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Low-Reynolds modelling of high-concentrated near-bottom suspended sediment transport

Erik A. Toorman
Hydraulics Laboratory, Civil Engineering Department, Katholieke Universiteit Leuven
Kasteelpark Arenberg 40, B-3001 Heverlee, Belgium
E-mail: erik.toorman@bwk.kuleuven.be

Extended Abstract

Introduction

Sediment transport studies at the scale of estuaries and coastal areas nowadays can be dealt with using 3D numerical models. For historical and computational reasons, the most advanced models solve the hydrodynamics for the suspension and the sediment mass balance equation, assuming that particles move at the same speed as the fluid, except for the gravitational settling. Because of the difference in vertical and horizontal grid spacing, vertical turbulent mixing is solved with a two-equation model, while horizontal mixing is usually done with a constant eddy viscosity model (or sometimes a basic Smagorinsky model). The hydrodynamics is usually calibrated on water level data, by tuning the roughness parameters. These models can predict general trends, but their quantitative prediction capacity remains poor. Closer examination shows that predicted velocity profiles usually deviate considerably from measurements. This is no surprise considering the fact that none of these models can simulate even the most elementary laboratory flume experiment. Many years of attempts to simulate sediment transport with numerical modelling and of analyses of experimental flume data has slowly revealed various problems that seem to have been underestimated in understanding sediment transport (Toorman, 2002; Toorman *et al.*, 2002; Toorman, 2003).

Suspension capacity

A numerical experiment with a standard sediment transport model with increasing sediment load allowed a study of the suspension capacity of open-channel shear flow (Toorman, 2002). This shows that the traditional suspension capacity criterion for a dilute water column is equivalent to a Rouse number (Z) equal to 1 and a constant flux Richardson number. However, confrontation against experimental data reveals that the true suspension capacity of the water column depends on the suspended load of the high-concentrated near-bottom layer. Therefore, the traditional criterion does not determine the true suspension capacity but rather corresponds to a stability limit. Another serious problem is the observation that the standard k-ε model always yields a limiting flux Richardson number of 0.25 (a consequence of the model constant values), which is much higher than found from experimental data.

Drag modulation

Since the first flume experiments two major observations were made: the apparent change of the slope (von Karman "constant" κ) of the log-law for the velocity profile and of the effective bottom roughness. The above mentioned suspension capacity experiment revealed that the standard modelling approach automatically yields a reduction of the slope of the log-law to a value deduced from the criterion $Z = 1$, which seems to be confirmed by experimental data. However, for natural particles, such as sand, the settling velocity is so high that the standard model does not succeed to keep the measured amount of solids in suspension.

A study of flume data reveals that the high-concentrated near-bed layer fulfils super-saturated conditions ($Z > 1$) and is not fully turbulent. This suggests that an additional suspension mechanism is in play. It is hypothesized that the turbulence generated in the wakes of the particles fills in this gap.

Interestingly, comparison of velocity profiles for non-cohesive sediment transport with high near-bottom concentrations in flat bottom flumes show exactly the same features as flow over a rough bottom and suggest apparent roughening of the bottom.

Hence, it seems that low-Reynolds modelling is necessary to simulate what is happening close to the bottom. However, a major drawback of most of the low-Reynolds models is that they are validated for smooth bottom conditions only and non-existent for suspensions. The few models for rough bottoms have been evaluated and still show some problems. Heredia *et al.* (2007) have tried to improve these models. Since most published experimental data do not provide sufficient detail, LES simulations have been carried out of flow over a wavy boundary (Widera *et al.*, 2009). These data have been averaged in time and space in order to provide average profiles over an entire wave. The resulting profiles show very similar characteristics as for suspension flow over smooth bottoms.

An alternative explanation for the apparent decrease of κ would be an increase of the effective shear velocity. The LES data indeed show a higher peak near the crest of the wave and some experiments with particles (e.g. Kiger & Pan, 2002; Righetti & Romano, 2004) also show a Reynolds stress peak, which is even higher for the particle turbulence than for the fluid flow. However, there is no evidence of such a stress peak in data for flume experiments with sediments at high concentrations (e.g. Cellino, 1998). The Reynolds stress data rather suggest that the additional wake generated turbulence is not accounted for in the Reynolds stress obtained from the traditional processing of the turbulence data (Righetti & Romano, 2004), and at the same time explains the strong reduction of the Reynolds stress in the (super-saturated) high-concentrated layer. Hence, the (apparent?) reduction of κ remains a puzzle.

A new low-Reynolds model

From these observations, it is concluded that a breakthrough in sediment transport modelling requires explicit modelling of the high-concentration effects in the transient benthic layer. Traditional Low-Reynolds two-equation turbulence models require a much too fine grid to be applicable to large scale sediment transport engineering studies. A new strategy is proposed (Toorman, 2010) which applies a new low-Reynolds mixing-length (ML) model in the near-bottom layer and a new low-Reynolds k-ε turbulence model in the water column above. The low-*Re* ML model is calibrated on DNS data for clear water flow, and new LES data for flow of a wavy bottom surface (Widera *et al.*, 2009) and provides the necessary boundary conditions for the low-*Re* k-ε model.

The standard sediment transport modelling approach (with constant Schmidt number) yields a serious underprediction of the suspended load in the outer water column (fig.1). Applying Toorman's (2008, 2009) theoretical Schmidt number closure, validated once more independently with the NS data of Muste *et al.* (2005), resulted in an improvement of the shape of the predicted sediment concentration profile (fig.1).

Based on the observations in the flume data of Muste *et al.* (2005) that the suspension capacity could be increased by the presence of more sediment, without any measurable variation in turbulence properties, the assumption is made that the necessary turbulence for suspending more particles must be generated in the wakes of the particles. Since this extra turbulent energy only occurs in the neighbourhood of the particles, the corresponding eddy viscosity (assumed to be proportional to the volume fraction) for the bulk suspension momentum en *k*-*ε* balance equations is only applied to a fraction proportional to the volumetric fraction of the particles, but for the sediment mass balance accounted for in full. This allows to reproduce the NS experiments from Muste *et al.* (2005) (Figure 1).

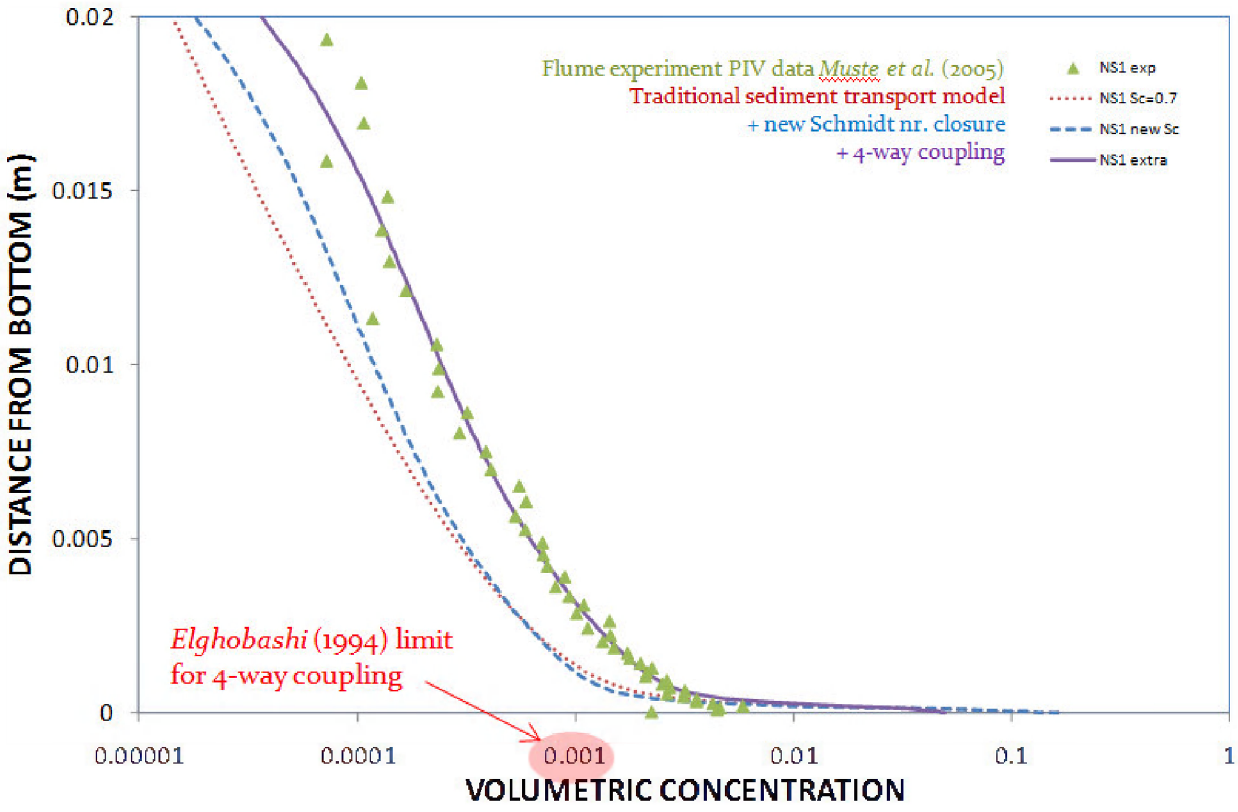

Figure 1: Simulation (with the KULeuven FENST-2D research code) of a flume experiment (run NS1) by Muste *et al.* (2005). Comparison between the "standard" model with constant Schmidt number, improvement of the profile shape when using Toorman's (2008, 2009) theoretical Schmidt number closure and the new improved mixture theory.

The particle wake generated turbulence has been modelled semi-empirically. However, attempts have been made to reconstruct the full set of equations for the suspension by a volume- or weight-averaged sum of the two-phase equations. This confirms that an important term is missing in the traditional sediment transport momentum equation, i.e. the "diffusion" stress (Manninen & Taivassalo, 1996), resulting from the velocity lag between the two phases. The fact is that its Reynolds-averaged form and the subsequent reconstruction of the TKE equations turns out to be very problematic.

The present work seems a promising road towards better understanding and modelling of high-concentrated suspension flow near the bottom.

Future work will focus on the refinement of the closure equation for the wake generated turbulence, further validation of the model and on the adaptation (including upscaling) of this boundary treatment methodology in large-scale sediment transport models used in engineering studies.

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