Study of Secondary Flow and Sediment Transport in a Laboratory-scale Model of a Meandering River

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Abstract: Secondary currents strongly influence shapes of meandering rivers and cause sediment deposition on the inner banks and erosion on the outer banks. We report the curved channel measurements on secondary flow effects on flow pattern and on bed formation. The laboratory experiments were performed with a steady discharge until an equilibrium conditions was reached. A physical hydraulic model of the Sai Gon river portion around Thanh Da peninsula in Ho Chi Minh City was built respectively at scales of 1:500 and 1:100 in the horizontal and vertical directions. Both streamwise velocity and transverse velocity were obtained using three-dimensional Acoustic Doppler Velocimeter while sediment transport rates were evaluated by a sand trap. Our laboratory investigation provided evidence of secondary flow development in terms of position and magnitude and the relation to the bed morphology of the studied river. These results emphasize the crucial role of secondary flow in river dynamics and can be attributed to the numerical simulation process.

Keywords: Experimental hydrodynamics, Secondary flow, Sediment transport, Meander, Telemac 3D

1. Introduction

Dams and reservoirs provide important functions such as electricity generation, flood control, and water supply. But by trapping sediment in reservoirs, dams interrupt the continuity of sediment transport through rivers, resulting in declining ecosystem health through alterations to hydrologic regimes and sediment supply. Downstream ecosystem changes associated with dams frequently are caused by reductions in natural flood events, altered seasonality of flows, channel incision, loss of morphological complexity, coarsening of surface bed materials, increased interstitial fine-sediment (sand and finer) content in surface and subsurface sediments, ([25], [6]). There is increasing evidence of channel erosion and ecosystem impacts resulting from sediment starvation downstream of dams, often termed hungry water [10]. With the acceleration of new dam construction globally, these impacts are increasingly widespread. In the Mekong River basin, over 140 dams are built, under construction, or planned [7]. Once they are all complete, there will be a 96\% reduction in sediment load to the Mekong Delta [11], thus the ongoing subsidence and land loss in the Mekong Delta are likely to accelerate. Reversing river ecosystem fragmentation is therefore a primary goal of dam removal as a restoration strategy. Dams are designed to release sediment, either through the dam or around the reservoir, using a range of proven techniques, each applicable to a range of conditions.

In this regard, sediment transport following dam removal to downstream needs to be studied. However, natural rivers are characterized by complex geometries and often adopt a meandering course which create an unbalanced turbulent stress distribution along the cross-sectional plane, thus leading to the formation of secondary currents [18]. Since bed shear stress parameter has a significant and fundamental role in sediment transport mechanism of rivers and alluvial channels, considering the effect of the secondary flow and velocity distribution on flow pattern in order to predict bed shear stress distribution in river and open channel bends is of high importance and has been the subject of scientific study for a quite long time. Accordingly, there have been a large number of studies conducted on secondary flow structure and shear stress distribution at meandering channel. In 1876, Thomson was the first to report the existence of spiral flow pattern in bend channels due to interactions between the secondary flow and lack of consistency in velocity profile along the channel [20]. Then in 1950, Shukry noticed a smaller kinetic energy of the lateral flow comparing to that of the longitudinal orientation [17]. Rozovskii observed the appearance of secondary flow for a shallow bend with a central angle of at least 100 degrees, and a 180 degree bend for deep ones [16]. Drinker used colored water to track the secondary flows and found that near the bed, flows went towards the internal bend, while that on the water surface oriented towards the outer bank [4]. Blanckaert and Graf conducted some studies on flow pattern in a 120 degree sharp bend, reported the second circulation cell in the 60 degree cross section near the outer wall, and stated that the vortex is directed in the opposite direction of the main vortex [1]. Vaghefi et al. designed a 180 degree sharp bend flume to study bed shear stress distribution along the bend and concluded that the maximum dimensionless bed shear stress occurred near the inner wall at the 40 degree angle [23]. Later, they observed from the streamlines drawn in cross sections that there are two persistent clockwise vortexed formed at the center (primary vortex) and near the inner wall of the bend (secondary vortex) [24]. Numerical study of secondary flow was also developed in the 1990s with accelerating computer power, giving access to 2D and 3D hydrodynamic model. For depth-averaged 2D model, dispersion approaches ([14], [5]) and angular deviation approaches ([16], [9]) are used to take into account the influence of secondary flow. The first approach put the shift in velocities through the additional stress terms in the equations of motion while the latter concentrate solely on the change in the direction of bed shear stress. The direct simulation of secondary flows using 3D models ([28], [27]) gives the most benefits as it enable the study of flow...
components, changes in free surface and bed topography, study 3-D flow pattern... with high precision but yet still limited for medium to small studied area since its time consuming. Booij [2], Stoesser et al. [19] modeled the flow pattern with Large Eddy Simulation Method (LES), solving the Navier-Stokes equations by employing different turbulence closure approaches.

In this paper, we will focus on the sediment transport during a dam removal on a meandering channel. A laboratory-scale model has been established to this purpose and numerical simulation will be performed by using hydrodynamic model Telemac. Our investigation is necessary to study the impact of dam removal on natural river, thereby giving effective operation processes for dam and lake management.

2. Experimental Investigation

In the present study, the physical model with meanders developed by Nguyen and Tra ([12], [21]) was used for comparative hydrological simulations 3D models. We then use the same physical model to study the sediment transport rates in meanders and to calibrate the numerical model.

The investigations of Nguyen and Tra (2005) were carried out in a 0.6 m-wide-flume at the University of Technology, Hochiminh city, Vietnam (see Fig. 1). This physical hydraulic model was based on a portion of Saigon River around Thanh Da peninsula, in which the Froude numbers were kept in a range similar to those of the prototype river (horizontal and vertical scales were 1:500 and 1:100 respectively) while maintaining the Reynolds number in the turbulent regime [15]. The length of the bend-generated channel section was 3.6 m and the wave length was 6 m, thus make a sinuosity of 1.67. The banks were non-erodible with a Manning’s roughness coefficient of 0.014.

![Fig. 1 Experimental setup ([12], [21]), in which 1: pump, 2: flowmeter, 3: grains feeding, 4: screens, 5: upstream reservoir, 6: water level gauge, 7: ADV gauge](image1)

Figure 2 represents the bathymetry of the flume and studied cross-sections. The visualization of the bend apex (section B) is shown in Fig. 3, of which the outer bank’s slope is more inclined than that of the inner bank. However, the thalweg of channel is more or less in the middle at the upstream and downstream of the bend. In the initial state, the cross-sectional water depths under bank-full conditions with a steady-state discharge of 29 m³/h were at a maximum of approximately 0.13 m, which corresponds to a width/height ratio of approximately 3.

![Fig. 2 Schematic plan view of the flume (with bathymetry) and its studied sections](image2)

In order to establish the condition of sediment release during dam removal in river, a 2 cm sand layer was disposed at the upstream channel. The grains were chosen to be highly uniform with a median diameter of 330 microns (see Fig. 4). At the upstream side, a grains feeding was set to ensure the sediment availability, while at the downstream end, the sediment is trapped in a tank in order to estimate the particle flux. A discharge of 29 m³/h was fixed in the flume and each run lasted for few hours until the equilibrium condition was reached, which means there is no significant changes in bed morphology and solid transport rates. It is worth noting that the range of flow rates and velocities in our experiments are much higher than the previous study, due to the need for sediment transport.

![Fig. 3 Cross-section at the bend apex (section B). The outer bank (left side) is more inclined than the inner bank (right side)](image3)

![Fig. 4 Granulometry analysis of sediment. The median diameter of sand is 330 μm](image4)
3. Numerical Methods
To analyze the influence of the secondary flow on the bed load transport, the non-hydrostatic Telemac-3D module was used to simulate the flow and the velocities close to the bed directly. This module belongs to the Telemac-Mascaret system, a finite element computer program developed by Electricité de France (EDF) and become open-source code since 2010. As a 3D hydrodynamics module, Telemac-3D solves the three dimensional Navier-Stokes equations with a free surface changing in time. It also offers various methods to model the influences of turbulence (Elder, constant viscosity, mixing length, Smagorinsky, k-ω, k-ε).

To analyze the sediment transport and morphodynamic problems, the hydraulic module was coupled with the morphology module Sisyphe. The latter can be applied in diverse environments, such as coastal, rivers, lakes and estuaries, for different flow rates, sediment size classes and sediment transport modes. The sediment transport (bed load and suspended load) is determined on the basis of the non-steady state flow field and the sediment properties for each node of the computational grid. The morphological changes are calculated by solving the Exner equation by means of finite-element or finite-volume method.

About 60,000 computation cells were used in the 3D model for the vertical discretization with 10 layers. Among the available turbulence models, the standard k-ε model was used for both vertical and horizontal turbulence model since their results agreed with the experimental measures conducted by Tra and Nguyen [22]. The first hydraulic simulations based on scenario of flows with no sediment transport in rough bed served to verify the reproduction of the secondary flow by the numerical model. When coupling with the sediment transport module Sisyphe, the transport formulae by Meyer-Peter and Muller was applied to determine the bed load transport as this formula has already proven itself in straight channel studies with the same transport material [8]. The “hiding and exposure” effect is neglected in simulation as the sand is considered as monodisperse.

4. Results and Discussion
First, we recall in Fig. 5 the results of PIV measures of longitudinal velocity at section A (upper left) and between the two studied sections B and C (upper right) conducted by Nguyen and Tra [13]. By using Ansys Fluent software (which solves the Navier-Stokes equation by Finite Volume Method), they can re-establish the surface flows with the same order of magnitude (Fig. 5, lower image). Our experiment was with a higher flow rate (about 2.5 times) and lower downstream stage, thus induce streamlines of 5 times faster (see Fig. 6) but the same trend was observed for both cases. Our simulation results, which represent the contours of flows, show good agreement with the previous study. At the bend apex (section B), the vectors from the inner bank direct toward the center of the section, then toward the outer wall along the downstream channel with increasing speed. The increase of flow velocity and centrifugal force strengthen secondary flow, and the currents are more likely to affect the outer bank. Besides, it should be noted the existence of the flow from the outer wall going toward the inner wall. This phenomenon can be observed more clearly with the ADV measures.

Fig. 5 Flow field obtained by PIV (above) and simulation (below) carried out by Nguyen et al. [13] – left image is at section A and right image is between section B and C.

Fig. 6 Visualization of surface velocity from Telemac 3D simulation

Evaluations of the secondary flow at the three studied transverse profiles, using tangent vectors of flow applied to the observed sections are shown in Fig. 7. The shown analysis of the transverse profiles indicates the subsequent decrease of the secondary flow in the numerical model (cross-section B to C). The decrease of the helical motion can be observed over a long downstream section. This behavior agrees with observations in the laboratory experiments of Wormleaton et al. ([26]) or studies by Blanckaert ([11]). Moreover, by comparing these simulations results with measurement of Nguyen and Tra ([22]) using ADV devices (see Fig. 8c), our secondary flow profiles show good agreement. One can observe the second circulation cells in the opposite direction of the other. Since these two vortices were found close to the surface, this result indicated that the flow from the inner bank directing toward the outer bank and the reverse flow might exist simultaneously. However, as shown in Fig. 8a and Fig.
reported by other researchers [3]. The phenomena has also been observed during the experiments that around the section B, the large grains are sorted in size. It can be observed during the bend, which maintains the transverse slope of the bed from the inner bank. This changes not only the characteristics of the flow in meandering channel but also the modification of topography due to the bed load transport process. The cross-section of bend apex changes rapidly with time and leads to the feedback between the flow (including secondary flow) and the bed topography. Stable shape of the cross-section will be achieved after a certain period of time, of which the outer bank’s slope is more inclined than that of the inner bank.

8b, there is continuous change of the two vortices in dimension during the simulation time. When the flow from the inner bank is dominant (Fig. 8a), the inner vortex grows larger than the outer one. Conversely, when the flow from the outer bank is dominant (Fig. 8b), the inner vortex dissipates significantly. The factors attributing to this change are not only the characteristics of the flow in meandering channel but also the modification of topography due to the bed load transport process. The cross-section of bend apex changes rapidly with time and leads to the feedback between the flow (including secondary flow) and the bed topography. Stable shape of the cross-section will be achieved after a certain period of time, of which the outer bank’s slope is more inclined than that of the inner bank.

Fig. 7 Visualization of secondary flow (by vectors) at different transverse profiles (A, B and C respectively). The simulation results were extracted at 30 minutes. The contours represent the main flow velocity in m/s

The observed bed evolution in Fig. 9 shows clearly the effect of centrifugal secondary cell around the meander bend, which maintains the transverse slope of the bed from the outer bank to the point bar on the inner bank. As this circulation cell goes downstream of the apex, its effect to the outer bank dissipate. Another aspect of centrifugal force is the sorting of grains size. It can be observed during the experiments that around the section B, the large grains concentrate at the scour hole while the small grains lie on the bar at the inner bank. This phenomena has also been reported by other researchers [3].

Fig. 8 Comparison between the simulations and ADV measures (lowest image, [21]) at the bend apex. The simulation results were extracted at 15 minutes (a), 35 minutes (b) and 30 minutes (c), from up to down respectively. The contours represent the main flow velocity in m/s

Fig. 9 Bed evolution at equilibrium condition
5. Conclusion
The experimental and numerical studies on meandering channel show that the evolution of meander bed form is formed by the secondary flow on the bed load transport. Our 3D hydrodynamic simulation coupled with sediment transport module gives reasonable position of erosion and deposition regions, and with reliable orders of magnitude. The existing of secondary circulation cell observed in previous studies can be reproduced in our simulation. We also noted the instability of these two vortices with time. This can be attributed to the modification in bed topography and the continuous energy exchange between the principal and secondary flow. The analyses presented here are limited to morphological simulation of a laboratory model, that is, clearly structured model geometry with steady discharge and boundary conditions. This would allow the verification of the release of sediment to natural channel shapes with complex geometries.

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References


