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Dan Nguyen

Miguel Uh Zapata

Georges Gauthier

Philippe Gondret

Damien Pham Van Bang

A TWO-PHASE NUMERICAL MODEL FOR THE WATER INJECTION DREGDING (WID) TECHNOLOGY: AN UNIFIED FORMULATION FOR CONTINUUM MECHANIC

D. PHAM VAN BANG(1), K.D. NGUYEN(1), M. UH ZAPATA(1),
G. GAUTHIER(2), P. GONDRET (2)
(1):Université Paris-Est, Laboratory for Hydraulics Saint Venant (ENPC – EDF R&D – CETMEF), c/o EDF R&D/LNHE, 6 quai Watier, F-78401 Chatou Cedex, FRANCE
damien.pham-van-bang@saint-venant-lab.fr
(2): Université Paris Sud, FAST (UMR CNRS 7608), Bat. 502 Campus Universitaire F-91405 Orsay cedex, FRANCE

This paper presents experimental and numerical studies on water injection dredging. A quasi 2D configuration is considered for the experiments. A (truly) 2D numerical model is used for the simulations. A general unifying theory is proposed for the two fluid model in order to correctly describe the solid-liquid transition for the particle phase. A good agreement is obtained on the crater sizes which are formed by the vertical (plane) jet impingement on sediment bed.

1. INTRODUCTION

Vertical jet-induced scour erosion in a sediment bed has been studied for many industrial applications such as aerospace or hydraulics. In Space engineering, the soil erosion or crater formation could generate problems for the launching or landing of spacecrafts as reported by Metzger et al. [1,2]. In Civil engineering, the Jet Erosion Test (JET) has been proposed for erodibility's assessment of soil material by Hanson & Cook [3] and Hanson & Hunt [4]. In Harbour engineering, similar configuration and phenomena are also reported for the Water Injection Dredging (WID) emerging technique by Lambert & Goudreau [5], Sigwald et al. [6] and Perng & Capart [7]. The interest for Water Injection Dredging (WID) technique, which was introduced during the eighties of the last century in the Netherlands, has been worldwide increased because the maintenance costs of navigation channels and the impact on environment are reduced as reported by Sigwald et al. [6] and Netzband et al. [8].

Investigations on erosion by a jet have been conducted under various conditions, mostly based under 3D axisymmetric conditions. Numerical simulations are fewer because the multi-physic (soil and fluid mechanics) character makes the problem very difficult at the sediment bed/liquid interface particularly. Metzger et al. [2], Weidner et al. [9] or Mercier et al. [10] considered a separation of the soil and liquid domains, empirical criteria to predict the evolving interface in order to adapt the computational grid to the liquid domain only. Kuang et al [11] considered a two-fluid model to compute fluid and sediment velocities in the whole domain, but the two-fluid formulation led to numerical artifacts (wavy interface and sediment recirculation, for instance) which is mainly due to the liquid like treatment for the sediment (solid) phase.

The present study aims to improve our understanding of the water injection dredging. Most of the difficulties are similar to the jet erosion test. The present approach considers the 2D (plane) submerged jet. Section 2 presents experiment set up to explore the 2D configuration. Section 3 presents improvement of the two-fluid formulation (i.e. similar to the model by Kuang et al. [11]) in order to produce the solid-like behavior of un-eroded sediment bed. This major improvement is able to describe the solid-like transition for the granular (or sediment) phase. Section 4 explores the prospects for developing and improving two-phase models for sediment transports.

2. EXPERIMENT SET-UP IN QUASI-2D

We consider their 2-D configuration illustrated by figure 1. A Hele-Shaw cell is used with a gap (between the two smooth parallel plates, 49.5cm x 20cm) equal to 3.2cm. The granular bed (10cm thick, uniform glass beads with density ρ_s=2.5t/m^3 and diameter d=400μm) is prepared by a fluidization procedure at solid fraction equal to 0.55. The horizontal flat granular bed is submitted to the vertical plane jet which shoots the bed from different distance, L, at various jet mean velocity U_J. The crater sizes (depth H and width D) are measured and non-dimensioned by the nozzle width, b (figure 1).

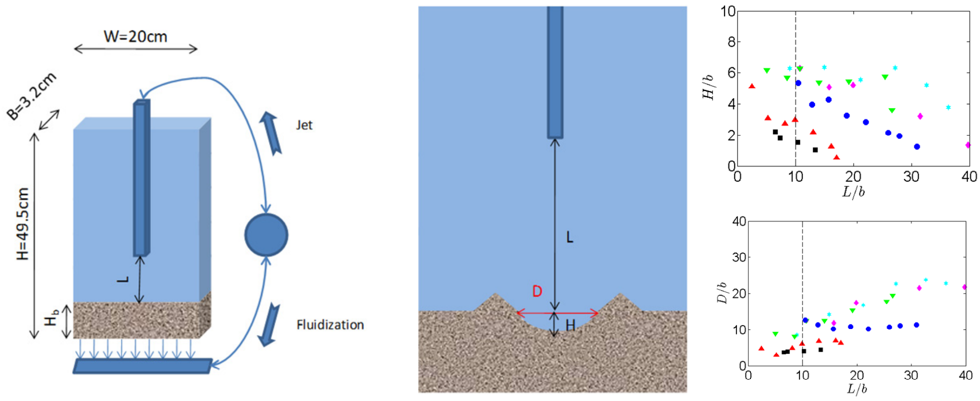

Figure 1. Experiment set up (left), definition of crater sizes (middle), results (right) in quasi-2D plane jet. Distance, L, depth, H, and width, D are divided by the jet nozzle size, b=4mm. The jet Reynolds number Re_J = 630 (■), 940 (▲), 1260 (●), 1570 (▼), 1730 (◆), and 1890 (*) based on b and mean velocity U_J.

The plane jet dredging capacity is estimated by jet Reynolds number ($Re_J = U_J b/\nu$ for $0.16 < U_J < 0.47$m/s) and Shield (or Erosion) number. As explained in Badr et al [12], the distance between nozzle and sandy bed is modified to account for the virtual origin, spreading angle and decay of the submerged plane Jet. The Erosion number is:

$$E = U_J \left(\frac{b}{L-\lambda} \right)^{1/2} \left(\frac{1}{(s-1)gd} \right)^{1/2} \quad (1)$$

where λ is the distance of the virtual origin from the nozzle outlet, s the solid to fluid density ratio, d the sediment diameter, g the constant of gravity.

The modified Jet-bed distance, L-λ, and the Erosion number, E, are used to re-arrange the results presented by figure 1 (right). The different points collapse into master curves with linear evolution (Figure 2) for $\lambda=10b$.

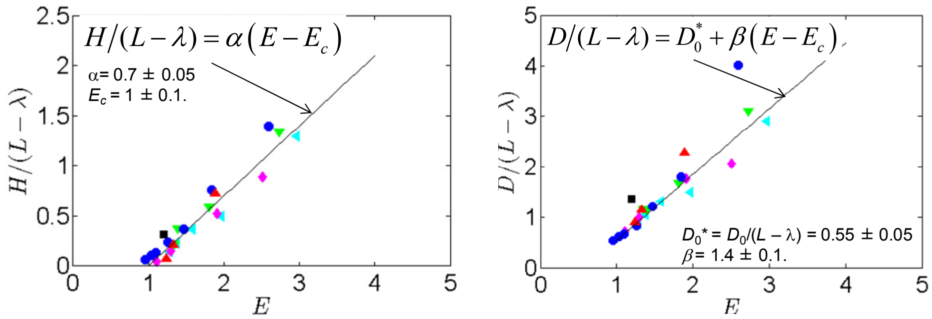

Figure 2. Crater sizes (depth H, width D) as function of Erosion number. Same data and legend as for figure 1. (redrawn from Pham Van Bang et al. [13])

3. NUMERICAL SIMULATION IN 2D

Two-fluid model

The two-phase numerical model is used for the simulation. The Euler/Euler formulation is fully described by Nguyen et al [14, 15] and Chauchat et al [16, 17]. For each phase k (is "f" for the fluid and "s" for the solid phase), the averaged governing equation reads:

$$\begin{cases} \dfrac{\partial}{\partial t}(\alpha_k\,\vec{u}_k)+\vec{\nabla}.(\alpha_k\rho_k\,\vec{u}_k\,\vec{u}_k)=\dfrac{1}{\rho_k}\vec{\nabla}.\left(\alpha_k\overline{\overline{\sigma_k}}\right)+\alpha_k\vec{g}+\vec{M}_k \\ \dfrac{\partial\alpha_k}{\partial t}+\vec{\nabla}.(\alpha_k\,\vec{u}_k)=0 \end{cases} \tag{2}$$

where α_k stand for the volume fraction of phase k (with $\alpha_s+\alpha_f=1$). $\vec{u}_k=(u_k,w_k)$, ρ_k and σ_k are the velocity, density and total stress tensor of phase k respectively. M_k is the inter-phase momentum transfer which accounts for interfacial momentum transfer, drag force.

The solver considers the sigma-transform to deal with the free surface, a projection method for the non-hydrostatic problem and a finite volume method on staggered regular or irregular grid. The time scheme is implicit in both, vertical and horizontal directions. Advection terms are handled by either hybrid or TVD schemes as described by Nguyen et al. [14, 15].

The solid-liquid transition of sediment phase

As pointed by Kuang et al. [11], unrealistic results for the motion of sediment are produced by the two-fluid model (Eq. 2). In particular, the bed/liquid interface is very wavy and sediment motion is predicted within the sediment bed. To improve this weak point, a new technique is implemented to describe the solid like behaviour for the un-eroded sediment and the liquid like behaviour for the eroded sediment. A general particle stress model resulting from the adaption of the proposition by Greenshields and Weller [18] is used. It reads:

$$\overline{\overline{\sigma_s}}=(1-F)\left[-p_s\overline{\overline{I}}+\mu_f\beta\left(\alpha_s\overline{\overline{D_s}}+\alpha_f\overline{\overline{D_f}}\right)\right]+F\left[2Gw_n\mathrm{dev}\left(\overline{\overline{D_s}}\right)-p_s^*\overline{\overline{I}}+\overline{\overline{\Sigma}}\right] \tag{3}$$

where F is a function having value between 0 and 1. p_s (p_s^*) is the particle pressure for the liquid-like (or solid-like, resp.) behavior. μ_f is the dynamic viscosity of continuous phase with β a non-Newtonian amplification factor, D_k the shear rate tensor of phase k. G is the shear modulus, w_n the time step. $\overline{\overline{\Sigma}}$ is the accumulation of solid, or elastic stress from the beginning of the loading.

It is worth noting that F=0 leads to the initial two-fluid model and F=1 to elastic solid-fluid model. The F-function plays an important role as it concerns the solid-liquid transition for the particulate (or sediment) phase. The variation of F between 0 and 1 is controlled by local Erosion (or Shields) number (Figure 3). The dynamic shape for the dredging induced craters is mainly dependent on the value of the Erosion number.

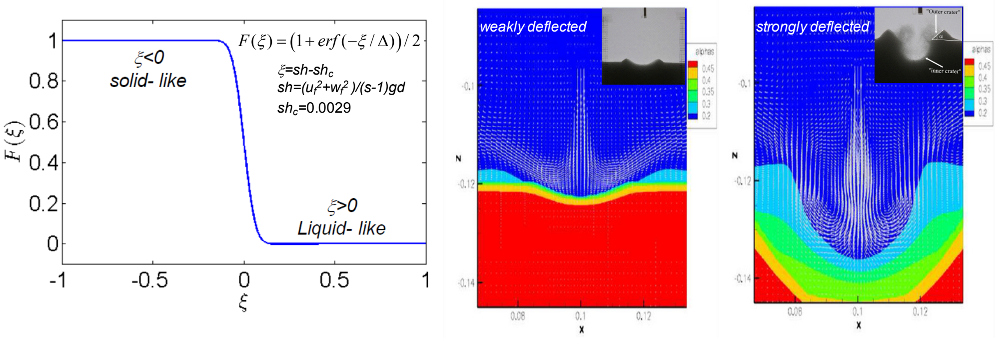

Figure 3. F-function for the solid-liquid transition of the particulate phase (left). Numerical predictions for low (middle) and high (right) value of Erosion number, E.

Validation based on crater sizes (*H*,*D*)

The 2D computational domain is 0.25m of height and 0.2m of width. A Poiseuille profile of velocity is imposed at the nozzle outlet, which is fixed at a distance L from the bed. According to the experiments, the dynamic shape of craters is obtained very quickly after a few seconds.

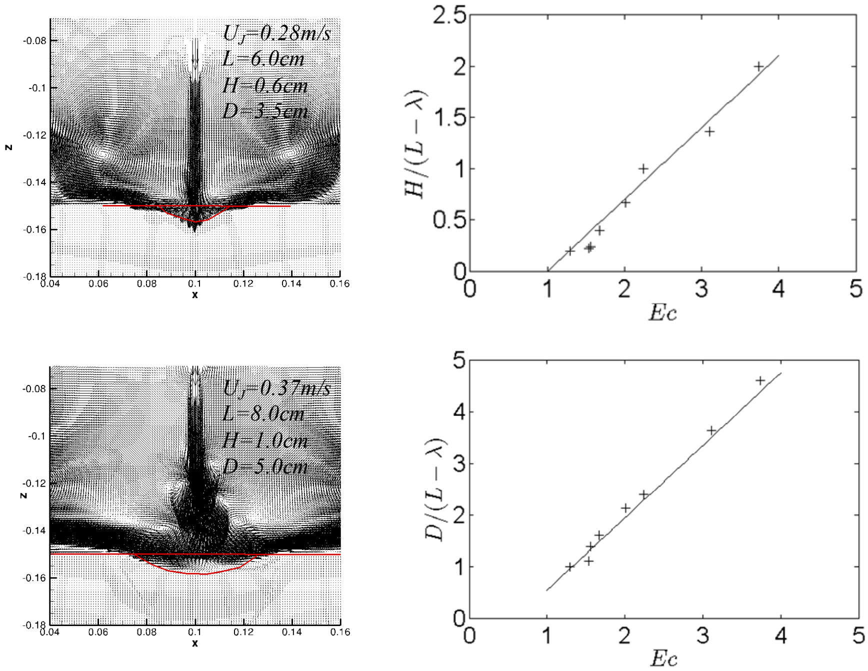

Figure 4: Simulation of erosion crater (M-mesh, left). Crater size from numerical experiments (b=4mm, right). Lines correspond to the scaling laws of depth and width (figure 2).

Three regular computing grids are considered with different space resolutions: a coarse mesh (C-mesh) of 101 x 126 points ($dx=dz$ =2 mm), a medium one (M-mesh) of 201 x 251 points, ($dx=dz$=1 mm) and a fine mesh (F-mesh) of 401 x 501 points ($dx=dz$ =0.5 mm, equivalent to about one grain diameter). Therefore it would not be pertinent to consider finer meshes. Four time steps (dt) are also investigated: 10^{-5} s, 5. 10^{-6} s, 4. 10^{-6} s and, 2. 10^{-6} s. The MPI (message passing interface) technique is implemented in order to distribute the computation on 8 cores and reduce the CPU time. From the comparison of results for different mesh sizes, it is concluded that the M-mesh with $dx=dz$=1mm and dt=5.10^{-6} sec are good compromise between CPU time and accuracy.

Figure 4 (left) presents the results for two different conditions of jet mean velocity, U_J, and impingement distance, L. A strong contrast in the fluid velocity field is observed between eroded sediment and non-eroded sediment bed regions. From these plots, crater sizes (depth H, width D) are measured and re-scaled in order to compare with data (figure 2). A good agreement between data and two-phase model is observed (Figure 4, right).

4. CONCLUSIONS

We have studied experimentally and numerically the crater sizes generated on a flat granular bed by a submerged plane jet which simulates the water injection dredging. A scaling law is proposed to formulate the measured depth and width of the crater. The two-phase model is successfully used to reproduce the data. The important and necessary improvement concerns the description of solid-liquid transition through a general unifying theory that conciliates both soil and fluid mechanics in the same finite volume model.

Future works will focus on the moving (or travelling) jet which is the real situation during the water injection dredging. For instance, the experiment by Perng & Capart [7] may be considered in the near future.

5. ACKNOWLEDGEMENTS

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