【Memoirs of Construction Engineering Research Institute Vol.59(papers) Nov.2017】

NUMERICAL PREDICTION OF MOVEMENT AND ACCUMULATION OF FLOATING OBJECTS IN MEANDERING RIVER

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ABSTRACT

In order to understand and manage the movement and the accumulation of solid objects in rivers and channels, a numerical simulation method has been constructed that predicts the movement of floating objects with assumed physical properties. The flow is simulated by a LES based method and the motion of solid objects is simulated by assuming different models including assumption of small passive particles and large and long bodies which are to approximate commonly seen objects that need to be regulated or managed for the safe passages of water and for the aesthetic value of the river and coastal environments. A trial simulation calculation is performed for objects in sharp bending reach of Perak River in Malaysia. It is found that passive particles, round bodies with drag and large long bodies with 3 degree of freedom motion on the surface show different transport and accumulation characteristics in meandering part of the river that may be important in devising control and management measures of floating objects.

1. INTRODUCTION

There are various objects that float on surfaces of rivers and channels that influence the aesthetic and other qualities of the natural and constructed streams. Large objects such as wood branches and debris that are washed into flows can not only influence the conveyance of the river streams but may impact the environment (Boogaard et al. 1)). Small trash like plastic bags and solid waste are impacting the ecology of the streams and the sea (Kudou et al. 2).). The flow conveyance can be impeded during floods and overflow and inundation can be caused. River structures such as the bridge piers and intake facilities are also susceptible to blockages due to floating and drifting objects (Hamid and Abdullah3)). Management of these floating objects in rivers is becoming a major issue in developed and developing countries (Boogaard et al.1)). Due to its detrimental effects, preventive measures are taken for the intake structures of hydropower stations (Hribernik et al. 4)). For prevention of debris clogging the intakes, diverter structures and trash traps are built. For the effective installment of such preventive devices or structures it is very important to know the characteristics of the movement of the floating objects with and without the devices. The trajectories of floating objects depend on the details of the surface flow, which is a part of the complex three-dimensional free-surface flow. Therefore, the flow in natural rivers with complex geometries needs to be known before tracking the floating objects is performed.

There are a number of methods of finding particle trajectories in rivers and in the sea. Depending on problems and applications difficulties of various levels and complexities arise(e.g. Griffa et al.5), Canelas 6) and Kimura 7)). The main factor is the scale of the flow and the size of the objects. In order to find the trajectories of floating objects and their effects on typical rivers the river flow will have to be simulated with certain accuracies and details of the mean flow and turbulence. We implement the computation of the motion of floating objects in a Large Eddy Simulation (LES) code (KULES, Nakayama8)) for rivers and channels. The LES allows simulation of large scale motion depending on the fineness of the numerical grid. Calculation of the detailed motion of the flow around individual objects will be beyond the usual resolution LES. Therefore two models of simulation body motion and its effects on the flow are considered. The first one assumes the mass and the size of the objects are negligible and the objects are regarded as passive particles. In this case, the flow calculation can be conducted without the effects of the floating objects. In the second model, the motion of each object is computed simultaneously with the flow to reflect the two-way interaction between the flow and the objects. The floating objects may be assumed to have the same density as the water in the river but with an assumed drag coefficient. The displacement effects due to the existence of the bodies are neglected. The bodies are assumed to have no preferred direction and the resistance is assumed to act in the direction opposite of the flow and with a known drag coefficient. They approximate the motion of trash and small debris.

Trial trajectory calculation is done for a meandering reach with multiple bends in flat low land. These are the stretches where the flow is complex due to complex geometry and secondary flows and trajectories of floating objects are difficult to predict

2. CALCULATION METHOD AND BASIC EQUATIONS

2.1 Method of computation of river flow

In order to construct a method of tracking floating objects, we need a good method of computing the flow field. When the sizes of floating objects are small and the number of objects is small, we may neglect the effects of the objects on the flow and the flow can be independently computed by considering the objects as passive particles. But when the objects are large and their obstruction to the flow is significant, we need to compute the hydrodynamic forces on the objects and the drag forces of the objects on the flow. To do it accurately for arbitrary shapes of objects, the flow around the object will have to be resolved sufficiently fine so the pressure and the shear stress distributions are obtained to evaluate the resultant forces and the moment. This full two-way Fluid-Structure Interaction (FSI) procedure, as was done in the present authors previous work (Nakayama et al. 9) with a single body in a flow, requires the body to be resolved by sufficient number of grid points. In a numerical computation that resolves the channel width only by a few hundred points, floating bodies of sizes smaller than, say 1/10th of the channel width cannot be resolved sufficiently. Here we consider cases in which the size of the floating objects may not be small to be considered passive particles but the numerical resolution of the overall flow is not fine enough to resolve the shapes of the objects. The hydrodynamic forces of the flow on the objects and the drag force of the objects on the flow are modeled by the drag and lift coefficient in a uniform flow in arbitrary direction.

We assume geometric characteristics of the bodies and the drag, lift and yawing moment coefficient in a uniform flow are known so that the forces can be estimated by knowing the local flow magnitude and the direction relative to the reference direction of the body. The method is expected to be a good approximation for objects of medium size like trash and small debris but not to cases with large objects with distinctive geometric features like wood trunks comparable to the width or the depth of the flow.

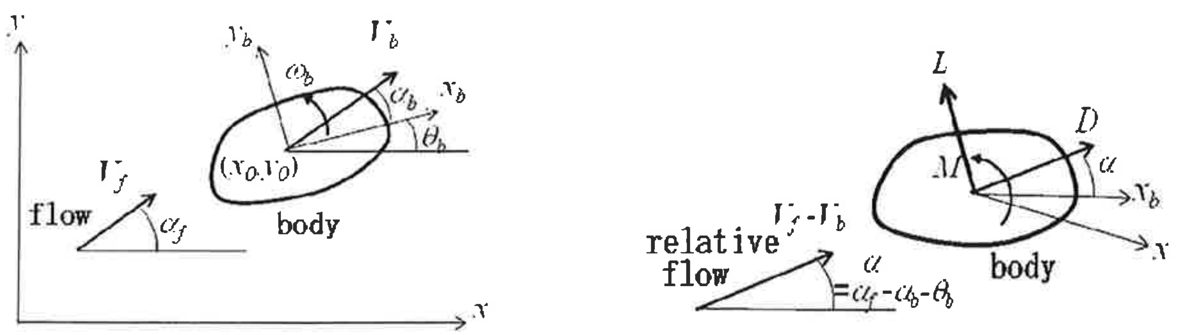
For the basic flow solver the Large Eddy Simulation method KULES developed by the present authors (Nakayama 8)) is used. The basic verifications in straight channel flows and a few applications to real rivers are given in Nakayama and Asami 10). It is the finite difference method on rectangular grid using the HSMAC iteration method (Hirt and Nichols11)) for the pressure coupling. The free surface motion is calculated from the nonlinear free surface conditions. The sub-grid model is the standard Smagorinsky model but the wall model based on the wall similarity for both low and high Reynolds numbers. The drag and lift forces from the body is included as extra body forces acting on the part of the flow occupied by the floating body.

2.2 Equations of motion of floating body

In computing the motion of floating objects, it is assumed that the specific weight of the objects is not too heavy so that they float on the water surface all the time and the motion is in the plane of the free surface. Therefore the velocity components only in the horizontal directions are computed from the equations of motion. Also the size of the objects is small compared with the grid size used to calculate the flow. This means the calculated flow around the body is almost uniform. So the force due to the flow can be parameterized by the local flow magnitude and the direction only.

Figure 1 depicts the body moving with three degrees of freedom in the horizontal (x,y) plane at the free surface. The coordinates (x,y) are fixed in space and coordinates (x_b, y_b) are fixed on the moving body also horizontal with the origin at (x_0, y_0). $\boldsymbol{V}_f = (u,v)$ is the velocity of water in the vicinity of the floating body on the free surface, $\boldsymbol{V}_b = (u_b, v_b)$ is the translation velocity and ω_b is the angular velocity of the floating body.

The motion of the body is caused by the hydrodynamic forces and moment which are calculated as drag force, lift force and the yawing moment. The drag force D is the component of the fluid force along the direction of the flow relative to the moving body. The lift force L is the component of the fluid force perpendicular to the relative flow direction. The direction is taken so that the direction of the flow, the direction of the positive lift force and the vertically upward direction


(a) In fixed coordinates

(b) Forces on the body

Figure 1. Two-dimensional motion of floating body on free surface.

form the right-hand coordinate axes. D, L and M are evaluated from the relative flow looked from the body (Figure 1(b)), from the usual definition of the lift, drag and yawing moment coefficients, C_D, C_L and C_M as follows.

$$
\begin{aligned}
D &= \frac{1}{2} C_D(\alpha) A_x \rho \left| V_f - V_b \right|^2 \\
L &= \frac{1}{2} C_L(\alpha) A_y \rho \left| V_f - V_b \right|^2 \\
M &= \frac{1}{2} C_M(\alpha) A_y l_x \rho \left| V_f - V_b \right|^2
\end{aligned}
\tag{1}
$$

where α is the 'angle of attack' of the flow relative to the body, A_x and A_y are the areas of the submerged part of the body cross section projected in the axial and transverse directions and l_x is the length of the body. The angle of attack α is defined by the direction of the flow relative to the body measured from the direction of the body axis θ_b

$$
\alpha = \alpha_f - \alpha_b - \theta_b \tag{2}
$$

Then the forces f_x and f_y acting on the body in the x and y directions and the moment f_m are

$$
\begin{aligned}
f_x &= D \cos d\alpha - L \sin d\alpha \\
f_y &= D \sin d\alpha + L \cos d\alpha \\
f_m &= M
\end{aligned}
\tag{3}
$$

where $d\alpha = \alpha_f - \alpha_b$ is the angle of the relative flow vector from x direction, and

$$
\begin{aligned}
\cos d\alpha &= \cos(\alpha_f - \alpha_b) = \cos\alpha_f \cos\alpha_b + \sin\alpha_f \sin\alpha_b \\
\sin d\alpha &= \sin(\alpha_f - \alpha_b) = \sin\alpha_f \cos\alpha_b - \cos\alpha_f \sin\alpha_b
\end{aligned}
\tag{4}
$$

and

$$
\begin{aligned}
\cos\alpha_f &= u / \left| V_f \right|, \quad \sin\alpha_f = v / \left| V_f \right| \\
\cos\alpha_b &= u_b / \left| V_b \right|, \quad \sin\alpha_b = v_b / \left| V_b \right|
\end{aligned}
\tag{5}
$$

So the equations of motion for the body are

$$m_b \frac{du_b}{dt} = f_x = D\cos d\alpha - L\sin d\alpha$$
$$m_b \frac{dv_b}{dt} = f_y = D\sin d\alpha + L\cos d\alpha \tag{6}$$
$$I_b \frac{d\omega_b}{dt} = f_m = M$$

where m_b is the mass of the body and I_b is the moment of inertia of the horizontal cross section of the body. The position (x_0,y_0) and the angle θ_b of orientation of the body are then obtained by integrating

$$\frac{dx_0}{dt} = u_b$$
$$\frac{dy_0}{dt} = v_b \tag{7}$$
$$\frac{d\theta_b}{dt} = \omega_b$$

with time.

Equations (1) are good representation of the hydrodynamic forces on the body when the flow around the object is uniform if there were no objects. This will be a good assumption if the non uniformity of the flow is of larger scale than the size of the bodies.

2.3 Brief description of numerical method

The numerical method used in the flow calculations are based on a HSMAC method (Hirt and Cook, 1972) extended to free surface flows. The standard Smagorinsky model is used for the sub-grid scale effects. The motion of the free-surface is computed from the kinematic condition in the cells containing the free surface. The pressure in the cells containing the free surface is not computed but set as the pressure boundary condition that the pressure on the free surface is equal to the atmospheric. The solution algorithm is close to the VOF method (Hirt & Nichols, 1981) but is limited to the single-valued function of the horizontal coordinates. The velocity component normal to the free surface is computed from the momentum equations so the wetting front can advance and retract over the dry ground. In the calculation, the motion of the wetting front is on the rough surfaces and is allowed only when the depth exceeds one half of the roughness height.

The boundary condition considers the wall model as done in the previous work Nakayama and Asami (2016) which explains more about the method used here. The bed roughness is incorporated as the roughness element height set in the boundary condition. The bed is considered fixed but the resistances due to the riparian vegetation are considered

A turbulence development region at the inflow section is set so the instantaneous velocity and pressure distribution at the downstream section of this region are recycled to the inflow section. The total flow rate is adjusted to match the prescribed hydrograph by multiplying a constant factor to the recycled velocity.

The equations of motion of the floating objects are solved by the explicit differencing. The motion of the bodies is much slower than the time scale of the flow calculation and the low-order time integration is sufficient. In the present computation, the time step for the flow calculation is 0.005s and the time scale of the drag forces on bodies with size 1m is close to 1s.

3. CALCULATION OF MEANDERING RIVER FLOW

Calculation was conducted for meandering river flow in a low land in Perak, Malaysia. Figure 2 shows the location of Perak River near the town of Teluk Intan in Perak State. This is the low flat land on the west coast of Peninsula Malaysia. Perak River meanders around before it empties into Melaka Strait and the bend in Teluk Intan is a very acute one and with a tributary flowing in, it makes the motion of floating objects very difficult to predict. The river makes almost 360 deg. wind within the area indicated by the white box. The radius of the curve is only about two times the river width and the effects of the bend are expected to be very strong. The bathymetric data were obtained from the Department of Irrigation and Drainage Department of Malaysia. There is a detailed survey of the bathymetry in the Teluk Intan area that are accurate 10m in horizontal direction and 0.1m vertically. There are some areas where the data are missing and they are supplemented from the areal images of the river surface.

Figure 2. The meandering river reach of Perak River in Malaysia. White box indicates the simulation area

The results of the flow calculation by the LES are shown in Figures 3. These are the results of flow simulation with fixed discharge of 2600m^3/s and the average velocity of about 1.5m/s in the inflow cross section. The average slope of the river surface in the area is about 1/4000. As seen in the aerial view, Perak River in this area bends acutely and near the inner banks of these bends there are some bars.

The bed roughness is represented by the equivalent sand-grain roughness height of 0.02m. In each of these cases the computational grid is a fixed rectangular of approximately 200 x 200 x 70 points and at least 30 points lie across any flow section. Calculation was started with an assumed initial flow of assumed logarithmic vertical distribution.

In Figures 3, the surface velocity distribution across representative transverse sections and the contours of the elevation of the free surface are shown. The surface velocity distribution indicates that there is strong effects of the bend and secondary flow but also indicate changes in the velocity magnitudes in wide and narrow passages. Also islands of various sizes affect the local velocity and the turbulence.

4. CALCULATION OF MOVEMENTS OF FLOATING OBJECTS

Calculations of floating objects are done using three assumed properties of the objects. In all cases the bodies are assumed to float on the surface all the time so that the weight may be assumed to be the same as that of the displaced water. The first is an assumption of passive particles that follow the motion of the water exactly. This assumption may be good for very small bodies that do not have directional characteristics. In this case no calculation of the body motion is needed and the velocities are interpolated from the surface flow velocity. The second assumption is the assumption that bodies do

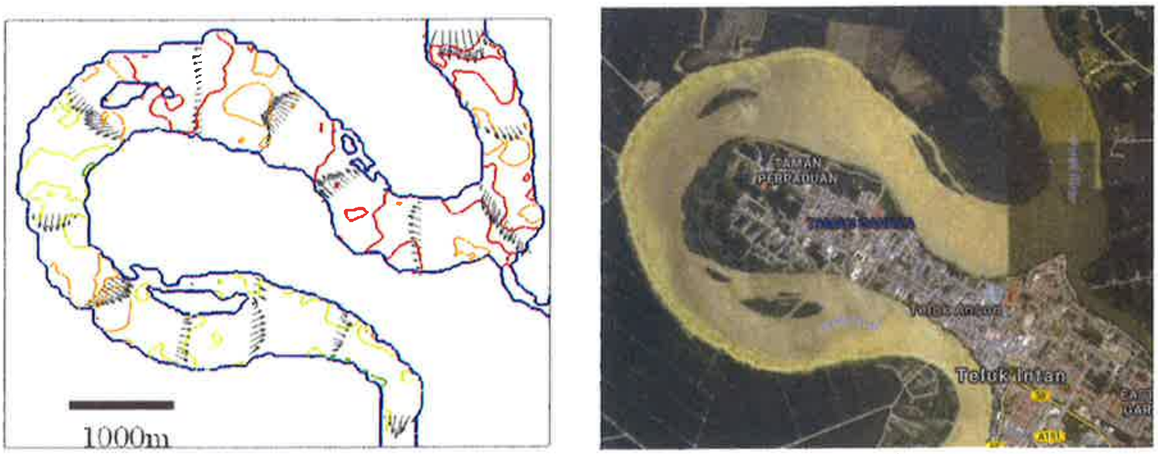
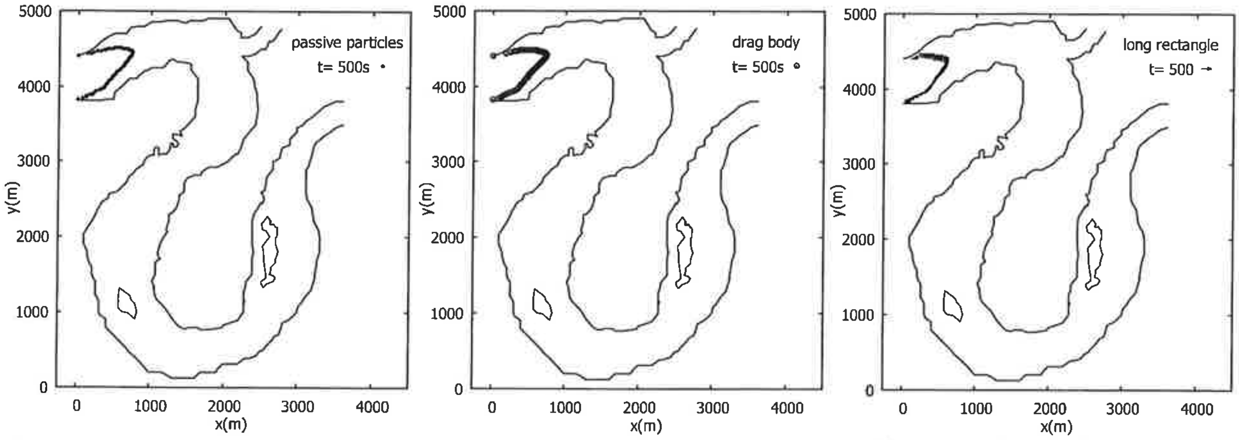


Figure 4. The average surface flow and the surface elevation.

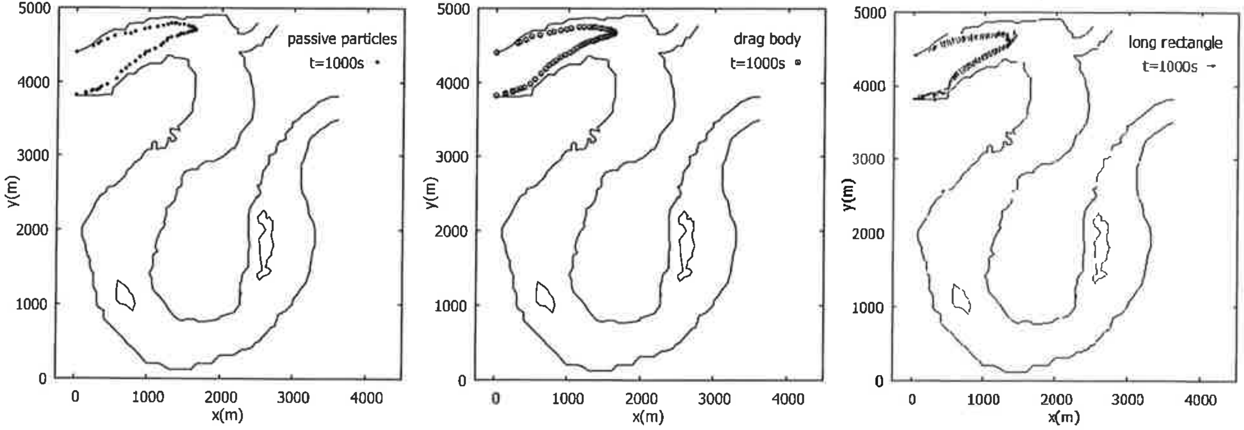
not have directional characteristics and the only force that act on the bodies are the drag forces due to the resistance of the body in a relative flow. So L and M in the equations are set to zero in Equation (4). In the calculation, the value of the drag coefficient C_D is chosen to be 0.4 corresponding to spheres in uniform flow at supercritical Reynolds numbers. The third case is when the bodies are large enough with arbitrary shape so the hydrodynamic forces are the drag, lift and the yawing moment as explained in the previous section. The values of C_D, C_L and C_M are 0.4 1.0 and -0.4 respectively. The value of the yawing moment coefficient is chosen to be something representative of long but stable shape. The diameter and the length are assumed to be 1.0m and 10.0m, respectively.

117 objects are placed at 5m meter interval across the inflow section of the river reach presently considered and the subsequent motions of these objects are traced. Figure 4 shows the positions of floating objects of three different types at

(a) t =500s, passive particles (b) t=500s, particles with drag (c) t=500s, long bodies



(d) t =1000s, passive particles (e) t =1000s, particles with drag (f) t =1000s, long bodies



(g) t =2000s, passive particles (h) t =2000s, particles with drag (i) t =2000s, long bodies

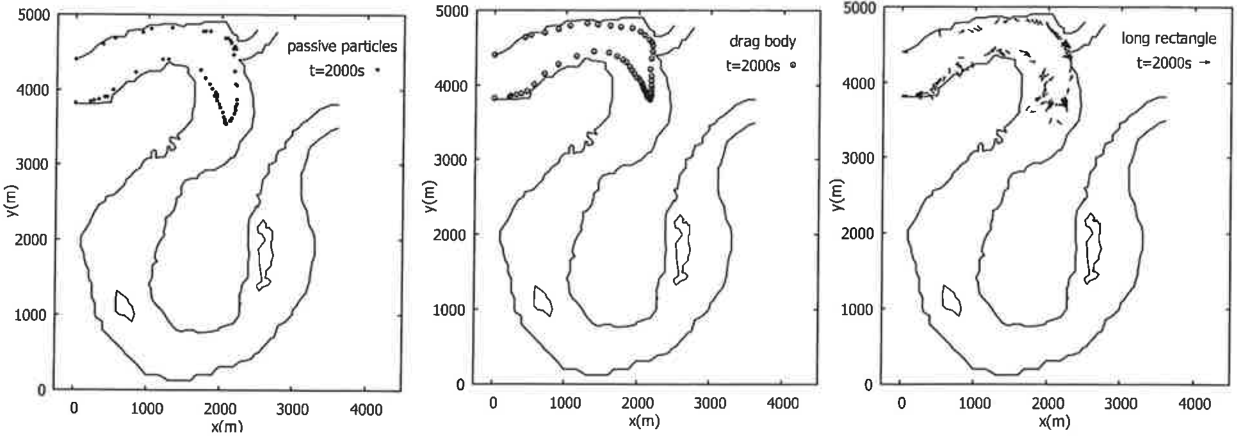
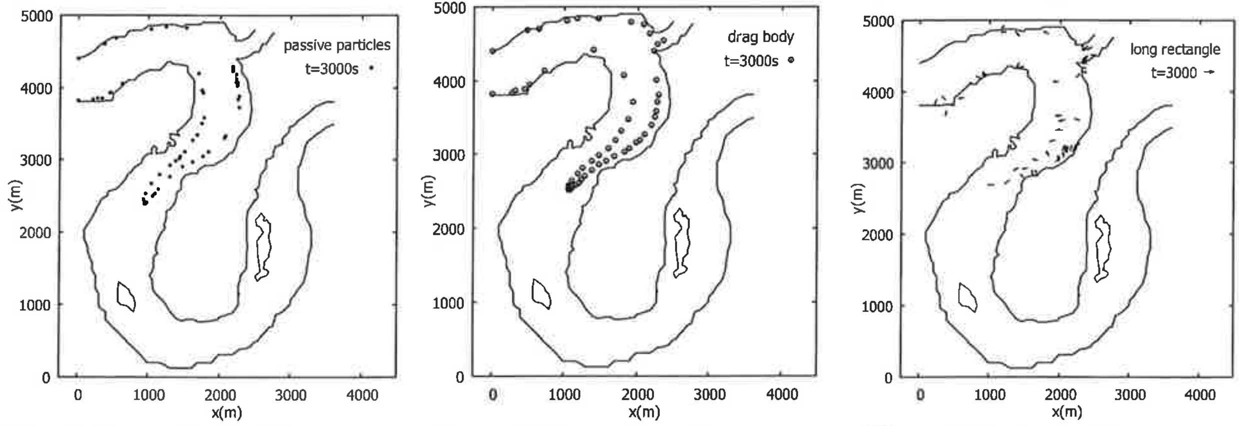


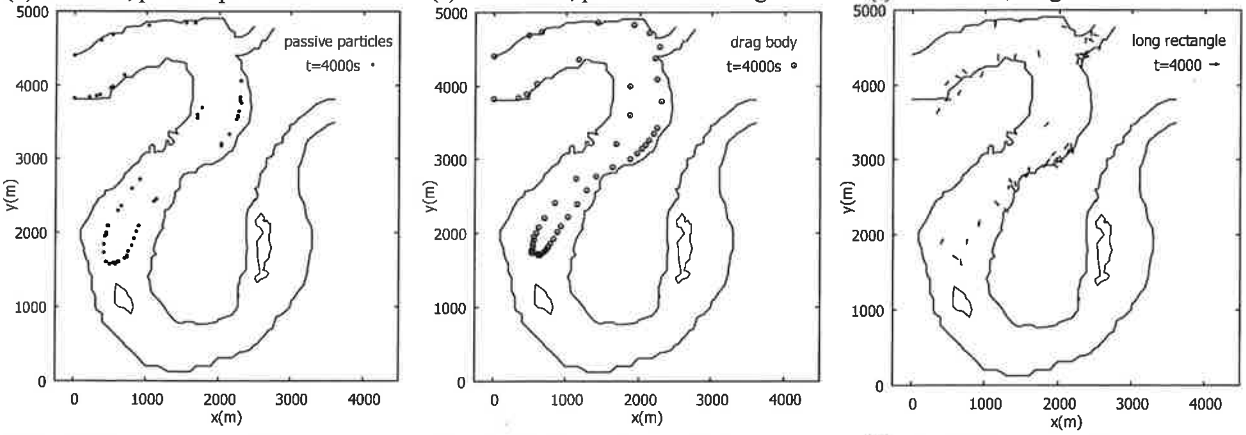
Figure 4. The initial movements of floating bodies of different properties after release at the upstream cross section.

time 500s, 1000s and 2000s after they are released at the upstream inflow section Figure 5 shows further development at later time of t=3000s, 4000s and 6000s. The passive particles are shown by small dots, the bodies with drag are shown in circles and the long bodies are indicated by arrows aligned in the direction of their axes. These are to examine how the bodies placed at different positions in the cross section are translated. It is seen that the trajectories of the objects are similar for the three assumed bodies. However, there are number of important differences among them. First the passive particles follow the flow motion exactly and they respond instantaneously to the changes of the flow field. The drag bodies receive only the drag forces that are in the direction of the relative flow and they also tend to follow the flow but with time lag in the response. Therefore the initial motion right after the bodies are released is slightly slower and the centrifugal force effects around the bend are also somewhat delayed. The long body has 10 times larger mass and the lag time is longer and that is why they seem to move slowest initially. The long body receives larger force and moves faster as

(a) t =3000s, passive particles (b) t =3000s, particles with drag (c) t =3000s, long bodies



(d) t =4000s, passive particles (e) t =4000s, particles with drag (f) t =4000s, long bodies



(g) t =5000s, passive particles (h) t =4970s, particles with drag (i) t =4620s, long bodies

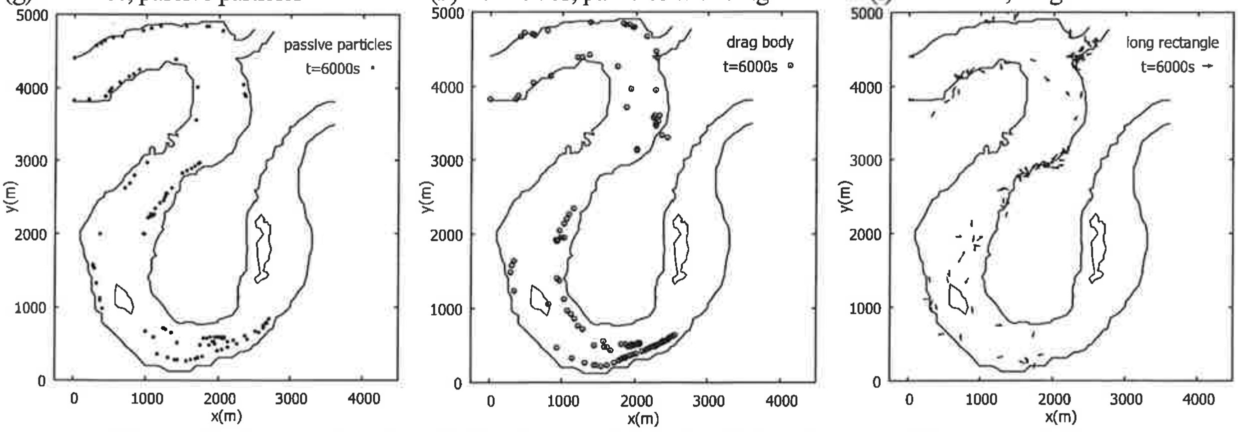


Figure 5. The movements of floating bodies of different properties around the bends.

(a) The location and direction of the picture taken

(b) The view of the river surface

Figure 6. The floating tree branch debris in the simulated area.

it rotates from the direction of the flow since the cross section along the axis is much larger than the cross section perpendicular to the axis. It is noted that they rotate unstably in the region where the tributary flow joins the main flow.

As to the accumulation on the banks, the passive particles and the drag bodies tend to stay within the flow and do not get washed on the banks. However, the long bodies accumulate on the banks, particularly on the outer banks they get washed up.

Although no detailed observation or measurements of the floating objects in the studies area yet, some survey was done. Figure 6 shows pictures of the surface of the part of Perak River that is simulated. The picture in Figure 6(b) was taken after a rainfall at the location and the direction of the camera shown in Figure 6(a). More tree branches are seen near the right hand side of the flow that is near the left bank after the confluence with a tributary. This is one of the areas the simulation indicated ling objects may drift and accumulate.

5. CONCLUSIONS

A LES based simulation method, that resolves the large scale motion of river flow that influences the transport of floating bodies the most, has been applied to track the trajectories of floating objects in rivers. The spatial resolution of LES is sufficient to resolve the shear producing turbulent motion and the secondary-flow effects but not fine enough to resolve the details of flow around the objects and drag and lift models along with the moment coefficient are assumed to reflect the interaction between the fluid and structure. These are intended to examine the trajectories of common objects on river surfaces such as trash and debris in rivers of scale much larger than the size of the objects and to find the effective methods of controlling them. Three models are used the the results are compared.

Although the results with the assumption of passive particles and bodies with mass and inertia, and bodies with directional characteristics are similar, there are significant differences in the reach with sharp bends. Bodies are transported faster along the thalweg of the river and very slow near the bank so the bodies initially aligned across the river width tend to align along the flow. It is found that the simple method of tracking passive particles is not accurate and can lead to incorrect prediction around curved channel. The motion of bodies with mass lags the flow motion so the secondary flow effects appear gradually and slowly. The long bodies that have larger resistance to flows perpendicular to it are influenced by its orientation to the flow and its yawing characteristics. If the long body aligns more perpendicular to the local flow it receives more drag force and follow the flow closely while, when it is aligned parallel to the flow, it receives less hydrodynamic force and responds slower to the changes of the flow. The different models of the floating objects will have to be further studied in different situations, but they need to be chosen carefully to simulate the motion of different sizes and characteristics of objects.

The present study is a step towards finding solution to various problems caused by floating objects on rivers. In the case of large objects with characteristic geometric properties such as the shape and the size, drag coefficient of varying values and its dependency on the relative flow direction can be assumed. It is a useful alternative method to more elaborate and expensive full fluid-structure interaction simulation.

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