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NUMERICAL SIMULATION OF HIGH-SPEED SEDIMENT ENTRAINMENT

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Sediment is eroded at high flow velocities in dredging practice and breaching of dikes and dams. Sediment pick up functions based on erosion experiments at low or moderate flow velocity mostly overestimate the pickup. Recently special pick-up functions are derived for the special conditions encountered during erosion at high flow velocity and solids concentration. The pickup functions are implemented in a 2D hydrodynamic RANS model which includes erosion and sedimentation. The results of the model are compared with experiments performed in flow loop of the dredging laboratory of Delft University of Technology.

KEY WORDS: Dredging, Breaching, Sediment Pickup .

1. INTRODUCTION

Hydraulic excavation of sand is a process often encountered in Dredging Engineering. Sand is eroded by high flow velocities using water jets. The erosion process that will take place can be compared with natural erosion due to the influences of waves and currents. The erosion velocities in dredging, however, can be several orders of magnitude higher than those found in natural erosion processes (Van Rhee, 2010). Sediment pick-up functions derived for natural erosion processes tend to overestimate sediment pick up. Special experiments were executed to study the erosion process at high flow velocity.

2. SEDIMENT ENTRAINMENT FUNCTIONS

The erosion velocity is often expressed as the difference between the pick-up flux and sedimentation flux:

$$v_e = \frac{E-S}{\rho_s(1-n_o-c_b)} \tag{1}$$

Where E = the erosion or pick-up flux, S = sedimentation flux, ρ_s= density of particles, n_0= porosity and c_b= near-bed concentration. The sedimentation flux reads:

$$S = \rho_s w_s c_b \tag{2}$$

Where, w_s= settling velocity (including the effect of hindered settling). The pick-up flux is often presented in non-dimensional form as:

$$\Phi_p = \frac{E}{\rho_s\sqrt{g\Delta D}} \tag{3}$$

Where g= acceleration due to gravity , D = particle diameter and Δ = specific density defined as $(\rho_s - \rho_w)/\rho_w$ .A pickup function provides the relationship between the pickup and flow and particle characteristics. For instance (Van Rijn, 1984):

$$\Phi_p = 0.00033 D_*^{0.3}\left(\frac{\theta-\theta_{cr}}{\theta_{cr}}\right)^{1.5} \tag{4}$$

Where θ = Shields parameter, which is a non-dimensionalised bed shear stress, and θ_{cr}= Critical Shields parameter, and D_* a dimensionless particle diameter defined as:

$$D_* = D\sqrt[3]{\frac{\Delta g}{\nu^2}} \tag{5}$$

Where, υ = kinematic viscosity. More pickup functions are available but these functions are empirical and calibrated on experiments with relatively low values of the concentration and flow velocity above the bed (bed shear stress). It was shown by (Van Rhee, 2010) that the existing pick-up functions for the situations typically encountered in dredging (high concentration and flow velocities) over predicted sediment pick-up. At low flow velocity (say < 1-1.5 m/s) the erosion process is mainly determined by the particle size. For higher flow velocity the bulk properties of the sandbed (permeability and porosity) are also influencing the pick-up (Van Rhee, 2010, Bisschop et al., 2015). The influence of permeability and porosity for high flow velocity can be included in existing pickup functions by adapting the value of the critical shear stress. The adapted critical shear parameter θ_{cr}' for a horizontal bed reads:

$$\theta_{cr}' = \theta_{cr}\left(1 + \frac{v_e}{k}\frac{n_l-n_0}{1-n_l}\frac{A}{\Delta}\right) \tag{6}$$

Where k = permeability, n_0= porosity of the sand bed, n_l= porosity at a loose state (often maximum porosity), v_e = erosion velocity and A = a coefficient. When the ratio between the erosion velocity and permeability is low the second term between brackets diminishes in Eq. (6) and the adapted critical Shields parameter becomes equal to the original critical Shields parameter. Note that now in the critical Shields parameter the erosion velocity appears. Therefore the erosion velocity can often not be written explicitly as a function of the flow parameters and must be solved iteratively. (Van Rhee, 2010) combined this approach with Van Rijn's pick up function and showed that agreement between experiments and the adapted pick up function of Van Rijn was much better compared to Van Rijn's original pick up function. The pick-up function adapted for high speed erosion is called Van Rhee's pickup function.

3. TWO DIMENSIONAL CFD MODEL

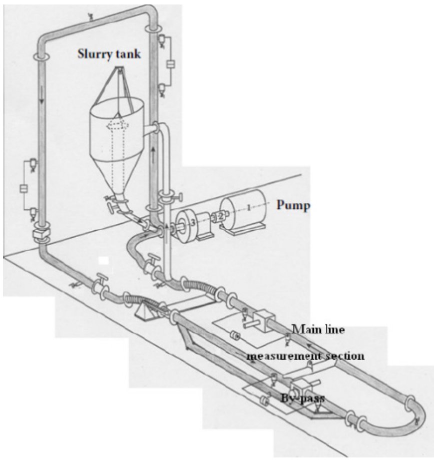
The pickup function of Van Rhee is implemented in a 2D computational fluid dynamics (CFD) model which includes the effect of a movable bed (due to erosion and sedimentation). In the CFD model the Reynolds Averaged Navier-Stokes equation are solved (mixture flow approach) with a k-ε turbulence closure. For details of the CFD model the reader is referred to (Van Rhee 2002). The CFD model is used to simulate erosion experiments performed at the dredging research laboratory of Delft University of Technology (Bisschop et al. 2015)

4. EXPERIMENTS

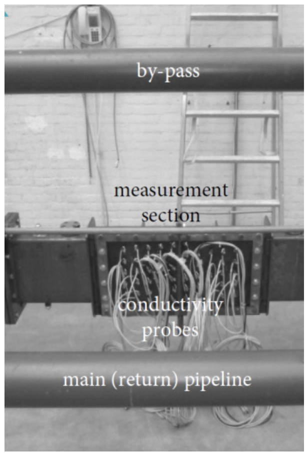
4.1. EXPERIMENTAL SETUP

In the Dredging Research Laboratory of Delft University of Technology erosion experiments were executed. Figure 1 shows an overview of the experimental facility. Bisschop et al. (2015) gives a detailed description of the experiments. The test arrangement consists of a closed circuit in which a sand-water mixture can be pumped through a parallel system of a closed measurement section and by-pass.

During the experiments the following quantities were measured: Density of the sand bed using a radioactive density meter that was adjustable in vertical direction. Hydraulic gradient by relative pressure gauges. Electromagnetic flow meter to measure the discharge through the measurement section and Temperature, sensor. The position of the top of the sediment bed was measured using conductivity probes. These conductivity probes consist of two electrodes placed at a distance of 7 mm and measure the concentration in the test section on that location. During an experiment the conductivity of 16 probes was measured. A sudden drop of the concentration in time marked the moment that the sand bed passed the location of the probe. The overall density of the mixture was measured using the pressure gradient in the upward and downward section of the circuit.



a. Overview flow loop



b. Measurement section

Fig.1 Experimental setup

4.2. TEST EXECUTION

The whole slurry tests was filled with clear water to check all instruments with a flow velocity of approximately 4 m/s. Subsequently sand was added to the flow loop and the concentration vertical was measured, in the test section using the radioactive density meter. The conductivity probes were calibrated using the values of the radioactive density meter. By opening the valve to the by-pass pipe and partly closing the valve to the measurement section the flow velocity in the measurement section dropped below the critical velocity and a sand bed was formed in the measurement section. After completely closing the valve to the measurement section, the remaining sand was removed from the slurry circuit. The erosion experiment was started by tuning the pump at the desired rotation speed and opening the valve upstream of the measurement section . Clear water flowed over the sand bed, starting the erosion process. The by-pass was kept open during the erosion experiment.

The erosion velocity was measured with the help of the conductivity probes. The measured hydraulic gradient was used to determine the effective bed shear stress during erosion. The sand used for the test was 'Geba' sand with the following cumulative distribution (see Table 1):

Table 1. Particle size distribution

Size [μm]	30	53	75	90	106	125	150	180	212	500
% smaller	0	1.1	3.2	7.8	21.8	49.9	80.2	91	98.5	100

5. RESULTS

Figure 2 shows the development of the flow velocity during a typical test. The continuous line is the bulk velocity calculated from the measured discharge and the cross section area of the measurement section (without a sediment bed), hence the bulk velocity when the sand layer would not be present. In reality a bed layer is present and the bulk velocity above the bed will be higher. The actual bulk velocity above the bed is indicated with the symbols in Fig. 2. The values at these symbols were determined when the sand bed passed a conductivity probe. Because the vertical position of these probes is known the height of the sediment bed and hence the flow depth can be determined. Using the discharge at that moment the bulk velocity above the bed can be determined.

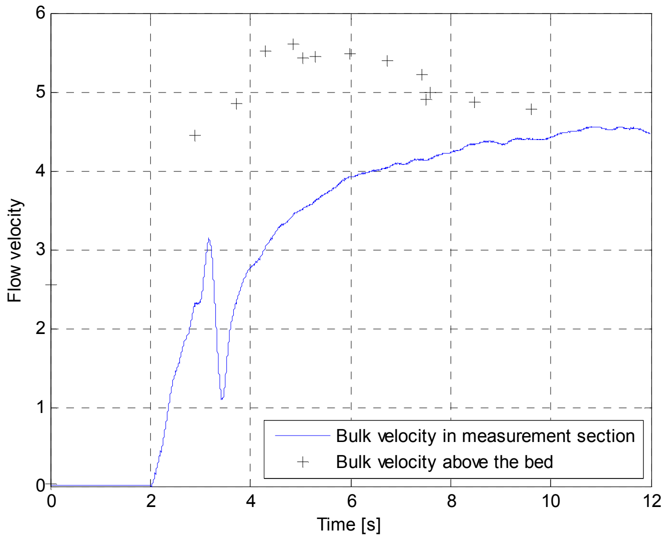


Fig.2 Flow velocity in the measurement section

Figure 3 shows the grid used for the computations and the bed level and concentration distribution at t = 8 s. Figure 4a (upper panel) shows the development of the measured concentration for a typical test. Most conductivity probes show a decrease in concentration the moment the sand bed passes the vertical position of a certain probe. Some probes show a slight increase and subsequent decrease in concentration. These probes were located above the sand bed at the beginning of the test. The probes are labeled **a** - **p**, where **a** is located closest to the bottom of the measurement section. The vertical distance between probe **a** and **b** = 5 mm, between **b** and **n** = 10 mm, between **n** and **o** = 30 mm, between **o** and **p** = 50 mm.

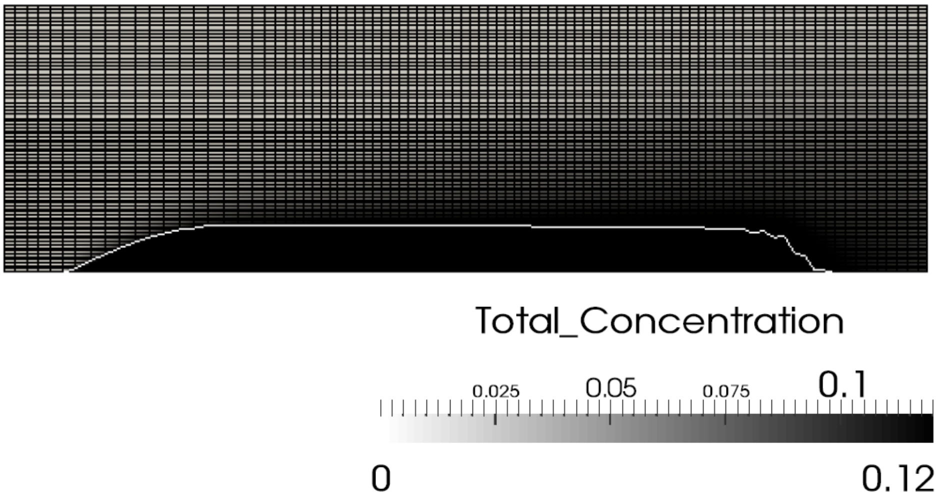


Fig.3 Computational grid, Bed height and concentration distribution at t = 8 s

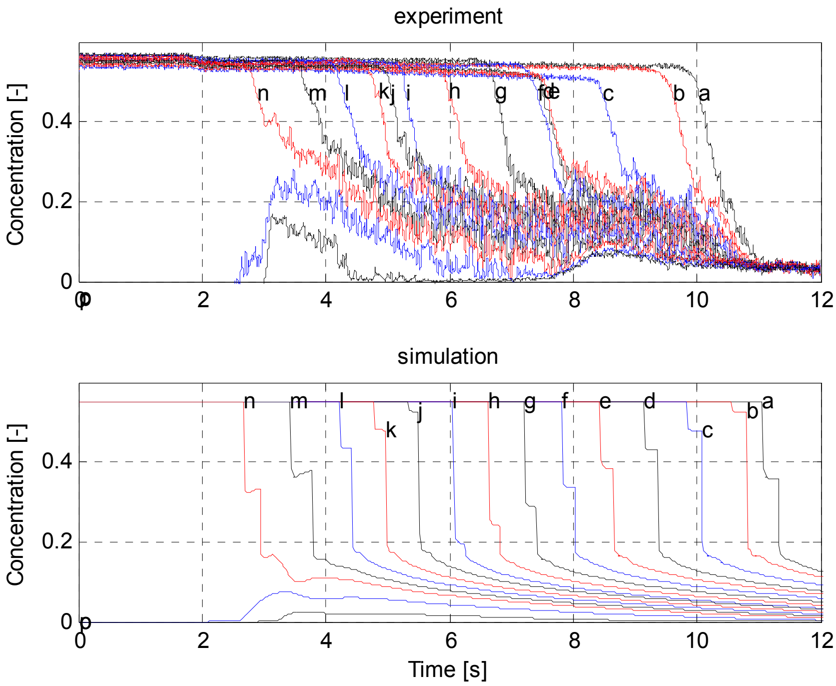


Fig.4 Measured and calculated concentration development

Figure 4.b (lower panel) shows the calculated development of the concentration for the computation. The concentration development is much smoother compared with the experiments which is to be expected with a RANS simulation where turbulence is modeled and averaged in time. The moment that probe '**n**' (the highest probe in the sand bed at the start of the test) is eroded is approximately at the same time for experiments and simulation. The time probe '**a**' is reached by the sand bed is at t = 10 s for the experiments and at t = 11 s for the simulation indicating that the pick-up rate in the experiments is slightly lower compared with experiment.

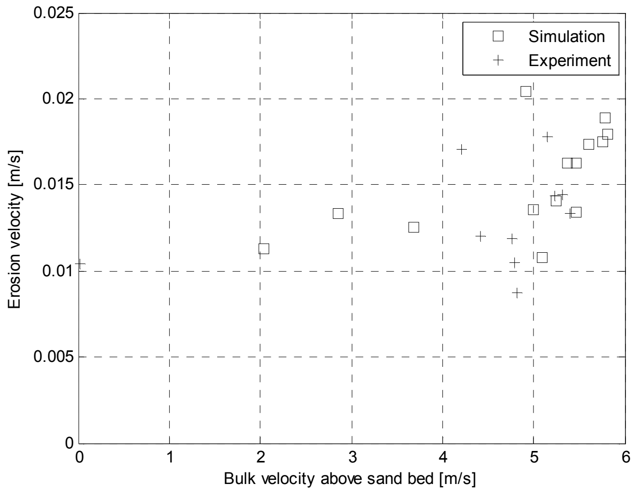


Fig.5 Comparison between the measured and calculated erosion velocity

Both for the experiments as the simulations the erosion velocity of the bed can be determined because the position of the bed as a function of time can be determined when the sand bed passes the conductivity probes. The measured and computed erosion velocity is plotted versus the bulk velocity above the bed in Fig. 5. The scatter is large both for the simulations as the experiments, but on average the erosion velocity between the experiments and simulations agree. More experiments with different sand types and flow velocities should be simulated but the results are encouraging.

5. CONCLUSION

The 2DV RANS CFD model with the pick-up function of Van Rhee was used to simulate high speed erosion experiments. The results of the model agree with experiment executed on fine sand with a D_{50} of 125 micron. More tests should be simulated in the future with different sand and flow velocities above the sand bed.

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