A classic example of failure due to the effect of initial condition in morphological computation in 2D numerical modelling

Hassan Kazi[1]*, Iqbal Tassawar[2]

[1]Independent Expert-River Morphology, Durham, United Kingdom
[2]Imperial College, London, United Kingdom
*Corresponding author, e-mail: iqbalhassankazi@yahoo.co.uk

Abstract

In the last few decades, both theoretical and experimental research have been carried out to understand the physics of the formation of large-scale migrating bed forms, called alternate bars. In alternate bar formation, sediment grain sorting effect is one of the most prominent phenomena. While the effect of sediment heterogeneity over uniform size was experimented in laboratory flumes, numerical models for morphology have often neglected the influence of sediment heterogeneity (Talmon, 1992). Most morphological modelling software (e.g. DHI, 2016) do not have provision of using graded sediment transport formula, e.g. Parker (1990) and Wilcock and Crowe (2003). A two-dimensional (2D) numerical model, applying Delft-2D River modelling software, with spatial and spatiotemporal variation of grain size, has been developed to establish the effect of sediment heterogeneity on bar formation. Two models have been developed; in one model, grain size field is functional to spatial co-ordinates; in the other model, grain size field is functional to local velocity field based on simplified idea of grain sorting. This paper presents results from the first model. Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic and transport simulation program for unsteady flow. Present 2D models use several tools: GRID2D for curvilinear grid generation; Delft2D-Flow/Mor for hydrodynamics of Saint-Venant unsteady flow equations, sediment transport and for bed level change through sediment continuity equation.

Keywords: sediment sorting, 2D modelling, Delft-2D

1. Introduction

River flow in alluvium consists of soil erosion products and material from river's bed. Over time, many typical river planforms evolve and one can see the shapes when taking a bird's eye view. Some examples of planforms are alluvial fan, meandering of river and delta of river mouth etc. Scientists are trying to understand and model mathematically the morphology of rivers. From a mechanistic point of view, it is basically the problem of flow and modelling the shape of the container. Therefore, it is a fluid mechanics problem but is highly complicated due to loose boundaries. Knowledge of sediment sorting, patterns and processes are important because it is fundamental to our understanding of modern and ancient fluvial systems (Carling and Dawson, 1996). Sediment sorting in gravel bed rivers exhibits complex, yet systematic patterns (see Figure 1). The bed surface of most gravel bed rivers is considerably coarser than the sub-surface or the gravel load transported over it, a phenomenon affecting river dynamics, morphology and ecology. The coarse surface layer, often called an armour or pavement, has been attributed to an inherent tendency for smaller grains to settle between larger ones during active transport of all sizes (Leopold et al. 1964; Parker and Klingeman, 1982), and to selective erosion or trapping of finer particles when the coarse grains are relatively immobile (Milhous, 1973, Sutherland, 1987). Patterns of sediment sorting in coarse-grained alluvial channels result from the segregation of particles with different physical characteristics during processes of erosion, deposition and transport. Perhaps, the most obvious manifestation of sorting occurs at the length scales with the downstream fining of the bed surface grain size. The earliest, frequently cited, report of such observation is that of Sternberg (1875) made on the river Rhine. Sternberg concluded that the weight of particles exponentially decreases in the downstream direction. This rule is normally referred to as Sternberg's law and seems very well to describe the reduction of particles due to abrasion.

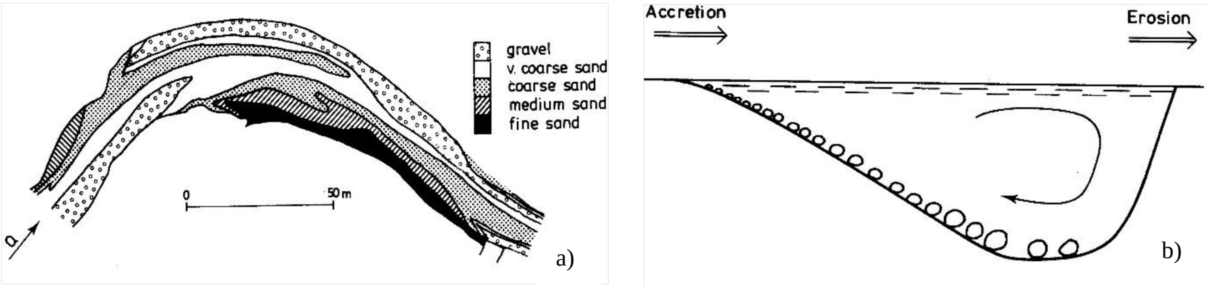

Fig 1: Sediment sorting at river bend (a) and at bed (b); Source (a): BRIDGE and BENNETT 1992)

The distribution of grain sizes at bends is also an important phenomenon. Due to down-slope transverse gravitational pull and secondary currents, grain sorting develops at river bends (Figure 1b). Size segregation also occurs at the grain scale and the bed form scale (Richards and Clifford, 1991). Most gravel bed rivers develop a surface layer, one or two-grain diameter thick, that is relatively coarse compared to the sand/gravel mixture beneath.

The need of graded sediment modelling was demonstrated by Mosselman et al. (1999). Application of a two-dimensional model at the Rhine bifurcation at Pannerden agreed better with prototype measurements than the results obtained from the mobile bed physical model. However, the numerical computation was carried out using spatially constant sediment properties and a spatially constant Chézy coefficient for hydraulic resistance, though the bed material indicates that sediment granulometry varies spatially due to grain sorting. Numerical computations were repeated recently using spatially varying grain size, and surprisingly it appeared no longer possible to predict the morphology. The causes and possible solutions were analysed theoretically by linear analysis (Mosselman et al. 1999). The linear analyses show that spatial variation in grain size can have large effects on the steady-state bed topography in rivers.

Due to unsteady flow in straight channel, an erodible bed becomes unstable and large-scale migrating bed forms, called alternate bars, develop (Struiksma and Crosato, 1989). However, alternate bars may also form under steady flow conditions. The changes in river morphology in response to such bed forms, whose height and wave length with flow depth and channel width, can have a significant impact on different aspects of river engineering. In the last few decades, both theoretical and experimental investigations have been devoted to understand the physics of the formation of such bed forms. At the Delft Hydraulics Laboratory, Struiksma and Crosato (1989) used a straight flume for the generation of alternate bars with uniform sediment. Lanzoni (1995 and 1997) used a straight flume for alternate bar generation for both uniform and graded sediment for flume experiments at Genoa University Laboratory for alternate bar generation with graded sediment. His test results show that the major and unambiguous effect of sediment heterogeneity is the decrease of bar height, and wave length tends to decrease with respect to the uniform sediment model.

Physical or mathematical models have often been developed for the prediction of morphological changes in rivers. An increasing number of studies were carried out with the help of 2D mathematical models (Olesen, 1987), and Talmon (1992). But most of the mathematical models neglect the influence of sediment gradation and its dependence over time and space. They only dealt with uniformly sized bed material. However, in case of large time and length scales, one-dimensional morphological models with the effect of sediment heterogeneity have been established (Ribberink, 1987).

2. Objectives

The main objectives of the research were to develop more insight of the alternate bar formation through numerical computation, and thus, to establish the effect of sediment heterogeneity on the formation of bars and to verify the results with theoretical analysis and with data obtained from flume tests. Thus, the research was aimed developing a 2D model of bed topography with spatial variations of grain size for computation of alternate bars from uniform grain size and for spatial variations of grain size and spatiotemporal variations of grain size.

3. Modelling Technology – Delft3D Flow/Mor

Reliable information on water quality, quantity, sediment transport and morphology can be obtained from numerical mathematical models. Delft3D-Flow/Mor (Deltares, 2014) is an integrated flow and transport modelling system. Delft3D-Flow solves the Navier Stokes equations for an incompressible fluid, under the shallow water and Boussinesq assumption. In the vertical momentum equation, the vertical accelerations are neglected, which leads to the hydrostatic pressure equation. In 3D models, the vertical velocities are computed from the continuity equation. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions are solved on a finite difference staggered grid. The water level points (pressure points) are defined in the centre of the continuity cell. The velocity components are perpendicular to the grid cell faces. The flow module provides the hydrodynamic basis for sediment transport and morphological computations. The sediment transport module for total and suspended load and morphological module for bed level changes use the flow field generated by the flow module. The present research used Delft2D-Flow/Mor as the 2D numerical modelling tool. This tool has been applied for generation of alternate bars comprising sediment grain size of constant value, spatial and spatiotemporal distributed value. Delft2D-Flow/Mor is supported by several other tools for generating orthogonal curvilinear grids, and generation of bed topography, spatially varying Chezy roughness, eddy viscosity field within the modelling domain. There is also graphical processing tool, GPP and Delft3D-QUICKPLOT for post processing of results and model data.

4. Model set-up

A 2D numerical model set-up for the flume set-up of Struiksma and Crosato (1989) was developed applying Delft2D-Flow/Mor to reproduce alternate bars as was observed in the flume results. The research mainly concentrates on the computation of alternate bars. Two types of alternate bars can be distinguished; namely forced and free bars. Forced bars under steady flow conditions do not propagate; they have uniform wave length but non-uniform amplitude with damping (positive or negative) in the direction of flow. Free bars under steady flow propagate downstream; free bars have non-uniform wave length and amplitude in the direction of flow; they are caused by inherent instabilities due to the interaction between water and sediment motion.

A model called D (x,y), with spatially varying grain-size, is established in 2D in Delft2D Flow/Mor as recommended in Mosselman et al. (1999). Model runs were carried out for both forced and free bars, and it is demonstrated how the results of the D (x, y) model differ from true representation of nature. Results from this model has been presented in this paper. A model called D (u), with spatiotemporal grain size variations as functional to local velocity (u) based on a simplified idea of grain sorting. This model provides the representation of the physical interactions in nature (Mosselman et al. 2003), and also similar to the linear analysis in Mosselman et al. (1999). How this D (u) model can replicate the non-linear system is investigated in the numerical computations. This model successfully demonstrated the effect of sediment heterogeneity. The bar height dams out appreciably and the wave length tends to increase with respect to uniform grain size (Mosselman et al, 2003). However, the D (u) model results are not part of this paper.

Details of flume set-up of Struiksma and Crosato (1989) replicated in the 2D model is presented in Table 1.

Flume length (m)	Flume width (m)	Flow (m^3/s)	Water depth (m)	Flow velocity (m/s)	Water surface slope (%)	Chezy Coefficient ($m^{1/2}/s$)	Froude No. (-)	Shields No. (-)	Sediment transport (m^3/h)
24	0.6	6.85x10^{-3}	0.044	0.26	3.00	22.6	0.39	0.37	2.0x10^{-3}

Table 1. Condition of straight flume set-up of Struiksma and Crosato (1989)

The length of the 2D numerical model was 30 m; width was 0.6 m; cell sizes were 0.25 m and 0.1 m in x- and y-directions respectively. In the forced bar 2D model, spatially varying grain size, (D (x, y), was generated using Eq. 1. $D_{50\ (uniform)}$ was used as 0.216 mm; several sensitivity runs were carried out by varying amplitude (0.05, 0.10, 0.20), phase (0, 45, 90, 120, 180 degrees) and wave length (±30%) in Eq. 1.

$$D_{50}(i,j) = D_{50}|_{\text{uniform}} + \widehat{D}_{50} \cdot \cos\left(\frac{2\pi}{L_1}x + \phi\right) \cdot \cos\left(\frac{\pi}{B}y\right) \qquad (1)$$

Where i, j are grid numbers in the x- and y-directions respectively, $D_{50\ (uniform)}$ is uniform grain size, $\widehat{D}_{50}$ is amplitude over the uniform size, L_1 is wave length, B is channel width and ϕ is phase angle.

Forced alternate bars have been simulated in the D (x, y) model. Forced bar is generated with steady asymmetric sediment supply at inflow boundary of the 2D model. The inflow of transport is prescribed at the two end grid points; asymmetric variations are obtained by linear interpolations in the Delft2D-Flow/Mor. At downstream boundary, equilibrium bed profile is used. The initial grain size field was perfectly in phase with pools and bars, i. e., coarser grain sizes were in the pool areas, and finer sizes were in the bar areas (Fig. 2). The run matrix of different grain size field carried out in 2D model is shown in Table 2.

Type of spatial variation in grain size	Amplitude $\hat{D}_{50}$ in m	Phase in degree	Wave length (L_1) in m	Presentation in Figure 8
Sensitivity on amplitude	$0.05D_{50\ (uniform)}$	0	6.55	a
	$0.10D_{50\ (uniform)}$	0	6.55	b
	$0.20D_{50\ (uniform)}$	0	6.55	c
Sensitivity on phase	$0.10D_{50\ (uniform)}$	0	6.55	d
		45	6.55	e
		90	6.55	f
		120	6.55	g
		180	6.55	h
Sensitivity on wave length	$0.10D_{50\ (uniform)}$	0	1.3*6.55	i
		0	0.7*6.55	j

Table 2. Set-up of the run-matrix of alternate bars in the Delft-2D model

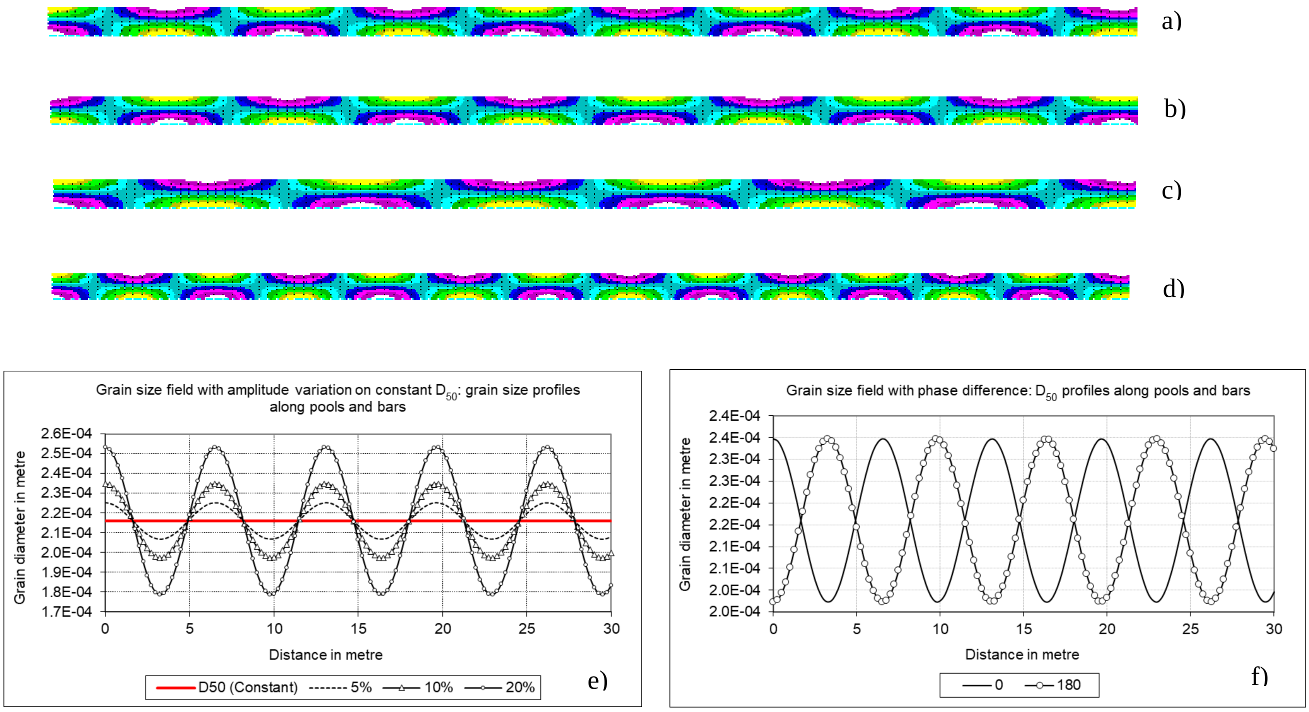

Fig 2: Alternate bars with phase 0^0 (a), phase 180 degree, phase 0^0 and wave length 30% longer (c), phase 0^0 and wave length 30% shorter (d), grain size distribution profile along alternate bars of phase 0^0, but of different amplitude of 5%, 10% and 20% higher than constant D_{50} (e) and grain size distribution profile along alternate bars of phase 0^0 and phase 180^0 (f)

5. Results and discussions

The amplitude of equation 1 has been varied as 5%, 10% and 20% over the constant size $D_{50\ (uniform)}$ size of 0.261mm. The grain distribution field is shown in Fig. 2a-d. From the simulation results, the velocity, depth and D_{50} profiles suggest (see Figures 4.9a and b) that the coarser grains are on the point bars, while the finer grains are on the pool and contradicts the natural phenomenon of formation of pools and bars (Sternberg, 1875, Mosselman et al. 1999, 2003), where finer particles deposits on the inner bend to form point bar and the pool is on the outer bend with higher depth and coarser particles. But in the present computation, due to initial grain size set-up in the D (x, y) model, finer grain size becomes the dominating function; simply more transport is generated for the finer particles from the bar area, thus, the pool and higher velocities are out of phase, and are developed in the areas in phase with the finer particles. Similarly, less transports are generated in the area of coarse particles where out of phase low velocities are detected (Fig. 3a-b). This is very much in contrary to the nature in the formation of alternate bars, where coarse particles move to the pool and finer particles to the point bars. Would the particle size be gradually allowed to adapt with the velocity field (Mosselman et al. 2003), the results would be in harmony with the nature. The conclusion is that the free forcing of the particle size distribution generated by the equation 1 is dominant than the imposed forcing at the boundary. The dominance of forcing is reflected in Fig. 3a-b.

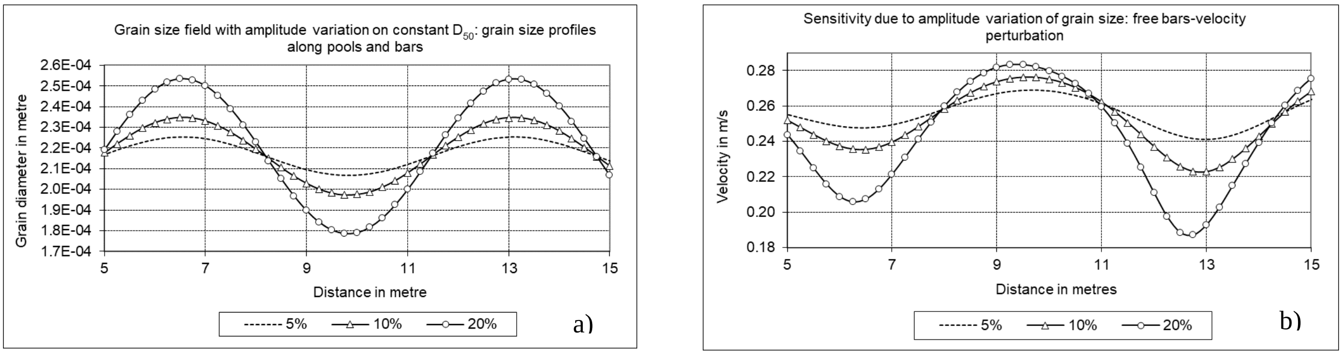

Fig 3: Grain size profiles along the pools and bars from 5%, 10% and 20% amplitude variation over the $D_{50\ (uniform)}$ size (a) and corresponding velocity profile from 2D model (b)

Variation on grain size fields has also been generated using equation 1 by changing phases from 0^0 to 45^0, 90^0, 120^0 and 180^0 degrees (see Fig.2a-b, only 0^0 and 180^0). The results are similar to the sensitivity on amplitude variations; only the grain size field is changed in a variety (different phases). From the D_{50} and depth perturbation, it is observed again that the higher velocity and the pool depth are produced at the finer particle side and the lower velocity on the coarse grain side (Fig 4a-b). This is very much pronounced in case of 180^0 phase, where the opposite phase of the grain size profile has put the depth perturbation to the opposite phase in respect to the 0^0 phase.

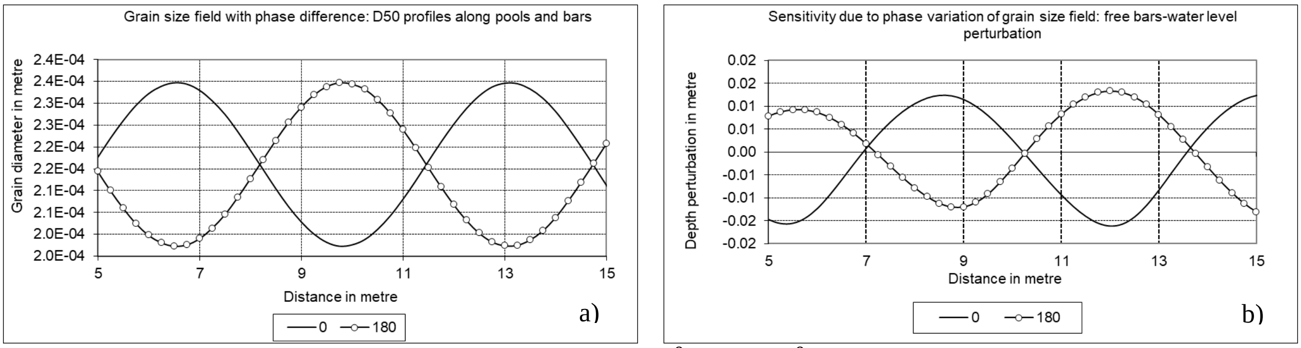

Fig 4: Grain size profiles along the pools and bars 0^0 and 180^0 phase variation $D_{50\ (uniform)}$ size (a) and corresponding velocity profile from 2D model (b)

The results, however, show an important finding that placing of the grain size fields affects the wave length and amplitude. The increase in the phase from 0 degree to 180 degrees decreases both the pool depth and the bar height (Fig4-b). The wave length also decreases with the increase of the phase (Fig4-b); the reasons would probably be the balance between the imposed forcing by the grain size field and the forcing imposed at the inflow boundary.

6. Conclusion and recommendations

Two-dimensional modelling with the numerical modelling tool, Delft2D-Flow/Mor, has been carried out to reproduce the formation of alternate bars, which were observed in a laboratory flume experiments. Effects of sediment heterogeneity on the formation of alternate bars have been modelled. Computations are carried out for both free and forced alternate bars. Spatial variations of grain size are used in the computation of the sediment transport. The D (x, y) model fails to represent the nature. The effects of grain sorting for alternate bars could not be reproduced. The free forcing imposed by the grain size field (which is constant over time) completely overrules the imposed inflow boundary conditions, what have been used to generate the free and the forced bars. The free and forced bars computed from the D (x,y) models are almost identical in spite of their different imposed inflow boundary conditions, because they use identical grain size field, which implies that the boundary conditions are immaterial when such grain size fields are imposed. The model simply ignores the effect of random sediment perturbation imposed at the inflow boundary to generate the free bars. The D (u) model successfully replicate the effects of grain sorting (Mosselman et al. 2003), which is though not part of this paper. Similar morphological computational failure can happen in 2D modelling for using spatially constant coefficient, e.g. Chezy or Manning's roughness value or Eddy viscosity. It is recommended to apply spatiotemporal field in case of morphological modelling where updating of river bed is employed.

Acknowledgment

The author gratefully acknowledges the support of WL-Delft Hydraulics (now Deltares), Delft, The Netherlands.

Reference

Bridge, J. S. and Bennett, S. J. (1992). A model for the entrainment and transport of sediment grains of mixed sizes, shapes and densities, Water Resources Research 28, 337-63.
Carling, P.A. and Dawson, M. R., (1996). Advances in fluvial dynamics and stratigraphy, *Wiley*.
Deltares (2014). Delft3D 3D/2D modelling suite for integral water solutions, Hydro-Morphodynamics, *User Manual, Version: 3.15.34158*.
DHI. (2016), MIKE21C, Curvilinear model Scientific Documentation.
Lanzoni, S. (1995). Experiments on free and forced bar formation in a straight flume, Q1774, *WL | delft hydraulics*.
Lanzoni, S. (1997). Experiments on free and forced bar formation in a straight flume, Q1774, *WL | delft hydraulics*.
Leopold, L. B., Wolman, M. G. and Miller, R. (1964). Fluvial processes in Geomorphology, *Freeman*, San Francisco.
Milhous, R. T. (1973), Sediment transport in a gravel-bottomed stream, PhD thesis, Oregon State University, Corvallis, Ore.
Mosselman, E., Sieben, A., Sloff, K. and Wolters, A. (1999). Effect of spatial grain size variations on two-dimensional river bed morphology, *IAHR Symposium on River, Coastal and Estuarine Morphodynamics*, Genova, September 1999.
Mosselman, E., Hassan, K. I. and Sieben, A. (2003). Effect of spatial grain size variations in two-dimensional morphological computations with uniform sediment, *Proc. RCEM 2003, 3rd IAHR Symp. on River, Coastal and Estuarine Morphodynamics*, Barcelona, Eds. A. Sánchez-Arcilla & A. Bateman, Publ. IAHR, Madrid, ISBN 90-805649-6-6, pp.236-246, 2003.
Olesen, K. W. (1987). Bed topography in shallow river bends, Doctoral thesis, Delft Univ. of Tech., (also: Communications on Hydr. and Geotechn. Engrg., *Delft Univ. of Tech*., Dept. of Civil Engrg., Rep87-1, ISSN 0169-6548.
Parker, G. (1990). Surface-based bedload transport relation for gravel rivers, *Journal of Hydraulic Research*, Vol.28, No. 4, 417– 436.
Parker, G. and Klingeman, P. C. (1982). Water Rsour. Res. 18, 1409-1423.
Richards, K. S. and Clifford, N. J. (1991). Fluvial geomorphology: structured beds in gravely rivers, *Progress in Physical Geography* 15, 407-22.
Ribberink, J. S. (1987). Mathematical modelling of one-dimensional morphological changes in rivers with non-uniform sediment, Doctoral thesis, *Delft Univ. of Technology*, Rep. 87-2, ISSN 0169-6548.
Struiksma, N. and Crosato, A. (1989). Analysis of a 2D bed topography model for rivers, *Water Resources Monograph*, River meandering.
Sutherland, A. J. (1987). Static armour layers by selective erosion in sediment transport in Gravel-Bed Rivers, *ed. Thorne, C.R. et al. 243-260, Willey*, London
Sternberg, H., (1875). Untersuchungen über langen und quer~pro~fil-geschiebeführende Flüsse, Zeitschrift für Bauwesen, Vol. 25.
Talmon A. M. (1992). Bed topography of river bends with suspended sediment transport, Doctoral thesis, *Delft Univ. of Tech*.

Talmon, A. M. (1992). Bed topography of river bends with suspended sediment transport, Doctoral thesis, Delft Univ. of Tech., (also: Communications on Hydr. and Geotechn. Engrg., *Delft Univ. of Tech., Dept. of Civil Engrg*., Rep. 92-5, ISSN 0169-6548.

Wilcock, P. R. and Crowe, J. C. (2003). Surface-based transport model for mixed-size sediment, *Journal of Hydraulic Engineering, ASCE*, Vol. 129, No. 2, 120–128.