Discrete element modelling of bedload transport

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Nous présentons un modèle pour décrire le transport solide par charriage à l'échelle de la particule. La phase granulaire est modélisée par la méthode des éléments discrets. La phase fluide est prise à partir de mesures expérimentales de profil fluide. Le couplage se fait uniquement en considérant l'effet du fluide sur les grains à travers la force de trainée. Les résultats du modèle sont comparés à une expérience particulière. Nous obtenons un accord satisfaisant compte tenu de la simplicité du couplage.

We present a model for the description of bed load transport at the particle scale. The granular phase was modelled using discrete element method while the fluid phase was characterized by a fluid profile taken from the experiment. The coupling between the two phases was done considering only the effect of the fluid on the particle, through the drag force. The results of the model were compared to particular experimental results. A good agreement was obtained on the particle velocity and solid volume fraction in function of the depth considering the simplicity of the coupling.

Key words

bedload, modelling, discrete element method**,** solid-fluid coupling

I INTRODUCTION

Bedload transport represents an important contribution to the sediment flux in a stream, and consequently has major implications in environmental flows and associated problems, such as floods for example. Bedload is characterized by particles transported along the bed in rolling, sliding or saltating motion. Although it has been studied since more than one century, an accurate description is still lacking. In particular, when approaching the threshold of motion the usual semi-empirical formulas such as Meyer-Peter and Müller [1] and Rickenmann [2] give estimations which are different by some order of magnitudes from the one measured in experiment.

Recently Frey and Church [3][4] pointed out the interest of an analysis of bedload as a granular phenomenon. In fact, as the phenomenon takes place at the interface between the fluid and a

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granular bed, it is strongly influenced by granular interactions, especially when considering conditions near the threshold of motion. Accordingly, the idea is to take advantage of the recent advances made in physics of granular media [5][6] and apply it to bedload. However such an approach requires to consider each particle independently and experimental measurements at the scale of the particle are mostly limited to two dimensions. In fact, while it is possible to get full-field three dimensional data in quasi-static cases (e.g. using synchrotron radiation or tomography), analysing bedload at the particle scale requires to be able to sample also dynamical cases which is today not possible. As the experimental studies are limited, it is interesting to use numerical simulation to be able to generalize analysis of the phenomenon to three dimensions and have access to all the quantities at the grain scale.

Until now, in bedload few simulations at the particle scale have been made, and they mainly focused on the sheet flow regime, where the number of layer of grain in motion becomes important [7-9]. For simulation nearer to the threshold of motion, we can cite for example pioneering work of Jiang and Haff [10] focusing on the segregation process, but also the work of Scmeeckle *et al.* [11] which focused on the effect of turbulent fluctuations due to the bed on the transport. However, these represent few studies and the use of numerical simulation can still be very valuable for the understanding and characterization of bedload.

Consequently, there is interest in developing a model to study bed load near the threshold of motion. Moreover, we have a set of experimental data in two dimensions (2D) with measurements made at the scale of the particle [12-14] which is available in order to validate the model before generalizing to three dimensions.

We present here a first version of our numerical model based on discrete element method (DEM) to describe the granular phase, coupled with a simplified fluid phase. After performing a sensitivity study on the results are compared with experimental data.

II EXPERIMENTAL DATA

We give here a rapid description of the experimental conditions we are going to reproduce in the simulation. The full experimental setup, analysis method and results are described further in [12-14].

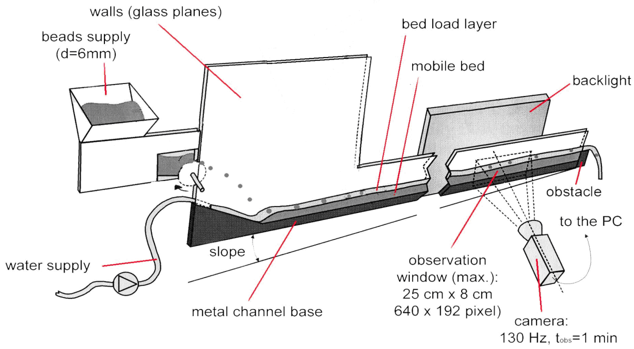


Figure 1. Scheme of the experimental setup.

A scheme of the experimental setup is presented in figure 1. Experiments were performed with 6mm diameter spherical glass beads entrained by a shallow turbulent and supercritical water flow down a steep channel with a mobile bed. The channel is two meters long, with a width of 6.5mm, slighlty above the width of the particles in order to have a quasi 2D situation. The channel inclination can be changed but is fixed at 10% in the results presented here. The water flow rate and the particle rate were kept constant at the upstream entrance and adjusted to obtain bedload transport equilibrium. The bed level is fixed thanks to an obstacle placed at the channel outlet. The water flow rate considered here gives a Shields number of about 0.1, while the solid flux at equilibrium is of 19.6 beads per second.

Flows were filmed from the side by a high-speed camera. Using image processing algorithms made it possible to determine the position, velocity and trajectory of all particles.

III MODELLING

The model consists in coupling DEM with a fluid phase. We focus here on the general description of the model and the application of the experimental case considered in the last part.

III.1 Granular phase

The granular phase is modelled using DEM, more precisely the so-called molecular dynamics formulation. This method has been applied to granular media first by Cundall and Strack [15] and has since been used extensively in different situation from quasi static to dynamic condition [16]. DEM is based on the explicit resolution of the equation of motion for every particle considering only nearest neighbour interactions. The particles are considered as non-deformable but can overlap each other : this allows to calculate explicitly the contact force from the overlap using a representative contact law. For more details, see [16].

We use the open source DEM software Yade [17] which allows us to benefit from a developed code while being able to modify the source code for our purpose.

The contact law has been chosen in order to fit the behaviour of the grains observed in bedload: from quasi static inside the bed to dynamic at the top of the bed where the particles are entrained by the fluid. It is necessary to have energy dissipation at the contact to take into account the dissipative character of a dynamic granular medium. Accordingly, we chose a simple and classical linear spring-dashpot law.

To compare the numerical data with the experimental one, we tried to reproduce the experimental situation while considering justified simplification for numerical efficiency.

As data are obtained at transport equilibrium, we used periodic boundary conditions in order to avoid boundary effects and finite size effects as much as possible. The base of the channel is made of sphere “glued” in the channel with a random altitude distribution chosen between 0 and 1 diameter, as done in the experiment.

The restitution coefficient (which determine the damping value) was set to 0.9 and we checked it has not an important influence within the range of the usual characteristic values (0.6 to 0.9).

III.2 Fluid coupling

As the fluid is turbulent, the numerical resolution of the fluid phase is complicated. There is today no satisfying solution in term of accuracy and computational time to handle the turbulent fluid numerically considering that there are discrete particles inside. As such, we decided to implement as a first step a one-way coupling : we consider only the effect of the fluid on the particles and not the effect of the particle on the fluid. This permits to take the fluid profile from the experiment to calculate the force applied on the particles. This is interesting for two reasons : first it is a simple basis that we can improve later; second, it allows to see if it is necessary to resolve the turbulence finely to describe the phenomenon.

The fluid profile is broken down in two parts : a part above the bed from measurements made on the stream without particles [18], and a part inside the bed, estimated from a fit of the particle velocity measured experimentally. This last point has been motivated by experimental results showing that the particles and fluid velocities are close inside the bed [19]. The profile obtained is logarithmic above the bed as expected in a turbulent flow, with an exponential decrease inside the bed.

This gives us for the downstream fluid velocity :

$$\begin{aligned} u_x(z) &= v_0 \exp\left(-300\,(z-z_0)\right), \quad z<z_0 \\ u_x(z) &= v_0 + u_s/K \ln\left(\alpha + (z-z_0)/k_s\right), \quad z>z_0 \end{aligned} \qquad (1)$$

where v_0 is the velocity of the bed at the interface, z_0 define the interface, u_S is the shear velocity, k_S is the roughness, K is the Von Karman constant and α is taken to ensure the continuity of the profile. z_0 was taken in order to get a solid flux similar to the one obtained in the experiment.

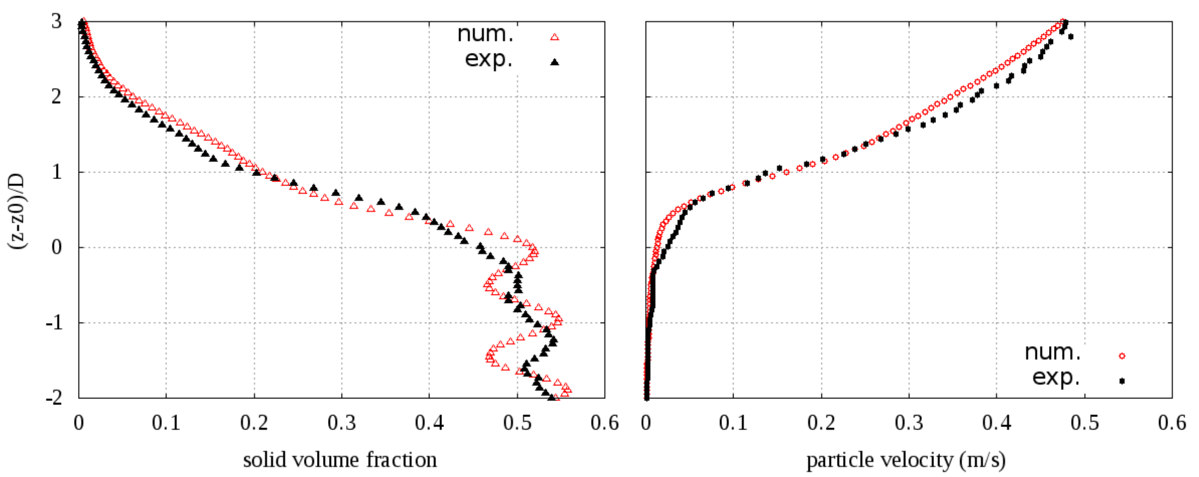
For simplicity, we restrict the force of the fluid on the particle to the drag which is known to be the main contribution. The drag coefficient is taken as $C_d = 0.5$.

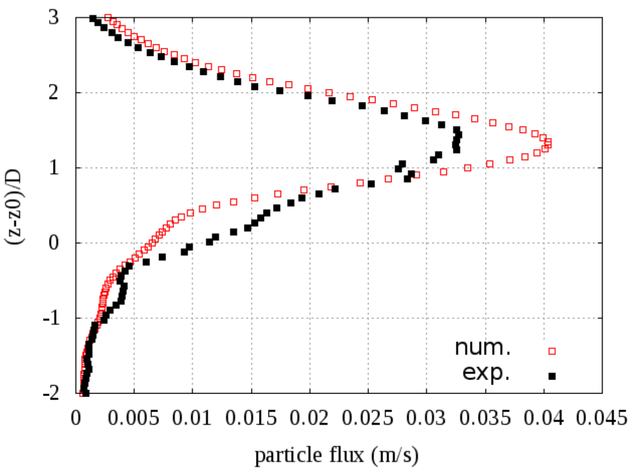
IV RESULTS

We performed a sensitivity analysis on the numerical parameters in order to be sure that the results do not depend on their values. First, the use of periodic boundary conditions is justified if the results are independent of the cell size and is reproducible. We found that a cell size of 200 diameter length allows the results to be reproducible. In this study the fixed particles at the base of the channel were created randomly at every runs, this means that the base generated does not influence the results. In order to be sure there is no other effect of the cell size on the results, we tested a cell of 1000 diameter length and found that there was no difference with the 200 diameter cell.

In DEM, the stiffness of the particles can usually be reduced without influencing the behaviour. It has the advantage to reduce computational time. Performing a sensitivity study, we found that in the situation considered, the mean quantities used (particle velocity and solid volume fraction depth profile) are independent of the stiffness if taken superior to 10^3. Accordingly we chose the stiffness of the particle to be of 10^4 for computational efficiency.

We consider now the results of the simulation and the comparison with the experiment. The comparison is made on the particle velocity and the solid volume fraction depth profiles. The data (numerical and experimental) are averaged in the streamwise direction and over time on 60 seconds runs. The solid volume fraction is defined as the ratio between the volume occupied by the particles and the total volume considered. The calculation is based on the discretization of the space along z in equal size layers, and the evaluation of the volume occupied by particles inside every layer. We chose a layer size small enough (0.1 diameter) such that the solid volume fraction depth profile does not depend on the layer size.





In figure 2, we see the comparison bet
the numerical one (red open symbol). The parti
and particle flux (fig. 2c, defined as the product
profile are plotted in function of the elevation
particles. Due to the periodic boundary conc
simulation such as the height of the downstrean
results, we adjusted the numerical profile on the
scale for the elevation on the figures is given wi
given by the height of the downstream obstacle
particles D.

On figure 2a, we can see for the particl
numerical results (open symbol) match well the experimental one (full symbol) with an exponential

decrease in the bed, followed by a linear part and a logarithmic profile above the bed. The agreement above the bed is particularly good while there is a small discrepancy at the interface between the quasi static and the dynamical bed ($z-z_0/D\sim0$). Similarly for the solid volume fraction (fig. 2b), the numerical data fit quite well the experimental one : we recover a similar value slightly superior to 0.5 inside the bed, and the trend is respected. Looking in more detail, we see that around the interface there is two differences : the shoulder around 1 is more strongly marked on the numerical curve than on the experimental one, and around 0 there is a decrease in the experimental data which is not present in the numerical one. The combined effect of the solid volume fraction and the particle velocity profile leads logically to a difference in the flux at the interface between numerical and experimental results (fig. 2c).

From these observations, we see that the general trends of the curve are recovered, even if there is some differences, in particular at the interface between the static bed and the bed in motion. This is not surprising as the description of the fluid is very rough, and stemming from two different measurements connected together at the interface. We can add that the effect of the particle on the fluid has not been taken into account in the upper part of the fluid, and we know that at the interface, the particles should clearly have an effect on the fluid. However, considering the simplicity of the coupling, numerical results show a strikingly good agreement with the experiments.

V CONCLUSIONS

We presented a discrete element model for bedload transport and compared it to experiment. We recovered the main features of the mean velocity and solid volume fraction depth profiles in function of the elevation. Even if the details are not exactly reproduced, it is clear that considering the simplicity of the coupling, the agreement is satisfying. To go further, we need to improve the quality of the description of the fluid and we plan to implement a two-way coupling using a turbulent mixing length 1D model for the fluid phase. This would allow us to reduce the fitting parameters and take into account the effect of the particle on the fluid which becomes important at the interface between the quasi static and the moving bed.

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