Comparison between particle-based and semi-empirical Sediment Transport Simulations of Scour around a Vertical Cylinder

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INTRODUCTION

Sediment transport in rivers and coastal regions affects most structures built in or besides those kinds of marine environments. One of the effects of interest is scour around structures e.g. pipelines, see Ahmad et al. (2019), or jacket structure, see Ahmad et al. (2019a), and the resulting strain on the integrity of the structure around which the scour is occurring. As the length scales of sediment particles and structures are usually very different it is inherently difficult to simulate sediment transport. A wide range of formulations for sediment transport can therefore be found in literature. However, for practical applications where speed is important most of the initiation of sediment transport and the quantification of sediment loads are today calculated using continuum-based methods relying on empirical relationship. The same is true for the open-source computational fluid dynamics model REEF3D::CFD which predicts scour on small and large scale using a bed-load transport rate based on the shear stresses near the sediment bed and a convection-diffusion equation for the suspended load are used for the global transport. In addition, a sand slide algorithm using Exner's formula is used to redistribute sediment on steep angles to account for local transport. The implementation of these processes is described in Ahmad (2018).

We aim to simulate the physics involved in particle transport on a more detailed level and explore the use of a Lagrangian approach to describe the sediment particles instead of the original Eulerian approach currently available in REEF3D::CFD. The model is capable of providing a 3D flow field for current, wave and combined current and wave conditions by solving the Reynolds-Averaged Navier-Stokes (RANS) equations together with the $k-\omega$ turbulence model. This flow field is then used in conjunction with a determinist model for entrainment and deposition and the level set method (Osher and Sethian 1988) for the main interface to simulate particle-based sediment transport.

METHODOLOGY

The Lagrangian approach utilizes the ability of REEF3D::CFD to simulate flow fields for laminar and turbulent conditions in current, wave and combined current and wave conditions. These flow fields are then fed to the particle model which computes three movements: the transport of suspended particles by advection, the deposition of suspended particles into the static particles which comprise the bed and the entrainment of formerly static particles from the bed. However, this approach of tracking individual particles is computationally expensive, therefore more efficient methods are required. A number of different approaches are available in literature depending on the type of use case. The multiphase particle in cell approach (MP-PIC) was developed by Andrews and O'Rourke (1996) as a combination of Euler-Euler and Euler-Lagrange model for dense particle flows to provide the advantages of both approaches, the high speed of Euler-Euler and the accuracy of Euler-Lagrange. It is most commonly used for application with a large number of particles which move at the same time e.g. fluidized beds. The Lagrangian particles in MP-PIC are no longer tracked as individuals, instead they are tracked as parcles of particles with identical properties. This grouping process was descriptively shown by Dymala et al. (2022) in their figure 2 depicted here as figure 1. This particle grouping drastically increasing computational performance. However, grouping particles together makes it impossible to resolve particle-particle collisions. MP-PIC therefore uses an inter-particle stress model to compute particle-particle collision and prevent solid volume fractions over the close-pack equivalent volume fraction.

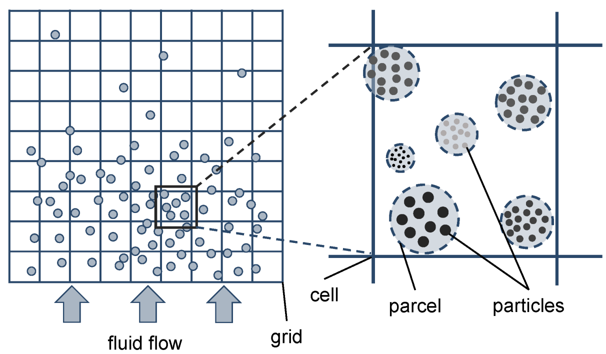

Figure 1 - Schematic of MP-PIC from Dymala et al. (2022)

Another option is the use of a Volume-averaged Reynolds-averaged Navier-Stokes equation (VRANS) for the static part of the bed similar to the approach for modelling porous structures by Sasikumar et al. (2020) in combination with individually tracked particles. This approach has the benefit of a drastically reduced number of actively moving particles which safes computational resources. However, this approach is only suited for application where the majority of particles stay stationary over most of the simulated time span.

NUMERICAL MODEL

Given a calculated flow field, the particle movement is calculated by solving a Newton Law of motion equation (Tavouktsoglou et al. 2021).

The following equation which incorporates drag and pressure forces as well as an expression for particle collisions.

$$\frac{d\vec{U}_p}{dt} = D_p\left(\vec{U}_f - \vec{U}_p\right) - \frac{\nabla p}{\rho_p} + \left(1 - \frac{\rho_f}{\rho_p}\right) g - \frac{1}{\theta_s \rho_p} \nabla \tau$$

The resulting particles movements are then coupled back with the flow field, to model the influence of the particles' movement on the flow. Depending on the formulation either an inter-particle stress for the use in MP-PIC or partially resolved particle-particle collisions with VRANS can be used for the particle collisions.

DISCUSSION

A Lagrangian sediment transport approach has the inherent average of a higher degree of resolvement of the particle physics, but it comes at the cost of an increased computational complexity. However, the required computational resources are relatively lower than the resources required for a fully resolved CFD-DEM simulation. Testing on scour around a vertical cylinder, figure 2 shows results of the current semi-empirical formulation. In comparison figure 3 shows the initial condition with a fully static bed made up of particles.

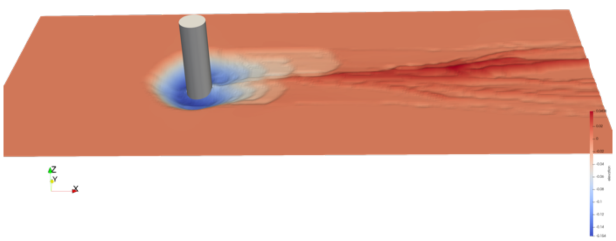

Figure 2 - Scour around a vertical cylinder using semi-empirical formulation in REEF3D::CFD

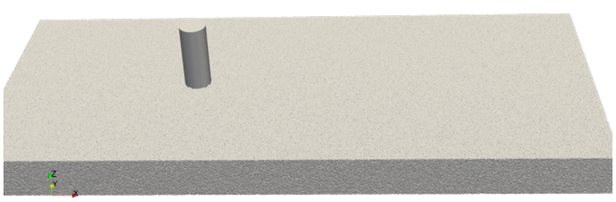

Figure 3 - Initial bed composed of particles for the simulation of scour around a vertical cylinder using a Lagrangian approach in REEF3D::CFD

CONCLUSIONS

The integration of particle based sediment transport enables REEF3D::CFD to simulate sediment transport in current and waves while attempting to resolve the sediment particle physics in more detail and not requiring the computational resources usually needed to run full CFD-DEM calculations. This approach provides valuable inside on other effects moving particles have on structures like for example mechanical stresses due to impacts or in futures projects the collapse of breakwaters due to local scour and the follow up effects.

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