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Towards the prediction of free-forming meander formation using 3D computational fluid dynamics

N. Rüther & N.R.B. Olsen

The present paper presents results of a 3D numerical simulation applied to a free-forming alluvial laboratory channel. Using computational fluid dynamics (CFD) the initial bed deformation as well as the propagation of meander bends was investigated. The model computed the river bed evolution over a real time period of 72 hours. On the basis of the simulation of water and sediment flow in an alluvial channel, different algorithms and parameters are applied and evaluated. Continuing the research of previous studies, the present paper focuses on the use of a free surface algorithm. Earlier investigations showed that the simplification of using a rigid lid approach for the water surface does not result in a sufficient agreement with the physical model data. The simulation was started from an initially straight grid, with neither sediment feed nor a geometrical perturbation at the inflow boundary. The results showed that three dimensional modeling of free forming meander is one step closer of having a predictor for alluvial channel migration. However, there are still uncertainties that have to be clarified in future investigations.

1 Introduction

The initialization and formation of meander bends is still a debated topic in the field of sedimentation engineering and geomorphology. The sediment transport in river bends is a complex phenomenon and influenced by many processes. E.g. the formation of bed forms in alluvial channels as well as the so-called helical flow. This characteristic flow exerts extra forces on the river banks, leading to possible bank retreat. The interaction of these processes and which one is dominating under certain flow conditions and how they are modeled numerically is still under investigation.

Modeling of sediment transport in river bends or meander related systems has been a topic of research over the last 30 years. Initially researches found universal relations for sediment transport on generally sloped river beds. The goal was to correlate the bed load transport rate in the transversal direction to that in the longitudinal one. The result were the first generation sediment transport models predicting transport rates in bended flow with the related bed deformation (Engelund, 1974, Odgaard, 1981 and Struiksma et al, 1985). With the time and increasing computer power, Duan et al (2001) presented a 2D hydrodynamic model on a structured grid, coupled with a sediment transport rate module, including algorithms for basal bank erosion to predict migration of meander evolution. The 2D hydrodynamic approach was enhanced with empirical formulas taking into account the effects of the three dimensional flow in a channel bend. In the study of Olsen (2003) a fully 3D model was presented and verified on the same data set Duan et al (2001) used. The model (Olsen, 2004) will be described in detail in chapter 2. The results from the simulation showed good agreement when predicting the meander migration from an initially straight channel with an upstream perturbation in terms of a single bend. Going one step further, Rüther and Olsen (2003 & 2005) showed first results on the simulation of meander evolution when using no initial perturbation. Their work focused on the formation of alternate bars and the initiation of meandering starting from a completely straight channel. The migration and rotation of meander bend could be modeled as well as characteristic meander bend topography. However, the results showed that the research is under current development and that the presented model configuration could predict only some characteristics observed in the meander experiment of Friedkin (1945). The goal of the present study was therefore to implement a free surface routine and to model the plan form evolution of an initially straight alluvial channel with neither an initial perturbation nor sediment feed from upstream and verify the CFD program on the data recorded by Friedkin (1945).

2 The Numerical Model

The numerical model used in the present study was developed by Olsen (2004). It solved the time-depending Reynolds-averaged Navier-Stokes equations in three dimensions to compute the water flow. The k-e turbulence closure scheme (Rodi, 1980) was used and the SIMPLE method (Patankar, 1980) was applied for computing the pressure. The discretisation method was based on a finite volume approach.

The free surface was computed by first solving the differential Equation (1). The difference in vertical elevation of the surface cell was then based on the pressure gradient . The obtained value was then corrected so that the final change in vertical distance in one cell was a function of the changes in the surrounding cells.

$$\frac{\partial z}{dx} = \frac{1}{\rho g} \cdot \frac{\partial p}{\partial x} \tag{1}$$

Simultaneously to these operations, the convection-diffusion equation for sediment concentration was solved. As boundary condition van Rijns’ (1984b) formula for the sediment concentration close to the bed was used. Additionally, the sediment continuity and empirical formulas (van Rijn, 1984a) were used to compute the bed load transport in order to predict the vertical changes in the bed morphology over time.

The model used a three dimensional unstructured grid with a mixture of tetrahedral and hexahedral cells to model the geometry. To allow changes in the bed morphology mainly in the lateral direction, the CFD program included an algorithm for wetting and drying (Olsen, 2000). This algorithm generated new cells in areas where erosion took place and let cells disappear where sediment deposited. Consequently the grid changed in shape and size over time as the geometry of the meandering river was formed. The criterion for the formation or disappearance of a cell was correlated to a certain minimum water depth ζ_1. A second value, ζ_2 was the responsible criterion for the formation of just one cell over the depth. Meaning, in areas with $\zeta_1 \leq y \leq \zeta_2$ only one cell was used and if $y \leq \zeta_1$ or $\zeta_1 \geq y$ cells will dry up or be wetted, respectively.

3 Results of the Numerical Simulation

The numerical model was setup similar to a physical model study performed by Friedkin (1945). A 40.0 m long tilting flume with a 12.0 m wide effective section was filled up with sand of about 0.6 m depth and an initially straight, trapezoidal shaped channel, with an average width of 0.6 m, a depth of 0.088 m and a slope of 0.009 was excavated.

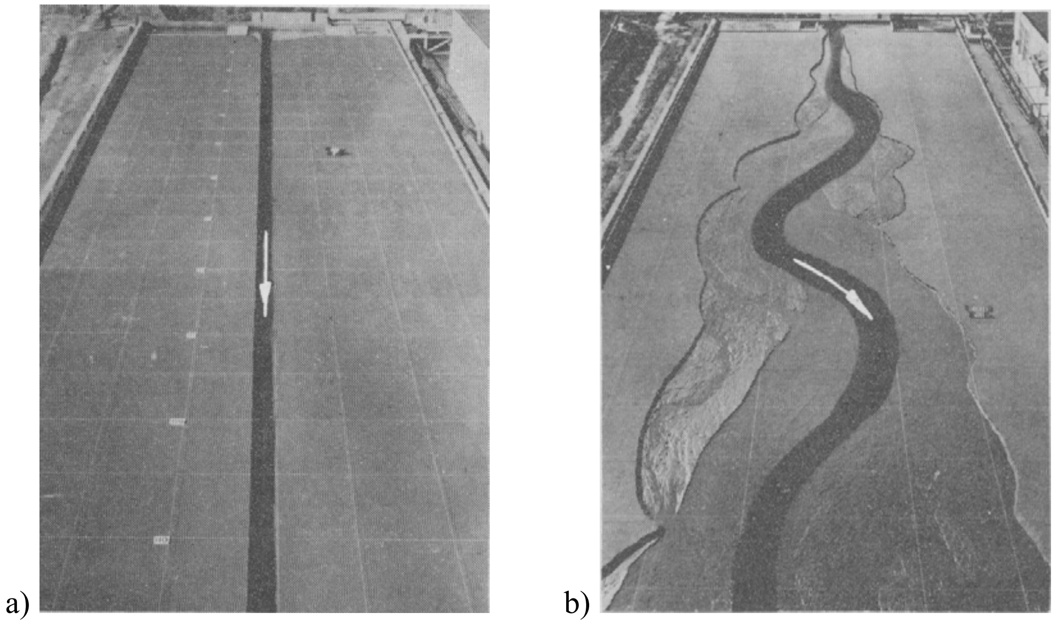

Abbildung 1 Initial condition, a) and developed meandering plan form b) in a physical model study. (Friedkin 1945)

It was then exposed to a constant discharge of 8.5 l/s with a water depth of 0.05 m. The sand material was fairly homogenous with a grain size distribution of d50 and d90 with 0.2 mm and 0.26 mm, respectively. Figure 1 shows the plan form after 72 hours duration of the experiments. The result showed a meandering channel with a maximum meander amplitude and wavelength of about 3.0 m and 12 m respectively. The meandering evolution started downstream of the first third of the channel length. In addition to this one can see that the bend size grow with increasing longitudinal distance.

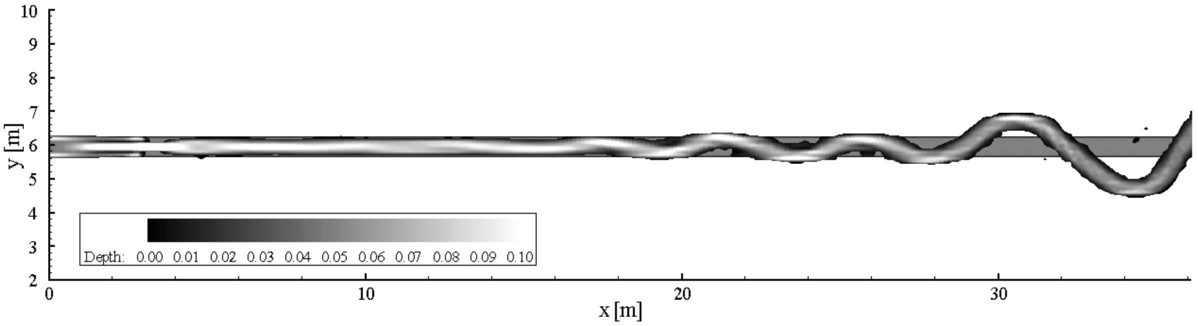

Abbildung 2 Simulation results with rigid lid approach

To illustrate the newly obtained results and to point out the improvement, they were compared to previously published results first. Figure 2 shows the meander formation when applying the rigid lid approach for the elevation of the water surface. The water level was continuously drawn down with a constant surface slope. Ruether & Olsen (2005) stated that the meander wavelength and amplitude was far underestimated and the location where the initially straight channel starts to alternate was far too downstream than compared to the physical model.

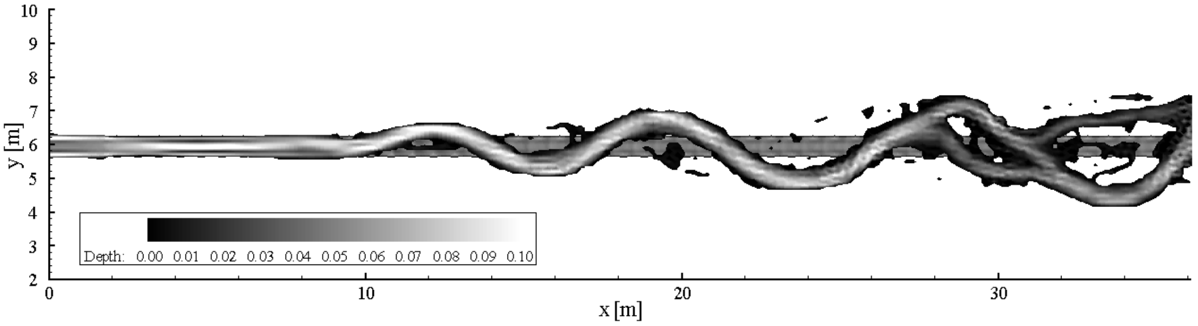

Abbildung 3 Simulation results with free water surface

Considering now the results obtained while applying the free surface algorithm, one can see the improvements clearly. Figure 3 shows the result of the developed meander formation. The location of the initiation of meandering, at around 11m of the channel, was clearly shifted upstream. In addition the one can see that the wave length was increasing. However the characteristic amplitude of the observed meander bends was not obtained in the numerical model.

One reason for the amplitude being too small might have been the fact that the sediment entrainment from the side was not sufficiently. The model was therefore extended with an algorithm that reduced the critical shear stress for sediment particles on side slope. The relation by Brookes (1963), Equation (2) was used and applied only in cells located at the side of the geometry. The reduction of the critical shear stress is expressed with a factor R defined as

$$R = -\frac{(\sin\alpha\sin\delta)}{\tan\Phi} + \sqrt{\left(\frac{(\sin\alpha\sin\delta)}{\tan\Phi}\right)^2 - \cos^2\alpha\left[1-\left(\frac{\tan\alpha}{\tan\Phi}\right)^2\right]} \qquad (2)$$

The factor R is a function of δ, the angle between the streamline and the direction of the bed shear stress, of α, the transversal slope of the channel bed and a slope parameter Φ, being similar to the angle of repose.

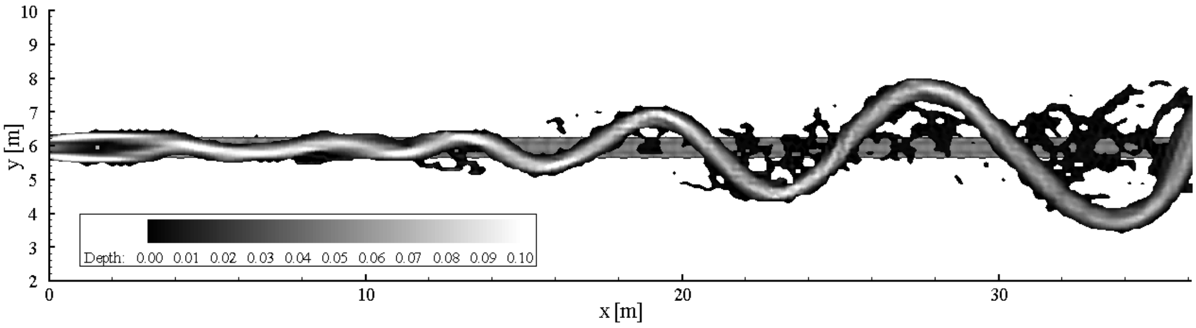

Abbildung 4 Simulation results with free water surface and a special algorithm for the initial motion of sediments on side slopes

In Figure 4 one can see the result using the improved numerical model simulating free forming meander formation. The wave length got slightly longer and the meander amplitude increased as well. The results showed that applying a free surface algorithm and a special treatment of the side cells improved the results.

4 Discussion

The result of a numerical model simulation of a free forming meander formation was presented in paragraph 3. In this paragraph the result is evaluated and compared to the physical model test (Friedkin 1945). The result is depicted in Figure 5. The center line of the meandering alluvial channel is extracted and illustrated with a solid line and compared against the centerline of the channel developed in the physical model test, marked with a dashed line.

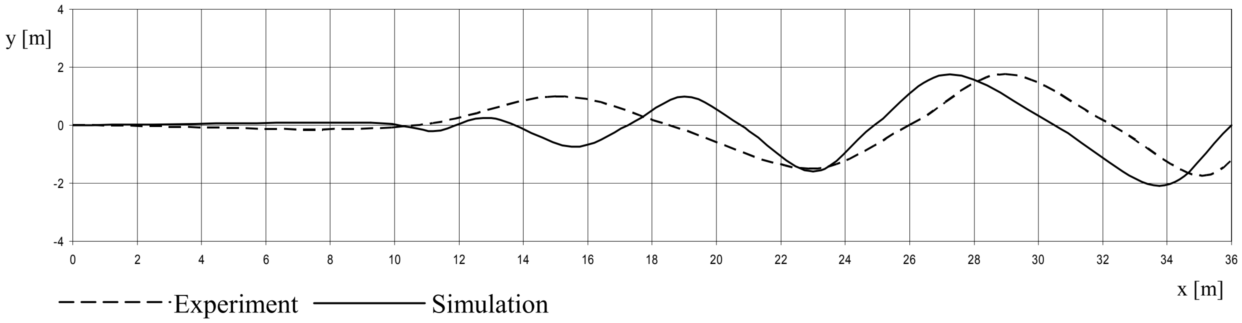

Abbildung 5 Centerline of the channel after 72 hours.

Considering first the upstream part of the channel, one can see that the initiation of alternation and meandering started roughly at the same location of the longitudinal coordinate of 11 m. However, looking at the consequent meander bends, one can see that the wave length in between x = 12 and 21 m was strongly underestimated by the numerical model, leading to the development of an additional bend. In contrast to that negative result stood the meander evolution in the most downstream end of the channel. The results showed that the wave length deviates 15 % from the physical model results, only.

When dealing the meander formation from an initial straight channel, the meander is increasing with increasing longitudinal direction. One can see from the Figure 5 that the growing amplitude at each location of the plan view matches very well to the measured values. This fact could be considered as the largest improvement compared to previous published results.

5 Conclusion

A CFD model has been used to simulate a self forming meander pattern over time. From an initially straight alluvial channel with neither an initial perturbation nor sediment feed, the model computes the initiation and the migration of the meander bends. Hence, the program predicts the process of erosion and sedimentation as well as the lateral movement of the channel. The results matched the measurements of the physical model study concerning the meander amplitude and downstream growth. The maximum meander wavelength was underestimated by around 15 %. The results showed that for the present case, model computing the free forming meander is functioning well.

Further research has to be carried out to improve the stability of the free surface algorithm and to test the model to other cases in order to obtain a universal predictor for meander formation in alluvial channels.

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