder.

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2. The flow model

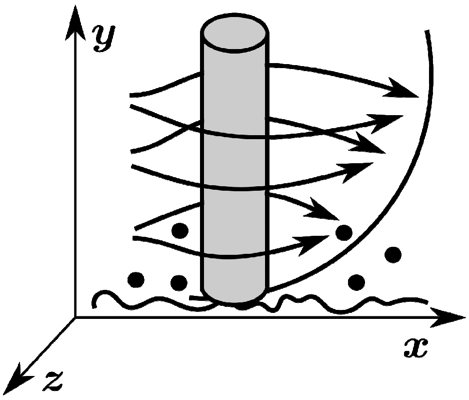

Figure 1. Scheme of average turbulent flow around cylindrical column with sand particles saltating above rough bed.

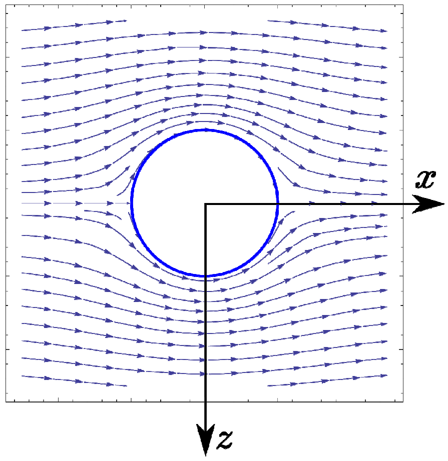

Figure 2. Potential flow in a horizontal plane around a vertical cylinder.

An averaged turbulent flow around cylindrical column with sand particles saltating above rough bed is consider here. The sand movement occurs mainly in region near bed, Fig. 1. We assume that the averaged flow around the cylinder is horizontally layered. The tree-dimensional problem of turbulent flow above bed and around a cylindrical column is thus reduced to a two-dimensional problem of flow around a cylinder in each layer. In each horizontal layer the flow is approximate as potential flow of ideal fluid around cylinder, Fig. 2.

Averaged turbulent flow

Consider a uniform turbulent flow above rough plane in semi-infinite space, with flow direction parallel to the x-axis. According to the Prandl mixing length theory and bed shear stress theory, the averaged velocity of turbulent flow is subject to logarithmic law:

$$u_{tx} = \frac{u_*}{\kappa} \ln\left(\frac{y}{y_0}\right), \tag{1}$$

where u_* is shear velocity, κ – Karman's constant, y - distance from the plane, y_0 - a constant depending on hydraulic roughness (Schlichting, 2004). A use of such approximation neglects turbulent fluctuations of the flow.

The logarithmic law of average velocity distribution was confirmed in many experiments, in pipes and in open channels, and for medium and large Reynolds numbers, see for example Nikuradse's (1933) work. In open channels the logarithmic law is valid only in the region of 30-40% of the depth of the flow above bed; and it is not valid near water surface and also close to the bottom.

It the model of a flow around cylinder we suppose that the average turbulent flow is horizontally layered. Hence, all turbulent fluctuations in each layer are neglected; each particle of the averaged fluid flow will stay in the same horizontal layer and there is no mixing of layers neither in front of nor past cylinder. The assumption might be true for a high enough cylinder or for a cylinder with a plane ceiling on its top. For description of two-dimensional flow in each layer we use the potential flow theory.

Two-dimensional inviscid potential flow around a cylindrical obstacle

Consider now an irrotational flow of incompressible, inviscid fluid around a cylinder of radius R_c, at point with radius vector $\vec{r}_c = (x_c, z_c)$, oriented so that its axis is normal to the flow. The magnitude of unperturbed fluid velocity is u, and it is directed parallel to the x-axis, $\vec{u} = (u, 0)$. If the reference frame is changed so that fluid velocity at infinity is zero, then the cylinder moves with velocity $-u$. Flow around the cylinder is the same as a uniform potential flow around a dipole located at the centre of the cylinder. A dipole is defined as a source and a sink of the same strength, when distance between them tends to zero; their strengths tend to infinity. Potential of the dipole is (Milne-Thomson, 1960)

$$\varphi(\vec{r}) = -\frac{R_c^{\,2}\vec{u}(\vec{r}-\vec{r}_c)}{\left|\vec{r}-\vec{r}_c\right|^2}, \tag{2}$$

where μ is strength of the dipole, $\mu = R_c^{\,2}u$. Velocity field generated by the dipole (or by moving cylinder) is

$$\vec{u}_c = -\vec{\nabla}\varphi. \tag{3}$$

The velocity field generated by a stationary dipole/cylinder with external flow is

$$\vec{u}_{tot} = \vec{u} - \vec{u}_c. \tag{4}$$

The flow on Fig. 2 is example of a potential flow of ideal fluid around circular cylinder in two-dimensional case.

To describe the two-dimensional flow around a cylinder the Prandtl's theory is used (see for instance Oertel, 2003). According to the Prandtl's theory, the flow of viscous incompressible fluid around a cylinder can be approximately represented as a combination of a potential flow of ideal fluid around cylinder and a flow in viscous sub-layer on cylinder surface. The thickness of viscous sub-layer depends on Reynolds number, $\delta \sim l/\sqrt{Re}$ that is determined by characteristic length (diameter of cylinder, $l = 2R_c$) and flow velocity at infinity u_∞: $Re = u_\infty l/\nu$, ν - kinematic viscosity of fluid.

For saltation purposes, if the thickness of viscous sub-layer is less than diameter of saltating particle, d, then the flow in viscous sub-layer can be neglected, as saltating particle remains in the sub-layer near cylinder surface relatively short time: $d \le 2R_c/\sqrt{u_\infty R_c/\nu}$. From this relationship a restriction for flow velocity at infinity can be found: $u_\infty \le 2R_c\nu/d^2$. The velocity u_∞ is estimated on half of the height of average saltation trajectory.

For Reynolds numbers greater than 40 the Karman's vortex street appears in flow after the cylinder. At Reynolds number greater than 2000, as illustrated in Fig. 3, the boundary layer separates and a vortex wake forms behind the cylinder. For calculation of the separation point Prandtl assumed the potential flow in the outer zone, which was defined by Eq. (4) and demonstrated in Fig. 2. However such flow assumes no separation of the boundary layer. Since the results derived by Prandtl are in good accordance with experiments, one can conclude that Eq. (4) describes flow sufficiently accurately at least in front of the cylinder, $x < x_c$.

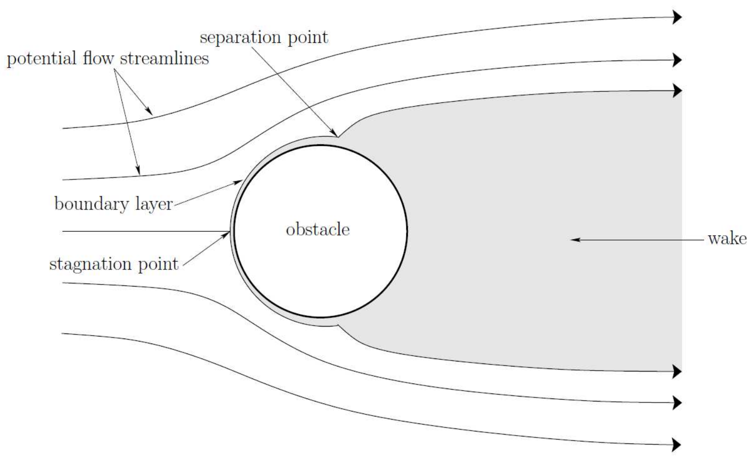

Figure 3. A flow separation on the surface of a circular cylinder, illustration by Fitzpatrick, 2012.

Model of tree-dimensional turbulent flow around a cylinder

Now consider a tree-dimensional case, where, how was mentioned above, the averaged turbulent flow is horizontally layered; velocity of each layer in absence of the cylinder is $\vec{u}_{tx}$. The velocity field in each layer in presence of cylinder is calculated by Eq. (4). Thus, the velocity field in three-dimensional case around the cylinder is defined as

$$\vec{u}_{tot} = \vec{u}_{tx} - \vec{u}_c \,. \qquad (5)$$

3. Saltation in turbulent flow around cylinder

In Kharlamova et al. (2012) there was offered a model of sand saltation in turbulent flow in wide open channel with rough bed. Now this model is modified for new conditions: for turbulent flow around cylinder.

The saltation of sand is simulated in velocity field defined by Eq. (5) in semi-infinite space, where the height of flow is indefinite. The particle is subject to gravity, buoyancy, drag, added-mass, Magnus forces and a moment of viscous force. Collision of saltating particle with cylinder surface is new in this model of saltation. This rebound is inelastic with the same coefficients of restitution and friction as those for collision of saltating particle with bed particles.

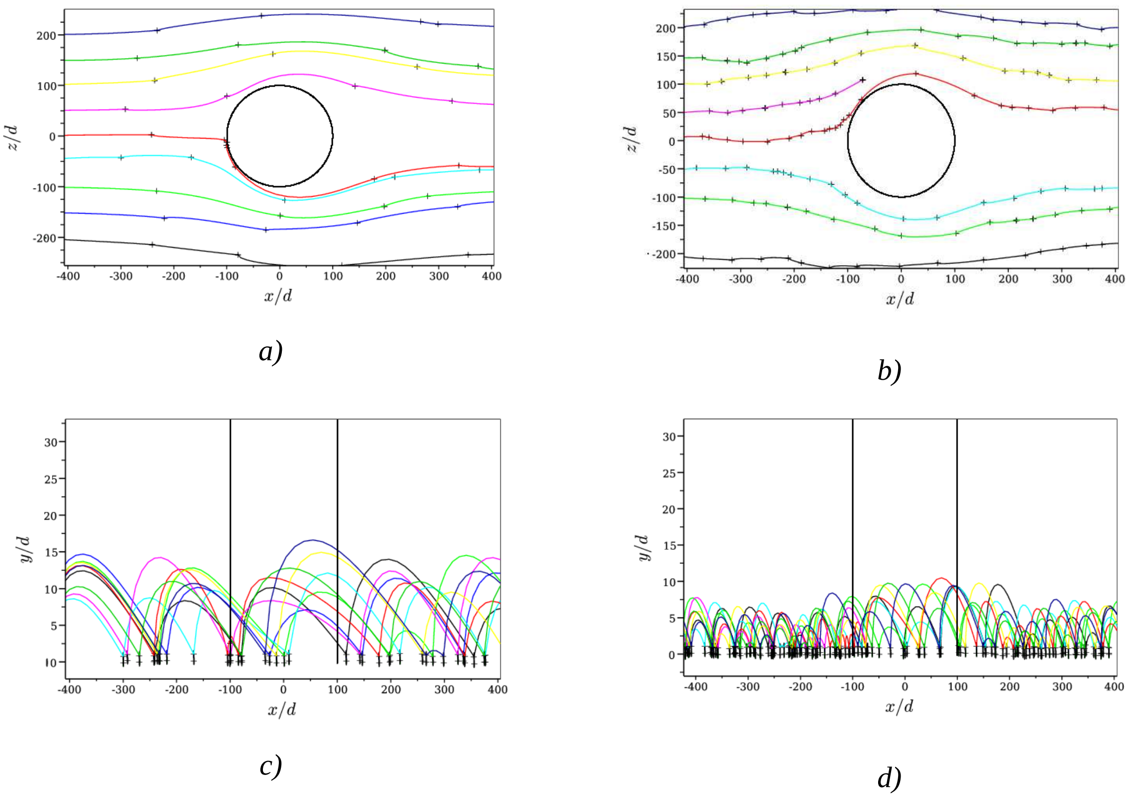

Figure 4. Examples of saltation trajectories in water in vicinity of vertical cylinder. Diameter of saltating and bed particles is d = 0.001 m. Diameter of the cylinder is 2R_c = 0.2 m. shear velocity in a),c) is u_* = 0.1 m/s, Re = 20000; in b), d) is u_* = 0.05 m/s, Re = 10000.

Figure 4 shows trajectories of saltating sand particles in water streams above rough bed and around cylinder. By "+"-signs denote points of collision of saltating particles with bed. The parameters used for water are: ρ = 1000 kg/m^3, ν = 10^{-6} m^2/s; for particle: d = 0.001 m, ρ_s = 2650 kg/m^3, and for cylinder: R_c = 0.1 m. Diameter of saltating and bed particles are the same. Shear velocity is u_* = 0.1 and 0.05 m/s, bed roughness is $k_s = d$, thus, a bed constant in velocity profile is $y_0 = d/30$. Reynolds number of the cylinder based on shear velocity is $Re = 2R_c\, u_* /\nu$.

Fig. 4 illustrates that particles moving with greater shear velocity have longer and higher jumps (*a*, *c*) than particles with lower velocity (*b*, *d*). At lower shear velocity the particles collide with bed more frequently than at higher shear velocity. The saltating particles collide with the cylinder only on its front side. It's worth noting that at the conditions used for simulation of Fig. 4 the saltating particles move mostly round the cylinder and do not touch it. The trajectories of the particles replicate the streamlines; and particles avoid the zone past cylinder, where turbulent wake should take place.

4. Discussion

The main advantages of the model of averaged turbulent flow around circular cylinder are its simplicity and simplicity of its application. Calculation of trajectories of saltating particles in thus complicated flow can be conducted more easily and faster with this model. The offered model can better describe the flow in front of cylinder and worse behind it. The model presents a crude guess for the flow and further enhancements will be subject of our next publications.

Fig. 4 shows an example of application of the offered flow model with arbitrary model parameters (diameter of cylinder, diameter of the particles, and shear velocity). In future the parameters of flow will be chosen from experimental works for verification of the saltation model in vicinity of the cylinder.

The use of potential flow theory and dipoles allows extension of the saltation model to the saltation in vicinity of several cylinders located in a row perpendicular to the flow, see Kharlamov & Filip (2012).

5. Conclusion

The present investigation offers a simple model of saltation in turbulent flow around a cylindrical column. It is supposed that the averaged turbulent flow is horizontally layered if the column is high enough. Hence, a tree-dimensional problem of averaged turbulent flow is reduced to a problem of two-dimensional flow in each layer. Flow in each layer is described by theory of potential flow of ideal fluid.

This model presents a first approximation of the problem; however, it has its advantages. It allows study of sediment transport in new type of flow geometry. The model can be used for fast estimation of sand movement around cylindrical obstacle and can be extended to the flow past several cylinders. It also can be used for determination of zones where solid particles collide with columns most frequently, and thereby, it can help prevent damage of such constructions.

Acknowledgement

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