

FINAL REPORT

Three-dimensional Computational Modeling of Turbulent Flow Field, Bed Morphodynamics and Liquefaction Adjacent to Munitions

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14. ABSTRACT This document reports the design, development, and results of three-dimensional (3D) computational models for underwater munition dynamics. Large amount of observational and empirical data has been gathered in field and laboratory studies to reveal the mechanisms behind the motion of munitions. However, there are still knowledge gaps for the physical and deterministic explanation of the phenomenology. This project aims to develop and utilize 3D computational models to predict the initiation of motion, continuous movement, and final deposition of munitions, which are important for site assessment and remediation actions. Two models were developed. The first model, ibScourFoam, is for the 3D scour simulations around munitions. The second model, modified from the DualSPHysics code, is for the coupled motion of fluid-object-sediment system. The models capture the key physical processes which control the motion of munitions, including turbulent flow, sediment transport and scour, granular material dynamics, and the rigid-body motion of munitions. In addition, these processes are coupled and thus the developed models can simulate their interactions. This final report presents the details of the model development, validation, and applications. Results have shown that the models can capture the dominant physical processes and help us gain new insights. The computer models also produces additional information, such as force time history as munitions move, which is extremely hard to measure in experiments but of great importance to munition dynamics.												
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LIST OF ACRONYMS

1D - One-dimensional
 2D - Two-dimensional
 3D - Three-dimensional
 ALE - Arbitrary-Lagrangian-Eulerian
 CFD - Computational Fluid Dynamics
 CFL - Courant-Friedrichs-Lewy
 DBS - Dynamic Boundary Conditions
 DoF - Degrees of freedom
 DP - Drucker-Prager
 EOS - Equation of State

GPU - Graphics Processing Unit
HBP - Herschel-Bulkley-Papanastasiou
IB - Immersed Boundary
MR - Munition Response
MRSON - Munition Response Statement of Need
RANS - Reynolds Averaged Navier-Stokes
SERDP - Strategic Environmental Research and Development Program
SPH - Smoothed Particle Hydrodynamics
UXO - Unexploded Ordnance

LIST OF SYMBOLS

$\mathbf{A}$ = stencil Matrix
 a = aspect ratio
 b = reference height for suspended sediment
 C = volumetric suspended sediment concentration
 C_b = sediment concentration near the bed ($z = b$)
 C_{ijk} = polynomial coefficients
 $\mathbf{c}$ = coefficients vector
 c = cohesion of the sediment
 Co_{min} = minimum Courant number
 C_{s0} = speed of sound
 C_μ = coefficient for wall model
 c_v = concentration in volume fraction
 D = deposition rate
 d = sediment grain diameter
 D_d = kinematic eddy diffusivity of suspended sediment
 E = entrainment rate
 E_y = Young's modulus
 $\tilde{E}$ = dimensionless entrainment rate
 f = net force acting on each particle on solid boundary

f_i = force per unit mass of particle i

$f(x)$ = field function

g = gravity constant

H = channel depth

h = smoothing length

$\mathbf{I}$ = identity matrix

I = moment of inertia

$\dot{j}_{sat}$ = yielded saturated sediment particles

$J^{\alpha\beta}$ = Jaumann rate

J_2 = the second invariant of the deviatoric shear stress tensor

K = sand slide diffusivity

k = turbulence kinetic energy

K_0 = sand slide diffusivity constant

k_s, k_s^+ = dimensional and dimensionless roughness height

M = mass of object

$\tilde{m}$ = index for the exponential growth of stress

$\mathbf{n}$ = normal direction vector

n = bed porosity

$\tilde{n}$ = power-law index that enables simulation of shear thinning or shear thickening behavior

p = pressure

P_k = generation rate

$\mathbf{q}$ = sand slide flux vector

q_0 = bedload transport rate for flat horizontal bed

$\mathbf{q}_b$ = bedload transport rate vector

q^* = dimensionless bed-load transport rate

R = submerged specific gravity of sediment

Re = Reynolds number

$\mathbf{R}_0$ = center of object

r_0, h_0 = radius and height of sand cylinder

t = time

U = mean velocity

$\mathbf{u}$ = flow velocity vector

u, v, w = flow velocity components

u_τ = shear velocity

$\mathbf{V}_b$ = velocity of rigid-body

v_s = sediment settling velocity

$w_0, \mathbf{W}$ = weight function, weight function matrix

$W(\mathbf{x} - \mathbf{x}', h)$ = kernel function

x, y, z = Cartesian coordinates

$\tilde{x}, \tilde{y}, \tilde{z}$ = local coordinates

y^+ = dimensionless wall distance

z_b = bed elevation

$\alpha, \beta, \beta^*, \sigma, \sigma^*$ = coefficients for turbulence model

β_1 = angle of local bed

β_2 = angle between local flow velocity and bed slope

δ = distance between a stencil cell center and the corresponding hit point

$\delta^{\alpha\beta}$ = Kronecker's delta function

ϵ = specific dissipation rate

$\dot{\epsilon}_i^{\alpha\beta}$ = deviatoric strain rate

γ = polytropic index

$\theta, \theta_c, \theta_{c0}$ = Shields number, critical Shields numbers for sloped and flat bed

μ = dynamic viscosity

μ_s = static friction coefficient

μ_{app} = apparent viscosity

μ_{susp} = suspension viscosity

ν = fluid kinematic viscosity

ν_p = Poisson's ration

ν_t = turbulence viscosity

$\mathbf{\Omega}_b$ = rotational velocity

$\dot{\omega}_i^{\alpha\beta}$ = spin-rate tensor

ρ = density of water

ρ_0 = reference density

$\sigma^{\alpha\beta}$ = total shear stress tensor

$\tilde{\phi}$ = polynomial function

ϕ_0 = angle of repose

τ = Reynolds stress vector

τ_b, τ_b = bed-shear stress vector, bed-shear stress

τ_c = yield stress

τ_y = Bingham yield stress

$\tau_i^{\alpha\beta}$ = viscous stress

$\dot{\tau}^{\alpha\beta}$ = deviatoric stress rate

τ_w = wall shear stress

I_1 = the first invariant of the deviatoric shear stress tensor

II_D = the second invariant of the deviatoric strain rate tensor

KEYWORDS

Munition Motion, Computational Fluid Dynamics, Immersed Boundary Method, Sediment Scour, Sand Slide, Smoothed Particle Hydrodynamics, Visco-elastoplastic Model

Abstract

Introduction and Objectives: Large amount of data has been gathered in field and laboratory studies to reveal the mechanisms behind the motion of munitions. However, there are still knowledge gaps for the physical and deterministic explanation of observations. The objective of this project is to develop and utilize three-dimensional (3D) computational models to describe the details of physical processes on flow and transport around underwater UXOs, which help us predict the initiation of motion, continuous movement, and final deposition of munitions. Modeling tools and capabilities achieved from this project, in conjunction with the physical insights gained, are important for site assessment and remediation actions.

Technical Approach: The 3D models capture the key physical processes which control the motion of munitions, including turbulent flow, sediment transport and scour, granular material dynamics, and the rigid-body motion of munitions. Two models were developed. One is the 3D scour model which can capture the scour and erosion around UXOs. To deal with the complex geometry of UXOs, an innovative immersed boundary method (IBM) was developed which can produce accurate and smooth wall shear. A new sand slide method was also invented to handle the sliding of sediment along steep slopes. The UXOs in the 3D scour model can be either fixed or move with some prescribed motion. The scour model is suitable for cases where UXOs are stationary, in-between movement steps, or moving at a much slower pace than the scour hole development. The second model is the 3D Smoothed Particle Hydrodynamics (SPH) model based on the open source DualSPHysics code. A multiphase approach for both phases of water and sediment has been used. The motion of munition is simulated with a 6-Degrees-of-Freedom (DoF) rigid-body motion solver.

Results: There are two key results. One is the advancement of UXOs modeling capability with the two new models. These models are valuable tools for the MR program. They complement other research projects, especially those field and lab-based projects. The second key result is the physical insights gained through the case studies with the models. With the 3D scour model, the detailed physical processes and their implication for UXOs dynamics are revealed. This project specifically investigated the effects of munition shape and angle of attack, both of which play an important role. There are many other physical parameters which can be investigated in future research. To reduce the parameter space, a dimensional analysis was performed. A unified scour time scale was proposed and the scour hole development is well captured by a saturation-growth curve. With the 3D SPH model, the penetrometer experiment and munition movement on beach face were simulated. Both cases captured the bulk dynamics and produced information on forcing, which is difficult to measure in experiments. There are also many other simulated cases on various aspects of the UXOs problem.

Benefits: One benefit is the availability of two powerful computer models which are previously not available. These models can benefit all other research projects supported in the program. Indeed, the 3D SPH model has already been used to collaborate with other projects on penetrometer study and munition of beach face. In future, these models, with careful calibrations, can be used to study many aspects of munition movement. Another benefit is that some of the findings, such as the scaling law, can be directly used in large scale prediction models.

1 Executive Summary

1.1 Introduction

This project addresses the research need outlined in MRSON-17-01 on the topic of “Characteristics of Munitions Underwater and Their Environment”. Comprehensive and physically-based computational models were developed to understand the initiation of motion, transport, and burial of underwater munitions. One SERDP sponsored workshop report on burial and mobility of munitions in the underwater environment identified the research need of using high-fidelity computational models to characterize the turbulent flow and sediment bed response in the vicinity of the munition object (Calantoni, 2014). This project responds directly to address this need.

Although previous computational modeling efforts have been carried out to understand underwater munition and object movement (e.g., the Vortex Lattice UXO Mobility model, Jenkins et al. (2007)) and they have produced very useful results, their capabilities are nonetheless restricted due to model assumptions or the neglect of some key physics. These models were mostly funded by ONR for the mine burial problem. For example, many of earlier computational models for mine burial did not consider the effect of turbulence. Very few considered the six-degree-of-freedom (6-DoF) motion of the object. Even fewer took into account the interactions between object and bed. With the new development in computational techniques, turbulence theory, and physics of granular materials, this project seeks to relax these limitations by building next-generation numerical models for underwater munition predictions.

The proposed 3D models incorporate the most important physical processes contributing to the fate of underwater munitions, which include turbulent flow field and its induced sediment transport, hydrodynamic forces on the munitions and their 6-DoF motion, and the behavior of the granular bed supporting the munitions. With the capability of the computational models, this project seeks to fill some of the knowledge gaps.

1.2 Objectives

There are two main objectives in this project:

- The first objective is to develop high-fidelity computer models to predict the initiation of motion and continuous movement of munitions. To the best of our knowledge, such model does not exist before this project. There are models which can capture some of the physical processes involved in underwater munition movement. However, these models are not

specifically designed for munitions and none of them can be readily used.

- The second objective is to use the developed models to simulate and analyze munition dynamics under different conditions. The models can be used to characterize the hydrodynamic forces on underwater munitions, model sediment scour around them, and predict their mobility. Different components of the models can be used independently to investigate a subset of physical processes. In addition, the computational modeling study complements and benefits from other Munition Response research projects. In particular, lab and field measurements provide abundant data. However, there are important quantities for munition dynamics that are almost impossible to be measured directly. For example, the force and turning moments acting on a moving munition are extremely hard to measure. The computer models developed in this project can simulate the forces and moments at any time during munition movement. This provides critical information for the central question of munition mobility.

Underwater munition dynamics is a very complex problem and many variables are at play, for example, wave and current condition, sediment characteristics, and munition properties and state. It is extremely difficult for any single research project to tackle all variables. However, with the availability of high-fidelity computer models, in conjunction with well-designed measurements and high-quality calibration data, it is possible to look at the processes individually and collectively. For example, if munitions are placed on mobile sediment bed, local scour is one key contributing factor for munition mobility. The 3D scour model developed in this project can be used to examine the details of turbulent flow field and local scour hole development around munitions. The computer models are also extremely useful for hypothesis testing. For example, one hypothesis regarding munition mobility is that the density of munitions controls the probability of burial or exposure. The computer model can run scenarios with different munition relative densities (in comparison with water and sediment densities) to investigate the system response.

1.3 *Technical Approach*

1.3.1 *Overview of research plan*

This project achieved the objectives through a two-phase research plan:

- Phase one: development and validation of computer models. This project developed two new 3D computer models to simulate the turbulent flow field, bed morphodynamics, porous bed response, and munition dynamics. The two models are suitable for different application scenarios. They can be used to study the initiation of motion, transport, and burial of underwater munitions through accurate calculation of hydrodynamic forces and moments, rigid-body dynamics, as well as granular material mechanics.
- Phase two: simulations and analysis with the new computational models. We studied several aspects of the munition mobility and its dependence on some key parameters, such as munition shape, density, flow angle of attack, and bed material properties.

Phase one for model development is a necessary step because there is no existing model which can

readily achieve all the goals and objectives in this project. As shown in this final report, there were some technical hurdles in our modeling capability. For example, we found some deficiencies in the computing methods reported in the literature. New sand slide method and immersed boundary method have to be developed to overcome these deficiencies.

1.3.2 *Structure and functionalities of new computer models*

The two new computer models are both for the simulation of munition movement and dynamics. However, their functionalities and application scenarios are different. One model is for 3D flow and scour around munitions. The munitions can be fixed in place or move with a prescribed motion. The 3D scour model itself cannot predict munition movement. The other model is based on the 3D Smooth Particle Hydrodynamics code DualSPHysics. It can simulate the dynamics of the coupled flow-munition-sediment under waves. However, it lacks the capability for capturing detailed turbulence and sediment transport.

To better appreciate the similarities and differences between the two models, the domain of interest and the physics of sub-components are shown in Fig. 1.1. In general, each sub-domain deals with one major physical process and the coupling between each sub-domain pair is through their common boundaries.

- CFD flow domain: This is the domain for the 3D scour model for turbulent flow and sediment transport with the presence of munitions. To track the deforming bed due to scour, an immersed boundary method is used to implicitly represent the bottom of the flow domain. The flow and sediment transport solver, *ibScourFoam*, has been implemented in the open source CFD package OpenFOAM (OpenCFD, 2015; Song et al., 2022).
- SPH granular sediment domain: This is a subdomain within the porous bed underneath the munition (see Fig. 1.1). This part is a subset of the porous bed domain. A smoothed particle hydrodynamics (SPH) method is used to model the granular sediment behavior and its interaction with the munition. The open source code DualSPHysics (Rogers et al., 2011) is used and adapted to fit the needs of this project. In fact, DualSPHysics utilize a two-phase modeling approach where both free surface flow and granular sediment can be modeled. This code can also model the 6-DoF motion of munitions with the simulated hydrodynamics forces and the granular material forces. We will denote this model as the 3D SPH model in this report.

This project only deals with the near-field processes, with the possibility of extending to far-field or coupling with other suitable large scale models in the future. For example, Delft3D has been widely used to simulate the process at both regional and local scales. It is possible to couple these large scale model with the ones developed in this project.

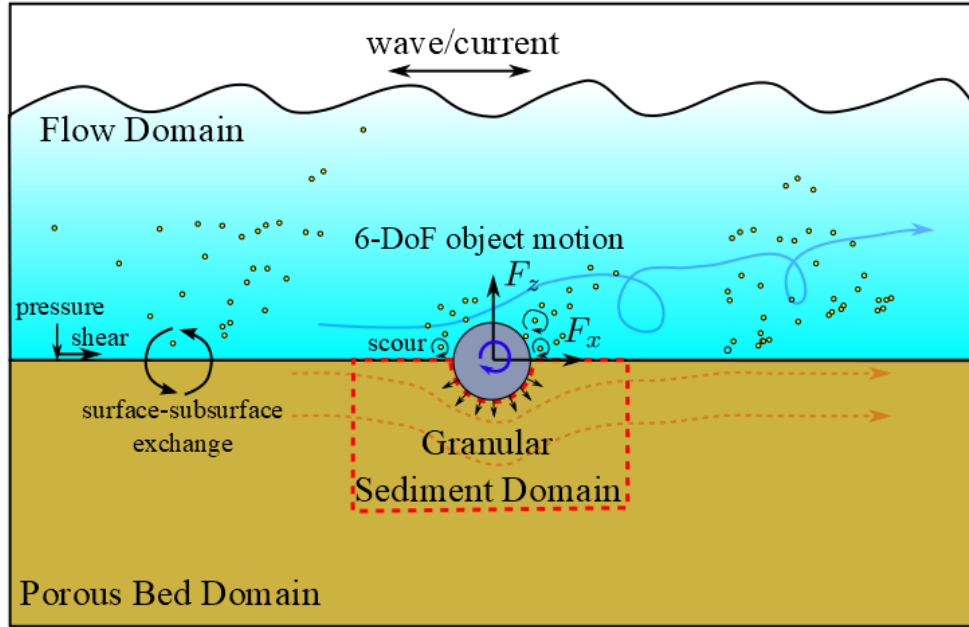


Figure 1.1: Modeling domain and physics for sub-components.

1.4 Results and Discussion

Corresponding to the two objectives of this project, there are two main results:

- The first result is the two computer models. Both are open source and readily available to others who want to use them in their own work. The first computer model for 3D scour was developed almost from scratch on the open source platform OpenFOAM. Two new numerical techniques are invented in this project to overcome some deficiencies in existing technologies, namely a new sand slide method and a new immersed boundary method. The second computer model was based on DualSPHysics and some modifications have to be made to the original code. Both models have been properly verified and validated. Part of the validation of these models uses cases and data in the literature which are not directly relevant to munitions. Thus, the details of validations are placed in the Appendices of the project final report.
- The second result is the physical insights and knowledge gained through the use of the two computer models. As already mentioned, there are many processes and variables in the underwater munition problem. It is impossible to study all these processes and variables in one project. Instead, we examined some of the important aspects. With the 3D scour model, the effects of munition shape and flow angle of attack were the focus. Dimensional analysis was performed and a new time scale for scour development was proposed to collapse the simulated data. The scaling analysis is useful to upscale the results and make them useful for operational forecast. With the 3D SPH model, two main cases were studied. One is the penetrometer experiments where the dynamics of a penetrometer dropping into water and sediment was simulated. Key model parameters for the saturated sediment and their

physical meanings were found. The second case is the movement of munition on beach face subjecting to dam-break type waves. The results of the model applications are summarized below and more details can be found in the final project report.

1.4.1 Results from the 3D scour model

The 3D scour model was used to simulate and compare with flume experiments where munitions were placed on supporting structure. In these cases, the munition objects were fixed so the flow/sediment dynamics is segregated from the granular material dynamics. Although it seems counter intuitive, cases studied here are good approximations for munitions moving at very low speed. Experiments have shown that when scour is the dominant factor for munition movement, munitions move slowly and sometime episodically, meaning they only move when the scour hole is large enough and the supporting sediment under the munitions collapses.

Two key parameters studied are the shape and flow angle of attack. Many previous studies simplified UXOs as cylinders. We found that UXO shape has great impact on the hydrodynamics, and the consequent scour and burial process. The shape effects also convolute with the flow's angle of attack, which makes it even more important to consider the shape of UXOs. Two angles of attack, 45° and 90° , were investigated. The bulk behavior of scour around UXOs is akin to scour around any slender object placed on sediment bed. However, the detailed scour process is significantly different. Figure 1.2 shows the comparison between cylinder and munition and the four distinctive stages identified during the process. Our results show that flow contraction near the two ends of UXOs, recirculation behind object, vortex shedding downstream, and jet-like flow under the object play dominant roles during different stages of scour. We further generalized the scour process around UXOs and other objects by a scaling analysis based on first principles of physics. A fitted saturation growth-rate equation relating scour development and time collapses data reasonably well. This scaling law can be used for large scale prediction where detailed 3D modeling is almost not feasible.

1.4.2 Results from the 3D SPH model

BlueDrop penetrometer simulations

The first case using the 3D SPH model is to simulate the BlueDrop penetrometer experiments where data were made available from Dr. Nina Stark whose research projects use the penetrometer to characterize sediments. The penetrometer was dropped into a tank filled with water over a sediment bed. Three experiments were performed and simulated where the main variable was the sediment property (loose, medium, and dense).

Numerical results show the robustness and accuracy of the proposed SPH multi-phase model (Fig. 1.3). The penetrometer case revealed the relative importance of control parameters in the model, with the Young's modulus playing a critical role in the response of the penetrometer. The model also provides the valuable force history information on moving objects and the force partition between water and sediment (Fig. 1.3(b)). Model results suggest that the force history for loose sediment has a more diffusive shape than that for dense sediment. Such force information is hard to obtain in experiments but of great importance for the mobility and stability of UXOs.

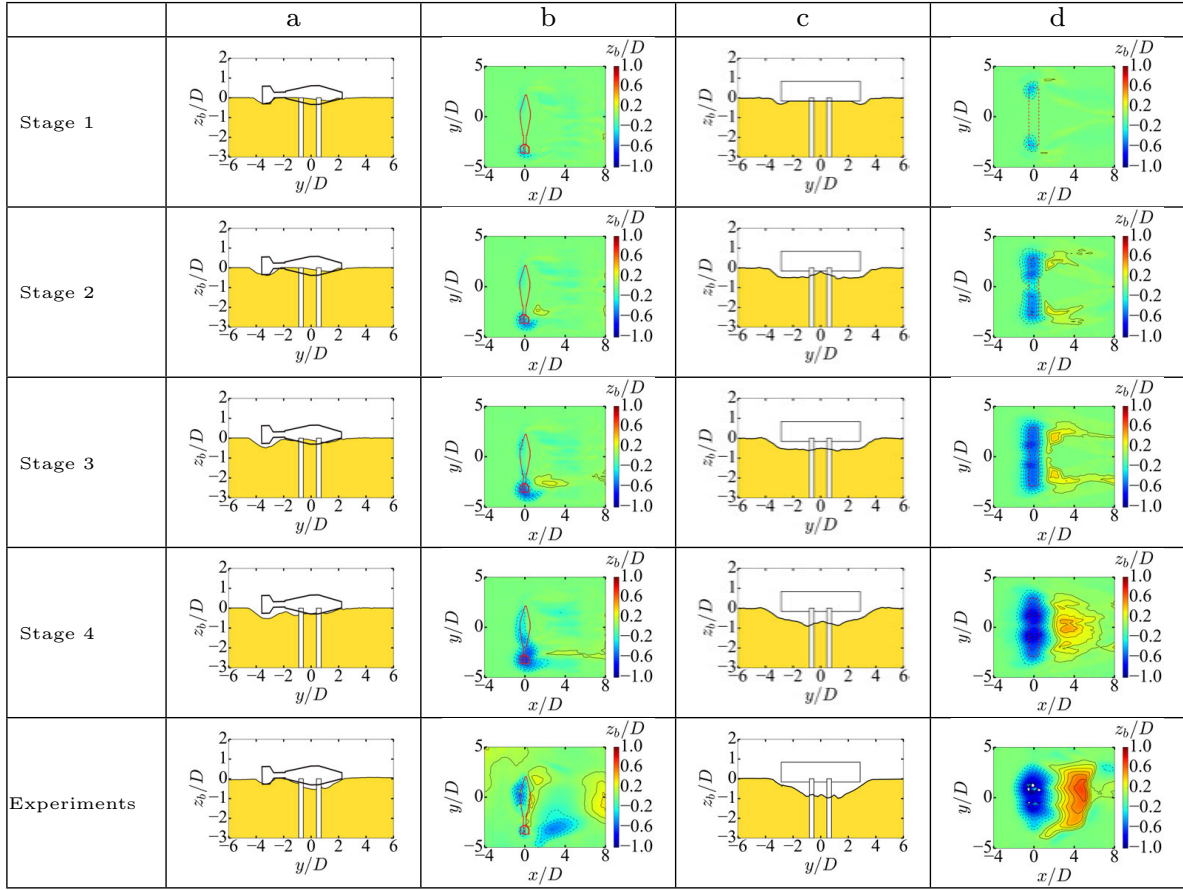


Figure 1.2: Simulated scour around a munition and a cylinder showing the effects of shape.

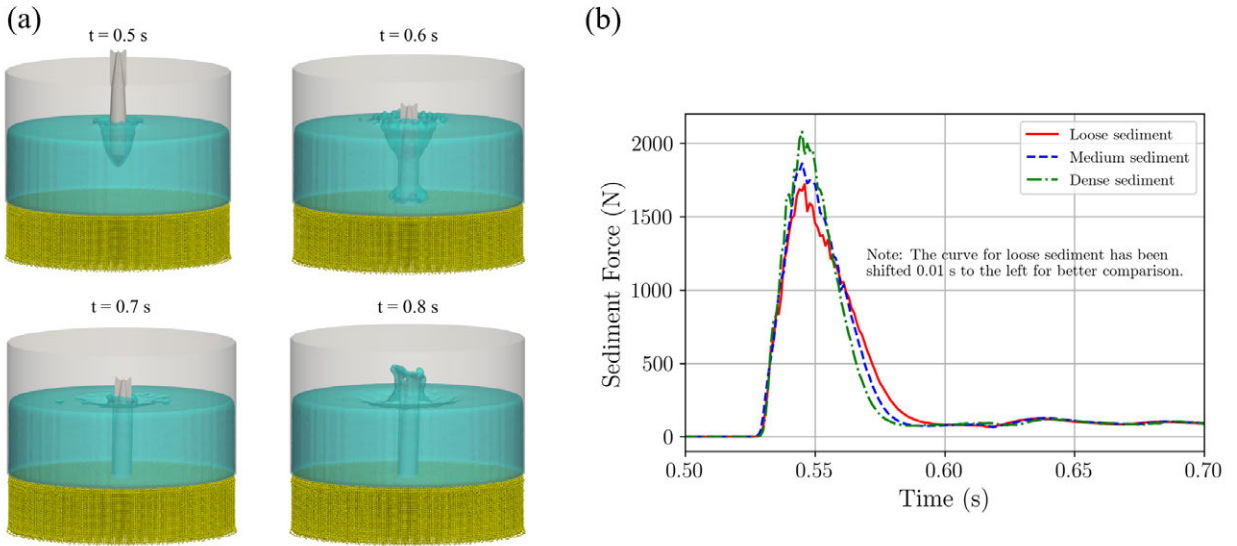


Figure 1.3: Simulated BlueDrop penetrometer dropping into water and sediment: (a) motion of penetrometer, (b) history of force on penetrometer imparted by sediment.

Munitions on beach face

The second case using the 3D SPH model is the simulation of munitions on beach face subjecting to dam-break waves. The setup is similar to flume experiments done in project MR-2503. The munition is simplified as a sphere and placed on sediment with some initial burial. The goal here is to quantify the hydrodynamic forcing and mobility of munitions. The setup is relatively simple. In the flume, a sloped beach was constructed with sediment and a sphere was placed in the middle of the beach. Dam-break wave was created by lifting a gate on the other end of the flume where initially a reservoir of water was held.

The simulated wave propagation, impacting on munitions, and munition movement qualitatively match with experimental observations. In addition, the 3D SPH model produced detailed force history on the munition. Figure 1.4 shows the simulated forces. In this plot, x is along the flume direction, y is the spanwise direction, and z is the vertical direction. Due to symmetry, the force along the spanwise direct F_y is almost zero. The motion of the sphere is mainly driven by the force in the x direction. From the figure, it is clear there are three spikes corresponding to the moments of initial wave impact, maximum wave force, and the impact against the end wall. Force analysis, in conjunction with simulated flow, helps us understand the whole process of munition movement.

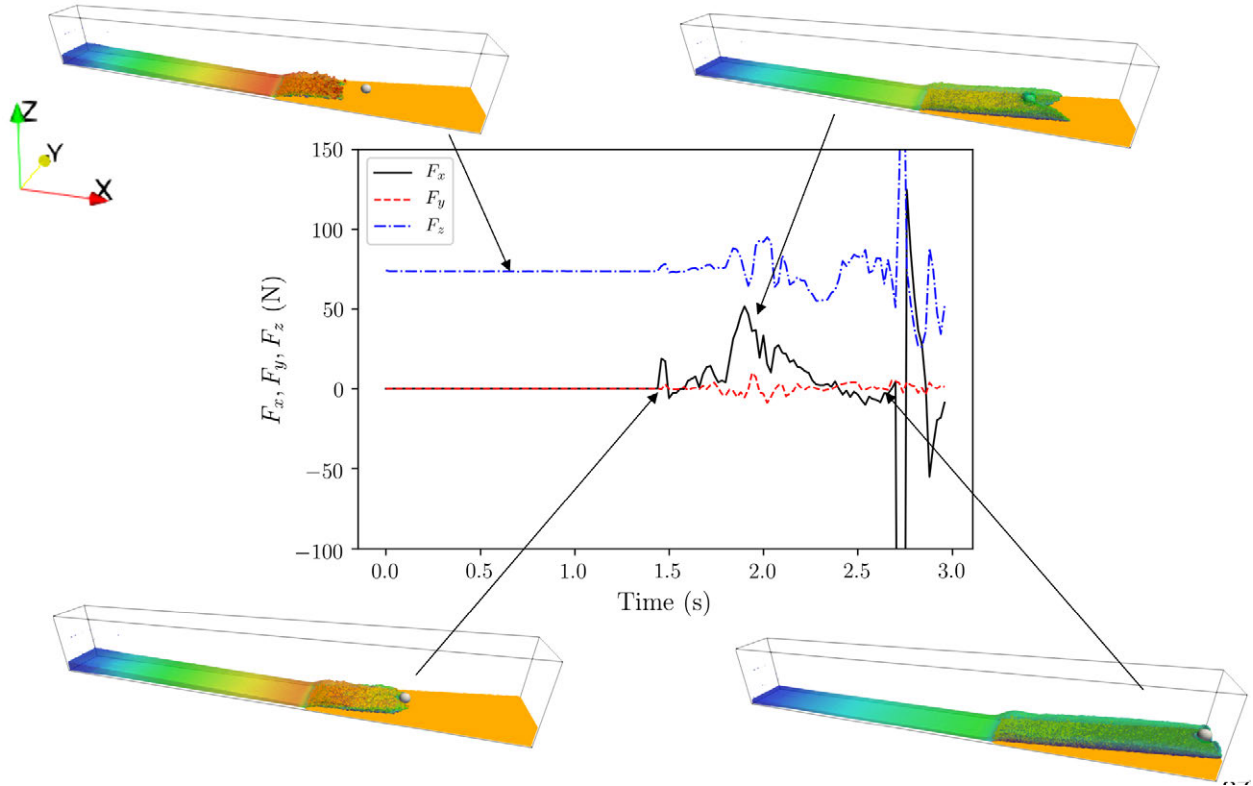


Figure 1.4: Force history on the munition placed on beach face subjecting to dam-break wave. The four representative moments are also shown.

1.5 *Implications for Future Research and Benefits*

The computer models developed in this project can be very useful to leverage and collaborate with other researchers supported by the MR program. Indeed, although not in the scope of this project, we already collaborated with some of other PIs on for example penetrometer and munition mobility on beach faces. There are many possibilities for future researches.

One important future work is for model improvement. The two computer models developed are very powerful. However, they have their limitations. For the 3D scour model, only bedload is currently considered and suspended sediment transport needs to be added. For the 3D SPH model, more reliable constitutive model for sediment should be added in future. Currently, the visco-elastoplastic multi-phase model for saturated sediment cannot correctly capture the full granular material dynamics. For example, the parameters have to be fine tuned case-by-case for the penetrometer and munition on beach face cases to match with experimental data. The current sediment constitutive relationship is also not able to fully capture the pore-pressure within sediment, thus it cannot simulation liquefaction. More advanced constitutive laws for sediment have to be implemented.

The high-fidelity computational models developed in this project require substantial computing power and most simulations take long wall time. To accelerate the computing, new technologies such as machine learning and artificial intelligence can be used. For example, surrogate computer models can be trained with deep learning technologies. Each run of surrogate models usually takes only a split of second.

Munition mobility and movement involve many processes and variables. In addition to the variables studied in this project, there are many other important aspects that should be investigated in future:

- How do the bottom conditions (e.g., roughness and bedforms) affect the munition stability? In this project, the bed is assumed to be flat before scour hole develops. In natural environments, bedforms such as ripples may exist. How the bottom topography affects the whole process is worth studying both numerically and experimentally.
- This project already showed that the force acting on a munition changes dramatically over time. The force depends on munition shape, angle of attach, and degree of burial, among many others. It is definitely not correct to use constant drag and lift coefficients in large-scale and long-term models. However, it is not feasible to perform detailed 3D simulations in large scale models. This is very common in multiscale problems. One way to address this might be parameterization with many pre-simulated 3D cases.
- Another way to address the scale problem and quantify the uncertainties associated with the parameters is to combine deterministic and stochastic approaches. All the work in this project is deterministic. However, there are substantial uncertainties due to our limited knowledge on the UXO dynamics and our model limitations. Deterministic models can provide reasonable range of parameters and the general trend on how these parameters affect local and short-term response of the system. Stochastic approaches can utilize these results to improve their probabilistic predictions. A risk-based decision-making is probably

more meaningful for such a complex problem. For example, the prediction of munition movement should be an ensemble of trajectories like the hurricane prediction in weather models.

- Bridging the time and spatial scales. Munition movement is definitely a multi-scale problem. High-resolution models can only be used for small to moderate spatial scales over a short period of time. However, practical applications often need predictions at regional scales over a storm even (hours to days). There are many methods for bridging scales, for example upscaling, multi-fidelity and multi-scale modeling, and blending deterministic and stochastic modeling.

One interesting question will be how munition's characteristics show their effects at different scales. Figure 1.5 shows two possible outcomes due to munition characteristics. We already show that at local scale, munition shape, density, and flow angle of attack play important roles. Whether their importance still applies at global scale over long term remains to be investigated. One possibility is that over the long run, the local scale differences may be averaged out and the bulk behavior of munition movement is more influences by the background climatology, storm conditions and seabed properties. On the other hand, the outcome could be the opposite, i.e., the trajectories of two different munitions released at the same location diverge over time. To find the answers to such questions, the local scale results (e.g., drag/lift force coefficients and scour rate) can be incorporated into regional and global scale models and perform stochastic simulations.

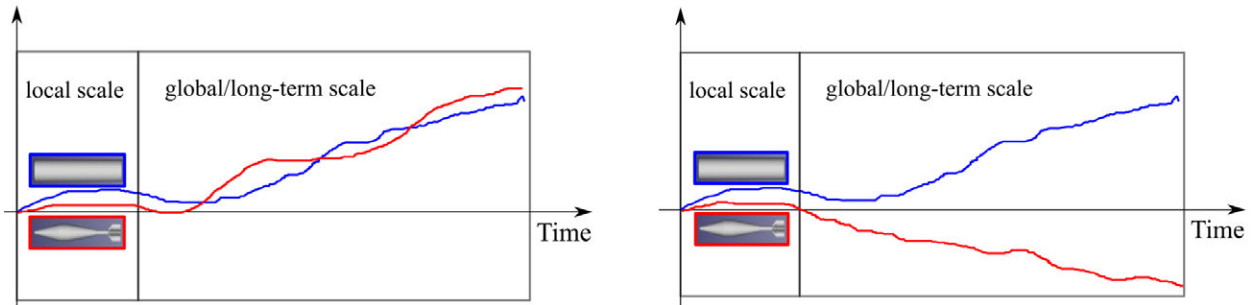


Figure 1.5: Munition characteristics effects across local and global scales. Two possible outcomes: the left figure shows the local effects are averaged out and the long-term trajectories of two different munitions follow each other. The right figure shows the opposite.

During this project, there were many discussions on what the data needs are for model calibration. The following is a partial list of what could be ideal purely from the point of view of a modeler. Some of them may be difficult or even impossible to do in the lab or the field. However, this list may generate new ideas for additional future research and collaborations.

- Munition object in an oscillatory channel or wave tank. The munition can be fixed on a supporting structure or free to move. In this project, we have performed some preliminary experiments in an unidirectional flume where the munitions were fixed on a supporting structure. Similar work can be done in an oscillatory channel or wave tank. It will be very valuable to measure flow and sediment movement, scour hole evolution, and force on object

(using a load cell fixed to the supporting structure). Pressure sensors can also be embedded in sediment to measure pore-pressure as the system evolves.

- Munition shape effect. In this project, we have done simple comparison between a munition and an equivalent cylinder. The differences are quite big. More representative shapes can be selected to perform similar studies and build a library of munitions information for operational use.
- Measurement of lift and drag forces on different munitions with different orientation, percentage of burial, and scour hole development. Currently, constant lift and drag coefficients are used in large scale models, which is obviously not right.
- Munition object in combined wave and current. It seems that very limited previous work has been done on this. Previous work either focused on unidirectional flow or oscillatory flow. But in reality, munition could be subject to both wave and current. The flow and sediment dynamics, and the corresponding munition movement, may be significantly different.
- Interaction of a munition with a single sand dune wave. Sand dunes exist in many coastal environments and they migrate. Sand dune movement may bury or expose a munition object. One can imagine that munition could be carried forward by a dune as it migrates, or the munition may stay. A hypothesis is whether a munition will be carried by a migrating dune depends on its density and length scale in comparison with dune height and length.

2 Objectives

This project is designed to achieve two main objectives: the development of high-fidelity computer models and the detailed analysis of model results on munition dynamics. Five tasks were performed to achieve the two objectives (Fig. 2.1).

- The first objective is to develop high-fidelity computer models to predict the initiation of motion and continuous movement of munitions. To the best of our knowledge, such model did not exist before this project. There are models which can capture some of the physical processes involved in underwater munition movement. However, these models are not specifically designed for munitions and none of them can be readily used.

Two computer models are developed in this project and each has its own focus. The first model is the 3D local scour model around munitions and the second model is the 3D SPH model for the fluid-munition-sediment system. The 3D scour model can simulate detailed turbulent field, sediment transport, and scour hole development. Munition can be fixed or move with a prescribed motion. The 3D scour model itself is not capable of predicting the munition movement. The 3D SPH model can simulate the coupled motion of fluid, sediment, and munition. However, its capability to simulate turbulent flow and sediment transport is limited.

- The second objective is to use the developed models to simulate and analyze munition dynamics under different conditions. The models can be used to characterize the hydrodynamic forces on underwater munitions, model sediment scour around them, and predict their mobility. Different components of the comprehensive models can be used independently to investigate a subset of physical processes. In addition, the computational modeling study complements and benefits from other Munition Response research projects. In particular, lab and field measurements provide abundant data. However, there are important quantities for munition dynamics that are almost impossible to be measured directly. This is one place that computer models can really contribute.

For example, the force and turning moments acting on a munition are extremely hard to measure. The force information is extremely valuable for us to assess munition mobility and movement. The computer models developed in this project can simulate the forces and moments at any time during munition movement. This provides critical information for the central question of munition mobility.

With the availability of the developed models, several hypotheses will be tested. One prevailing hypothesis regarding munition mobility is that the density of munitions controls the probability

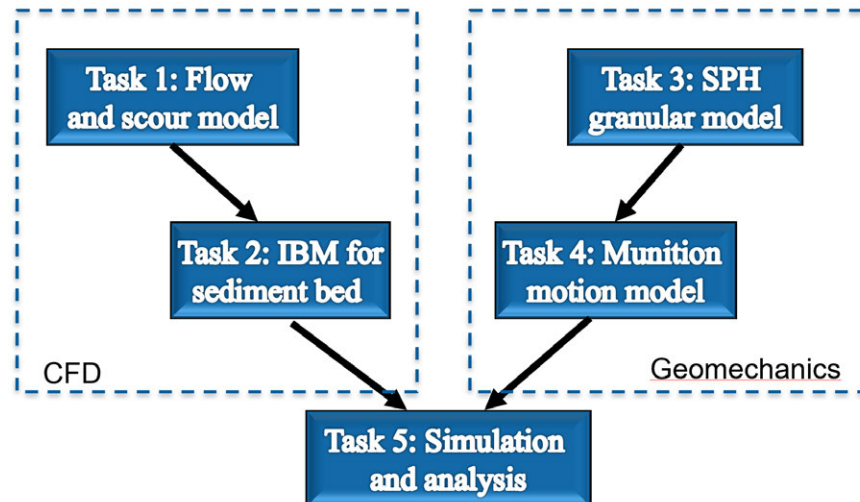


Figure 2.1: Research tasks to achieve the project objectives

of burial or exposure. As shown in the results section, the developed 3D SPH model is well suited to test this hypothesis.

With careful calibration, the computer models can be used to investigate various aspects of the munition dynamics. This project studied some of these aspects and the results can be used as a foundation for further work in the future. Example questions relevant to munition dynamics are as follows (some of the following have been studied and the rest are good candidates for future work):

- Are the empirical drag and lift coefficients accurate enough to calculate the initiation of munition motion? These coefficients have been extensively used in many simple conceptual models for munition stability. How do the forces on munitions change as they move under wave and current?
- What are the effects of munition characteristics, such as relative density and shape?
- What are the effect of flow characteristics, such as the angle of attack in unidirectional currents?
- How do the bottom conditions (e.g., roughness and bedforms) affect the munition stability? Bedforms, such as ripples and sand waves, exist in many underwater environments. Their existence changes the landscape for munitions. The movement of bedforms can potentially bury or expose munitions.
- What are the differences between waves and current in their dislodging and transporting of munitions? Do the cyclic motion of waves and the induced rocking effect enhance or suppress munition mobility?

3 Background

Ranges and training areas in many military installations may have left significant amount of munitions in their adjacent water bodies (rivers, lakes, coastal areas, and estuaries). Munitions deposited underwater have different sizes ranging from 20 mm to 125 mm and they act as discrete mobile objects in aquatic environment (Figure 3.1 (a)). Their presence poses as potential threat to human health and safety, as well as the environment. Therefore, predicting the fate of munition object is of great interest.

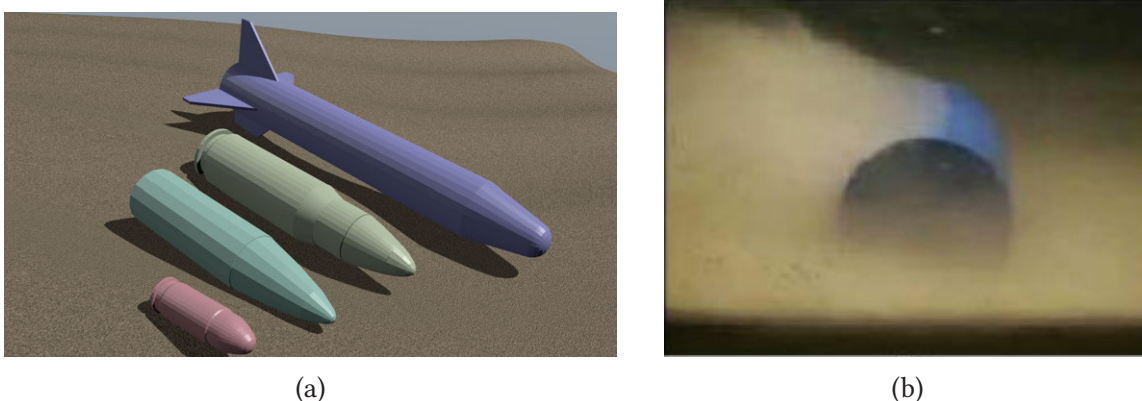


Figure 3.1: The fluid-bed-munition system: (a) examples of munitions with various shapes and sizes (not to scale), (b) experiment of a short cylinder on a sandy bed in an oscillatory tunnel (Hydrosystems Lab, University of Illinois at Urbana-Champaign, Catano-Lopera (2005)). The cylinder gradually sank into the bed under the cyclic forcing of the flow.

The initiation of motion, transport, and fate of underwater munitions are resulted from the interactions among flowing water, sediment bed, and munitions themselves. For example in Figure 3.1 (b), a cylinder, as a surrogate for sea mine, was placed on a sandy bed and the flow was oscillatory. It was observed that the cylinder gradually sank into the bed over time. During the sinking of the cylinder, there is a host of processes happening simultaneously. The following key physical processes have been identified (Liu, 2008): turbulent flow, local scour, pore-pressure response and potential liquefaction, granular sediment movement, as well as the rigid body motion of munitions. On top of all these processes, large scale (regional) morphology acts as the background for local phenomena to take place. Bed morphology is very relevant in shelf, near-shore, delta, and riverine environments. The observed bed morphology is the result of nonlinear motion of flow and sediment, which forms a coupled system of wave/current/sediment. The presence of munitions in this system adds another layer of complexity (Figure 3.2 (a)). To fully understand the

physical transport of underwater munitions, it is necessary to have high fidelity models which consider all the physical processes and the interactions among different components in the system. Modeling effort ignoring any of these processes may result in inaccurate or even erroneous predictions.

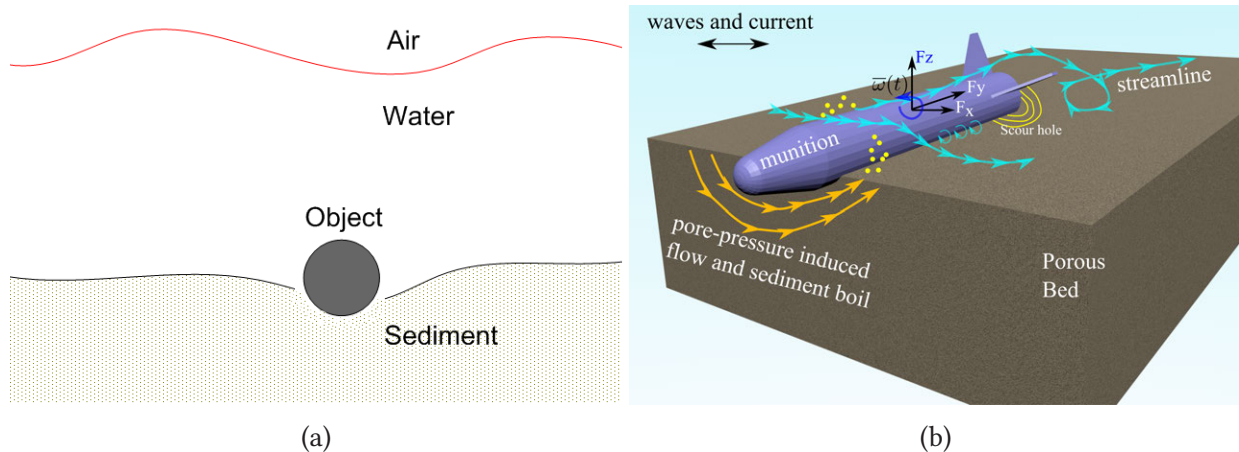


Figure 3.2: The interactions within the fluid-bed-object system: (a) conceptual model of the water-sediment-munition system, (b) physical processes that control the fate of underwater munitions.

To characterize the motion of underwater munitions and their environment, each of these physical processes needs to be fully understood and accurately modeled. Figure 3.2 (b) shows a conceptual drawing of all the contributing processes. Up until now, our understanding of these problems is still limited. The following describes these processes and the difficulties that hinder the advancement in this field, which sets up the stage to describe the work done in this project:

- **Difficulty to describe the 3D flow field:** When munitions are placed under water, the turbulent flow fields locally accelerate and decelerate adjacent to these objects, develop shear layers and enhance particle mixing, shed vortices, and disturb the bed material (Sumer et al., 1992, 1993; Liu and García, 2008). Fluid pressure is also changed. The alteration depends on many factors. Chief among them are the geometric shapes and the degree of burial of munitions. The flow field disturbance is also affected by the munition protrusion relative to the bedform sizes. One can imagine that a munition hiding in the trough of a big sand dune field will impose less influence as compared to one resting on the dune crest. In the field, there are unlimited combinations of geometric shape, burial depth, and bedform size. A fundamental question needs to be addressed is whether we can reduce the parameter space through either physical experiments or numerical modeling. In the past, charts of dimensionless parameters have been proposed with the help of scattered data points from lab or field under limited conditions. In this project, we seek to develop computational models which can be used to explore much bigger parameter space, compare with measurement data, and provide fuller and more detailed description of the flow process.
- **Difficulty to model scour and granular material collapse concurrently:** The munitions change sediment transport route and pattern, and consequently create local scour. The removal of basal sediment near the munitions undermines their foundation, reduces

the bed supporting capacity, and results in collapse. This cycle of scour and bed collapse continues until an equilibrium is reached. The gradual scouring and the sudden collapse of bed are hard to model due to two reasons. One is that we do not fully understand the coupled physical process. To describe the sediment motion, we need to well resolve the turbulent flow field. In addition, the criterion for and timing of bed collapse are much controlled by the local slope stability and the properties of the granular sediment. Both of them are still hard to capture. The second reason which hinders the model development is the large domain deformation due to these dynamic processes and their associated meshing problems. The boundary of simulation domain needs to be constantly updated to reflect the system dynamics. To deal with these difficulties, this project used a hybrid approach. An immersed boundary method (IBM) is used to track the scoured bed and a smoothed particle hydrodynamics (SPH) method is used to model the granular sediment behavior underneath the munition.

The motion of munition may also be linked to other granular material phenomena. For example, the granular convection, also named the “Brazil nut effect”, happens when the granular material is subjected to shaking or any other cyclic loading (Ehrichs et al., 1995). During the fluid-like granular convection process, the largest particles usually float to the surface. However, for particles like munitions, if their densities are much larger than the underlying granular sediment, they may sink. The Brazil nut effect, or simply the granular sorting due to density contrast, has been speculated as one possible mechanism which drives the burial of munitions. The SPH granular material model proposed in this work will have the capability to test this speculation.

- **Difficulty to quantify the critical condition for munition to move:** Analysis of munition object for the initiation of motion needs to consider the lift and drag forces acting on the object (James, 1990). One can imagine that unless the hydrodynamic condition is extremely energetic, objects like munitions can only saltate, roll, or slide along the bed. The moments of lift, drag, buoyancy, and gravitational forces around a pivot point are at balance at the critical condition. This idea has been used in many previous studies on the initiation of motion of sediment particles (e.g., Wiberg and Smith, 1987; Niño and Garcia, 1994; Nino et al., 2003). However, the saltating particle in these researches had similar sizes as the bed sediment and a pivot point can be defined when two particles are in contact. In the case of munition over sediment bed, the size of munition is usually much larger than the sediment. A contact surface between the munition and the granular bed, instead of a pivot point, better describes what happens when a munition starts to move. In addition, most previous work used the mean turbulent boundary layer shear stress to calculate the lift and drag forces on the object. By the use of the single parameter of mean shear, they neglected the effect of object size relative to the bedform/ripple height, munition density, shape, and orientation. To accurately quantify the critical condition of munition movement, it is necessary to either directly measure the forces or through high-resolution computational fluid dynamics models as done in this work.
- **Difficulty to couple a munition’s rigid-body motion with all other processes:** The motion of a munition is driven by fluid forces, gravity, and the supporting force of the bed. In such a highly coupled system, all these forces are directly impacted by the co-evolution

of flow, porous bed, and munition motion. Thus, the computational model should be able to accommodate the dynamic change of domain boundaries and interfaces between different parts. In the past, computational techniques were limited and thus such a model was not feasible. Nowadays, new methods have emerged and will be used in this project.

- **Difficulty to model possible liquefaction:** Under extreme storm conditions and with certain geotechnical properties of the bed, pore pressure within some area of the bed could accumulate due to the loose nature of sediments and poor drainage. The nonuniform distribution of pore pressure creates high pressure gradient, especially in the region adjacent to munitions. High pore pressure can soften the stress-strain behavior of the sediments. It may eventually cause liquefaction and affect the supporting capacity of the sediments. Based on this fact, the porous-bed response is another contributing factor to the stability of munition (Madsen, 1978; Mei and Foda, 1981; McDougal et al., 1989; Foda et al., 1993; Jeng, 1996; Sumer et al., 1999; Gao et al., 2003).

The computational modeling effort performed in this project complements all other SERDP-funded projects, e.g., MR-2320 (led by Dr. Joseph Calantoni), MR-2319 (led by Dr. Peter Traykovski), and MR-2410 (led by Dr. Marcelo H García), among many others. Field and laboratory measurement have gathered large amount of data and to some degree revealed the mechanisms behind the motion of munitions. However, their researches are largely observational and empirical. There are still knowledge gaps for the physical and deterministic explanation of the phenomenology at both near-field and far-field scales. There is a strong research need on detailed and physically-based computational modeling. This point has been made very clear by numerous researchers funded under this program in the workshop report (Calantoni, 2014).

4 Materials and Methods

In this project, two main models were developed and/or improved to capture the physical processes involved in the dynamics of underwater UXOs. The first main model is the CFD model, *ibScourFoam*, for turbulent flow, sediment transport, and erosion/scour around UXOs. The second main model is the SPH code which can be used to simulate the couple process of free surface waves, sediment bed response, and object movement. In this section, both models are described with the emphasis on the innovations and new methods resulted from this project.

For the CFD model, two main innovations are necessary. One is on the innovative method to deal with sand slide over a bed slope exceeding the angle of repose. The second innovation is the use of the Immersed Boundary Method to track the bed movement as a result of sediment erosion. Both innovations are necessary for successful simulation of sediment transport and scour around UXOs.

Much of the content in this section and the result section has been published in peer reviewed journal papers or in the process of revision. Specifically, the sand slide method presented in Section 4.1 has been published in Song et al. (2020). The 3D scour model using the new immersed boundary method has been published in Song et al. (2022). The 3D SPH model is in a manuscript in revision.

4.1 Sand slide method for 3D scour models

4.1.1 Introduction

Computational scour modeling has gained significant popularity due to its proven value for engineering design in practice and the fundamental understanding of the erosion process (Brørs, 1999; Liang et al., 2005; Roulund et al., 2005; Liu and García, 2008; Khosronejad et al., 2011; Escarriaza and Sotiropoulos, 2011). Almost all scour models couple hydrodynamics and sediment transport. The hydrodynamics part provides the flow field, which is the solution of either the three-dimensional (3D) Reynolds Averaged Navier-Stokes Equation (Wilcox, 2006) or two-dimensional (2D) depth-averaged shallow water equations (Liu et al., 2008). The sediment transport part calculates the fluxes of bedload and suspended load (Garcia, 2008). It also updates the bed elevation based on the conservation of sediment mass, i.e., the Exner equation (Exner, 1920, 1925). A scheme diagram for a typical scour model is shown in Fig. 4.1. In such models, the hydrodynamics component provides flow field and bed shear stress which are used to calculate sediment transport fluxes. The fluxes of sediment moving along (bedload) and into/out of (suspended load) bed result

in the bed elevation change which can be described with the Exner equation as

$$\frac{\partial z_b}{\partial t} = \frac{1}{1-n} (-\nabla \cdot \mathbf{q}_b + D - E) \quad (4.1)$$

where $z_b(x, y)$ is the bed elevation. x and y are the two horizontal coordinates, respectively. n is the porosity of the bed, $\mathbf{q}_b$ is the bedload transport rate, D and E are the deposition and entrainment flux of suspended load, respectively.

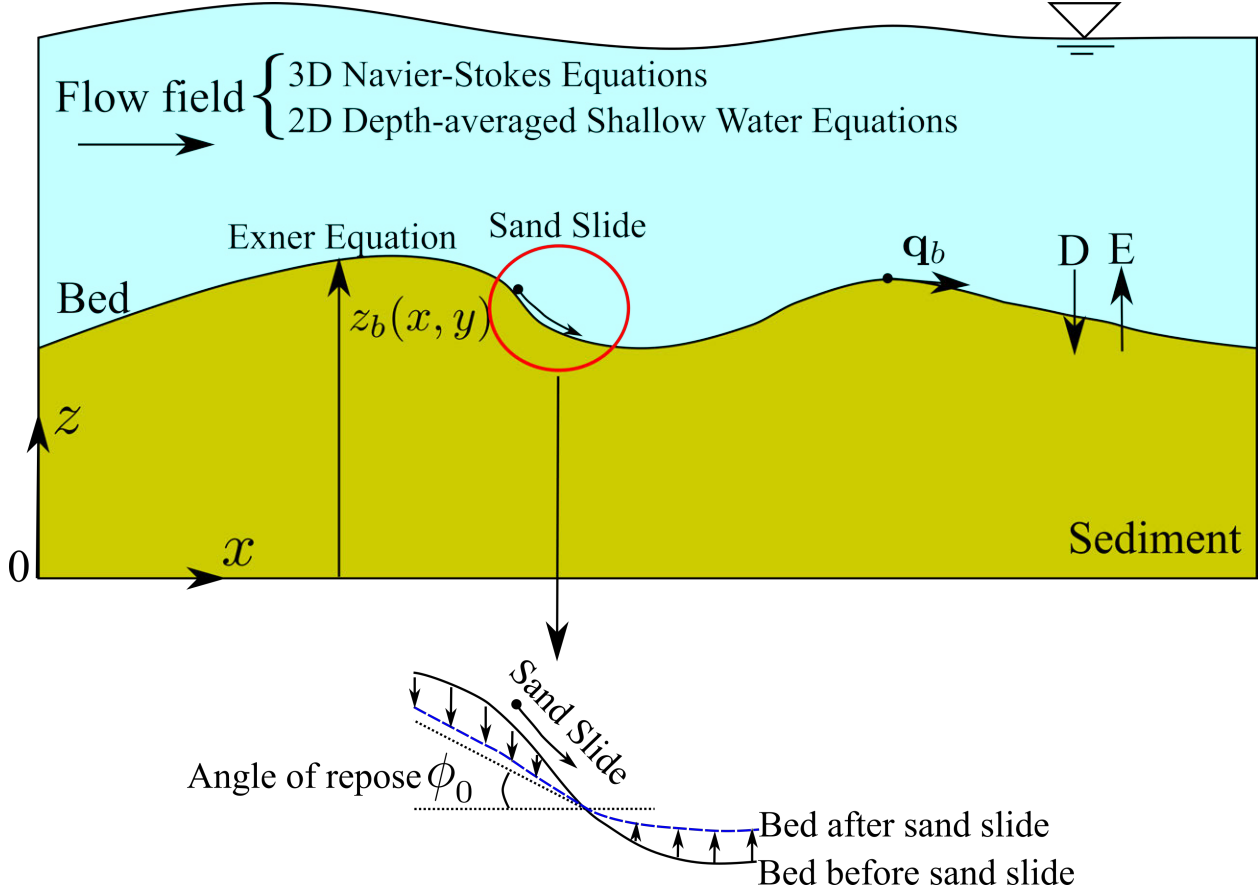


Figure 4.1: Scheme diagram of a typical scour model with the definition of different components. The sand slide part is highlighted.

Sand slide is an essential component of all such scour models because the Exner equation does not take into consideration of the angle of repose ϕ_0 . Consequently, the solution of the Exner equation may result in the situation of local bed slope exceeding the angle of repose. To deal with this, a scour model needs to let sediment slide down the excessive slope until bed slope everywhere is less than or equal to ϕ_0 . Such treatment is illustrated in Fig. 4.1 (zoom-in view).

In general, sand slide treatment should conserve mass and be based on physics. In addition, it should give a unique bed elevation solution, not depend on bed mesh type, and be computationally efficient. Unfortunately, there is no existing sand slide model which satisfies all above requirements. Nevertheless, good scour modeling results have been reported in literature with

their respective sand slide models. The reason may be that sand slide was not significant in those cases, or the sand slide was treated with special care.

The first type of existing treatment is through the correction of bedload transport rate. This is a straightforward approach and is somewhat physically-based because the effect of sand slide is an additional flux of sediment down the slope. The influence of excessive bed slope is taken into account by adding a correction term in the bedload transport rate (Struiksma and Crosato, 1989; Chesher et al., 1993; Brørs, 1999). For example, Brørs (1999) gave the following correction to the bedload flux

$$\mathbf{q}_b = \mathbf{q}_0 - C|\mathbf{q}_0|\nabla z_b \quad (4.2)$$

where $\mathbf{q}_0$ is the bedload transport flux on flat bed. The second term on the right-hand side of Eq. 4.2 is attributed to sand slide which results in the additional flux of sediment. This additional term is proportional to bedload transport rate and bed slope. The proportionality coefficient C is in the range of 1.5 to 2.4 according to laboratory measurements of bedload transport on sloping beds (Whitehouse, 1998). Despite its physical origin, this correction for sand slide needs careful calibration of the coefficient C . Moreover, it does not guarantee the bed slope not exceeding the angle of repose. In fact, it only alleviates the excessive bed slope problem. For bed areas with very large bed slope and high bedload transport rate, this approach may even over-correct the bed.

Roulund et al. (2005) developed a similar sand slide method based on a correction to the bedload transport rate. In their method, the bedload transport rate is related to the mean transport velocity of the sand particle $\mathbf{U}_b$. First, the sediment particle velocity is calculated based on the force balance for a particle on a slope. Larger bed slope will result in faster moving sediment particle down the slope because of gravity. Then, the bedload transport rate is updated with the new estimated sediment particle velocity and the Exner equation is solved to update the bed elevation. This procedure is repeated until bed slope everywhere is below or equal to the angle of repose. The physics of this sand slide method is more meaningful than the simple correction in Eq. 4.2. However, its use is still limited because of the force balance assumption for a particle on a slope. Indeed, a sediment particle may accelerate or decelerate as it slides down a slope. In addition, the mean transport velocity depends on the size of sediment particle. Thus, if a mixture of sediment is simulated, then each sediment size group needs to be considered separately.

The second type of existing treatment is termed the “geometric sand slide model” because they are mostly based on geometric operations on the bed mesh without considering the sand slide physics. In such methods, the bed elevation z_b is adjusted in areas where the bed slope exceeds the angle of repose. As a result, one advantage of geometric sand slide model is high efficiency. It only needs to adjust areas where the bed slope exceeds the angle of repose. However, adjusting bed elevation in one area may result in exceeding bed slope in its neighboring area. Thus, an iteration is usually adopted to ensure global bed slope compliance. In addition, the final bed may depend on the order of bed adjustment. In cases where many areas of the bed exceed the angle of repose, the iteration may converge to different final bed configurations depending on which area is adjusted first and the order of other areas follows that. It is noted this conclusion is based on the authors’ implementation of one geometric method which may not capture all the variants of such method in the literature. It is possible certain specific implementation may not have these weaknesses. Regardless, there is no rigorous investigation or mathematical proof on the

convergence of these methods. In other words, the iteration may diverge or oscillate.

One example of the second type treatment is reported in Liang et al. (2005). Their method was developed in a vertical 2D scour model and the bed elevation z_b was thus only a function of x . If the bed slope between two neighboring nodes exceeds the angle of repose, the two nodes are moved vertically in opposite directions such that the bed angle is exactly ϕ_0 (see Fig. 4.2a for internal nodes and Fig. 4.2b for boundary nodes). A smoothing step is followed in their method to stabilize the bed. This sand slide treatment is very simple and easy to be implemented. However, this treatment does not strictly enforce sediment mass conservation. In the derivation of the elevation adjustment dz for the two neighboring nodes, only the mass balance in the area between the two nodes is considered. This may create mass conservation problem for the area next to the two adjusted nodes. With the illustration in Fig. 4.2a, the increase of elevation z_b at x_i will artificially add mass to the area bounded by x_{i-1} and x_i . The same problem is also observed for boundary nodes as shown in Fig. 4.2b. Conversely, the lowering of the bed at x_{i+1} will remove sediment mass to the area bounded by x_{i+1} and x_{i+2} . The global mass balance is broken if the addition and removal on both sides are not equal, which will happen if a nonuniform grid in the x direction is used. In an effort to solve the mass balance problem in this method, an avalanche function approach has been proposed (Marieu et al., 2008; Niemann et al., 2010). This function adjusts the bed elevation z_b at both the two adjacent nodes and the neighbouring area to ensure the bed angle compliance. Regardless, this type of treatment has only been demonstrated with vertical 2D models.

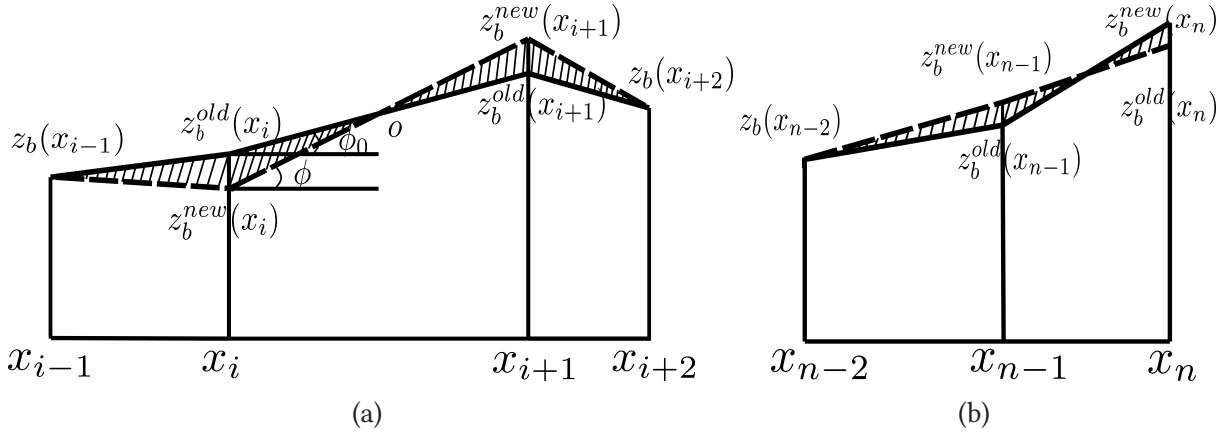


Figure 4.2: Illustration of the one-dimensional geometric sand slide method in Liang et al. (2005): (a) elevation change in an inner grid, (b) elevation change on a boundary grid.

Jacobsen (2015) presented a 3D scour model and reported a geometric sand slide method on a 2D unstructured bed mesh. It is worth noting that in 3D scour models, the bed is a 2D surface described by the function $z_b(x, y)$ in 3D space. In their method, if a bed face has a slope exceeding the angle of repose, its face normal vector is re-calculated by forcing the face slope to be the angle of repose. Then, the vertical displacement of all vertices is calculated with the new face normal vector. In addition, these displacements are corrected to satisfy sediment mass conservation. The key to mass conservation in their method is the “dual-mesh” approach for the face-to-vertex interpolation of bed elevation. Their sand slide method also requires iterations (termed “recursive functions” in their paper) which start with the steepest faces and their immediate neighbors. The

required iterations for convergence may be large. In addition, the non-planar faces are ignored in their method and thus mass imbalance may be severe in some cases.

Another geometric sand slide method for a 3D scour model has been reported in Khosronejad et al. (2011). Their method is very similar to the one in Liang et al. (2005). However, instead of adjusting the elevations of bed nodes (vertices), it corrects the elevations of face centers. The advantage of this approach is that it conserves mass and is easy to be implemented. As a result, this method and its variants have been used in many 3D scour models (Khosronejad et al., 2012; Afzal et al., 2015; Zhang et al., 2019). However, it also needs an iterative procedure to sweep over all faces in the bed mesh and ensure global bed slope compliance. In addition, the final bed is not only dependent on the sequence of the sweep but also related to the bed mesh type.

Based on the literature review, there is a need to develop a sand slide model which strictly conserves mass, is based on physics, gives a unique bed elevation solution, and does not depend on bed mesh type. Such a model should also be computationally efficient and can be universally applied in any scour models. This work proposes a model which satisfies all these requirements. The idea is based on the diffusive nature of sand slide process and thus the slide flux is proportional to bed surface gradient. As a result, the sand slide process is governed by a diffusion equation for bed elevation. The diffusive sand slide flux is however limited by whether the bed slope is below or above the angle of repose. This method is based on physical processes rather than direct manipulation of bed elevation at grid points.

In the following, the derivation of the diffusive sand slide model is presented first. Then, the physical meaning and determination of the diffusion coefficient are discussed. Following that, the special numerical schemes to discretize the diffusion equation are described. Two cases are presented in the results section to show the performance of the new method.

4.1.2 Slope-limited diffusive sand slide method

Physical Basis and Mathematical Formulation

The new method is inspired by the ubiquitous geophysical sediment slide process on hillslopes in Nature. Under the combined effect of tectonic uplifting force and gravity, hillslopes show great resemblance of sand slide surfaces in scour holes. In geoscience, sediment transport on hillslopes is modeled as a simple diffusive process (Culling, 1960, 1963). The diffusive nature of the process is due to the fact that the particle transport rate on a hillslope is proportional to the slope of topography. According to Fick's law of diffusion, the diffusive sand slide flux can be written as

$$\mathbf{q} = -K\nabla z_b \quad (4.3)$$

where $\mathbf{q}$ is the sand slide flux and K is the sand slide diffusivity (L^2/T).

In the context of sand slide, one deviation from the Fick's law is that the flux is limited by the bed slope. If the bed angle is less than or equal to the angle of repose, there is no sand slide and thus the flux should be zero. To reflect this, the diffusivity K should be a conditional function as follows:

$$K = \begin{cases} K_0, & \text{if } |\nabla z_b| \geq \tan \phi_0 \\ 0, & \text{otherwise} \end{cases} \quad (4.4)$$

where K_0 is the diffusivity once sand slide initiates and has a constant value in this work. The physical meaning of K_0 and its value will be discussed later.

The effect of bed slope on hillslope sediment flux has indeed been considered in the geoscience literature. For example, Roering et al. (1999) proposed a nonlinear relationship for the sediment flux which has the form of

$$\mathbf{q} = -\frac{K_0}{1 - (|\nabla z_b|/\tan\phi_0)^2} \nabla z_b. \quad (4.5)$$

where K_0 corresponds to the constant in Eq. 4.4 and is related to the net force resisting transport, gravity, particle density and the effective coefficient of friction. Instead of a conditional function as in Eq. 4.4, a continuous nonlinear function is used to model the effect of bed slope. In their formula, when the bed angle approaches the angle of repose, the sand slide flux increases quickly to infinity to avoid very steep bed angle. On the other hand, when the bed angle is small, their formula recovers the linear relationship in Eq. 4.3.

For simplicity, this work adopts the simple linear model in Eq. 4.3. The sediment diffusive flux in Eq. 4.3 must satisfy the mass conservation which leads to

$$\frac{\partial z_b}{\partial t} = K \nabla^2 z_b. \quad (4.6)$$

Given proper boundary and initial conditions, the solution of this equation can update the bed elevation due to sand slide. An iteration is also needed until the bed angle in the whole domain is below or equal to the angle of repose.

In order to use this diffusive sand slide model, there are two important issues to be addressed. One is the specification of the diffusion coefficient K_0 and another is the numerical schemes to solve Eq. 4.6.

Diffusion Coefficient K_0 For hillslopes, the driver for sediment moving down a slope is the climatic forces, e.g., surface runoff and gravity. The diffusion coefficient K_0 in Eq. 4.5 depends on the amplitude and frequency of these external forces (BenDror and Goren, 2018). In the context of sand slide in scour models, the only driving force is gravity. The speed of sand sliding down a slope should be proportional to the bed slope. The larger the bed slope, the larger the sand slide flux. The proportional constant is the diffusion coefficient K_0 .

The diffusion coefficient constant K_0 should depend on sediment properties, flow condition, and bed slope. There is no previous study on this dependency. However, the slope correction term in Brørs (1999) (Eq. 4.2) can be used to analyze the dependency. Comparing the correction term in Eq. 4.2 and the flux formula in Eq. 4.3, one can find

$$K_0 \sim C|\mathbf{q}_0|. \quad (4.7)$$

The rationale for this scaling relationship is that when the bedload flux is large, the bed morphological change is more active and thus more chances for the bed to have faces steeper than the angle of repose. Therefore, it may be reasonable to assume the proportionality between K_0 and the bedload flux $|\mathbf{q}_0|$. For cases where suspended load is significant, the value of K_0 should also

include the effects of suspended load. For implementation, the maximum $|\mathbf{q}_0|$ around the sand slide region can be used to calculate the constant K_0 . The value of K_0 should not be too small to avoid long sand slide computation. It should not be too large either to avoid over-correction. For simplicity, a proper value for K_0 can be estimated and kept constant for the duration of simulation.

In our implementation, the sand slide step is placed after the solution of the Exner equation. Within each time step, the sand slide Eq. 4.6 is solved in an iterative fashion until the angles of all bed surfaces are below or equal to the angle of repose. Therefore the iteration time step Δt for sand slide is a pseudo time step to control the number of iterations and sand flux within each iteration. Indeed, the value of Δt has the same effect as the diffusion constant K_0 . As such, the specification of Δt and K_0 should be considered concurrently. If the sand slide is under no water condition (i.e., for the sand column collapse case shown later), the constant K_0 is not related to the sediment transport flux but a numerical value to control the sand slide iterations. Thus Δt and K_0 are only required to ensure numerical stability ($\Delta t / \Delta x^2 \leq 1 / (2K_0)$) and avoid over-correction of the bed slope. Δx is the mesh grid size.

4.1.3 Numerical schemes

The finite volume method (FVM) is used to solve the diffusive sand slide equation in Eq. 4.6. It automatically guarantees mass balance if the diffusive flux is evaluated consistently across the interface between adjacent control volumes (Versteeg and Malalasekera, 2007; Ferziger and Perić, 2002).

For a 2D bed mesh consisting of faces, the solution variable z_b is stored at the face center. Integrating Eq. 4.6 over a control volume (a face in this case) and invoking the divergence theorem, one can get

$$\int_V \frac{\partial z_b}{\partial t} dV = \int_V K \nabla \cdot (\nabla z_b) dV = \int_S K \nabla z_b \cdot \mathbf{n} dS \quad (4.8)$$

where V is the control volume, S is the surface of the control volume (edges bounding the bed face in this case), and $\mathbf{n}$ is the normal vector on the surface S . For the temporal derivative in Eq. 4.8, a first-order Euler scheme is used in this work. On a 2D bed mesh, the surface integral becomes the summation over the edges, i.e.

$$\int_S K \nabla z_b \cdot \mathbf{n} dS \approx \sum_{\text{all edges}} K_f (\nabla z_b)_f \cdot \mathbf{n} S_f \quad (4.9)$$

where the subscript f denotes the value on the edges and S_f is the edge length. For the bed slopes at edges $(\nabla z_b)_f$, the central differencing approach is employed. The diffusive flux term $K_f (\nabla z_b)_f$ on the edges can then be approximated as

$$K_f (\nabla z_b)_f = K_f \frac{z_{b,P} - z_{b,N}}{\overline{PN}} \quad (4.10)$$

where P and N denote two neighbouring faces and $\overline{PN}$ is the distance between the two face centers (see Fig. 4.3).

The edge diffusion coefficient K_f in Eq. 4.10 is computed with Eq. 4.4, which depends on the edge bed slope $|(\nabla z_b)_f|$. Three different gradient schemes can be used to discretize $|(\nabla z_b)_f|$. The first scheme uses the same linear central differencing as in Eq. 4.10, which is termed “linear gradient scheme (LGS)” in this chapter:

$$S_0 = |(\nabla z_b)_f| = \left| \frac{z_{b,P} - z_{b,N}}{PN} \right| \quad (4.11)$$

where S_0 is bed slope. In this method, only the bed elevations of faces P and N are involved.

The second scheme uses a more complex method which involves more faces around the edge. The bed elevation is firstly interpolated from face centers to edge centers with a distance-weighted interpolation scheme, i.e.,

$$z_{b,f} = f_x z_{b,P} + (1 - f_x) z_{b,N} \quad (4.12)$$

where the weight $f_x = \overline{eN}/\overline{PN}$, $\overline{eN}$ is the distance between the edge center and the face center N . Then, the divergence theorem is used to evaluate the bed elevation gradients at face centers, i.e., $(\nabla z_b)_P$ and $(\nabla z_b)_N$, as

$$\nabla z_b = \frac{\int_V \nabla z_b dV}{V} = \frac{\sum_{\text{all edges}} z_{b,f} \mathbf{n}_f S_f}{V} \quad (4.13)$$

Finally, the bed elevation gradient at the shared edge between faces P and N is calculated with a linear interpolation as

$$S_0 = |(\nabla z_b)_f| = |f_x (\nabla z_b)_P + (1 - f_x) (\nabla z_b)_N| \quad (4.14)$$

It is clear that the second scheme involves more faces around an edge for the evaluation of its bed gradient (see Fig. 4.3). This makes a crucial difference in the sand slide results because of the discrete nature of numerical method. With the second scheme, the bed elevation gradient $(\nabla z_b)_f$ at an edge not only depends on the elevation difference between two neighbouring faces, but also those of the surrounding cells marked as gray in Fig. 4.3. In essence, $(\nabla z_b)_f$ calculated in this way contains the bed elevation information not only in the edge normal direction, but also in the diagonal direction. This represents more physically what happens in reality. When sand slide happens, sediment particles will slide in all directions in which the slope exceeds the angle of repose. Because Gauss’s divergence theorem is used in this second scheme, it is termed “Gauss nonlinear gradient scheme (NGGS)” in this work.

One should notice that this NGGS for bed slope evaluation in Eq. 4.4 is not consistent with the linear discretization of bed elevation gradient in solving the governing equation Eq. 4.6. This inconsistency needs to be addressed because the following situation may happen. In this situation, the edge slope $(\nabla z_b)_f$ in Eq. 4.9 is different than the edge slope used for the conditional K evaluation in Eq. 4.4. For example, the edge slope $(\nabla z_b)_f$ may be zero, but the diffusion coefficient K_f is not because the real bed slope is larger than angle of repose. As a result, the sand slide flux $K_f (\nabla z_b)_f \cdot \mathbf{n} S_f$ in Eq. 4.9 is zero, which is wrong. This may cause some residual faces to always have slopes larger than the angle of repose even after many iterations. The effect of these remaining faces may accumulate and eventually make the scour simulation diverge. This is because the residual faces can make some local elevation spiky and distort the mesh. A highly

distorted mesh can easily deteriorate the hydrodynamics result (Liu and García, 2008). To address this problem, a combination of both schemes (GNGS+LGS) is used. At the beginning, GNGS is used until the sand slide process reaches semi-equilibrium. If there are still faces exceeding the angle of repose, LGS is then used to remove them.

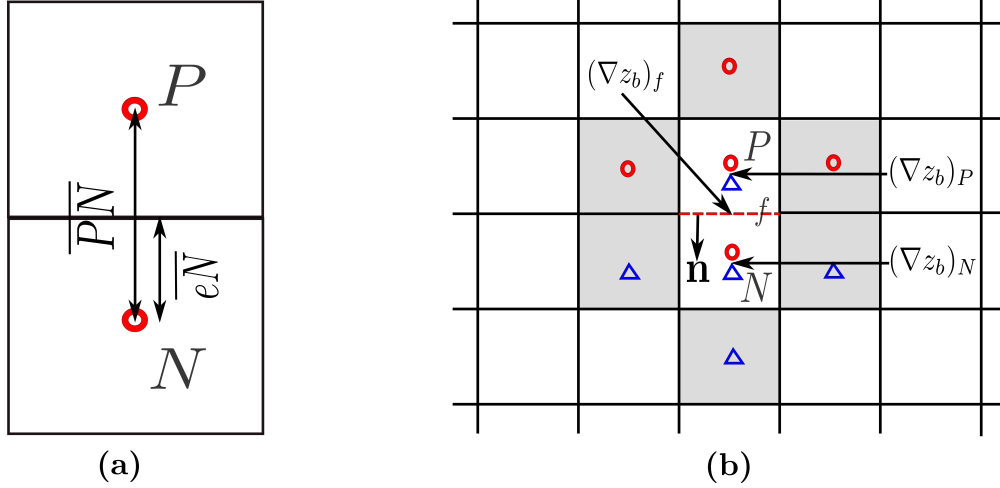


Figure 4.3: Two methods for the evaluation of bed elevation gradient at edge center $(\nabla z_b)_f$. (a) For the first method using a simple linear central differencing, only faces P and N are involved. (b) For the second method, additional faces marked with gray shade are used. The faces marked with circles are used for the calculation of bed elevation gradient $(\nabla z_b)_P$ at the face center P ; the cells marked with triangles are used for the calculation of the bed elevation gradient $(\nabla z_b)_N$ at face center N .

The sand slide method and related numerical schemes introduced above have been implemented using the open source computational physics platform OpenFOAM (OpenFOAM Foundation, 2018). The detailed implementation of the diffusive sand slide method with all schemes is embedded in an existing 3D scour model presented in Liu and García (2008) and the 3D immersed boundary method scour model developed in this project. The basic structure of scour models is the same as shown in Fig. 4.1 where the sand slide part uses the new method in this section.

4.2 3D scour modeling with the immersed boundary method

4.2.1 Introduction

Local scour, induced by accelerated flow field and sediment transport around coastal and riverine structures and objects, is a common phenomenon with great importance for engineering practice. Most local scour formulas are of empirical nature. The research and practice communities have long desired to have more reliable and deterministic means to predict the hydrodynamics and morphodynamics that govern the scour process. High-fidelity computational modeling is one of the increasingly popular means thanks to the advancements in computing techniques and power. This section describes and demonstrates one such model which has the potential to handle

scour around objects and structures with complex geometries, a difficult task for many existing models.

Since the 1970s, many numerical scour and sediment transport models have been developed. They can be classified into one-dimensional (1D) models, two-dimensional (2D) models, and three-dimensional (3D) models. One-dimensional models are not adequate for the simulation of local scour. Some 2D scour models solve 2D Reynolds-Averaged Navier-Stokes equations (RANS) for 2D scour problems, such as scour under pipelines or scour due to submerged wall jets (Liang et al., 2005; Fuhrman et al., 2014; Larsen et al., 2016; Yan et al., 2020). The other 2D scour models solve the depth-averaged shallow water equations (Liu et al., 2008, 2016). However, vertical fluid motion is very prominent in the vicinity of structures and is a primary contributor to local scour. Thus, depth-averaged models should theoretically not be used for local scour modeling. In practice, they are often used anyway to obtain flow information, such as velocity magnitude and water depth, to be plugged into empirical formulas to estimate scour depth.

Due to the three-dimensional nature of local scour, both hydrodynamically and morphodynamically (Fredsoe and Sumer, 2002), 3D models are naturally needed. A typical 3D scour model consists of at least three parts, namely a hydrodynamic solver to obtain the turbulent flow field of waves and currents, a sediment transport solver to calculate sediment fluxes, and a bed evolution solver to update the bed position due to sediment motion (Figure 4.4). For practical purposes, the hydrodynamic solver usually uses the Reynolds-Averaged Navier-Stokes equations (RANS) approach to model turbulent flow, although some models also adopt computationally more expensive approaches such as Large Eddy Simulation (LES). The sediment transport solver calculates the bed-load transport rate with empirical formulas and the suspended load transport rate with an advection-diffusion equation. The bed evolution part solves the bed sediment mass balance equation, i.e., the Exner equation, usually in conjunction with a sand slide treatment to ensure the resulted bed slope does not exceed the angle of repose (Roulund et al., 2005; Liang et al., 2005; Khosronejad et al., 2011; Jacobsen, 2015; Song et al., 2020).

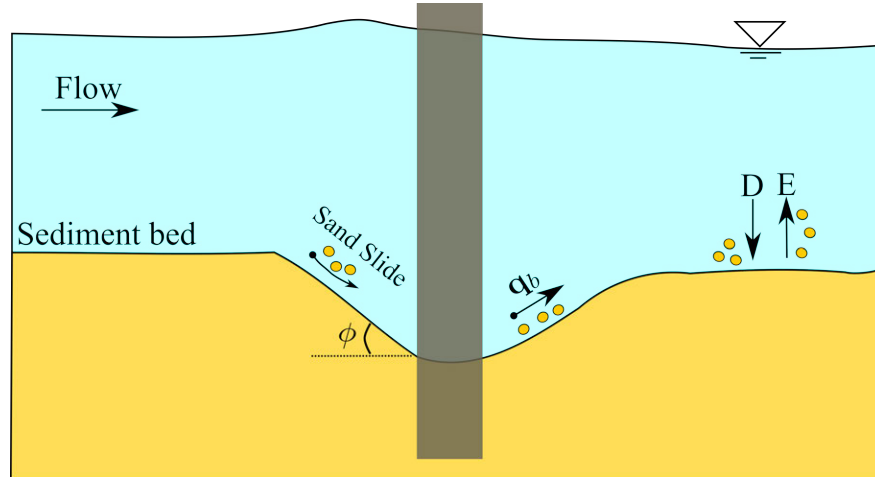


Figure 4.4: Scheme diagram of a scour model: q_b is the bed-load transport rate, D is the deposition rate, and E is the entrainment rate.

Computationally, one key difficulty in all 3D scour models is how to track the interface between

fluid and sediment. Several approaches have been proposed in the literature. One approach is the Arbitrary Lagrangian-Eulerian (ALE) method (Chen, 2006; Liu and García, 2008; Liu et al., 2016; Song et al., 2020). In this approach, the bed surface is a boundary of the computational domain for the flow field. As the bed evolves, the boundary and computational mesh deform accordingly. Though simple, this approach is very limited for practical use. The deformation of mesh may cause excessive stretching and compression such that mesh quality deteriorates and simulation fails. In addition, the ALE approach can only be used for very simple geometry, such as a vertical pile (Roulund et al., 2005; Liu and García, 2008; Zhao et al., 2010; Baykal et al., 2017).

The second approach to bed tracking is the two-phase Eulerian-Eulerian model (Link et al., 2012; Nagel et al., 2020). Both water and sediment are modeled as continuous phases, whose interactions can be added into their respective governing equations. One example is the *sedFoam* model (Cheng et al., 2017). It is built with the open-source computational physics platform OpenFOAM (OpenFOAM Foundation, 2018). With this approach, the bed interface is implicitly modeled and its interaction with structures can be captured without complicated geometric operations. This method has shown good performance in simulating scour processes (Cheng et al., 2017; Chauchat et al., 2017; Nagel et al., 2020). However, this approach heavily relies on the parameterization of non-Newtonian behavior of sediment-water mixture, a field still in need of more research.

The third approach to bed tracking is the immersed boundary (IB) method, which is used in this work. The IB method was first proposed in Peskin (1973) to simulate blood flow in hearts and has flourished since then in many fields of fluid dynamics. The basic idea of the IB method is to use a fixed background mesh which does not conform to a solid boundary. Instead, the boundary is “immersed” within the simulation domain and its effect on the flow is enforced implicitly (Tamaki et al., 2017; Capizzano, 2011; Zhou, 2017; Song et al., 2020; Xu and Liu, 2021). In the context of scour modeling, the bed is treated as an immersed boundary and can move as scour hole develops. The bed surface is independent of the background mesh and thus the moving bed does not cause any geometric change.

The 3D scour model presented in this section adopts a sharp-interface immersed boundary method. The bed is represented by an unstructured triangular surface mesh embedded in the background mesh (Afzal et al., 2015, 2020; Ahmad et al., 2020; Khosronejad et al., 2011; Song et al., 2020). Sediment fluxes are calculated on the immersed bed surface based on simulated wall shear stress. Thus, it is critical to obtain accurate and smooth wall shear from the IB method. Non-smoothness is often observed in simulated wall shear due to the arbitrary wall distance caused by the moving boundary and the different behaviors of wall functions in different sublayers of the near-wall region. Recently, two improved methods for smooth wall shear were developed in Song et al. (2020) and Xu and Liu (2021) for $k - \epsilon$ turbulence model. A similar method of Song et al. (2020) was used in the current 3D scour model under the framework of $k - \omega$ model. Additionally, a physically-based slope-limited diffusive sand slide model is used to correct the bed in areas where the slope is larger than the angle of repose (Song et al., 2020).

The organization of the rest of the section is as follows. First we describe the numerical methods of the 3D scour model, including the $k - \omega$ SST-SAS turbulence model, the immersed boundary method, the bed morphodynamic solver, and the coupling between the hydrodynamic solver and morphodynamic solver. The scour model is validated against experimental data, followed by an

application to scour around a relatively complex structure (see Appendix C).

4.2.2 Numerical model for 3D scour

The scour model, *ibScourFoam*, proposed in this work is implemented in OpenFOAM version 5.x (OpenFOAM Foundation, 2018). The immersed boundary method part is based on the algorithm in Xu and Liu (2021), which utilizes some data structures and code functionalities in the original immersed boundary method in the foam-extend project, a branch of OpenFOAM development (Jasak et al., 2014). The source code and the simulation cases used in this chapter are publicly available on GitHub (<https://github.com/psu-efd/ibScourFoam>).

Hydrodynamic model This section first describes the 3D RANS equations and the $k - \omega$ SST-SAS model for turbulence. Then, the immersed boundary method and the near-wall treatment are introduced.

The 3D incompressible Reynolds-Averaged Navier-Stokes equations can be written as:

$$\nabla \cdot \mathbf{u} = 0 \quad (4.15)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\frac{\nabla p}{\rho} + \nabla \cdot [(\nu + \nu_t) \nabla \mathbf{u}] \quad (4.16)$$

where $\mathbf{u}$ is the Reynolds-averaged flow velocity, p is the mean pressure, ρ is water density, ν is kinematic viscosity, and ν_t denotes the eddy viscosity.

The $k - \omega$ model has been proven to have better performance in the near-wall region and numerical stability (Wilcox, 2006). In this work, the $k - \omega$ SST-SAS model (Egorov and Menter, 2008) is adopted and its governing equations are:

$$\frac{\partial k}{\partial t} + \nabla \cdot (\mathbf{u}k) = \nabla \cdot [(\nu + \alpha_k \nu_t) \nabla k] + P_k - C_\mu k \omega \quad (4.17)$$

$$\begin{aligned} \frac{\partial \omega}{\partial t} + \nabla \cdot (\mathbf{u}\omega) = & \nabla \cdot [(\nu + \alpha_\omega \nu_t) \nabla \omega] + \alpha \frac{\omega}{k} P_k - \beta \omega^2 \\ & + \frac{2}{\alpha_{\omega 2}} (1 - F_1) \frac{1}{\omega} \nabla k \nabla \omega + Q_{SAS} \end{aligned} \quad (4.18)$$

where k denotes the turbulence kinetic energy, ω denotes the specific dissipation rate. $P_k = \nu_t \mathbf{S}^2$ is the production term, $\mathbf{S} = \sqrt{2\mathbf{S}_{ij}\mathbf{S}_{ij}}$ is a scalar invariant of the strain rate tensor $\mathbf{S}_{ij} = 0.5[(\nabla \mathbf{u})_{ij} + (\nabla \mathbf{u})_{ji}]$. To reduce the length of the text, additional terms and coefficients in the model can be found in Song et al. (2022).

Immersed boundary method with smooth wall shear The hydrodynamic solver utilizes a background mesh that conforms to the simulation domain including in-stream structures. However, the mobile sediment bed is modeled as an immersed boundary in the format of an STL (STereoLithography) surface (Figure 4.5). The size of the background mesh needs to be larger than the physical domain, especially in the vertical direction. This is to leave enough room for the bed to evolve.

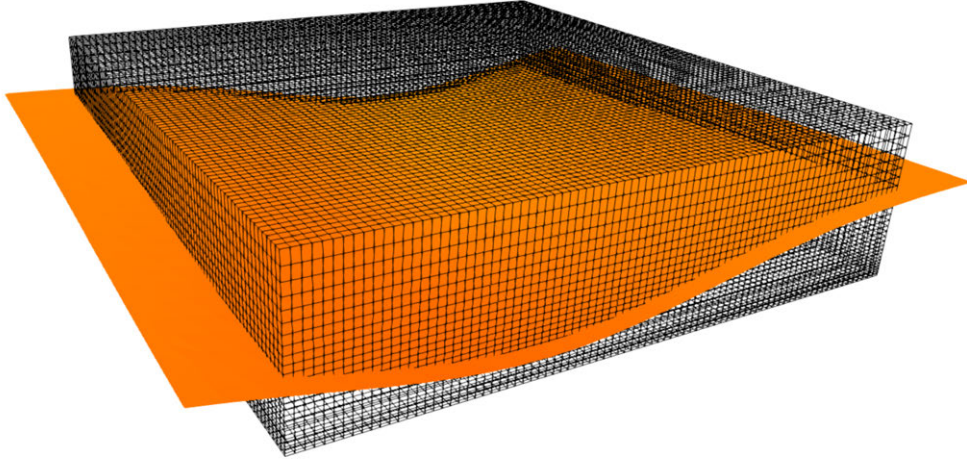


Figure 4.5: Schematic view of a 3D background mesh and an embedded immersed boundary for a mobile sediment bed.

In the adopted IB method, three different types of cell types can be identified depending on their relative position to the immersed bed surface (see Figure 4.6): 1) the cells that intersect with the immersed boundary and have their centers located on the fluid side are identified as IB cells; 2) the cells fully on the fluid side are identified as fluid cells; and 3) the cells centered on the solid (sediment) side are called solid cells. In the hydrodynamic solver, only the flow variables of fluid cells are solved. Flow variables of solid cells are set to zero. For the IB cells in between, the flow variables are set according to a wall model.

In the wall model, three different point types are specified in the near-wall region as shown in Figure 4.6. The first point is the IB cell center; the second is the image point (IP) on the normal line to the immersed boundary that passes through the IB cell center; the third is the hit point (HP), which is the intersection of the normal line and the immersed boundary. The flow values at IPs are interpolated from their neighboring cells.

The distance between an IP and the immersed boundary is set to $d_{IP} = 3 l_*$, where l_* is the minimum dimension of the IB cell. Through extensive experimentation, this distance gives the most reasonable result for all test cases. Near the bed, if the cells have comparable size, this distance is almost uniform. In many existing methods, d_{IP} is set to be proportional to y_{IB} , which is the distance between an IB cell and the immersed boundary. However, since IB cells can have arbitrary distances to the immersed boundary and the distances change when the bed is evolving, d_{IP} in many existing methods can have arbitrary and non-uniform values. One consequence is spiky wall shear stress. As will be shown next, d_{IP} is a key variable in the wall function which controls the accuracy and smoothness of wall shear.

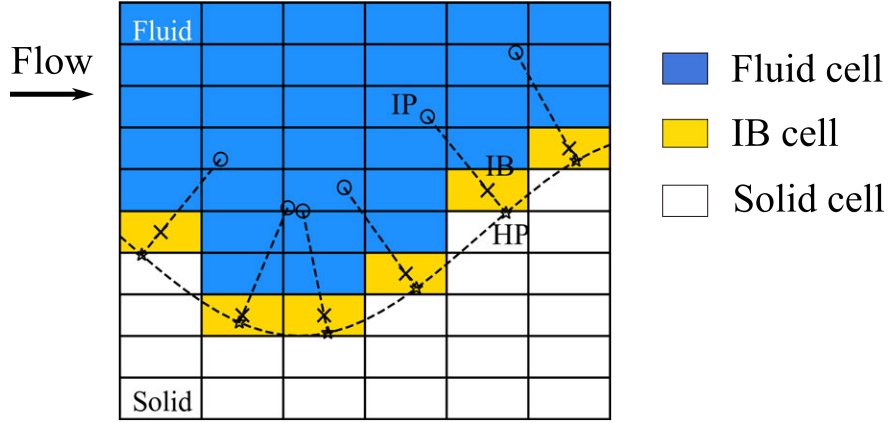


Figure 4.6: Schematic of cell classification in the IB method.

The wall function in the IB method is as follows. It is assumed that an IP and its corresponding IB cell's center are on the same log-law velocity profile, which can be written as:

$$u^+ = \frac{1}{\kappa} \ln(E' y^+) \quad (4.19)$$

where $u^+ = u/u_\tau$ and $y^+ = y u_\tau / \nu$ are the dimensionless velocity and wall distance, respectively. The shear velocity is denoted as u_τ and the wall shear is $\tau = \rho u_\tau^2$. E' is a wall roughness parameter related to the roughness of the boundary.

With the interpolated velocity at an IP, u_{IP} and the distance d_{IP} , the log-law can be written as:

$$\frac{u_{IP}}{u_\tau} = \frac{u_{IP}}{y_{IP}^+ \nu / y} = \frac{1}{\kappa} \ln(E' y_{IP}^+) \quad (4.20)$$

From this equation, the Newton-Raphson method can be used to solve for y_{IP}^+ iteratively using the following formula (OpenFOAM Foundation, 2018):

$$y_{IP,i+1}^+ = \frac{y_{IP,i}^+ + \kappa y u_{IP} / \nu}{1 + \ln(E' y_{IP,i}^+)} \quad (4.21)$$

Here i is the iteration number. Then, the shear velocity, u_τ , can be calculated based on the definition of y_{IP}^+ .

Another issue in the IB method is the velocity profile between an IB cell center and the immersed bed boundary. If the distance y_{IB} is too small, it may create numerical instability if a log-law profile is used (even if the IB cell is indeed in the log-law layer). To address this, a linear velocity distribution between the IP and HP is assumed for the purpose of assessing the velocity at IB (see Figure 4.7). We found this is a good and reasonable approximation to the log-law when y_{IB} is not large (which is the case for immersed boundary methods). The slope of the linear profile is

equal to the slope of the log-law profile at the IP. In essence, it is a linear extension of the log-law velocity profile to the wall. To maintain the same value of the shear stress on the immersed boundary ($u_\tau^2 = (\nu + \nu_t)\partial u / \partial y$), the eddy viscosity is held constant between IP and HP. This approach has been previously used in Tamaki et al. (2017) and Song et al. (2020). It has shown good performance in velocity and wall shear stress predictions. Another advantage of this method is that it avoids the discontinuous behavior of different wall functions used in the laminar sublayer and the log-law layer.

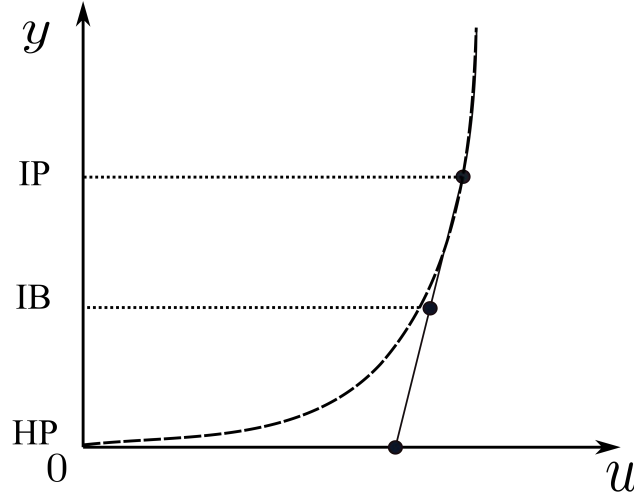


Figure 4.7: Velocity profile in the boundary layer. The dash line is the original profile. The solid line is the modified profile.

Based on the method described above, the tangential velocity, $u_{IB,tan}$, at the IB cell center is calculated as:

$$u_{IB,tan} = u_{IP,tan} - \left(\frac{\partial u^+}{\partial y^+} \right)_{IP,tan} (y_{IP} - y_{IB}) u_\tau \quad (4.22)$$

where $\partial u^+ / \partial y^+ = 1 / (\kappa y^+)$. The normal velocity, $u_{IB,norm}$, satisfies the non-penetration condition and is given as:

$$u_{IB,norm} = u_{IP,norm} \frac{d_{IP}}{d_{IB}} \quad (4.23)$$

The turbulence kinetic energy, $k = u_\tau^2 / \sqrt{C_\mu}$, is approximately constant in the near-wall region (Kalitzin et al., 2005). Here, $C_\mu = 0.09$. Since the eddy viscosity $\nu_t = k / \omega$ is also approximately constant between an IP and an IB cell center to maintain a constant shear stress (Tamaki et al., 2017), ω_{IB} is also a constant in this region such that ω_{IB} at the IB cell center can be calculated as:

$$\omega_{IB} = \omega_{IP} = \sqrt{\omega_{vis}^2 + \omega_{log}^2} = \sqrt{\left(\frac{6.0\nu}{0.075y_{IP}^2}\right)^2 + \left(\frac{k^{1/2}}{C_\mu^{1/4}\kappa y_{IP}}\right)^2} \quad (4.24)$$

As a proof of the efficacy of the modified wall function described above, a 2D benchmark case for the turbulence flow over a flat plate is presented in Song et al. (2022). The simulated wall shear and friction coefficient match well with experimental data.

4.2.3 Bed morphodynamic model

Currently, the morphodynamic model can only simulate the bedload. In all cases shown in this report, suspended sediment transport is insignificant. The morphodynamics is solved on a unstructured triangular mesh, which is used as the immersed boundary for the flow solver. The bedload transport rate for a flat, horizontal bed is calculated by the empirical formula proposed in Engelund and Fredsøe (1976),

$$\frac{q_0}{\sqrt{Rgd}} = \begin{cases} 18.74(\theta - \theta_c)(\theta^{1/2} - 0.7\theta_c^{1/2}), & \text{if } \theta > \theta_c \\ 0, & \text{if } \theta < \theta_c \end{cases} \quad (4.25)$$

where R is the submerged specific gravity (1.65 for quartz), d is the sediment grain size, $\theta = |\tau|/(\rho g R d)$ is the Shields number, and θ_c is the critical Shields number, which can be calculated from the modified fit to the Shields diagram (Parker et al., 2003)

$$\theta_{c0} = 0.5 \times (0.22Re_p^{-0.6} + 0.06 \times 10^{-7.7Re_p^{-0.6}}) \quad (4.26)$$

To include the effect of local bed slope and local flow direction, the critical Shields number is adjusted by

$$\theta_c = \theta_{c0} \left(\cos \beta \sqrt{1 - \frac{\sin^2 \phi \tan^2 \beta}{\mu_s^2}} - \frac{\cos \phi \sin \beta}{\mu_s} \right) \quad (4.27)$$

where β is the angle of local bed slope, ϕ is the angle between the velocity and bed slop, and μ_s is the static friction coefficient.

The evolution of the bed elevation is then solved from the Exner equation,

$$(1 - n) \frac{\partial z_b}{\partial t} = -\nabla \cdot \left(q_0 \frac{\tau}{|\tau|} \right) \quad (4.28)$$

where z_b is the bed elevation, and n is the porosity of the bed. The Exner equation only considers the conservation of mass for bed sediment. It does not consider other factors such as the stability of the granular bed if the angle exceeds the angle of repose. To correct that, a sand slide model must be applied. In this work, the sand slide model based on slope-limited diffusion is adopted (Song et al., 2020).

4.2.4 Hydrodynamics and morphodynamics coupling

The flow, sediment transport, and bed evolution are interdependent. Thus, a monolithic (fully-coupled) approach in which all of the governing equations are solved simultaneously would be computationally expensive. Similar to most previous scour modeling work, a sequential coupling method is used (see Figure 4.8). A fully-developed flow field is pre-simulated with an rigid bed as the initial condition. Then, flow and sediment transport are solved sequentially during each time step. The wall shear stresses at HPs on the immersed boundary are calculated with the wall model. The HPs are not necessary at the centers of triangles of the immersed bed surface mesh. Thus, an interpolation is used to get the wall shear at the triangle centers of the bed surface. From there, the sediment transport rate is calculated, and the Exner equation is solved to get the new bed elevation. Once the bed surface is moved, the whole coupling loop starts again.

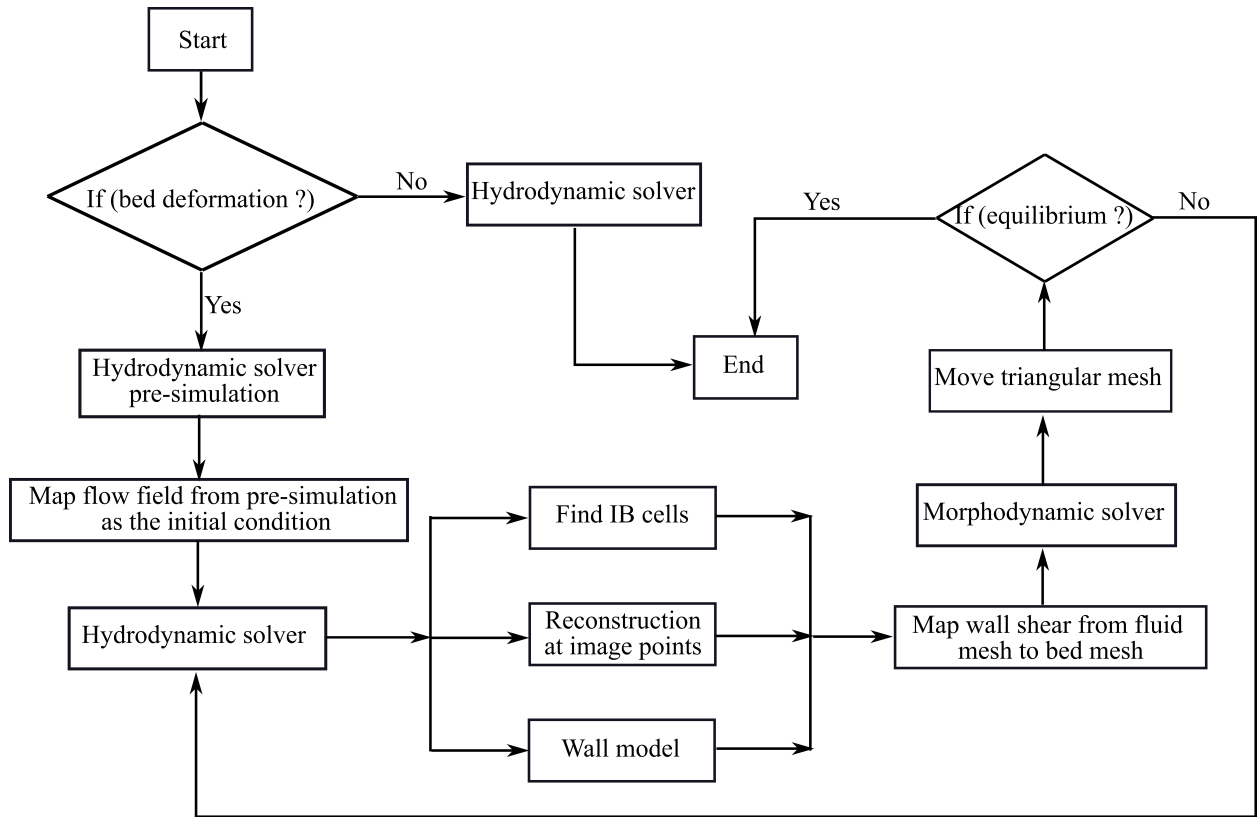


Figure 4.8: Flow chart of the scour model

For practical purpose, this sequential coupling approach is valid because sediment transport is a relatively slow process, i.e., the morphodynamic time scale (t_m) is much larger than that of hydrodynamics (t_h) (Liu and García, 2008; Termini, 2011; Afzal et al., 2015). In fact, most scour models take advantage of this to accelerate the simulation by using a morphological factor α :

$$\alpha = t_h/t_m, \quad \alpha \ll 1 \quad (4.29)$$

During each time step, the change of bed elevation is amplified by $1/\alpha$. The exact value of α to be used may vary from case to case. A balance between computing speed and accuracy should be

sought. Different values have been used previously. For example, Ponce et al. (1979) suggested the range of $0.01 \leq \alpha \leq 0.05$. In the context of immersed boundary method, the numerical stability must also be considered. In one time step, the bed elevation change at any location should not exceed the size of an IB cell. This is to avoid spurious oscillations caused by the direct change of a computational cell from solid to fluid (or vice versa) without first transitioning to an intermediate IB cell (Kim et al., 2001; Lee et al., 2011).

4.2.5 Code implementation

The scour model was implemented in the OpenFOAM version 5.x (OpenFOAM Foundation, 2018) based on the algorithm of the *pisoFoam* solver. The scour model contains three parts: the pre-processing of IB information required by the IB method, the flow solver of *pisoFoam* with a new wall model described in the previous section, and the morphodynamic calculation. The finite volume method (FVM) was used to solve the governing equations of hydrodynamics and morphodynamics on unstructured meshes. The discretization schemes used for simulations are listed in Table 4.1.

Table 4.1: Summary of discretisation schemes used for simulations (see OpenFOAM user manual for more details).

	Discretisation scheme
Time scheme	backward
Gradient scheme	Gauss linear U : Gauss linearUpwind grad(U)
Divergence schemes	k : Gauss upwind ω : Gauss upwind
Laplacian scheme	Gauss linear corrected
Interpolation scheme	linear
Surface normal gradient scheme	corrected

4.3 SPH model for the coupled processes of fluid-object-sediment system

The SPH model adopted in this work is the *DualSPHysics* code (Crespo et al., 2015). Modifications have to be done to suit the needs of munition movement problems. This section describes the details of the SPH model and the formulations used within.

4.3.1 SPH formulation

In SPH method, the continuous domain is discretized into a discrete number of particles. These particles can carry material properties such as density, mass, stress etc (Bui et al., 2008). These properties can move with the material velocity of the particle. The material properties of each

particle are calculated through the use of summation process over its neighboring particles. Integral representation of a field function $f(\mathbf{x})$ can be written as:

$$\langle f(\mathbf{x}) \rangle = \int_{\Omega} f(\mathbf{x}') W(\mathbf{x} - \mathbf{x}', h) d\mathbf{x}' \quad (4.30)$$

where $W(\mathbf{x} - \mathbf{x}', h)$ is the kernel function and h is the smoothing length which defines the influence domain of W . The smoothing function $W(\mathbf{x} - \mathbf{x}', h)$ should satisfy the following conditions. The first one is the normalization condition which has the form of

$$\int_{\Omega} W(\mathbf{x} - \mathbf{x}', h) d\mathbf{x}' = 1 \quad (4.31)$$

The second condition is that when the smoothing length approaches zero, the smoothing function should approach the delta function:

$$\lim_{h \rightarrow 0} W(\mathbf{x} - \mathbf{x}', h) = \delta(\mathbf{x} - \mathbf{x}') \quad (4.32)$$

The third is the compact support condition:

$$W(\mathbf{x} - \mathbf{x}', h) = 0 \quad \text{when } |\mathbf{x} - \mathbf{x}'| > \kappa h \quad (4.33)$$

where κ is a constant defines the effective area of the smoothing function.

Following the work of Fourtakas and Rogers (2016), the fifth-order Wendland kernel (Wendland, 1995) with compact support of $2h$ is used in this research. It has the form of

$$W(R, h) = a_d \left(1 - \frac{R}{2}\right)^4 (2R + 1) \quad (4.34)$$

where $R = |\mathbf{x}_i - \mathbf{x}_j|/h$ and the normalization constant a_d can be selected as $7/4h\pi^2$ and $21/16h\pi^3$ in 2D and 3D space, respectively.

4.3.2 Discretization of governing equations

With the above definitions in the SPH method, the governing equations can be discretized. The rheological characteristics of the domain are described by the Lagrangian form of the Navier-Stokes equations, which are discretized using the SPH scheme to approximate the multiphase flows. Greek superscripts α and β denote coordinate directions. In the following equations, the notation of Einstein's summation is used. The continuity and momentum equations in Lagrangian form can be written as

$$\frac{d\rho}{dt} + \rho \frac{\partial u^\alpha}{\partial x^\alpha} = 0 \quad (4.35)$$

$$\frac{du^\alpha}{dt} = \frac{1}{\rho} \frac{\partial \sigma^{\alpha\beta}}{\partial x^\beta} + g^\alpha \quad (4.36)$$

where u denotes the velocity, g is the gravitational acceleration, and σ is the total stress tensor. In a fluidic approach, the stress tensor consists of two components: the isotropic pressure p and the viscous stresses τ (Fourtakas and Rogers, 2016)

$$\sigma^{\alpha\beta} = -p\delta^{\alpha\beta} + \tau^{\alpha\beta} \quad (4.37)$$

where $\delta^{\alpha\beta}$ is Kronecker's delta function.

In the SPH formulation (Violeau, 2012), the Navier-Stokes equations can be approximated as

$$\frac{d\rho_i}{dt} = \rho_i \sum_j^N \frac{m_j}{\rho_j} (u_i^\alpha - u_j^\alpha) \frac{\partial W_{ij}}{\partial x^\alpha} \quad (4.38)$$

$$\frac{du_i^\alpha}{dt} = \sum_j^N \left(\frac{\sigma_i^{\alpha\beta} + \sigma_j^{\alpha\beta}}{\rho_i \rho_j} \right) \frac{\partial W_{ij}}{\partial x^\beta} + g_i^\alpha \quad (4.39)$$

which are applied to each SPH particle i in the domain.

4.3.3 Equation of state

To approximate an incompressible fluid, an equation of state (EOS) (Batchelor, 2000; Monaghan, 2005) is needed to link pressure to density. In this study, the following form is used:

$$p = B \left(\left(\frac{\rho}{\rho_0} \right)^\gamma - 1 \right) \quad (4.40)$$

where ρ_0 is the reference density and B is based on the compressibility which is proportional to the speed of sound of the fluid as

$$B = \frac{C_{s0}^2 \rho_0}{\gamma} \quad (4.41)$$

and γ is the polytropic index which usually takes the value of 7 (Monaghan, 2000) and C_{s0} is the numerical speed of sound calculated as

$$C_{s0} \geq 10u_{max} \quad (4.42)$$

where u_{max} is the maximum velocity magnitude in the domain.

4.3.4 Density diffusion term

Within *DualSPHysics*, it is also possible to apply a density diffusion term, which introduces a diffusive term to reduce density fluctuations. The state equation describes a very stiff density field, and together with the natural disordering of particles, high-frequency low-amplitude oscillations will populate the density scalar field (Molteni and Colagrossi, 2009). *DualSPHysics* uses a diffusive term in the continuity equation, which has the form of

$$\frac{d\rho_i}{dt} = \sum_j m_j \mathbf{v}_{ij} \cdot \nabla_i W_{ij} + 2\delta_\Phi h C_{s0} \sum_j (\rho_j - \rho_i) \frac{\mathbf{r}_{ij} \cdot \nabla_i W_{ij}}{\mathbf{r}_{ij}^2} \frac{m_j}{\rho_j} \quad (4.43)$$

This represents the original density diffusion formulation by Molteni and Colagrossi (2009), with the free parameter δ_Φ that needs to be assigned a suitable value. This can be explained as the addition of the Laplacian of the density field to the continuity equation. As for the value of coefficient δ_Φ , 0.1 is recommended for most applications.

4.3.5 Boundary conditions

In the SPH method, the wall boundary condition applied in this work is the dynamic boundary conditions (DBC) (Crespo et al., 2007) where particles representing the wall are organized in a staggered arrangement and satisfy the same equations as the fluid particles but their position and velocity are prescribed. The advantages of the DBC include the straightforward implementation and the treatment of arbitrary complex geometries. This makes them particularly suitable to be used within the GPU code *DualSPHysics* (Crespo et al., 2015).

4.3.6 Time integration

The time stepping algorithm used in this work is an explicit second-order predictor-corrector integrator scheme. The scheme predicts the evolution in time at two half-time steps. These values are then corrected using the forces at half time steps, followed by the evaluation of the values at the end time step (Gomez-Gesteira et al., 2012). The scheme is bounded by the Courant-Friedrichs-Lewy (CFL) condition, the maximum force term, and the numerical speed of sound as demonstrated by Monaghan (1989). In addition, an extra restriction is imposed based on the viscous forces. The CFL condition reads

$$\Delta t = Co \times \min \left(\min_i \sqrt{\frac{h}{|f_i|}}, \frac{h}{C_{s0}}, \frac{h^2}{\nu} \right) \quad (4.44)$$

where f_i is the force per unit mass of particle i and Co_{min} is the Courant number set to 0.1 in this work and ν is the kinematic viscosity. The same time integration scheme is used for both phases using the minimum Δt resulting from the CFL condition.

4.3.7 Fluid phase model

The fluid phase is treated as a simple Newtonian fluid and thus the Newtonian constitutive law is used. The viscous stresses $\tau_i^{\alpha\beta}$ are computed as

$$\tau_i^{\alpha\beta} = 2\mu\dot{\epsilon}_i^{\alpha\beta} \quad (4.45)$$

where μ is the dynamic viscosity of water and $\dot{\epsilon}_i^{\alpha\beta}$ is the deviatoric strain rate, defined as

$$\dot{\epsilon}_i^{\alpha\beta} = \frac{1}{2} \left(\frac{\partial u_i^\beta}{\partial x_i^\alpha} + \frac{\partial u_i^\alpha}{\partial x_i^\beta} \right) - \frac{1}{3} \frac{\partial u_i^\gamma}{\partial x_i^\gamma} \delta^{\alpha\beta} \quad (4.46)$$

where u denotes the velocity, Greek superscripts α and β denote coordinate directions by employing Einstein's summation, and $\delta^{\alpha\beta}$ is Kronecker's delta function.

The SPH approximation of Eq. 4.46 may be written as

$$\dot{\epsilon}_i^{\alpha\beta} = \frac{1}{2} \left(\sum_j \frac{m_j}{\rho_j} u_{ji}^\beta \frac{\partial W_{ij}}{\partial x_i^\alpha} + \sum_j \frac{m_j}{\rho_j} u_{ji}^\alpha \frac{\partial W_{ij}}{\partial x_i^\beta} \right) - \frac{1}{3} \left(\sum_j \frac{m_j}{\rho_j} u_{ji}^\gamma \frac{\partial W_{ij}}{\partial x_i^{\gamma\gamma}} \right) \quad (4.47)$$

This model has been validated for a range of free-surface flows as described in the paper of Fournakos and Rogers (2016).

4.3.8 Sediment phase model

Elastic solid state

The solid state of sediment is assumed to have an isotropic linear behavior, which obeys the yield criterion. The deviatoric stresses rates $\dot{\tau}^{\alpha\beta}$ are evaluated in line with the well-known elastic relations, i.e.

$$\dot{\tau}_i^{\alpha\beta} = \frac{E}{1+\nu} \dot{\epsilon}_i^{\alpha\beta} \quad (4.48)$$

where E denotes the Young's modulus and ν refers to the Poisson's ratio.

For large deformation of the sediment phase, a stress rate that is invariant with respect to rigid-body rotation must be employed. To obtain a material frame independent formulation, Eq. 4.48 is replaced by the Jaumann rate with respect to the elastic spin (Ulrich et al., 2013; Ulrich, 2013; Ghaitanellis et al., 2018)

$$\dot{\tau}_i^{\alpha\beta} = \frac{E}{1+\nu} \dot{\epsilon}_i^{\alpha\beta} + \tau_i^{\alpha\gamma} \dot{\omega}_i^{\gamma\beta} - \dot{\omega}_i^{\alpha\gamma} \tau_i^{\gamma\beta} \quad (4.49)$$

where $\dot{\omega}_i^{\alpha\beta}$ denotes the spin-rate tensor

$$\dot{\omega}_i^{\alpha\beta} = \frac{1}{2} \left(\frac{\partial u_i^\beta}{\partial x_i^\alpha} - \frac{\partial u_i^\alpha}{\partial x_i^\beta} \right) \quad (4.50)$$

The final form of the adopted deviatoric stresses reads

$$\dot{\tau}^{\alpha\beta} = \frac{E}{1+\nu} \dot{\epsilon}^{\alpha\beta} + J^{\alpha\beta} - \frac{1}{3} J^{\gamma\gamma} \delta^{\alpha\beta} \quad (4.51)$$

where $J^{\alpha\beta}$ is the Jaumann rate.

Drucker-Prager yield criterion

To determine the state of the sediment SPH particle (yielded or unyielded), a yield criterion is used to relate the maximum shear strength of the soil sediment to the hydrodynamic shear strain at the fluid-soil interface. Note that compression is assumed to be positive. Considering a simple shear case where no motion in the sediment phase takes place until a critical value of shear stress τ_y (Bingham yield stress) is reached, the fluid stresses acting on the sediment are in equilibrium with the yield strength of the sediment (Fourtakas et al., 2013), i.e.

$$\sqrt{J_2} - |\tau_y| \geq 0 \quad (4.52)$$

where J_2 is the second invariant of the deviatoric shear stress tensor $\tau^{\alpha\beta}$ defined as

$$J_2 = \frac{1}{2} \tau^{\alpha\beta} \tau^{\alpha\beta} \quad (4.53)$$

The rate-dependent isotropic Newtonian fluid expression for the viscous stresses is written as

$$\tau^{\alpha\beta} = 2\mu \dot{\epsilon}^{\alpha\beta} \quad (4.54)$$

Then the following equality is obtained

$$\sqrt{J_2} = 2\mu\sqrt{II_D} \quad (4.55)$$

where the term II_D is the second invariant of the strain rate tensor defined as

$$II_D = \frac{1}{2}\dot{\epsilon}^{\alpha\beta}\dot{\epsilon}^{\alpha\beta} \quad (4.56)$$

Thus, the critical threshold for the sediment yielding at the interface can be written as

$$|\tau_y| < 2\mu\sqrt{II_D} \quad (4.57)$$

At this point, a yield criterion for the sediment phase is needed to provide the critical value of the sediment shear stress. In this study, the Drucker-Prager yield criterion is selected. The Drucker-Prager model (Drucker and Prager, 1952) is written in a general form as

$$\sqrt{J_2} - \alpha_\phi I_1 - \kappa_c = 0 \quad (4.58)$$

where I_1 is the first invariant of the deviatoric shear stress tensor. The parameters α_ϕ and κ_c can be determined by projecting the Drucker-Prager (DP) onto the Mohr-Coulomb yield criterion in a deviatoric plane:

$$\alpha_\phi = \frac{\tan(\phi)}{\sqrt{9 + 12 \tan^2(\phi)}} \quad \kappa_c = \frac{3c}{\sqrt{9 + 12 \tan^2(\phi)}} \quad (4.59)$$

where ϕ is the internal angle of friction and c is the cohesion of the sediment.

Finally using Eq. 4.57 yielding will occur when the following equation is satisfied

$$\alpha_\phi I_1 + \kappa_c < 2\mu\sqrt{II_D} \quad (4.60)$$

4.3.9 Viscoplastic fluid state

The viscoplastic fluid state of sediment is considered to be fully saturated and is modeled as a slightly compressible pseudo-Newtonian fluid in line with the works of Fourtakas and Rogers (2016). The viscous term is obtained as a function of the apparent viscosity (μ_{app}) as

$$\tau_i^{\alpha\beta} = 2\mu_{app}\dot{\epsilon}_i^{\alpha\beta} \quad (4.61)$$

The apparent viscosity of the sediment is calculated using the Herschel-Bulkley-Papanastasiou (HBP) model (Papanastasiou, 2002). Thus, in this work the symbol μ_{HBP} is used to denote the apparent viscosity, i.e. $\mu_{HBP} = \mu_{app}$. The HBP model reads

$$\mu_{HBP} = \frac{\tau_c}{\sqrt{II_D}} \left[1 - e^{-m\sqrt{II_D}} \right] + 2\mu |4II_D|^{\frac{n-1}{2}} \quad (4.62)$$

where m controls the exponential growth of stress and n is a power-law index that enables simulation of shear thinning or shear thickening behaviour. Note that when $m = 0$ and $n = 1$ the model reduces to a Newtonian model, whereas when $m \rightarrow \infty$ and $n = 1$ a simple Bingham model is recovered. The parameter τ_c is the yield stress that should be defined by a yield criterion. The advantage of the HBP model is that it provides information on the pre-yield and post-yield region and thereby avoids the need of setting a maximum threshold for the viscosity as required in other pseudo-Newtonian approaches.

Suspension treatment

When the shear stress of fluid τ_{fluid} is larger than the yield stress of the sediment τ_y in the interface between flow and sediment, the sediment particles will be suspended into the fluid. This sediment entrainment by the fluid can be controlled by using a concentration volume fraction of the mixture $c_{v,i}$ in the form of

$$c_{v,i} = \frac{\sum_{j \in 2h}^N \frac{m_j}{\rho_j}}{\sum_{j \in 2h}^N \frac{m_j}{\rho_j}} \quad (4.63)$$

where the summation is defined within the support of the kernel and j_{sat} refers to the yielded saturated sediment particles. The size of the concentration sampling is chosen to be the same as the kernel support size of SPH. When a sediment particle is suspended, it is modeled as a pseudo-Newtonian fluid using Eq. 4.61. The suspension viscosity can be related to the volumetric concentration by

$$\mu_{susp} = \mu f(c_v) \quad (4.64)$$

A suspension viscosity is calculated based on the Vand experimental colloidal suspension equation (Vand, 1948) of sediment in a fluid assuming an isotropic material with spherically shaped sediment particles:

$$\mu_{susp} = \mu e^{\frac{2.5c_v}{1-\frac{39}{64}c_v}} \quad c_v \leq 0.3 \quad (4.65)$$

Eq. 4.65 is applied only when the volumetric concentration of the saturated sediment particle within the SPH kernel is lower than 0.3 which is the upper validity limit of Eq. 4.65. Hence, when a yielded sediment particle volumetric concentration is below the threshold of 0.3, the sediment particle is treated as a Newtonian fluid, retaining its properties with the exception of the viscosity that follows the Vand Eq. 4.65. At that point the particle is entrained by the fluid.

4.3.10 6-DoF motion of rigid object

To compute the motion of a moving object with 6-DoF, rigid-body dynamics equations need to be solved (Monaghan, 2005). The basic equations can be written as follows:

$$M \frac{d\mathbf{V}_b}{dt} = \sum_k m_k \mathbf{f}_k \quad (4.66)$$

$$I \frac{d\mathbf{\Omega}_b}{dt} = \sum_k m_k (\mathbf{r}_k - \mathbf{R}_0) \times \mathbf{f}_k \quad (4.67)$$

where M is the mass of the object, I is the moment of inertia, $\mathbf{V}_b$ is the velocity of the rigid-body, $\mathbf{\Omega}_b$ is the rotational velocity of the body, and $\mathbf{f}_k$ is the net force acting on each particle at the solid boundary. The net force on each boundary particle can be calculated with all surrounding fluid particles used by the kernel function and the smoothing length. $\mathbf{R}_0$ is the center of the object and k indicates the boundary particle on the rigid-body surface. Thus, force contributions to the entire rigid-body are summed. After calculating the translation and rotational velocities of the rigid-body, the velocity of each particle $\mathbf{V}_i$ on the rigid-body surface can be updated as

$$\mathbf{V}_i = \mathbf{V}_b + \mathbf{\Omega}_b \times (\mathbf{r}_i - \mathbf{R}_0) \quad (4.68)$$

5 Results and Discussion

In this chapter, the results using the developed 3D scour model and the SPH model are presented. During the course of this project, to properly validate and verify the 3D models, extensive validations have been done. Results in this chapter are mostly for UXOs and munitions. To reduce the length of the chapter, other results, such as those for model validation, verification, and demonstration, are in the appendices (see Appendices B and C)

5.1 *Results for 3D modeling of scour and burial of underwater unexploded ordnances (UXOs)*

The mobility, burial, and exposure of UXOs are multifaceted processes, depending on flow condition, sediment transport, granular material dynamics, the shape and density of the munitions, etc. Despite the complexities of the system, recent studies mostly focused on one physical process at a time and ignored the couplings among them. Furthermore, most previous studies simplified the complex geometry of UXOs as cylinders or tapered cylinders (Rennie et al., 2017; Friedrichs et al., 2018; Gilooly, 2018). In fact, the shape of munition can greatly affect the hydrodynamics and local sediment transport. Rennie et al. (2017) and Garcia and Landry (2018) showed that a tapered cylinder has a larger scour depth than a simple cylinder, and the tapered end rotates downstream under current. In reality, munitions are more complex than tapered cylinders. They typically have a tapered head, a streamlined body, and a thin tail with fins.

The complexity of UXO shape and the effects on scour process in its vicinity have not been fully examined. The effects include the scour pattern, scour depth, and their temporal evolution. All these will affect the stability of munitions. For example, experiments and field observations have found that as the scour hole develops, a munition may roll into the scour pit. In addition, if a munition is initially buried, the scour process can expose and mobilize it again.

The purpose of this study is to investigate the effects of UXO shape on flow and scour. Our hypothesis is that the shape of the munition affects the flow and scour around partially buried UXOs. To test this hypothesis, we performed both flume experiments (not funded by SERDP) and computational modeling for scour around a real munition and a surrogate cylinder. To separate the flow and scour processes from other physical processes such as granular material mechanics and UXO six degree-of-freedom motion, the objects in this study are all fixed on a supporting structure. This is a reasonable and necessary approximation because otherwise all the involved physical processes will interact with each other and make the analysis extremely complicated.

Field observations have shown that UXOs are mostly stable while experiencing local scour. Only when the scour hole is large enough, UXOs will lose their stability, initiate an incremental movement, and then find their new stable position.

Another important aspect of UXO mobility is flow's angle of attack. Similar to any flow around bluff bodies, the angle of attack controls the flow separation, drag and lift forces on the body, and the wake dynamics. For UXOs, the effects of angle of attack and shape are convoluted. To shed some light on the combined effect, we firstly simulated turbulent flow (without sediment transport) over the munition and surrogate cylinder with 90° angle of attack on an initial flat bed and an equilibrium scoured bed. The dominant flow structures during the initial and equilibrium stages of the scour process were analyzed. We will discuss the hydrodynamic drivers for the onset of scour around the munition and surrogate cylinder and how they affect the subsequent scour progression. In addition, scour simulations were performed for two different angles of attack, i.e., 45° and 90° , for both munition and surrogate cylinder cases. Based on the results, we propose a method to estimate the time scale of local scour. We also derive a general formula for the temporal scour process around munitions with different angles and shapes.

5.1.1 Flume Experiment

The flume experiments were conducted in a tilting and recirculating hydraulic flume with dimensions of 15.24 m in length, 1.52 m in width, and 0.91 m in depth, as shown in Fig. 5.1 (a) and (b). It is equipped with an instrument carriage, which allows measurements to be taken horizontally, laterally, and vertically. The data collected in the flume included initial and final bathymetry, as well as 3D velocity in the vicinity of an object after equilibrium scour has been reached.

The test flume was partially filled with sand, and the test bed was flattened with a scraper. The bed depth is 0.3 m and the sediment size is uniform with a median grain size, d_{50} , of 0.67 mm. The submerged specific gravity of sediment, R , is 1.65. The objects were placed on a foundation (cradle) made of two crosses, which make the objects stationary. The foundation is fully buried in the sand bed (shown in Fig. 5.1 (b)). In the upstream region of the flume, a transitional zone paved with large cobblestones is used to ensure the incoming flow is fully developed when it approaches the objects.

After the preparation of bed and positioning the test object on the cradle, the hand-held Artec Eva 3D scanner, was used to capture the initial bathymetry. This scanner uses the structure-from-motion method to generate 3D surfaces from a series of photographs. In the next step, the flume was slowly filled with water to ensure the bed material did not move. Then each test was started by delivering flow into the upstream tank of the flume. When equilibrium was reached, velocity was measured with a Nortek VectrinoPlus acoustic Doppler velocimeter (ADV). We measured velocity in a vertical slice that passes through the symmetry plane of the flume. The streamwise range of the measurement section is from $x/D = -4$ to 8, where x is the streamwise coordinate with $x = 0$ being at the center of an object, and D is the diameter of object. At each measurement location, velocity was measured at five elevations above the flat bed, i.e., 1.5, 3, 4.5, 6 and 7.5 cm. Then the pump was shut off and the flume was slowly drained. The final equilibrium bed was scanned again with the 3D scanner.

The flow condition was designed such that the sediment transport is in the clear-water scour

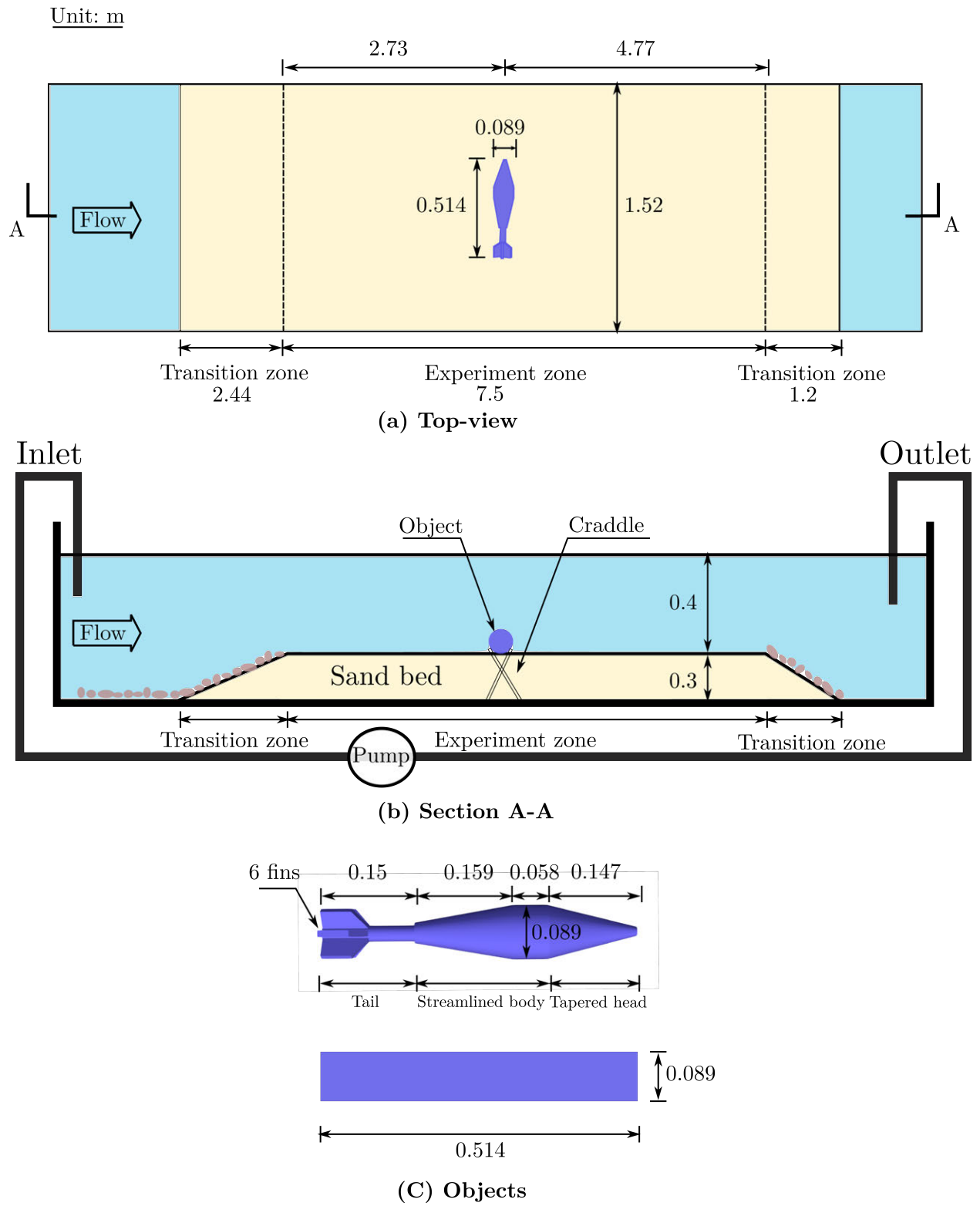


Figure 5.1: Details of the experiment setup: (a) top-view, (b) side-view, and (c) munition and surrogate cylinder

regime. The Reynolds number $Re_D = UD/\nu$ is 2×10^5 , and the Froude number $Fr_H = U/\sqrt{gH}$ is 0.11, where U is mean velocity, H is water depth, ν is kinematic viscosity, and g is the gravity acceleration. The free surface effects is minor in the experiments since the ratio between the flow depth and the object's diameter is large ($H/D > 4$). The dimensionless critical shear velocity $u_{\tau 0}/U$ is 0.06, where the critical friction velocity $u_{\tau 0}$ is calculated from the modified fit to the Shields diagram (Parker et al., 2003). The Nikuradse's equivalent roughness of bed, k_s , is fitted to be 0.01 m with the mean velocity profile measured from the upstream of the scour section as presented in Song et al. (2022), considering the effects of the transitional section filled with large cobble stones in the upstream region. The dimensionless critical velocity U_c/U is around 1, which makes the experiments in the clear-water scour regime.

The experiments were conducted for two objects on the sand bed including an inert munition and a surrogate cylinder. The munition is made of a tapered head, a streamlined body, and a tail with six fins. Its length, L , is 0.514 m and its maximum diameter, D , is 0.089 m. Details of the munition are shown in Fig. 5.1 (c). The surrogate cylinder has the same maximum length and diameter as the munition, more details of which can be found in Fig. 5.1 (c) and Song et al. (2022). The flow depth ($H = 0.4$ m) and the mean incoming channel velocity ($U = 0.22$ m/s) are the same in two flume experiments. For the angle of attack value of 90° , the longitudinal direction of the objects is perpendicular to the incoming flow (as shown in Fig. 5.1).

Initially, the munition and cylinder were partially buried to a depth of 1.45 cm and 2.8 cm (measured at the symmetry plane of the flume), respectively. Because the diameters of the tapered head and finned tail of the munition are not the same, the initial burial is slightly different between the two objects to ensure the percentage of burial is comparable. Both munition and cylinder were level when placed on the cradle. In the following discussion, y is the transverse coordinate with $y = 0$ at the symmetry plane of the flume; z is the vertical coordinate with $z = 0$ at the non-deformed bed.

5.1.2 Computational Modeling Setup

The computational modeling in this study included the flow-only simulations and scour simulations.

Flow-only simulations

The flow-only simulations were performed without sediment transport. The flat bed and equilibrium bed measured from experiments were used as the bottom boundaries. Due to the large Reynolds number and the complexity of the objects, large eddy simulations (LES) using the open-source platform OpenFOAM were performed to simulate the large vortices (OpenFOAM Foundation, 2018). A dynamic one-equation subgrid-scale model was used to model small eddies (Kim and Menon, 1995). A wall model were used to capture near-wall flow dynamics. The simulation cases of flow around the horizontal cylinder on flat and scoured beds were referred to as HCF and HCS, respectively. Similarly, the cases for the munition were referred to as HMF and HMS.

Scour simulations

In scour simulations, the coupled process of hydrodynamics, sediment transport, and bed evolution was simulated with the *ibScourFoam* model developed in Song et al. (2022). The turbulent flow was simulated by solving the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations. The $k-\omega$ SST-SAS model was adopted. The scour process is slow and takes several days to reach equilibrium in experiments. Thus, it is prohibitively expensive to adopt other turbulence modeling approaches such as LES. An immersed boundary (IB) method was used to deal with the evolving bed and its interaction with the complex geometries of objects. One key variable is the wall shear stress imparted on the sediment bed. The new near-wall treatment proposed in Xu and Liu (2021) and Song et al. (2022) was used to obtain accurate and smooth wall shear.

For both flow-only and scour simulations, the computational domain and setup are illustrated in Fig. 5.2 and summarized in Table 5.1. The computational domain for the flow-only simulations has a length, width, and height of $24.3D$ ($7.3D$ upstream and $17D$ downstream), $17D$, and H , respectively (Fig. 5.2 (a)). The mesh has approximately 13 million cells and is refined near the bed and objects. The wall cell is approximately 1.6 mm in size. The maximum dimensionless wall distance, y^+ , on the scoured bed is approximately 25, and the average y^+ is approximately 3. A shear-free rigid lid was used for the free surface. The two sides and the objects were treated as smooth walls. The sediment bed was treated as rough wall with the Nikuradse's equivalent roughness k_s equal to 0.01 m, which was fitted from the measured incoming velocity profiles in experiments.

Table 5.1: Summary of computational modeling setups.

	flow-only simulations	scour simulations
Mean flow velocity U (m/s)	0.22	0.22
Water depth H (m)	0.4	0.4
Maximum object diameter D (m)	0.089	0.089
Maximum object length L (m)	0.514	0.514
Domain size (length $\times$ width $\times$ height)	$24.3D \times 17D \times H$	$25D \times 14D \times (H+1.4D)$
Total number of cells	13 millions	8 millions
Maximum near-wall y^+	25	18
Bed Nikuradse's equivalent roughness k_s (m)	0.01	0.01
Median grain size d_{50} (mm)	-	0.67
Critical Shields number θ_{c0}	-	0.016

The domain and setup for scour simulations are similar to those for flow-only simulations. Figure 5.2 (b) shows the example of scour simulation around munition. The domain has a length, width, and height of $25D$ ($8D$ upstream and $17D$ downstream), $14D$, and $H + 1.4D$, respectively. The upper domain for water has a height of H and the lower domain for sediment has a height of $1.4D$. The mesh has approximately 8 million cells and is refined near the objects and expected

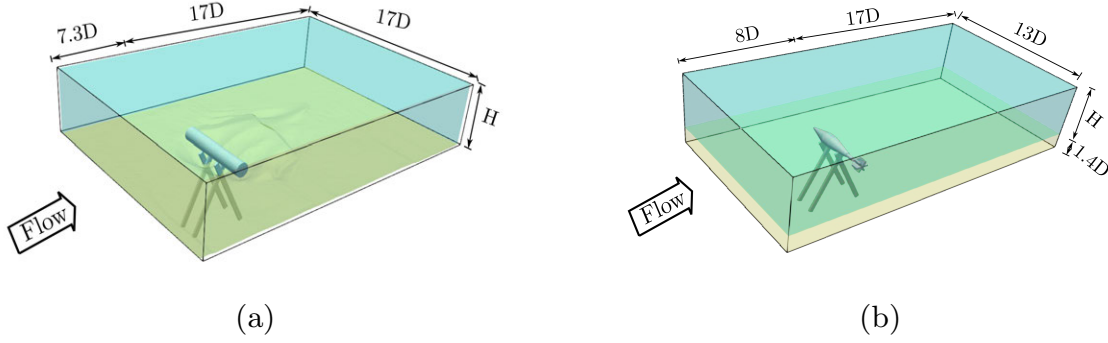


Figure 5.2: Example computational domain and setup: (a) Flow-only (showing cylinder with equilibrium scoured bed as an example), (b) Scour simulation (showing munition as an example).

scour region. The wall cell is approximately 1.6 mm in size. The maximum dimensionless wall distance, y^+ , on the scoured bed is approximately 18, and the average y^+ is approximately 10. The simulations of scour around the cylinder with angles of 45° and 90° were referred to as case SC45 and SC90 respectively. Similarly, the simulations of scour around the munition with angles of 45° and 90° were referred to as cases SM45 and SM90.

5.1.3 Results and Discussion

Experimental results and observations

The equilibrium bathymetries in experiments captured with the 3D scanner and bed elevation contours are shown in Fig. 5.3. The solid lines in the contours represent the position of cylinder and munition. It can be observed the scour depth and pattern for munition and cylinder are strikingly different due to the difference in shape. The scour hole under the cylinder is larger than that under the munition. For cylinder, the maximum scour depth, $z_{b,max}$, is about $1.11D$. The maximum length of scour along the longitudinal direction of the cylinder, $l_{b,max}$, is about $7.64D$. The maximum width of scour along the streamwise direction, $w_{b,max}$, is about $4.94D$. Scour starts near the two ends of the cylinder as two separate scour holes. As two scour holes expand, they join at the center of the cylinder along its longitudinal direction. After that, a gap is formed between the cylinder and scoured bed. Part of the incoming water flows underneath the cylinder, contracts and accelerates, erodes more sediment, and increase the size of the gap. The supporting cradle (two crosses) are also gradually exposed to water and consequently two separate scour holes form around them (in the same fashion as bridge pier scour). The maximum scour happens in the two scour holes around the cradle crosses.

The scour around the munition is different. As shown in Fig. 5.3 (b), (d), and Fig. 5.4 (c), three scour holes appears around the munition. The main hole is under the main body (Fig. 5.4 (b) and (c)). The secondary scour hole is in the immediate downstream of the tail shown in Fig. 5.4 (c). The third hole appears under the tail which is much smaller comparing to the other two. The size and shape of the main scour hole can have implications on finding the burial and exposure of the

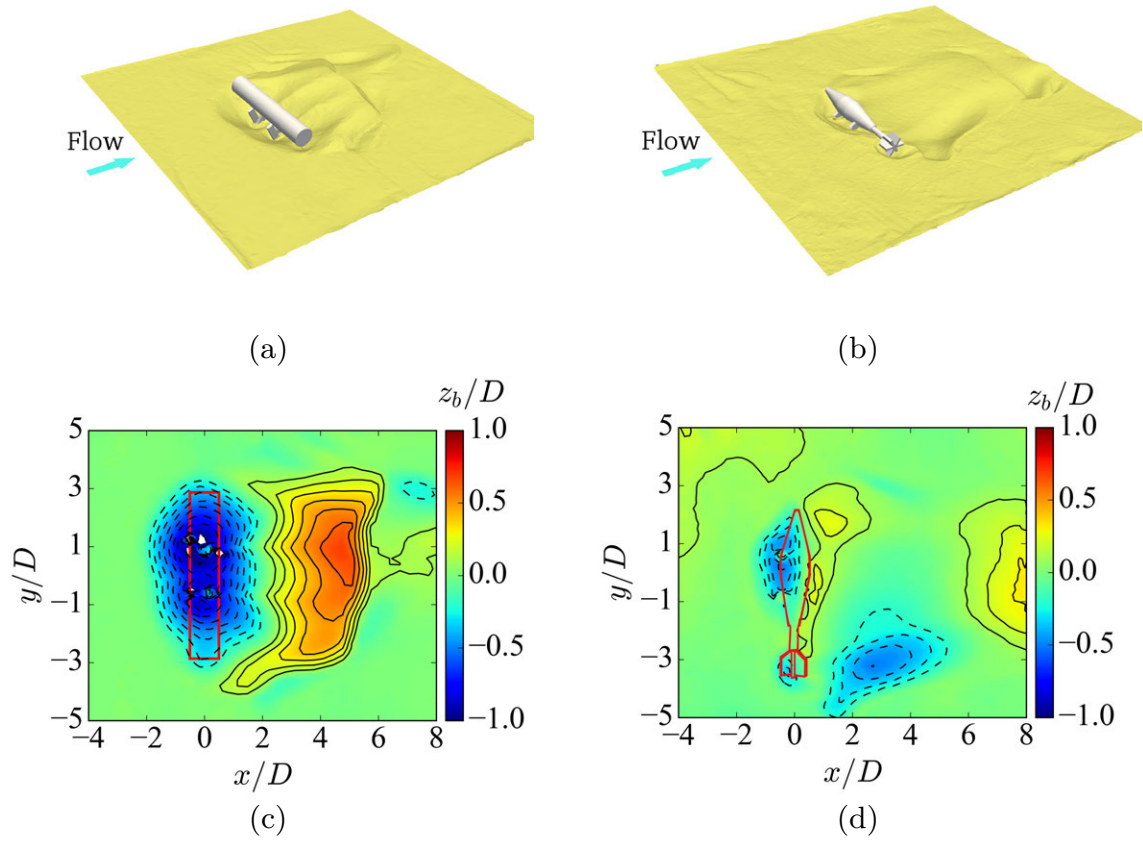


Figure 5.3: 3D equilibrium bathymetries from experiments with the 90° angle of attack: (a) 3D view for cylinder case, (b) 3D view for munition case, (c) 2D bed contour for cylinder case, and (d) 2D bed contour for munition case.

munition. For munition, the maximum scour depth, $z_{b,max}$, is about $0.51D$; the maximum length of scour along the longitudinal direction of munition, $l_{b,max}$, is about $6.97D$; and the maximum width of scour along the streamwise direction, $w_{b,max}$, is about $2.56D$. Hence, the main scour hole in the munition experiment is shallower and narrower than that in the cylinder experiment. In addition, the main scour hole in the munition experiment only exists under the upstream side of the munition. On the downstream side, there is significant sediment deposition such that the main hole is not through. As a result, only the upstream side of the cradle is exposed to flow, resulting in negligible scour around the two crosses of the cradle.

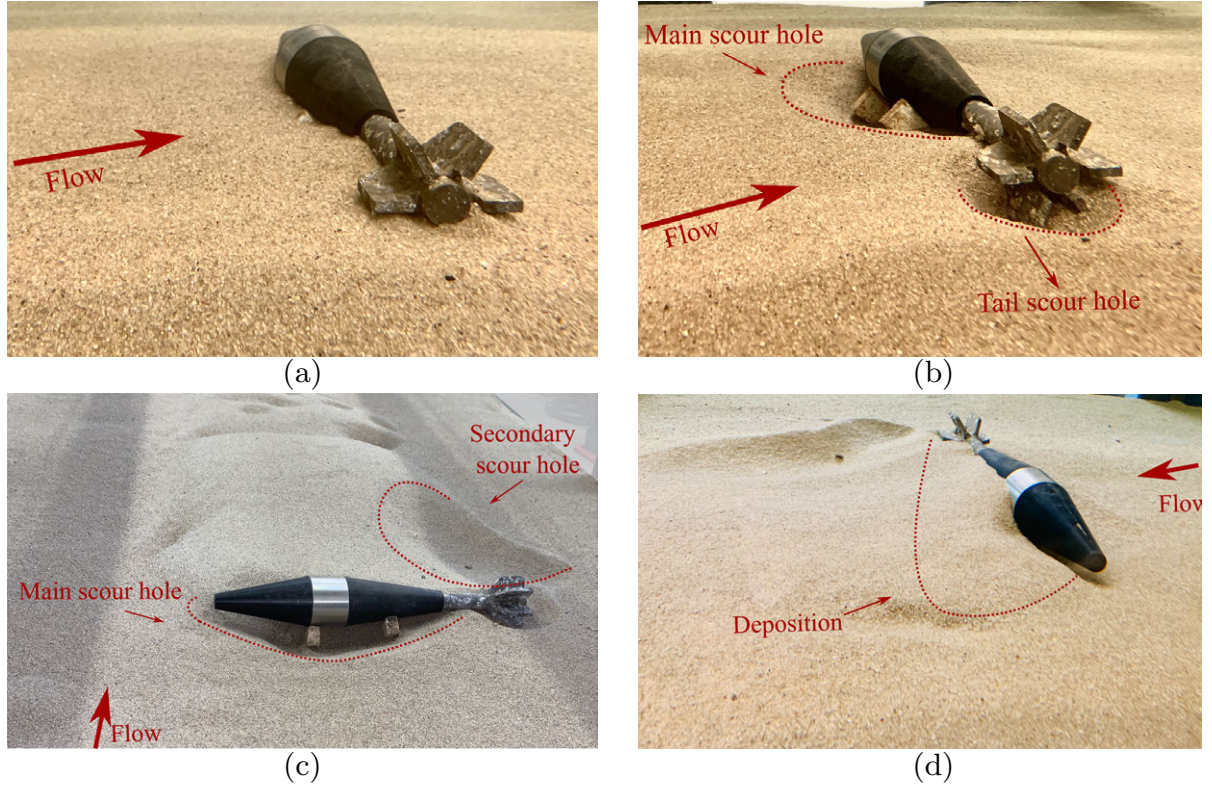


Figure 5.4: Munition experiment: (a) Initial bathymetry, (b) Final bathymetry, (c) Downstream view of the main and secondary scour holes, and (d) Downstream deposition.

The deposition bars behind the two objects further show the effect of shape. The deposition bar behind the cylinder starts at $x/D=2$ because its scour hole underneath is through and flow pushes sediment further downstream. The maximum deposition height is about $0.69D$, and the maximum deposition width in the streamwise direction is about $2.8D$. The deposition bar is formed by the sediment moved out from the scour hole under the cylinder. However, the deposition in the munition experiment (Fig. 5.4 (d)) is attached to the downstream face of the munition. As a result, flow cannot pass underneath the munition. A recirculation zone was observed downstream, which brought sediment from a long distance away to the immediate downstream of the munition. In other words, the deposition bar behind munition is made of sediments from two sources. One is the excavation from under the munition and the other is from downstream. The

maximum deposition height is about $0.3D$ and the maximum deposition width in the streamwise direction is about $1.0D$, both of which are smaller than those in the cylinder case.

Simulated flow around objects on the initial flat bed

Simulated mean flow around cylinder (case HCF) and munition (case HMF) on the initial flat bed reveals the mechanism for the initiation of scour process. Figure 5.5 shows the simulated streamlines on the center plane for both cases. Similar to flow over a horizontal pipeline with infinite length on a bed, the flow field is characterized by small vortices at the upstream and downstream corners of the objects. There is also a primary recirculation in the wake region (Mao, 1987). Comparing the cylinder and the munition cases, the recirculation zone behind the cylinder is larger than that behind the munition. This is due to the shape difference between the two. The tapering of munition diameter and the fins break the symmetry and interrupt the development of wake. Similar observation can be made from the pressure coefficient ($C_p = p/0.5\rho U^2$) on the surface of objects shown in Fig. 5.6 (a) and (b). The dots inside the circle denote the positive pressure and those outside denote the negative pressure. It is observed that the magnitude of the pressure coefficient on cylinder is larger than that on munition. It is again due to the shape difference and how blunt the object is. The pressure distribution has great impact on the hydrodynamic force on these objects and consequently their mobility.

The shape not only affects the pressure on the objects, but also the pressure on the sediment bed. Figure 5.6 (c) shows the pressure coefficient along the flat bed on the symmetry plane. The pressure is near zero upstream, but increases as the flow approaches the objects. The pressure drops to a negative value on the downstream side of objects due to flow separation. Although not considered in our current scour model, pressure gradient (Δp) between upstream and downstream causes seepage flow through the sediment underneath the objects. This pressure gradient exerts an upward force on sediment particles in the downstream region and thus increases their mobility. Piping and fluidization could happen if the pressure gradient exceeds certain threshold. To assess the potential for piping, the criterion in Chiew (1990) and Sumer et al. (2001) is used:

$$\frac{1}{\gamma} \frac{\partial p}{\partial x} = \frac{P_A - P_B}{\gamma \overline{AB}} \geq (s - 1)(1 - n) \quad (5.1)$$

where γ is the specific gravity of water, $\overline{AB}$ is the distance between points A and B, s is the specific gravity of sediment, and n is the porosity of sediment. From the simulated results, the pressure gradient for both cases HCF and HMF is less than 0.1, which is much smaller than the criterion of $(s - 1)(1 - n) = 0.99$ where $n = 0.4$ and $s = 2.65$. Thus piping is negligible for the flow conditions studied in this work. However, there might be situations, such as during storm, the pressure gradient might be a high enough and piping could be a significant contributor to the whole process.

Scour in this study is mainly induced by the turbulence around the objects. Specifically, the flow contraction around the two ends of the objects is responsible for at least the initial stage of scour process. A portion of approaching flow is diverted laterally along the upstream face of the objects and contracts around the ends where the flow velocities are the largest. The remaining incoming flow passes over the objects and there is a very weak down-flow zone at the base of upstream

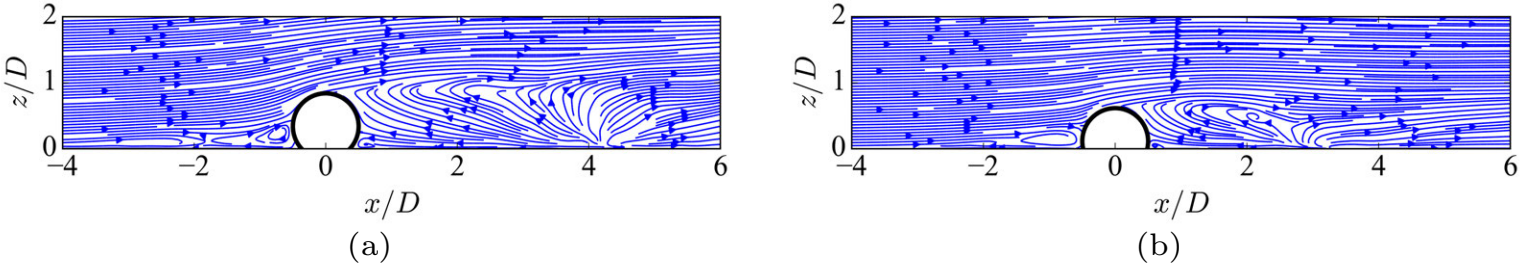


Figure 5.5: Streamlines on the symmetry plane: (a) case HCF, (b) case HMF.

side. Figure 5.7 shows the similarities and differences in flow structure between case HCF and case HMF. In both cases, the horseshoe vortices (HVs) on objects' ends are due to the necklace vortices induced by the down-flow in the front and the flow separation on the two sides.

The simulated wall shear stress on the flat bed in case HCF and case HMF are shown in Fig. 5.8 (a) and (b). The wall shear stress, τ , is made dimensionless with the background wall shear, τ_0 . The ratio between the two is the amplification of wall shear due to the presence of objects. The maximum amplification of wall shear stress happens around the two ends of objects, which is caused by flow contraction and HVs shown in Fig. 5.7. Comparing the two objects, the wall shear is amplified in a much wider area around the cylinder than the munition. However, the maximum amplification happens near the fins of the munition due to its complex shape.

Simulated flow around objects on equilibrium scoured beds

The flow dynamics at scour equilibrium is different from that at the initial stage. The simulated flow around the cylinder (case HCS) and munition (case HMS) on the scoured bed obtained from experiments is analyzed and presented in this section.

Figure 5.9 shows instantaneous out-of-plane vorticity contours and mean flow streamline patterns on three vertical planes for the cylinder case. The vertical planes are on slices $y/D = 0, 0.9$, and 1.69 (note $y/D = 0$ is at the center of object). Similar plots for the munition case are shown in Fig. 5.10.

For the cylinder case, the flow structure on the center slice ($y/D = 0$) shows three main features: the down-flow in front of scour hole (in rectangle 1), the vortex shedding off the cylinder (in rectangle 2), and the wake and flow recirculation behind the deposition bar (in rectangle 3). When approaching the upstream edge of scour hole, the incoming flow is split into downward flow toward the scour hole and upward flow over the cylinder. The downward flow acts like a jet through the gap between the cylinder and the scoured bed. In conjunction with the flow separation along the upstream edge of the scour hole, there is a small recirculation near the upstream side of the scour hole, which causes sediment particles being pushed upstream and up the slope. This is commonly observed in scour holes. This recirculation in the scour hole also causes the significant wall shear stress amplification on the upstream face of the scour hole (see Fig. 5.8 (c)). It is interesting to note that this recirculation disappears on vertical slice $y/D = 1.69$ near the

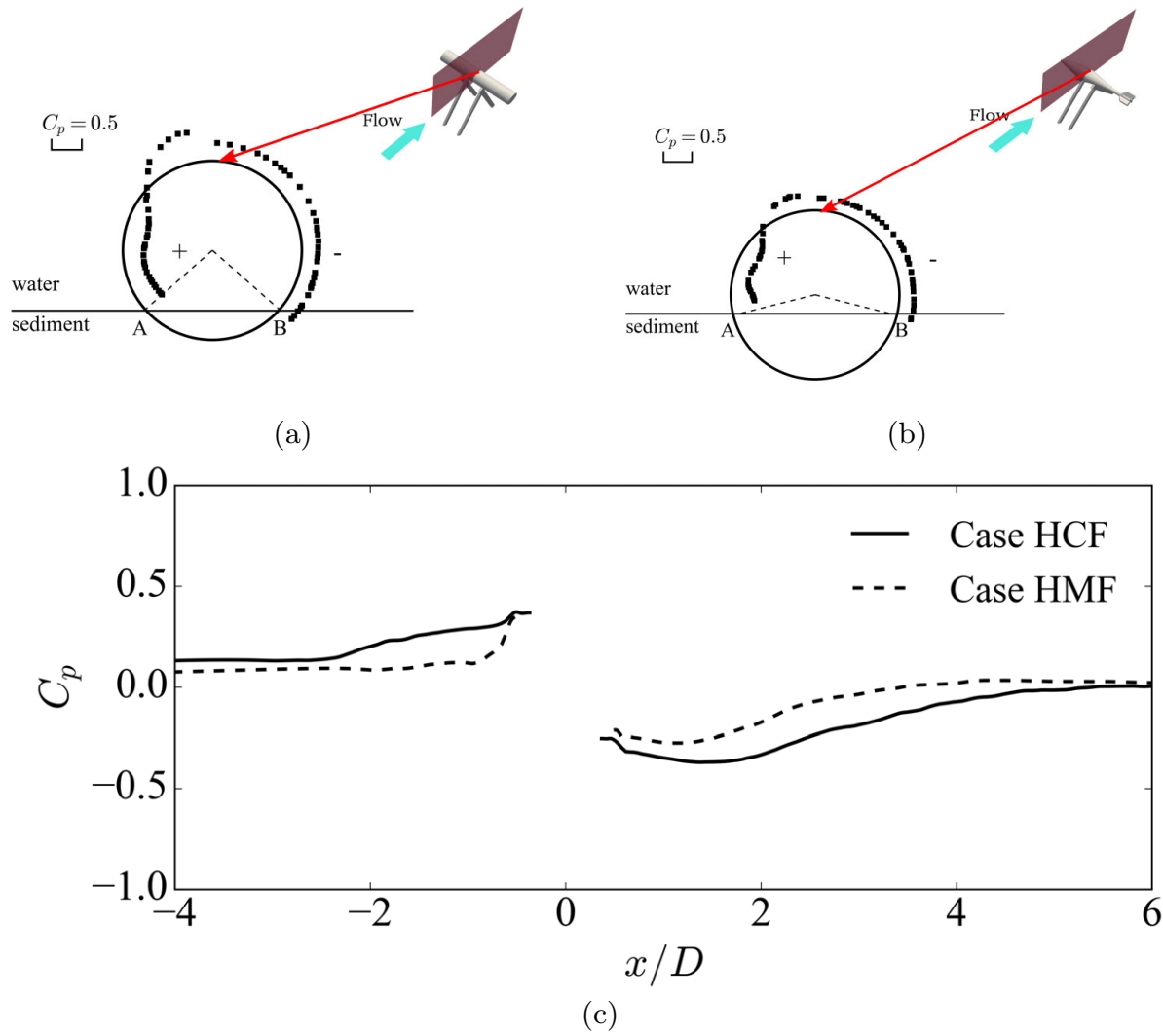


Figure 5.6: Pressure coefficient distribution: (a) pressure coefficient on cylinder through the symmetry plane of the flume (case HCF), (b) pressure coefficient on the munition (case HMF), and (c) pressure coefficient along the bed.

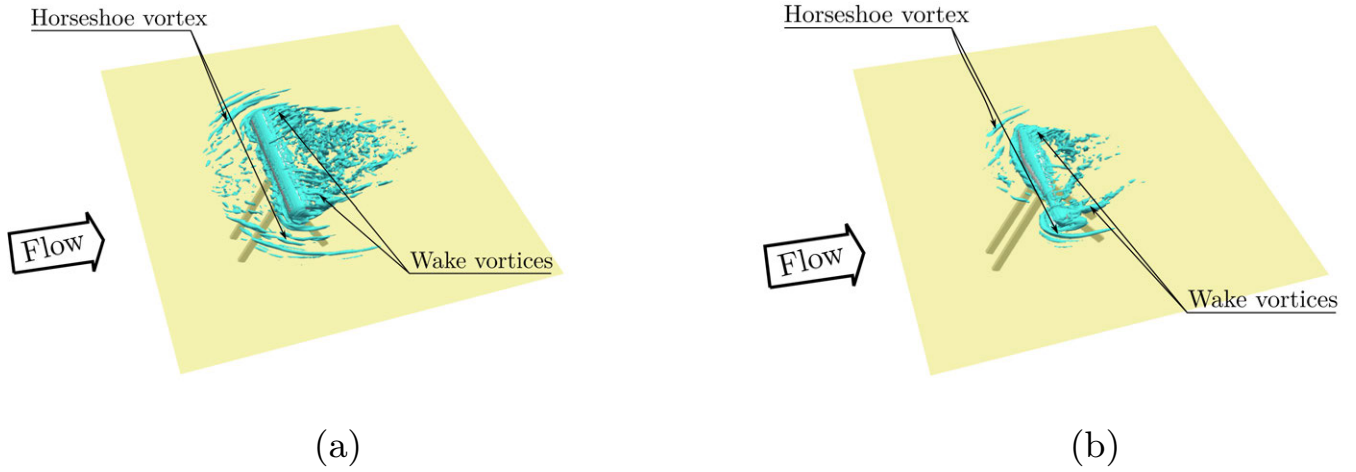


Figure 5.7: Simulated flow structures with initial flat bed: (a) case HCF, (b) case HMF.

end of the cylinder due to the end effect. The vortex shedding off the cylinder result in in the formation of two opposing vortices. The negative vortex shedding from the lower side of the cylinder sweeps the downstream surface of scour hole together with the jet flow. As a result, the wall shear stress shows high amplification in that area (Fig. 5.8 (c)). In addition, a large flow recirculation occurs behind the downstream deposition bar.

Flow field is different for the munition case as shown in Fig. 5.10. The three vertical slices are located at $y/D = 0, 1.69$, and -3 . The scour hole is much smaller and the backside of munition is covered with sediment. On the center slice ($y/D = 0$), a small vortex occurs upstream between the munition and the scoured bed, which moves sediment particles upward along the upstream face of the scour hole. This was observed in experiments. After being pushed up the slope, the sediment particles slide downward episodically due to gravity. The amplification of wall shear stress mainly occurs on the upstream scoured bed (Fig. 5.8 (d)). There is no jet flow under the munition as observed in the cylinder case.

On vertical slice $y/D = -3$ near the tail of munition, the flow behavior is more complex because of the fins. The fins generate intense vortex shedding and impinging on downstream bed (see streamlines in Fig. 5.10). As a result, there is weak erosion on the upstream side near the fins and strong erosion on the downstream side. This the cause for the small scour hole near tail and large secondary scour hole observed in experiment (see Fig. 5.4).

From the comparison of flow fields around cylinder and munition, it is discovered that the shape effect on flow and the resulted scour is significant. Hydrodynamically and morphologically, a cylinder with a uniform diameter is not a good surrogate for real munition which has complex geometry. The detailed analysis on the simulated flow field with LES shed some light on the cause of significantly different scour processes around the two objects.

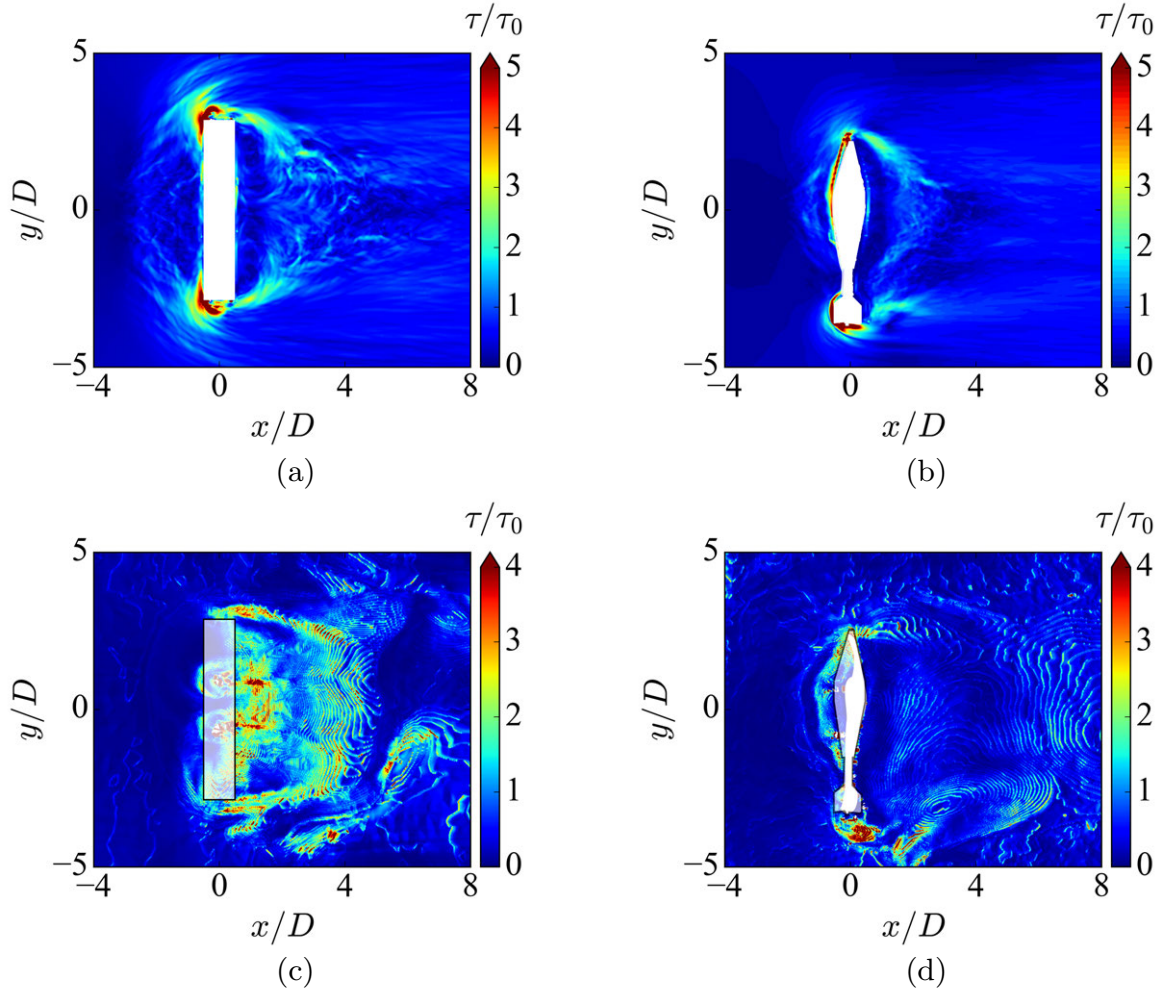


Figure 5.8: Mean wall shear stress around the objects on flat bed: (a) case HCF, (b) case HMF; Scoured bed: (c) case HCS, (d) case HMS.

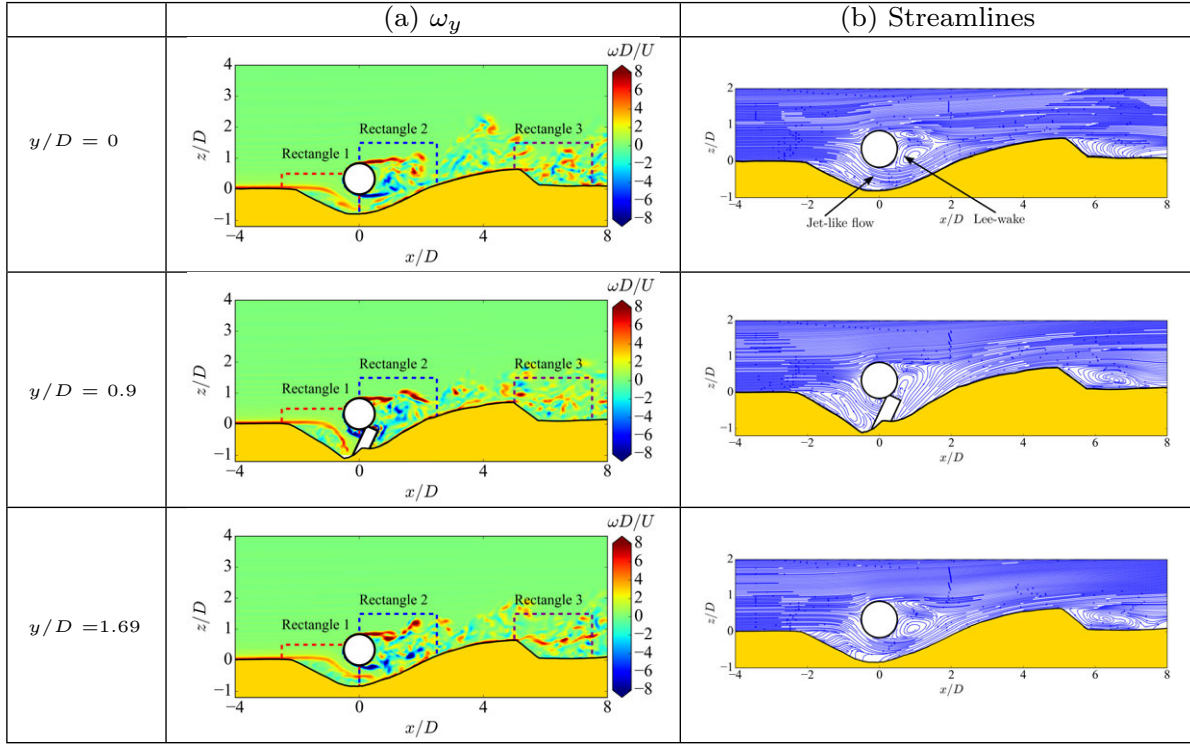


Figure 5.9: Simulated flow field for cylinder case HCS: (a) The instantaneous vorticity contour (out-of-plane), (b) The mean flow streamlines. The plots are on three vertical planes located at $y/D = 0, 0.9$, and 1.69 .

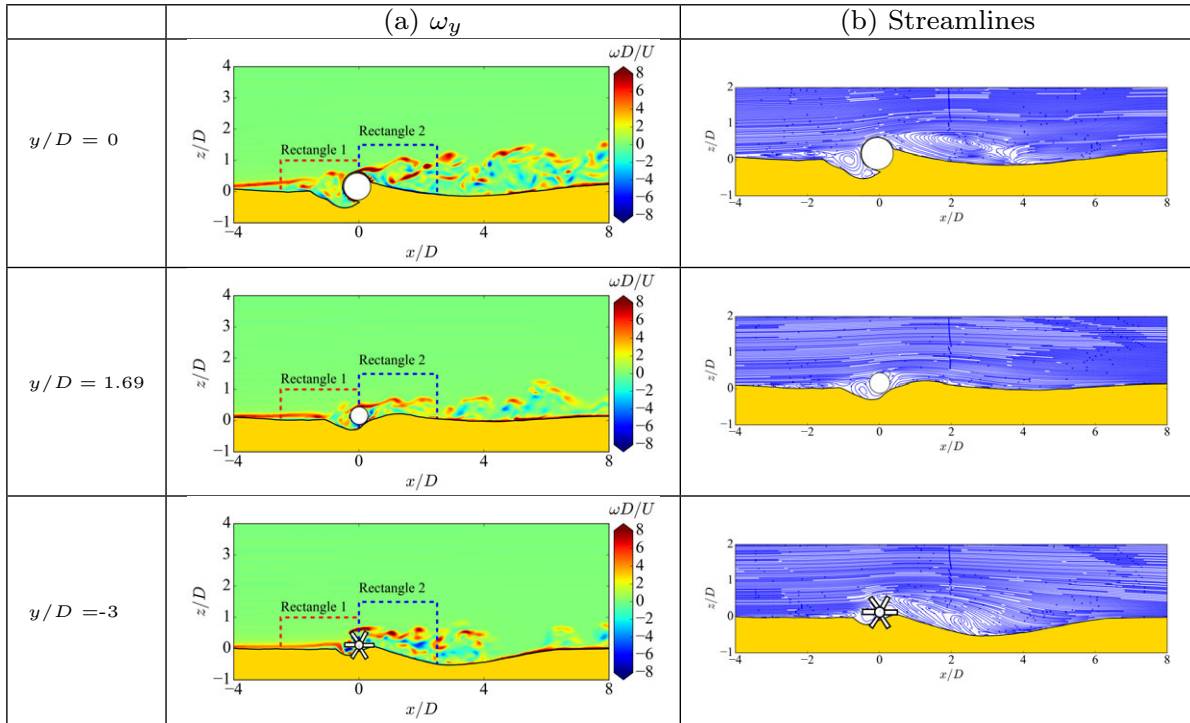


Figure 5.10: Simulated flow field for munition case HMS: (a) The instantaneous vorticity contour (out-of-plane), (b) The mean flow streamline. The plots are on three vertical planes located at $y/D = 0, 0.9$, and -3 .

Simulated scour processes

More insights have been gained through the analysis of the simulated scour processes. With cylinder and munition at the angles of attack of 45° and 90° , the shape and angle effects on scour and burial are discussed.

The simulated scour processes for both cylinder and munition at four representative stages with the angle of attack of 90° are shown in Fig. 5.11. For comparison, the experimental results are also plotted. In the figure, column (a) shows the vertical slice across the channel at $x/D = 0.45$ for case SM90 where the deepest scour occurred. Column (b) shows the corresponding bed contour plots. Similarly, column (c) shows the vertical slice across the channel at $x/D = 0$ for case SC90 where the deepest scour occurred. Column (d) shows the corresponding bed contour plots.

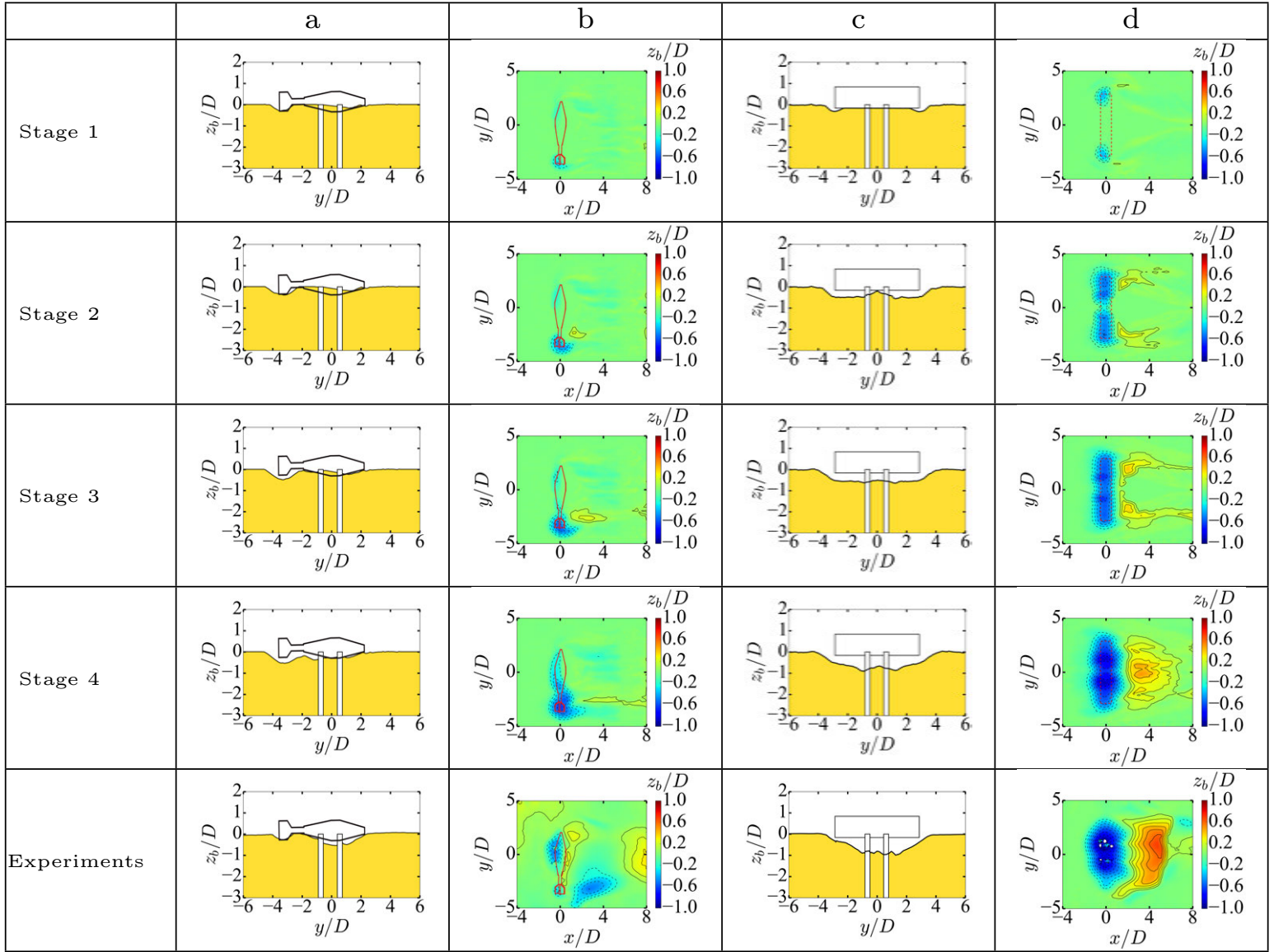


Figure 5.11: Time evolution of scour around cylinder and munition for cases SM90 and SC90. Column (a) shows the vertical slice at $x/D = 0.45$ for case SM90 where the deepest scour occurred. Column (b) shows the corresponding bed contour plots for the munition case. Column (c) shows the vertical slice at $x/D = 0$ for case SC90 where the deepest scour occurred. Column (d) shows the corresponding bed contour plots for the cylinder case.

At the first stage, the scour processes in both cases are similar as scour is initiated by flow contraction and horseshoe vortex near the ends of the objects as discussed in Section 5.1.3. At the second stage, the behaviors of scour in case SC90 and SM90 start to differ. A jet-like flow develops in the gap between the cylinder and the bed during the first stage. As the jet flow passes through the gap, it contracts (Fig. 5.9) and accelerates the erosion in the scour hole. Sediment is then

washed away from the scour hole and deposited downstream about 2 to 6 diameters away.

However, for the munition case, flow contraction under the tapered head is weaker than that under the cylinder because of the decreasing diameter along the tapered head. The incoming flow does not have enough strength to break through the sediment on the downstream side of the munition. On the downstream side, the recirculation in the wake zone (see Fig. 5.10) surprisingly picks up sediment particles far downstream (about 2 to 6 diameters away) and brings them to the immediate downstream side of munition.

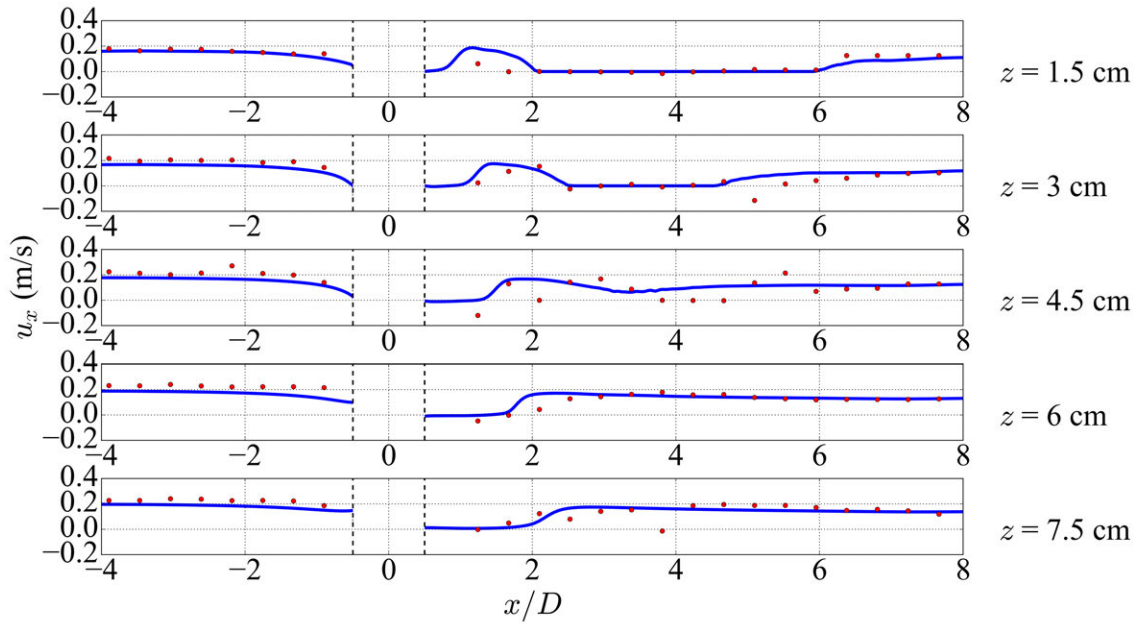
At the third stage, two scour holes near the ends of the cylinder case expand along the longitudinal direction and merge in the middle, gradually exposing the two crosses of the supporting cradle. For the munition case, the scour hole only expands along the upstream face of the munition. Its downstream side is covered by sediment brought by the wake recirculation.

The fourth and final stage of simulated scour and experiments are shown in Fig. 5.11. Although with some discrepancies, the scour model captured the major features of the scour pattern around both objects. For example, the model captured the main scour hole near the tapered head of the munition and the downstream scour hole induced by the tails. This model also predicted that the flow cannot break through the space between munition and bed. In general, the modeled scour pattern for the cylinder case matches better with experiments than the munition case. This is of course understandably due to the geometric complexity of munition.

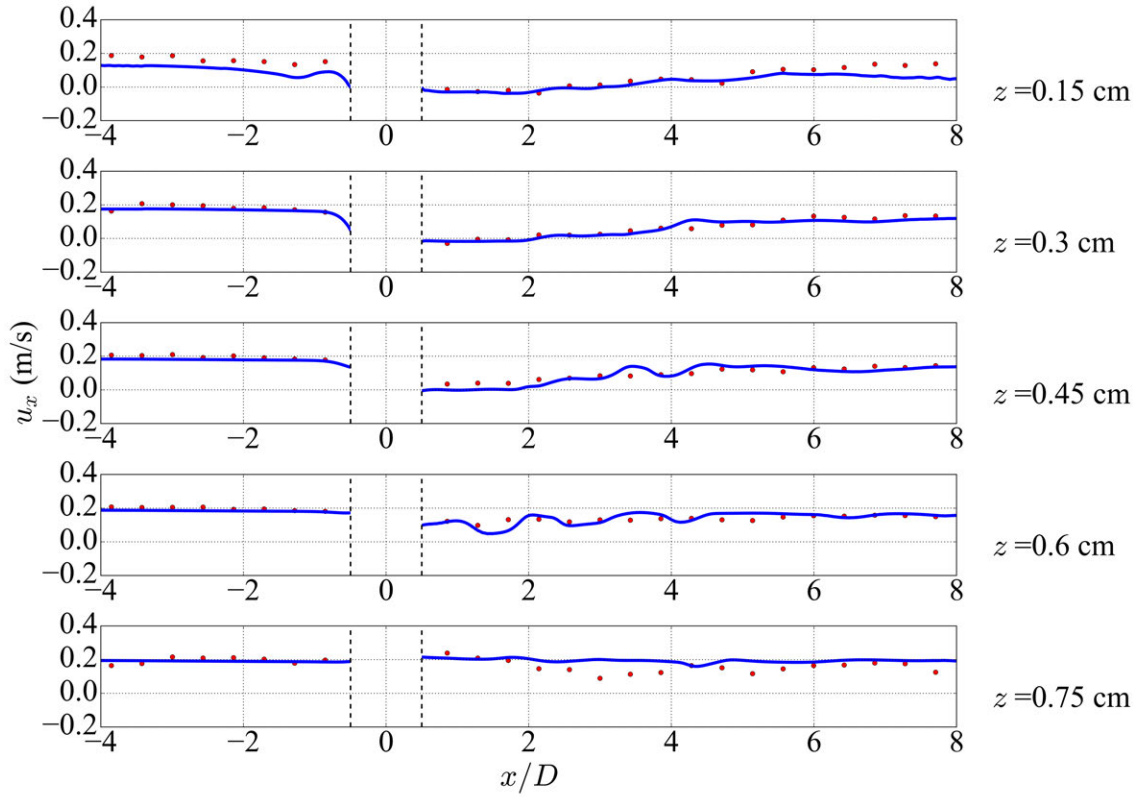
For the munition case, the main discrepancies between simulation and experiment are as follows. In experiment, the burial of the munition on the downstream side is more than the simulation result. This is due to the weaker simulated recirculation in the wake. Higher-order numerical schemes and better turbulence model may improve the recirculation strength. The scour model also overpredicted the scour depth under the munition tail. In hydrodynamic simulations, we observed the breaking of the large horseshoe vortex by the fins into smaller and weaker vortices. Therefore, sediment particles under the tail were less mobile. On the other hand, the RANS model used in the scour model cannot fully capture the complex flow process induced by the fins. The wall shear under the tail is overpredicted, which resulted in a larger scour hole.

With the scour model, we also compared the simulated velocity with experiments at equilibrium. Figure 5.12 shows the streamwise velocity, u_x , measured from the experiment (red dots) and predicted by the scour model (solid blue lines) on vertical slice $y/D = 0$ for cases SC90 and SM90. The black dashed lines represent area occupied by the objects. Velocities at four different elevations from the bed are plotted. The comparison shows that the model predicted reasonable velocities in both cases with 90° angle of attack. Although the burial of the munition on the immediate downstream side is underestimated by the scour model, the negative streamwise velocities near the wall (at $z = 1.5$ cm, pointed to upstream direction) induced by the flow recirculation are well captured in case SM90. In contrast, the streamwise velocities near the wall in case SC90 are positive because of the jet flow rushing out from the scour hole.

The angle of attack further complicates the scour process. We analyzed and compared the simulated scour results for cylinder and munition with 45° and 90° angles of attack. The streamlines at the initial stage and the time evolution of scour of case SC45 and SM45 (both with 45° angle of attack) are shown in Fig. 5.13. Only three obvious scour stages were observed with 45° angle of attack.



(a)



(b)

Figure 5.12: Streamwise velocities on the vertical slice $y/D = 0$ at four different depth: (a) case SC90, (b) case SM90. Experimental results are shown as red dots.

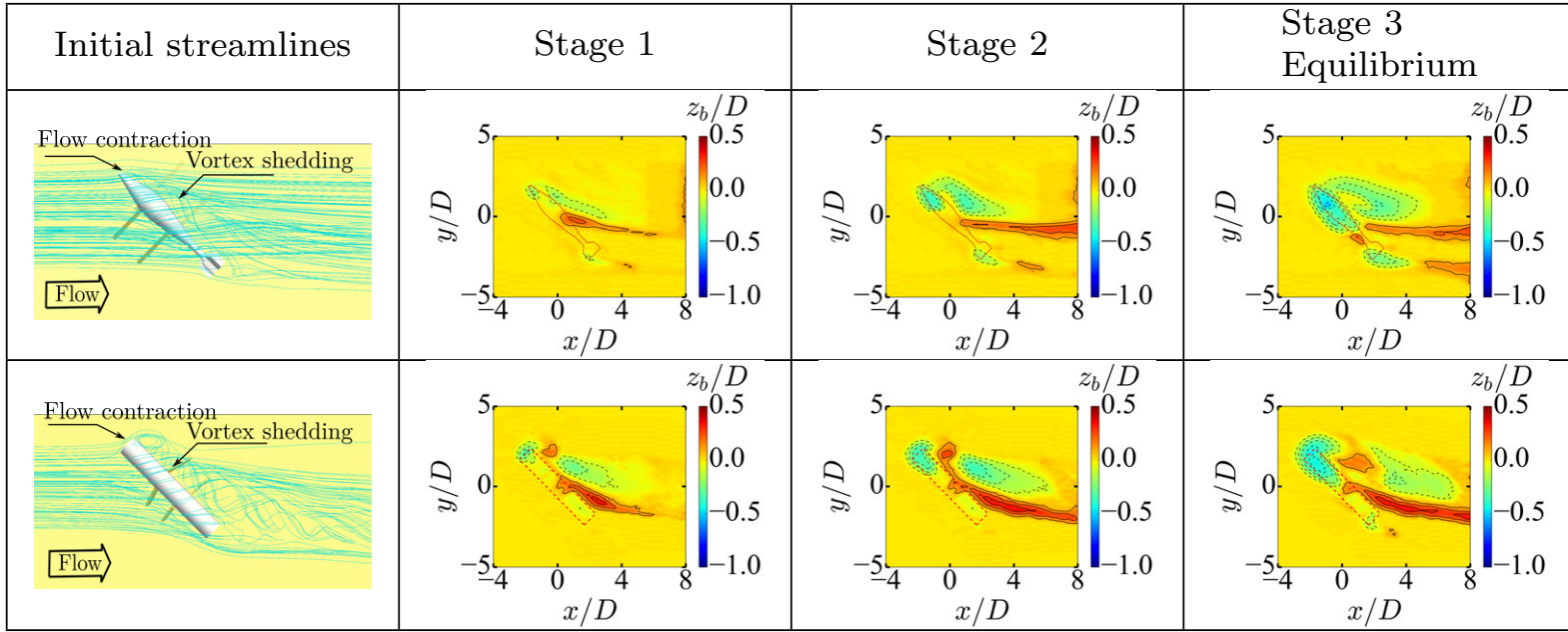


Figure 5.13: The streamlines at the initial stage and the evolution of scour around cylinder and munition for case SC45 and SM45.

At the initial stage, the incoming flow contracts and accelerates when it passes over the leading edge of both objects. Significant wake vortices are induced on the immediate downstream side of the objects (helical streamlines). Thus, two separate scour areas start near the leading end of the objects and the downstream side under the vortex shedding area. The erosion in the cylinder case is stronger because of its leading end is more blunt. At the first stage, for both cases, an elongated deposition bar starts to form, which extends from the center of objects to about six diameters away downstream.

At the second stage, scour under the objects expands along the longitudinal direction of the objects. In the SM45 case, the scour hole under the leading end of munition merges with the scour hole downstream. However, the scour hole under the leading end of cylinder is deeper, which induces a small deposition bar that separates the scour hole under the cylinder and the scour hole downstream. In addition, a small scour hole initiates under the trailing end of objects in both cases.

At the third stage, the scour hole under the leading edge of the objects further expands to the middle and then reaches equilibrium. In both cases, the scour pattern is similar since the scour is concentrated on the leading end. Vortex shedding and turbulence generated at the trailing end is carried to downstream rapidly. As a result, scour is weak at the trailing edge of objects. With 45° angle of attack, the tail of munition is the trailing end. The effects of the complex fins on munition's tail are not as significant as in the case with 90° angle of attack. Because of this, the scour pattern is similar at the trailing end around cylinder and munition with 45° angle of attack.

Scaling analysis of scour

In an effort to shed more light on the scour process and generalize the findings, a scaling analysis was performed based on physical principles and data generated in this work.

Scour around objects is a three-dimensional complex process. In addition to maximum scour depth, the scour volume (Vol_s) is another important indicator for UXO mobility. Based on dimensional analysis, the scour volume can be written in a functional form as

$$\frac{Vol_s}{Vol} = f \left(\frac{U}{U_c}, \frac{H}{D}, \frac{L}{D}, \frac{d_{50}}{D}, \frac{t}{t_0}, \alpha_{AOA}, \alpha_{shape} \right) \quad (5.2)$$

where Vol is the effective blockage volume of an object perpendicular to the flow direction, t_0 is the time scale of scour, U is flow velocity, H is flow depth, d_{50} is sediment diameter, U_c is sediment critical velocity, L is object length, D is object diameter, α_{AOA} is the angle of attack factor, α_{shape} is the shape factor, and t is time.

The effective blockage volume, Vol , represents the blockage effects of the object to flow, which can be related to an object's total volume V as:

$$Vol = \phi(\alpha_{shape}, \alpha_{AOA})V \quad (5.3)$$

Here, ϕ is a coefficient depending on an object's shape and the angle of attack, which can be quantified by the shape factor α_{shape} and the angle of attack factor α_{AOA} , respectively. We use the cylinder case with the 90° angle of attack as the base, whose ϕ value was set to 1.0. The ϕ values for munition and the 45° angle of attack need to be rated with experimental and simulation data. In this work, we calculated the ϕ values for cases SC45, SM90, and SM45 to be about 0.23, 0.27, and 0.25, respectively. It is clear that ϕ is not a linear function of angle of attack or shape. In future work, more shapes and angles of attacks need to be investigated to better constrain the functional relationship between ϕ and object shape and angle of attack.

Another essential variable in Eq. 5.2 is the time scale of scour, t_0 , which depends on flow and sediment properties. The main scour driver of all cases in this work is flow contraction. Thus, the flow contraction and wall shear amplification around object control the scour time scale. As a first-order approximation, the contraction velocity can be estimated with potential flow theory around a circle, whose diameter is equal to the length of the munition, as shown in Fig 5.14. The tangential velocity on the surface of the circle is $2U \sin(\beta)$ where β is the angle coordinate in the cylindrical coordinate system (Acheson, 1991). The maximum velocity, $2U$, occurs on the top and bottom of the circle when $\beta = \pm 90^\circ$. The maximum velocities predicted by the computational model are less than but close to $2U$ for all four scour cases. Therefore, this approximated contraction velocity can be used as a velocity scale for sediment transport estimation.

The wall shear velocity on sediment bed, u_τ , can be calculated from the approximated contraction velocity by (Chen et al., 2019):

$$\frac{2U}{u_\tau} = 5.75 \log \left(\frac{12.2H}{k_s} \right) \quad (5.4)$$

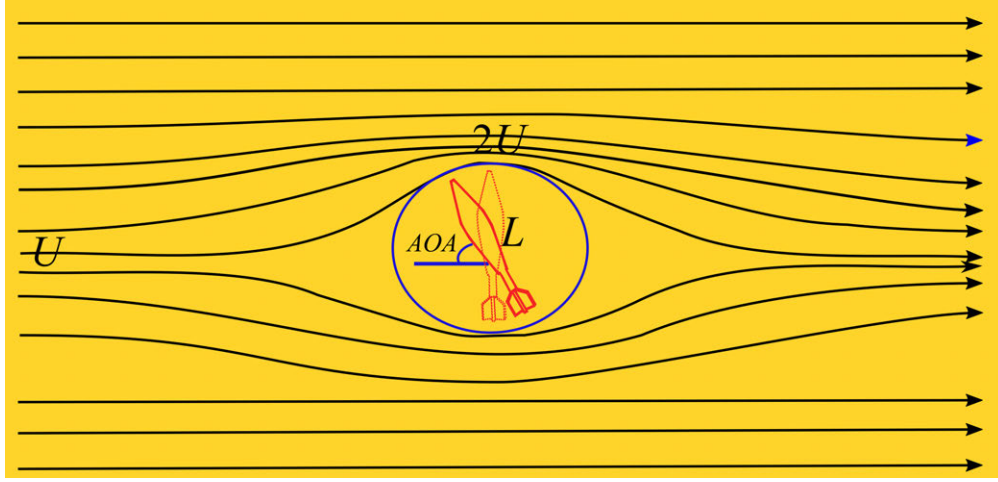


Figure 5.14: Scheme diagram of flow contraction around the objects.

Then the bedload transport rate q induced by the wall shear can be calculated with the empirical formula proposed in Engelund and Fredsøe (1976):

$$\frac{q}{\sqrt{Rgdd}} = \begin{cases} 18.74(\theta - \theta_c)(\theta^{1/2} - 0.7\theta_c^{1/2}), & \text{if } \theta > \theta_c \\ 0, & \text{if } \theta < \theta_c \end{cases} \quad (5.5)$$

where $\theta = |\tau|/(\rho g R d)$ is the Shields number, and θ_c is the critical Shields number.

The length scale of scour hole is the diameter of object, D . Hence, the time scale of scour can be approximated as:

$$t_0 \sim D^2/q \quad (5.6)$$

For all cases studied in this work, the time scale t_0 has the value of about 556 s.

For all four scour cases, the parameters on flow, sediment and geometry, i.e., U , U_c , H , D , d_{50} , and L in Eq. 5.2 are the same. In addition, the shape factor α_{shape} and the angle of attack factor α_{AOA} have been considered in the effective blockage volume, Vol . Therefore, the dimensionless scour volume Vol_s/Vol is only dependent on dimensionless time t/t_0 . With the simulated scour data, a saturation growth-rate equation was fitted and has the following form:

$$\frac{Vol_s}{Vol} = \frac{4.4t/t_0}{7.27 + t/t_0} \quad (5.7)$$

The simulated scour volume data and the fitted curve are plotted in Fig. 5.15. The plot shows that the scaling analysis collapses the data reasonably well and the fitted saturation growth-rate equation captures the temporal evolution of scour volume.

It is interesting to note that for all four cases, the asymptotic value for the dimensionless scour volume Vol_s/Vol is about four. The scour equilibrium is reached at about $t/t_0 = 40$. Scour develops very quickly in the early stage of $t/t_0 < 10$, which accounts for about 60% of scour volume. For the time period of t/t_0 between 10 and 30, additional 30% of scour occurs. The main scour driver in this period is the flow contraction in the scour hole under object. For the

remaining period, the scour process drastically slows down and only about 10% scour occurs. This information is useful not only for our understanding of the process, but also for large scale models where detailed scour simulation is impossible.

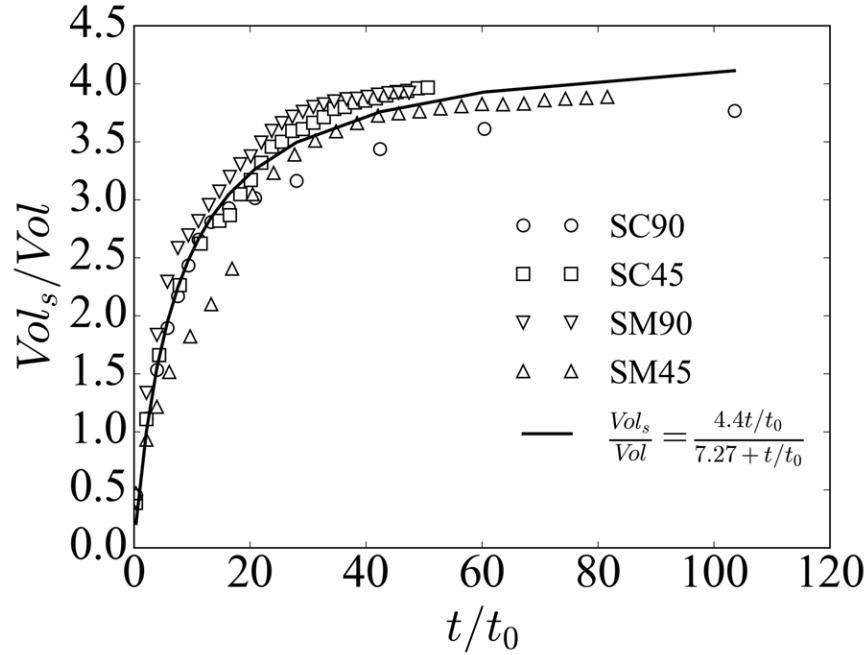


Figure 5.15: Temporal development of the scour volume.

5.1.4 Conclusions

We presented the results and analysis of a comprehensive experimental and computational study on scour and burial of underwater UXOs. Specifically, the effects of object shape and angle of attack were investigated. A cylinder and a munition with 45° and 90° angles of attack were studied. The results show that shape and angle of attack are two important factors which create unique hydrodynamics and morphodynamics around UXOs.

To investigate the hydrodynamics, flow-only simulations were performed with flat bed and equilibrium scoured bed from experiments. For morphodynamics, scour simulations were performed and validated with experimental results. Both flow-only simulation model and scour simulation model produced reasonable results in comparison with experiments. The detailed analysis of the simulated flow fields show that the main driving flow mechanisms evolve as the scour hole develops from initial stage to equilibrium. The scour hole around the cylinder is larger than that around the munition because of the larger blockage effect of cylinder. The contraction flow around the cylinder is much stronger and it creates a complete scour hole under the cylinder. However, for munition, because of its tapered head and relatively slender body, the contraction flow is not strong enough to clear the sediment underneath. The recirculation flow in the wake of a munition even moves some downstream sediment to the backside of the munition. We also found that at 45° angle of attack, the scour around the leading end is strengthened and the scour

around the trailing end is weakened. The strengthening and weakening are comparable between cylinder and munition.

To gain more insight and generalize the findings, a scaling analysis was performed based on first principles and dimensional analysis. The analysis proposed the time scale for scour hole's temporal evolution. It is based on potential flow theory and bedload transport rate. The dimensionless total scour volume, instead of the scour depth, was used to better quantify the 3D scour process. Based on data generated in this work, a general saturation growth-rate equation was fitted between the dimensionless scour volume and dimensionless time. The fitted equation collapses the data reasonably well despite the complexity of the hydrodynamic and morphodynamic processes. Future research is needed to better constrain the parameters and coefficients used in the scaling analysis.

5.2 *Other simulation results with the 3D scour model*

During the course of the project, many other cases were simulated using the 3D scour model. Some of the cases were performed due to the interest of the MR program. Others are cases done to test the capability of the model. Cases in this section are not published, mostly due to their hypothetical nature and there is no lab/field data for calibration and comparison. Nevertheless, these cases are of value to the Munition Response program. In the future, if lab or field data are obtained, the 3D scour model can be readily used for those cases.

5.2.1 *Scour around munitions with a prescribed motion*

The 3D scour model can handle the motion of objects (as long as the motion is known). In this section, the case is the simulation of scour around a mobile munition initially laying on an erodible bed. The simulation setup is shown in Fig. 5.16. The channel has a water depth of 0.2 m and a sand depth of 0.1 m. The inlet velocity is 0.5 m/s and the median sediment diameter is 0.26 mm. The munition, which has a maximum length of 194 mm and maximum diameter of 51 mm, is assumed to move vertically downward with a velocity of 0.4 mm/s.

Figure 5.17 shows the bed elevation at equilibrium. The munition is marked with blue. The incoming flow decelerates due to the presence of the munition leading to concentrated deposition just upstream of the munition. Erosion occurs immediately downstream of the munition, with the deepest scour downstream of the broadest part of the munition. Additionally, there is no scour under the munition. As the erosion begins below the narrower parts of the munition (the tip or the narrow circle near the end of the munition), the munition's prescribed downward motion fills the developed scour hole. At the same time, the sand under the munition is pushed to the surrounding areas of munition. The deformation of the bathymetry changes the distribution of sediment as well as the granular forces acting on the munition. In future work, the simple prescribed motion of the objects can be replaced by experimentally observed real motion or a full six degrees-of-freedom motion model for the object. With more realistic prescribed munition motion, the relationship between bed deformation bathymetry and the munition's movement can be further investigated.

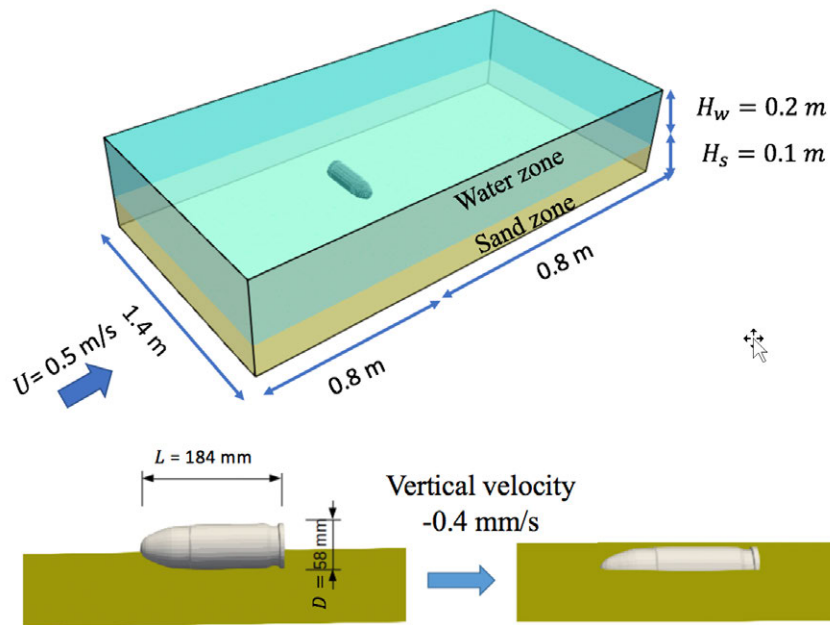


Figure 5.16: Setup for simulation of scour around a munition sitting on a sediment bed.

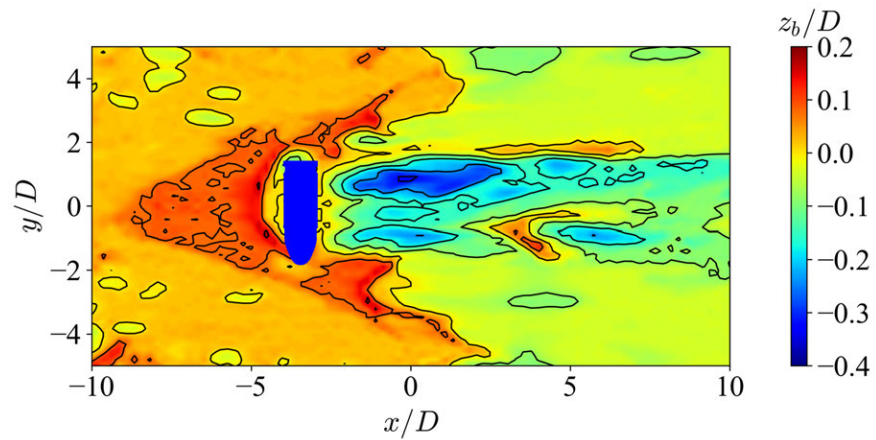


Figure 5.17: Simulation result of bed elevation at equilibrium for scour around a munition with prescribed motion.

5.2.2 Scour around munitions at different angles with a prescribed motion

To further demonstrate the use of the 3D scour model, four more hypothetical cases were simulated. In these cases, the munition moves with a prescribed motion. The munition sinks down into the bed at a fixed speed for a short period of time, mimicking the process observed in many flume experiments. The flow angle of attack was also varied. Figures 5.18 to 5.20 show the cases for the flow angles of attack of 0, 45, and 90 degrees. Each figures shows four representative moments during the simulated scour process, from the initial flat bed to the final equilibrium. It is clear to see that the scour processes and the final equilibrium bed are influenced by the flow angle of attack.

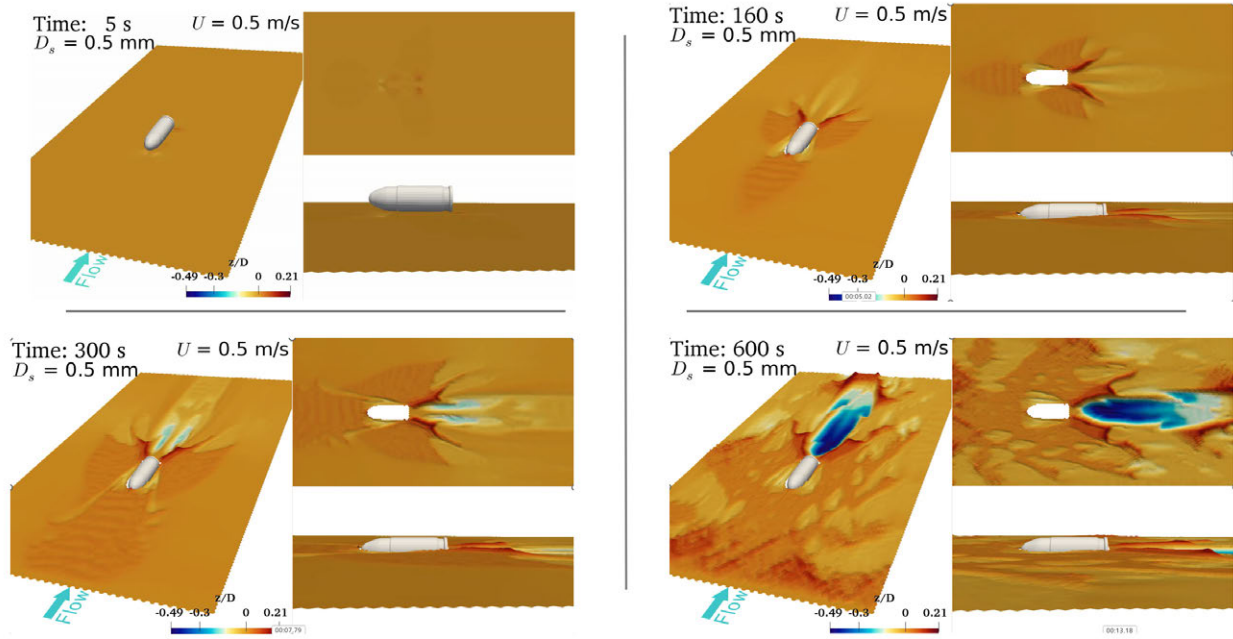


Figure 5.18: Simulation result of bed elevation at equilibrium for scour around a munition with prescribed motion. The munition is at 0 degree angle of attack.

The 3D scour model can not only capture the scour around munitions, but also the burial process. When sediment supply from upstream exceeds the transport capacity of flow, the bed will experience accretion and munitions on bed will be buried. The immersed boundary method in the 3D scour model is perfect to capture this burial process. Figure 5.21 shows such a case. The excessive sediment supply from the inlet boundary creates a sand wave which approaches the munition and buries it.

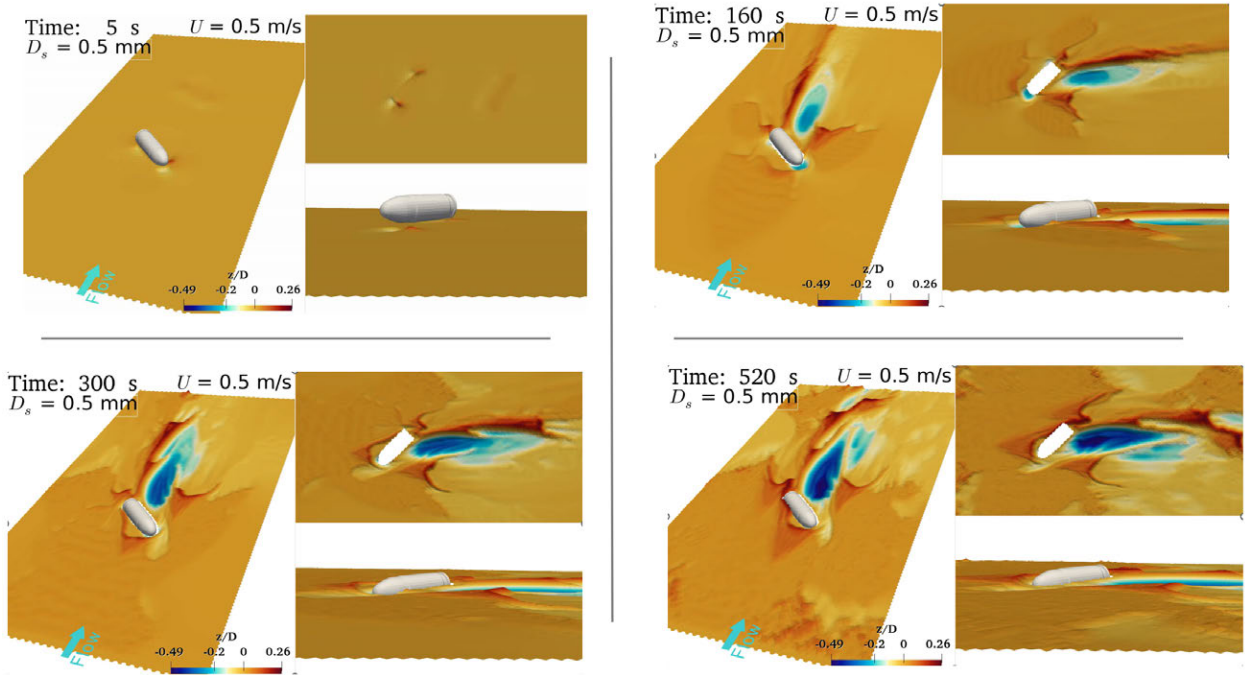


Figure 5.19: Simulation result of bed elevation at equilibrium for scour around a munition with prescribed motion. The munition is at 45 degree angle of attack.

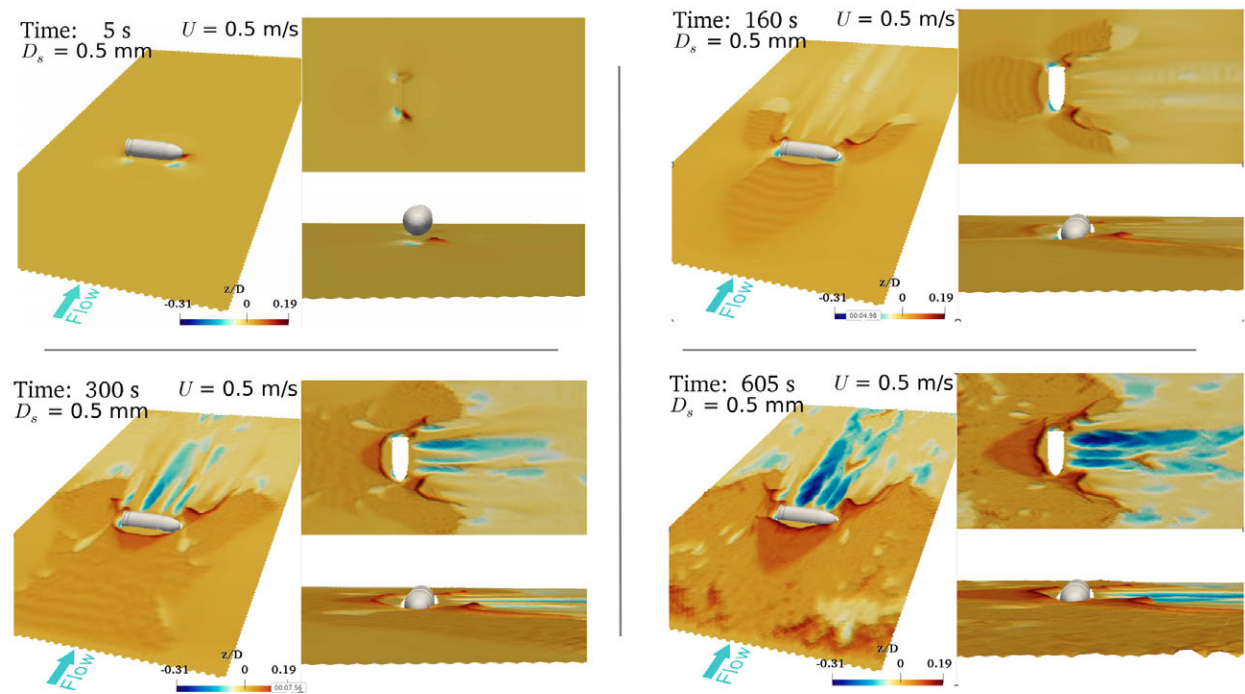


Figure 5.20: Simulation result of bed elevation at equilibrium for scour around a munition with prescribed motion. The munition is at 90 degree angle of attack.

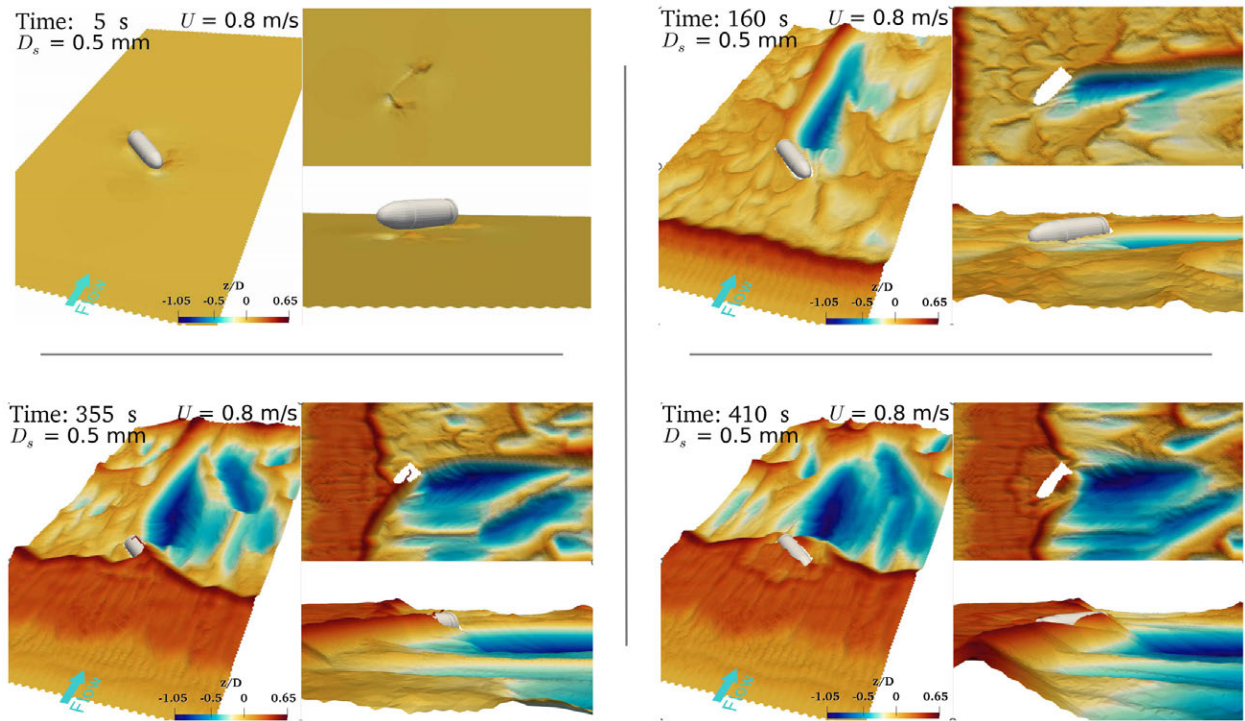


Figure 5.21: Simulation result of bed elevation at equilibrium for scour around a munition with prescribed motion. The munition is at 45 degree angle of attack. This case is different from the one in Fig. 5.19. The inlet sediment supply creates a sand wave.

5.3 Results of 3D SPH model

5.3.1 BlueDrop penetrometer

The developed 3D SPH model was used to simulate the 3-D BlueDrop penetrometer experiments reported in Albatal et al. (2020). BlueDrop is a portable free-fall penetrometer, which is shown in Fig. 5.22 and can be used to estimate in-situ sediment strength of surficial sea floor sediments in subaqueous areas of difficult access (Stark, 2016). This small lightweight penetrometer is suitable for deployment from vessels of variable size and infrastructure and can be easily configured for deployment from submersibles (Stark et al., 2013). This makes the probe compatible for use in areas such as narrow canyons, highly energetic areas, and close offshore structures. As the BlueDrop penetrates into sediments, its acceleration time history is recorded at a sampling rate of 2 kHz by five embedded accelerometers; the stiffness or strength of the sediment can be assessed by analyzing the recorded acceleration vs. depth (Stoll et al., 2007; Stark et al., 2012).

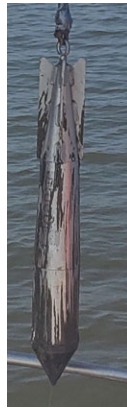


Figure 5.22: BlueDrop penetrometer (Stark, 2016).

The 3-D penetrometer experiment is a perfect case to test the capability of the 3D SPH model. It is simple and yet has all the components of the flow-object-sediment system. The coupling among all these components is very strong and the dynamic evolution occurs in a short duration. Experimental results have shown that the response of the penetrometer is sensitive to the type of sediment, which is the only significant variable in all experiments. Calibration with experimental data thus will reveal the control parameters in the model for sediment characterization. As will be shown later, the present model also augments the experiments, after careful calibration, by providing more physical insights, e.g., hydrodynamic and sediment forces, which are extremely hard to measure in experiments.

Three penetrometer tests were conducted with loose, medium, and dense sediments. Fig. 5.23 shows a conceptual sketch of the experimental setup. The container was a steel ring of 1.2 m in diameter (being part of a large-scale Cone Penetration Test calibration chamber) and 1.0 m in height. The penetrometer has a total length of 0.631 m and a weight of about 7.372 kg using the conical steel tip. In the experiments, the depth of the fluid and sediment was 0.4 m and 0.2 m, respectively. In the SPH simulations, to avoid the influence of the tank bottom particles, the sediment depth was increased to 0.3 m. The release height of the penetrometer was slightly dif-

ferent among the three tests. After the penetrometer was released, its acceleration (deceleration) time history was recorded by the embedded accelerometer; its vertical velocity time history was obtained from the integration of the acceleration with time and checked via visual observations of deployment height and penetration depth. Additional data from this laboratory experiment series was previously published in Albatal et al. (2020).

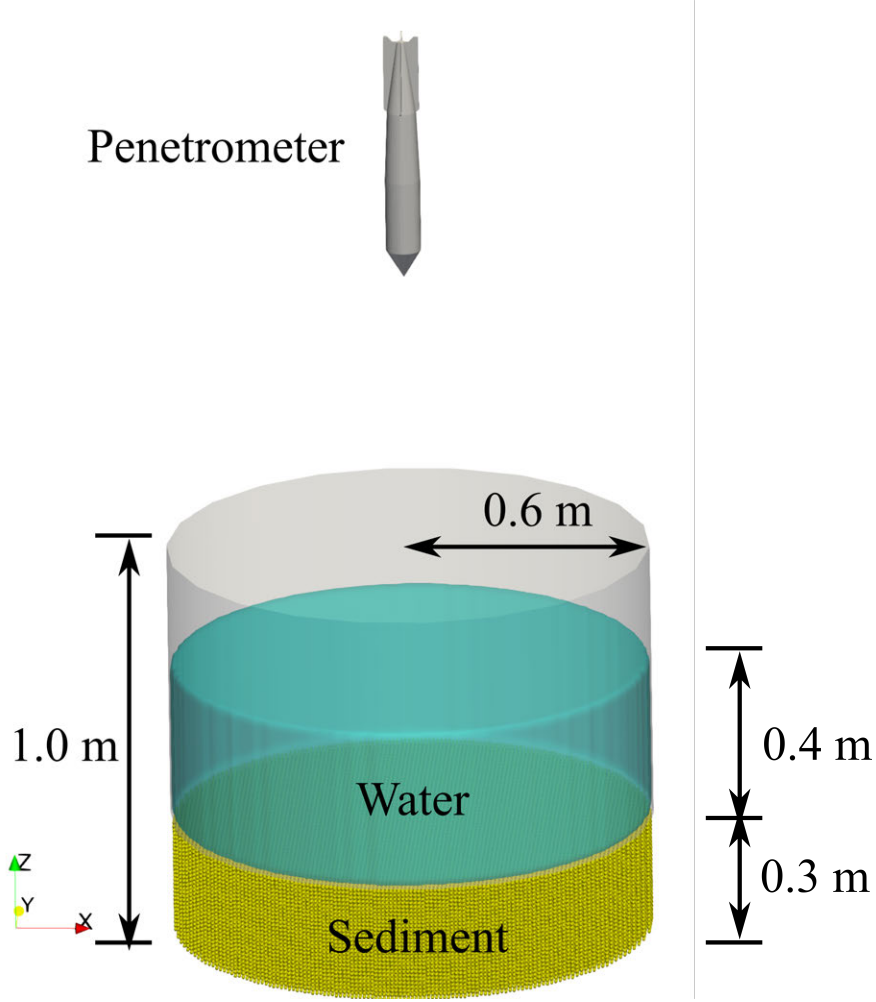


Figure 5.23: Experimental and simulation setup for penetrometer tests.

Figure 5.24 shows different stages, i.e., before and after the penetration into sediment, of the simulation for the loose sediment case. The main input parameters used in the simulations are summarized in Table 5.2. The drop height was obtained from the experiments; however it was slightly adjusted to match the water-entry velocity based on the free-fall of the penetrometer. Other parameters, including the Young's modulus E , Poisson's ration ν , cohesion c (though the sediment is assumed to be non-cohesive, in real scenarios the sediment may be somewhat cohesive, so a small value is provided for the sediment cohesion in this study), and friction angle ϕ , had typical values based on the consistency of the sediments (Obrzud et al., 2012; Kezdi, 1980) ; and m, n were calibrated against the test results. To demonstrate the calibration process, Fig. 5.25 shows the effect of m on the simulation results for loose sediment as an example. Fig. 5.25 indi-

cates that m has a negligible effect on the model simulation, hence a typical value of 100 is used for all three cases.

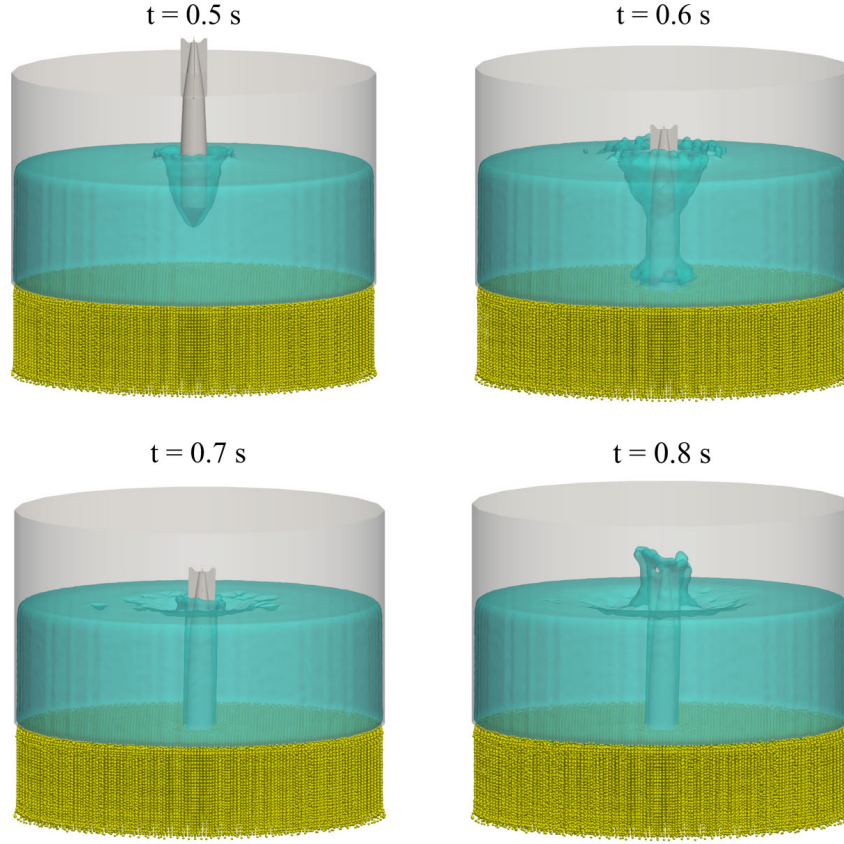


Figure 5.24: Simulation of penetrometer penetrating into loose sediments at four representative times $t = 0.5$ s, 0.6 s, 0.7 s, and 0.8 s.

The effects of two key parameters, E and n , on the simulation results are discussed below. The definitions of inflection depth and penetration depth of the penetrometer are shown in Fig. 5.26. The inflection depth is defined when the deceleration of the penetrometer reaches its maximum value in the sediment layer while the penetration depth is defined when the velocity of the penetrometer reaches zero. Fig. 5.27(a) plots the effect of E , which controls the stiffness of the sediment in the elastic solid state, on the simulation results for the loose sediment case. The results for other sediment types are similar. It shows that as the value of E increases and the sediment becomes stiffer, the penetration depth decreases. Fig. 5.27(a) shows that $E = 20$ MPa results is the best overall match with the experimental observations in terms of the penetration depth and trajectory; hence, this value is used for loose sediment (see Table 5.2). The E values for the medium and dense sediment cases are similarly obtained and the results are not presented herein.

After the E values are calibrated in all three cases, the effect of n on the simulation results is studied. The power-law index n controls the visco-plastic fluid state of the sediment. Fig. 5.27(b) shows that for the calibrated E value, the penetration depth increases as n decreases. Fig. 5.27(b) shows that $n = 1.0$ results in the best overall match with the experimental observations in terms of the penetration depth and trajectory; hence, this value is used (see Table 5.2). Comparing

Case	E (MPa)	ν	c (kPa)	φ (°)	m	n	μ (Pa·s)	Bulk Density (kg/m ³)	Drop Height (m)
Loose	20	0.48	1	30	100	1	100	1900	1.3548
Medium	25	0.48	1	33	100	1	100	2000	1.3827
Dense	60	0.48	1	36	100	1	100	2100	1.3836

Table 5.2: Parameters for penetration simulations

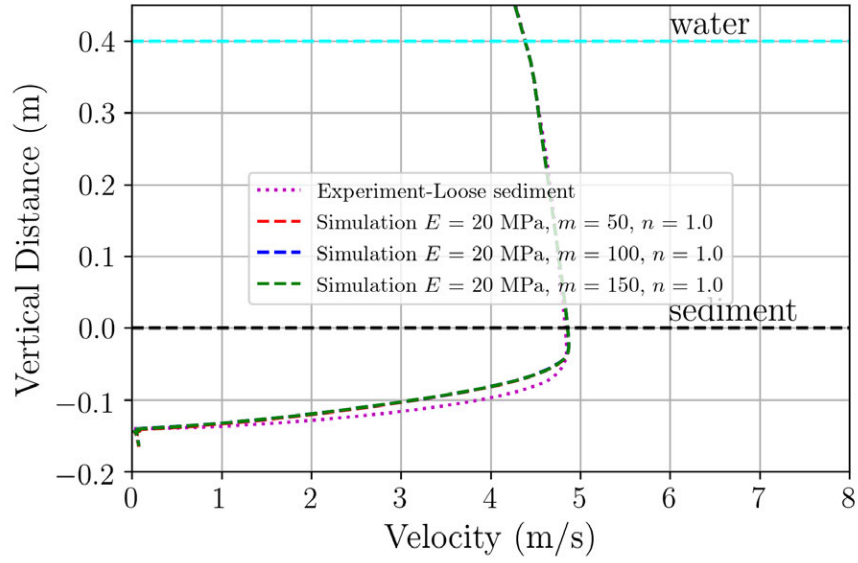


Figure 5.25: Effect of m on velocity response (loose sediment).

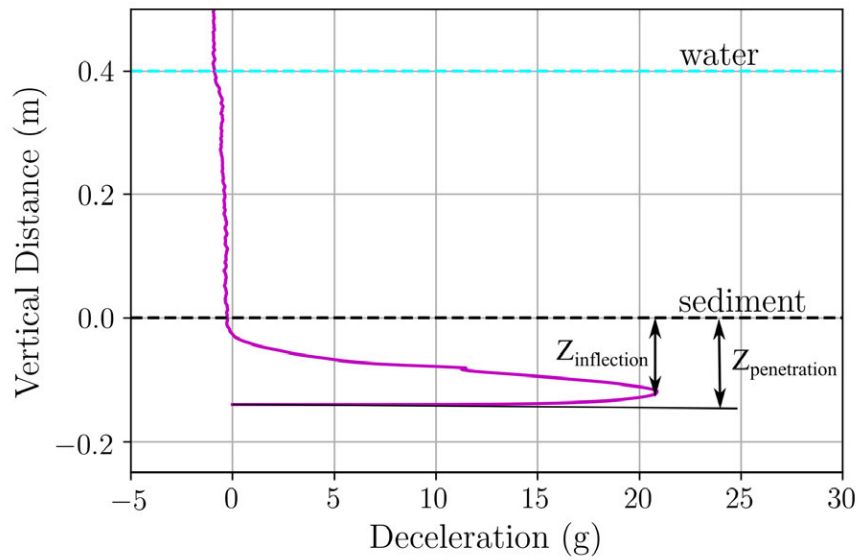


Figure 5.26: Definition of inflection depth and penetration depth.

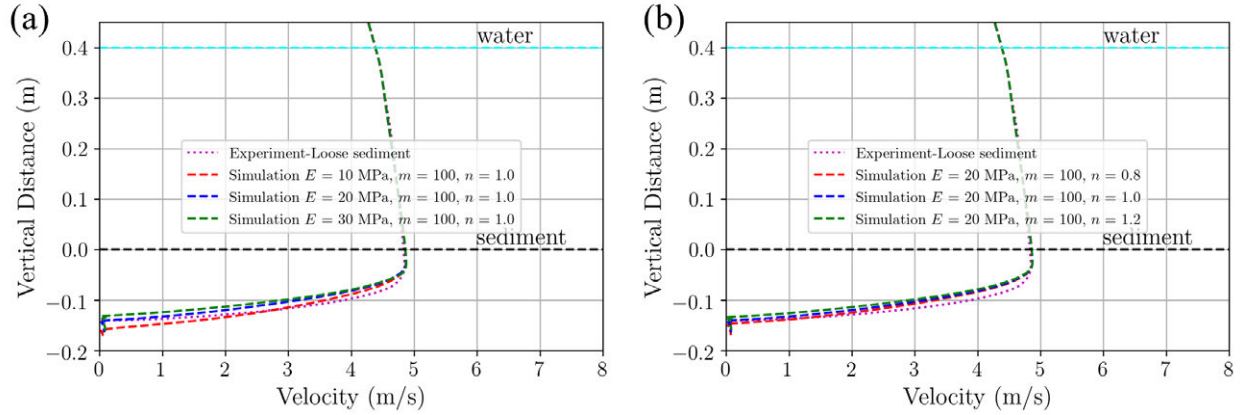


Figure 5.27: Effects of model parameters on velocity response for the loose sediment case: (a) effect of E , (b) effect of n .

Fig. 5.27(a) with Fig. 5.27(b), it is evident that E has a more significant influence on the simulation results than n ; therefore, a constant n value is used for all cases. Another rationale for this simplified treatment is that in the visco-plastic fluid state of the sediment, a significant deformation has accumulated and the effect of initial density of the sediment is likely erased, which is similar to the concept of critical state soil mechanics.

Fig. 5.28(a) and (b) summarize the effects of E and n on the penetration depth of the penetrometer for all three sediment cases. Similarly, their effects on the inflection depth are plotted in Fig. 5.28(c) and (d). The results indicate that the penetration depth decreases as the relative density of the sediment increases from loose to dense, E increases, and n increases. All these trends make physical sense. In addition, the effect of n on the penetration depth becomes relatively insignificant when the relative density of sediment and the corresponding Young's module E increase. For the inflection depth, the conclusion is similar to that for the penetration depth, except that the effect of n is even less significant as evidenced by the almost flat curves in Fig. 5.28(d).

Besides velocity, acceleration of the penetrometer, which is normalized by the gravitational acceleration g , was also studied. In this work, deceleration is defined as positive. For all three cases (loose, medium, and dense sediment), the acceleration of the penetrometer undergoes the following process. First, the downward acceleration is kept at the constant of g because of free fall. Then, it gradually decreases as the penetrometer enters into the water layer, which imparts increasing hydrodynamic resistance. As the penetrometer enters into the sediment layer, acceleration transitions rapidly to a deceleration because of the sediment impact force. Within the sediment layer, the deceleration reaches a maximum value before decreasing to zero when the penetrometer comes to an abrupt stop. Using the loose sediment case as an example, Fig. 5.29 (a) and (b) show the effects of E and n on the evolution of acceleration/deceleration with vertical distance. It shows that as E increases from 5 MPa to 40 MPa and as n increases from 0.8 to 1.2, the maximum deceleration slightly increases as the sediment becomes stiffer and more viscous. From the comparison between the two subfigures in Fig. 5.29, it is clear that the peak deceleration is more sensitive to the Young's module E . This makes physical sense because the whole impacting process is rapid and the viscous effect is secondary.

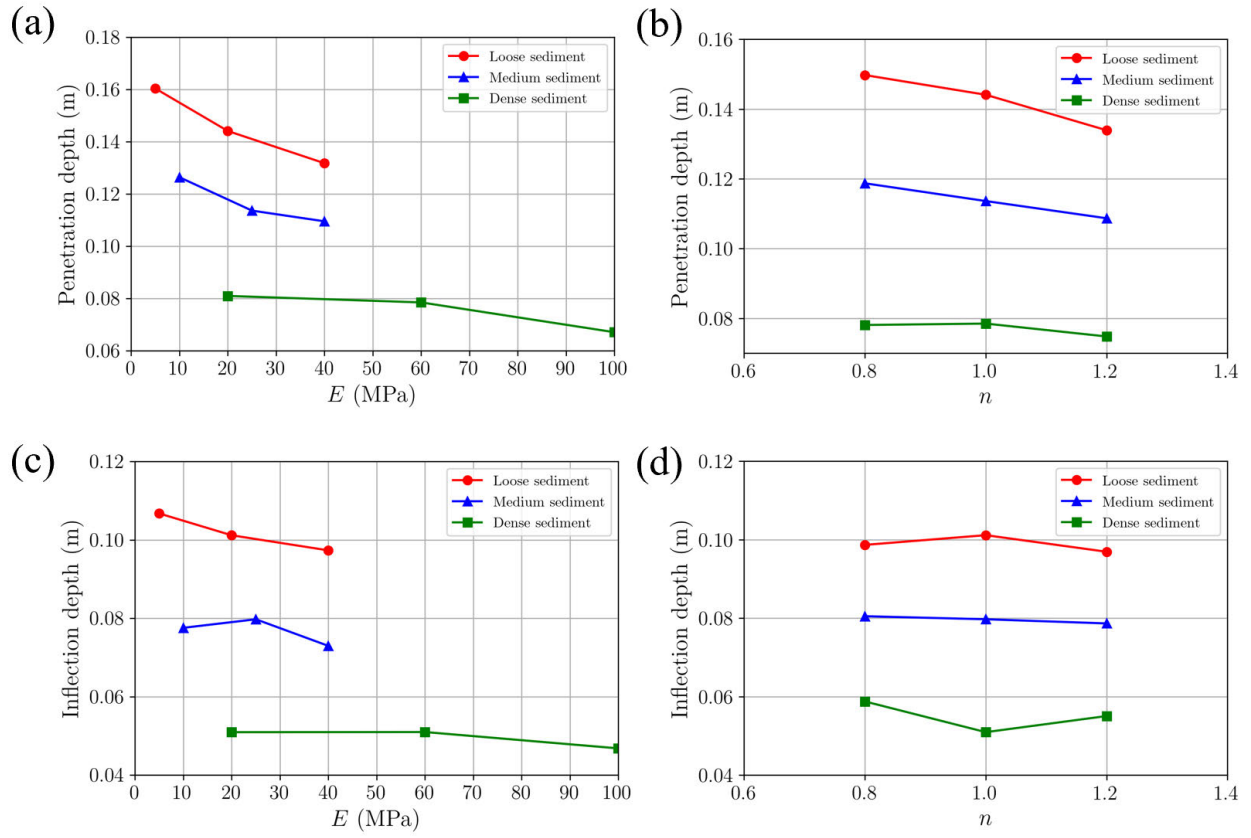


Figure 5.28: Effects of model parameters on penetration and inflection depths: (a) effect of E on penetration depth, (b) effect of n on penetration depth, (c) effect of E on inflection depth, (d) effect of n on inflection depth.

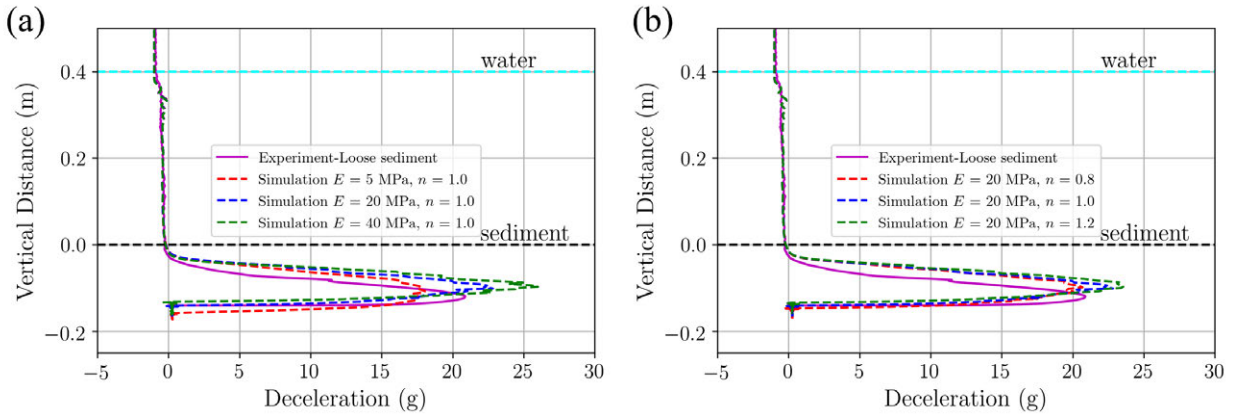


Figure 5.29: Effects of model parameters on acceleration response: (a) effect of E , (b) effect of n (loose sediment).

One important capability of the developed SPH model is that it can calculate the time history of the forces on the penetrometer. This is important information which is hard to measure in experiments, particularly for ruggedized portable free fall penetrometers. Further, the forces acting on the object from different phases (water and sediment) can be calculated separately and their relative contribution can be analyzed. Such force separation is important for many applications and engineering designs. Fig. 5.30 (a), (b), and (c) plots the vertical forces, i.e., the total F_z , water force ($F_{z,water}$) and sediment force ($F_{s,sed}$), for the loose, medium and dense sediment cases, respectively. One can imagine that forces along the vertical z direction are dominant and are negligible along the horizontal x and y directions; hence, only the forces along z direction are presented herein. Fig. 5.30 (a-c) show that as the penetrometer enters into the water layer and sediment layer at approximately 0.43 s and 0.54 s, respectively, the resistance forces from the water layer and sediment start to increase. The dense sediment layer provides the highest resistance while the loose sediment layer gives the lowest. The resistance force from the water layer is much smaller than that from the sediment layer. Water resistance force is relatively independent of the sediment condition since the drop height for three cases is almost the same. Fig. 5.30(d) plots the sediment force time histories for the three cases. It is clear that as the sediment becomes denser, the peak impact force from sediment also increases. Further, the rising limb of the sediment forces follows similar slope, which is in contrast to the falling limb. It is observed that the slope of the falling limb is smaller when the sediment is loose. In other words, the force history is more “diffusive” in loose sediment. In the present study, only the impact penetration in sands was studied. For more complex sediments, such as clays, whether this “diffusive” nature of sediment force still holds needs to be investigated in future studies.

In conclusion, the coupled dynamics of flow-object-sediment systems is important for both fundamental understanding of how these systems work and engineering applications. To study such systems, the 3D SPH numerical model can be used to capture the physical processes which govern the evolution of the system’s state. The development and validation of an improved SPH multi-phase model have been presented. The implementation of a visco-elastoplastic sediment model by adding the elastic behavior of the sediment and 6-DoF rigid-body motion into an existing DualSPHysics code has been validated using experimental results. Satisfactory results are obtained in the 3-D penetrometer simulations for loose, medium and dense sediments. The simulated inflection depth, penetration depth, velocity and acceleration profiles of the penetrometer, and maximum penetrometer acceleration showed good agreement with the experimental results. It is found that the Young’s modulus E plays an important role in the response of the penetrometer. As E increases, the inflection depth decreases and the maximum penetrometer acceleration increases. The model can also produce valuable information such as force history on moving object attributed to water and sediment separately, which is difficult to obtain in experiments. It is concluded that the developed and validated visco-elastoplastic sediment model coupled with the 6-DoF rigid-body model can be used to simulate complex flow-object-sediment systems. Using this modeling framework, new sediment rheological models can be added for different granular material behaviors. One limitation of the current model is that its formulation cannot correctly capture the pore-pressure dynamics. More advanced soil constitutive relationships should be adopted in future research. Another limitation of the current model is that the parameters, such as the Young’s module, may need to be tuned case by case. Although the physical meanings of all the parameters are clear, the multi-parameter calibration process is currently performed in serial

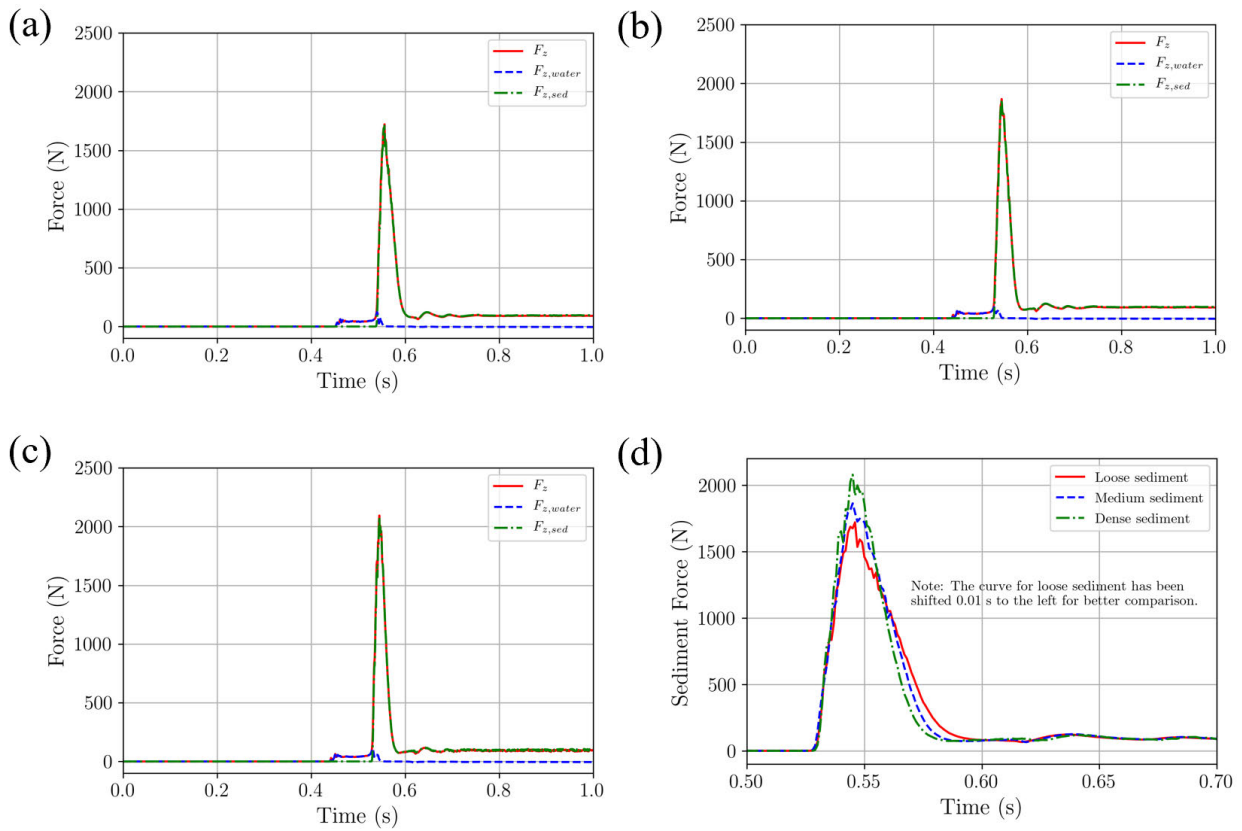


Figure 5.30: Comparison of vertical forces acting on penetrometer from loose, medium, and dense sediments.

based on our understanding of their relative importance. For example, for the same sediment, the calibrated parameter values may be different in various cases. More rigorous calibration methodology should be used.

5.3.2 *Density effect on munition mobility*

Previous researches have shown that the relative density is probably the most important parameter that affects munition mobility. Demonstration of a simple shake box with water, sand, and a sphere performed by researchers at the Naval Research Laboratory has clearly shown the different motion trajectory of spheres with different densities.

In this section, three hypothetical cases were run to show the effect of munition density. The relative density ratios between munition and water are $\rho_{munition}/\rho_{water} = 1.2, 4.0,$ and 7.8 , respectively. There are referred to low, medium, and high density ratios. The relative density ratio between sediment and water is kept at constant ($\rho_{sediment}/\rho_{water} = 2.0$). In fact, here the sediment density refers to the density of the saturated sediment made of both sediment particles and water. The whole box is subject to oscillatory shaking with a frequency of 3 Hz and an amplitude of 5 cm.

The three cases with different relative munition density ratios show the expected motion trajectory. Figures 5.31 to 5.33 show the results for the three cases, in the order of low, medium, to high relative density ratios. It is clear that when the munition's density is relatively low, the initially buried munition floats up. For the munition of medium relative density ratio, it stays at the bed without floating up or sinking down. For the munition with high density ratio, it quickly sinks down into the sediment bed under the oscillatory motion of the box. All above shows the drastic effect of munition density on its mobility and movement.

With the 3D SPH model, the forces on the munition can be analyzed. For example, Fig. 5.34 shows the displacement and force history on the munition with medium density ratio. In this plot, x and z refer to the horizontal and vertical directions, respectively.

The developed 3D SPH model can handle not only simple shapes such as those shown in the previous cases, but also any arbitrary shape. To demonstrate this, a more realistic case was simulated where the shape of a hypothetical munition (with tapered head and tail fins) was placed on a sediment bed and subject to oscillatory flow. In this case, the sediment part is not shaking as in the previous cases. The whole setup is similar to experiments performed in oscillatory tunnels, which mimic the wave boundary layer near sediment bed. The simulated density ratios are $\rho_{munition}/\rho_{water} = 7.8$ and $\rho_{sediment}/\rho_{water} = 2.0$. The oscillatory flow's frequency is 0.5 Hz and the amplitude is 0.3 m. Figures 5.35 and 5.36 shows the start and end of the simulation. At the beginning, the munition is sitting on the sediment bed with half burial. At the end of simulation, due to the interactions among flow, sediment and munition, the munition is almost fully buried inside sediment. This is mainly due to the high relative density of munition.

5.3.3 *Munition mobility on beach face*

Munitions are often found on beach subjecting to breaking waves. Other researchers have studied this both in the lab and in the field, for example the project MR-2503 done by Dr. Jack Puleo's

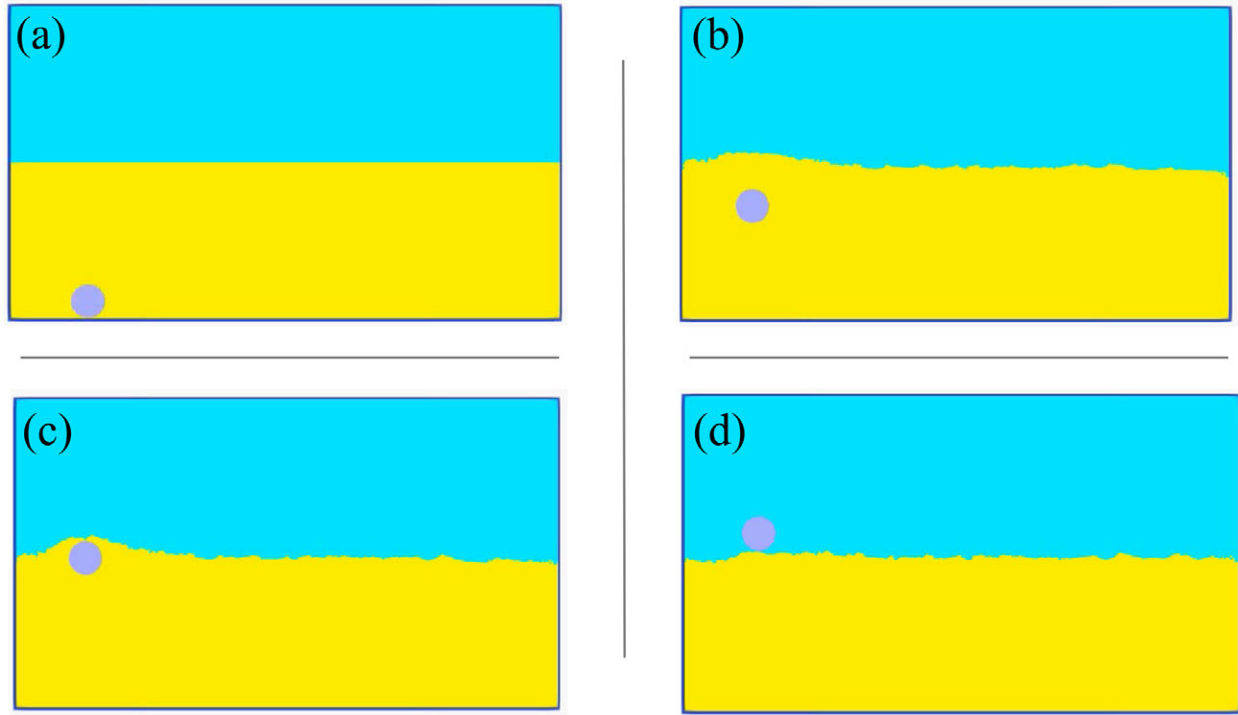


Figure 5.31: Munition motion under oscillatory shaking. Density ratios are $\rho_{munition}/\rho_{water} = 1.2$ and $\rho_{sediment}/\rho_{water} = 2.0$.

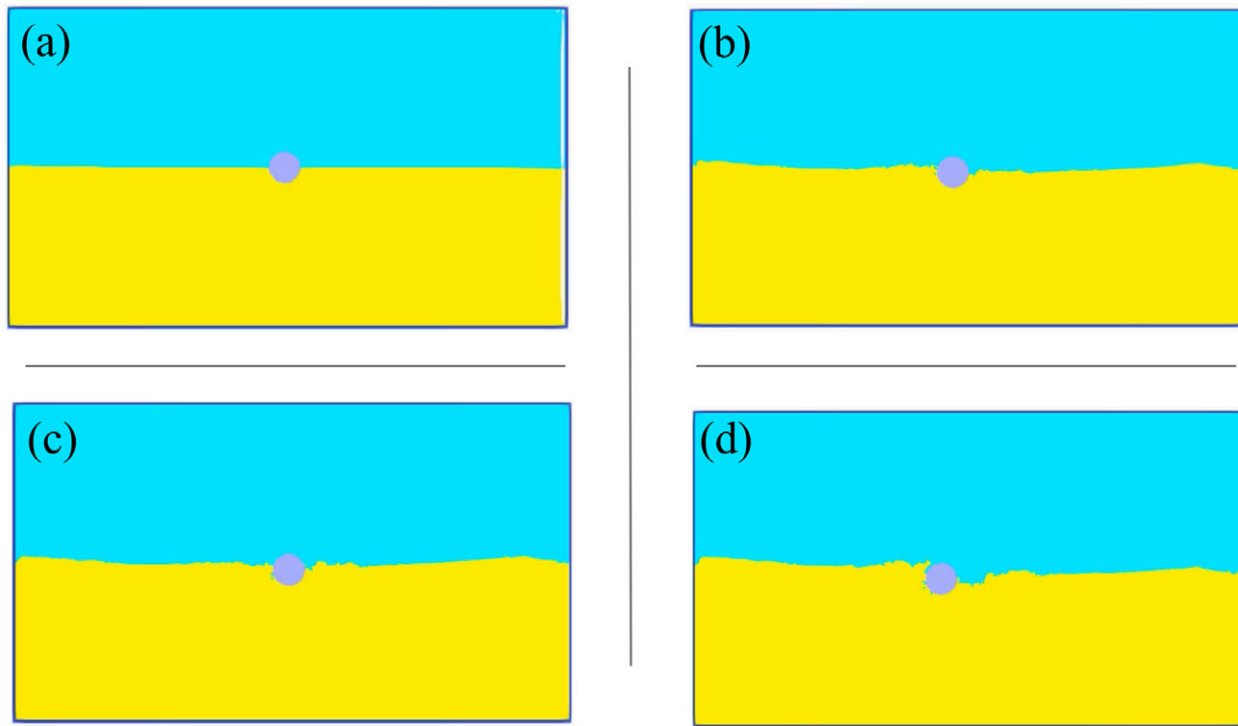


Figure 5.32: Munition motion under oscillatory shaking. Density ratios are $\rho_{munition}/\rho_{water} = 4.0$ and $\rho_{sediment}/\rho_{water} = 2.0$.

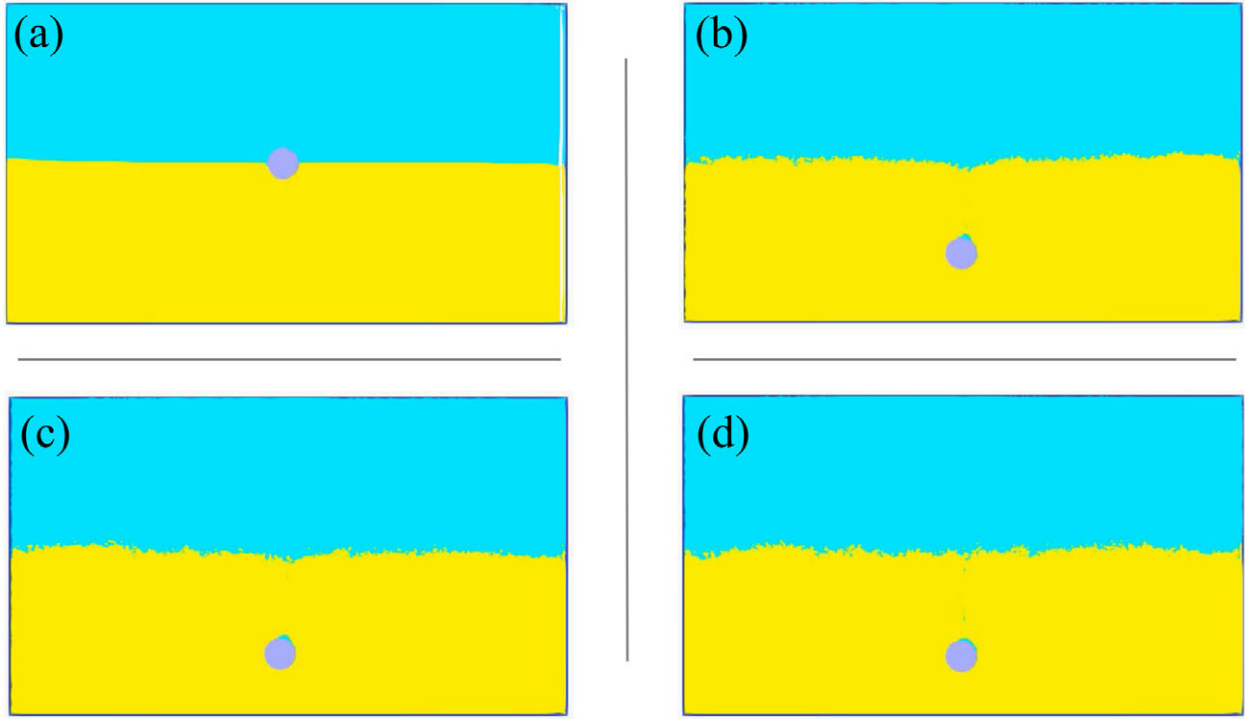


Figure 5.33: Munition motion under oscillatory shaking. Density ratios are $\rho_{munition}/\rho_{water} = 7.8$ and $\rho_{sediment}/\rho_{water} = 2.0$.

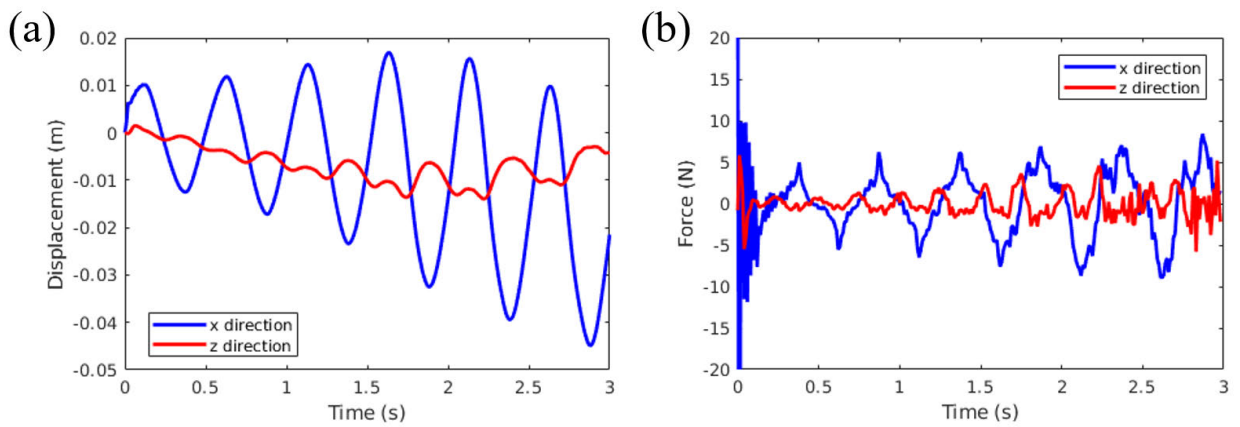


Figure 5.34: Munition displacement and forces under oscillatory shaking. Density ratios are $\rho_{munition}/\rho_{water} = 4.0$ and $\rho_{sediment}/\rho_{water} = 2.0$.

3D munition on sediment bed under oscillatory flow

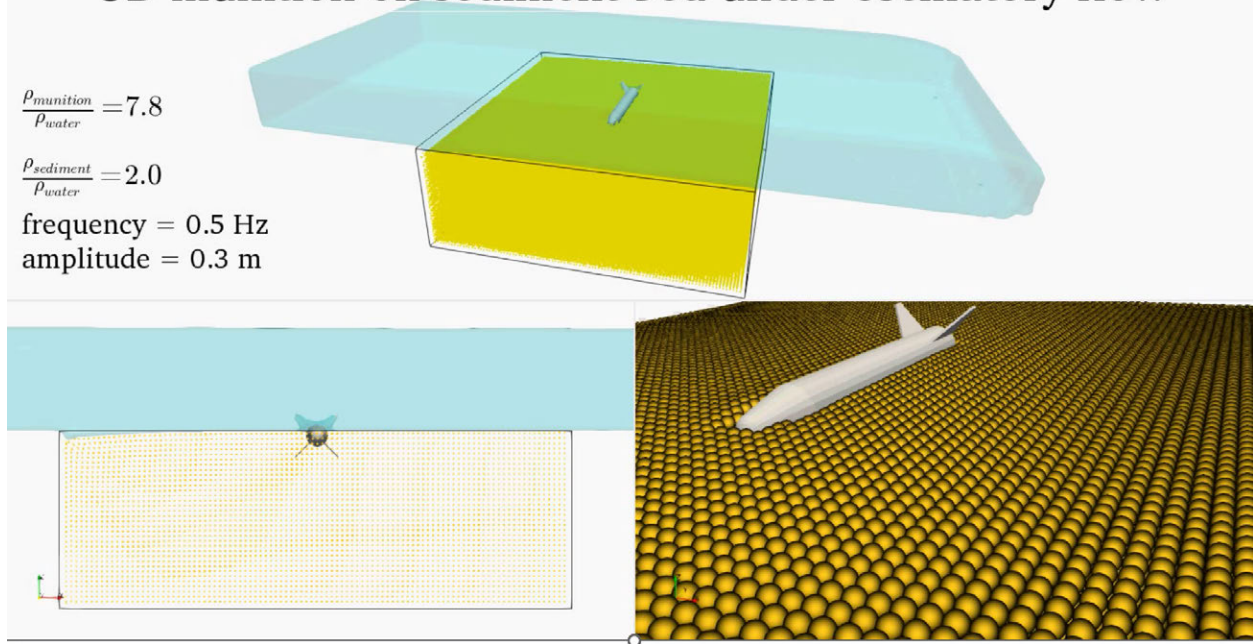


Figure 5.35: A real munition under oscillatory flow (at the start of simulation). Density ratios are $\rho_{munition}/\rho_{water} = 7.8$ and $\rho_{sediment}/\rho_{water} = 2.0$. The oscillatory flow's frequency is 0.5 Hz and the amplitude is 0.3 m.

3D munition on sediment bed under oscillatory flow

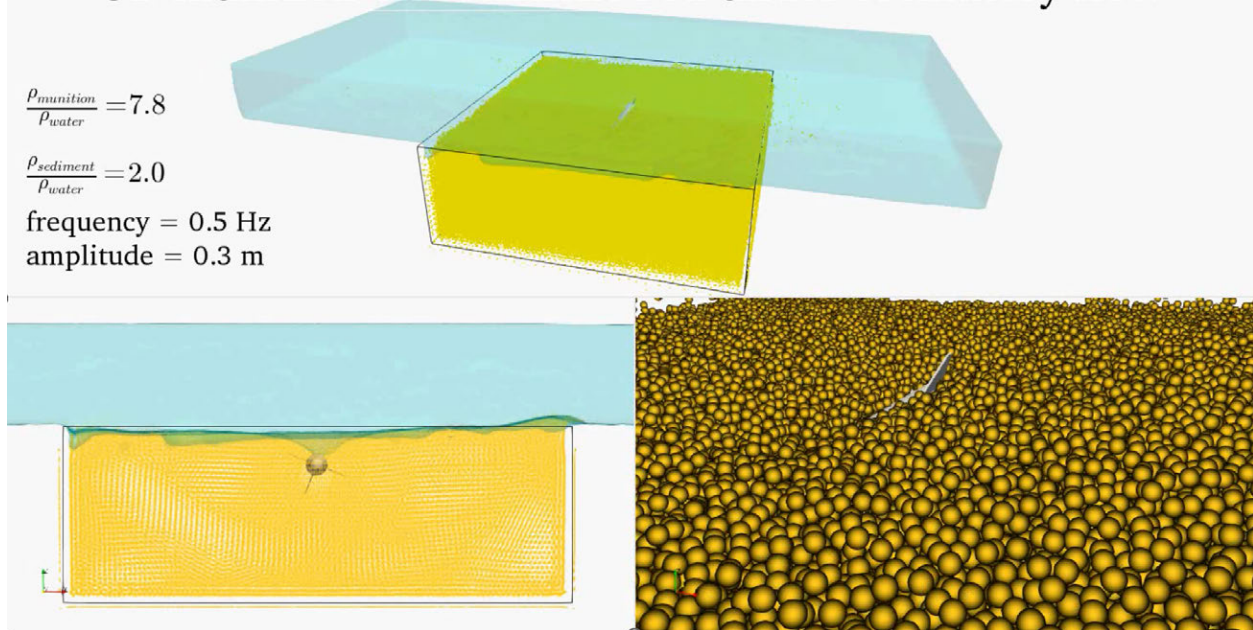


Figure 5.36: A real munition under oscillatory flow (at the end of simulation). Density ratios are $\rho_{munition}/\rho_{water} = 7.8$ and $\rho_{sediment}/\rho_{water} = 2.0$. The oscillatory flow's frequency is 0.5 Hz and the amplitude is 0.3 m.

group at the University of Delaware.

The case shown in this section is to simulate munitions on beach faces subject to dam-break type waves. The setup is similar to flume experiments done in MR-2503. The munition is simplified as a sphere and placed on sediment with some initial burial.

The goal here is to quantify the hydrodynamic forcing and mobility of munitions. The setup is relatively simple. In the flume, a sloped beach was constructed with sediment and a sphere was placed in the middle of the beach. Dam break wave was created by lifting a gate on the other end of the flume where initially a reservoir of water was held.

Figures 5.37 to 5.40 show four representative moments in the simulated process from the initial state, the moment that the wave impacts the sphere, the moment that the sphere starts to move, and the moment that the sphere is pushed to the end wall of the flume. It is interesting to observe that there is a lag between the impact of wave and the motion of the sphere. It means the mobilization of the sphere takes some time, not instantaneous.

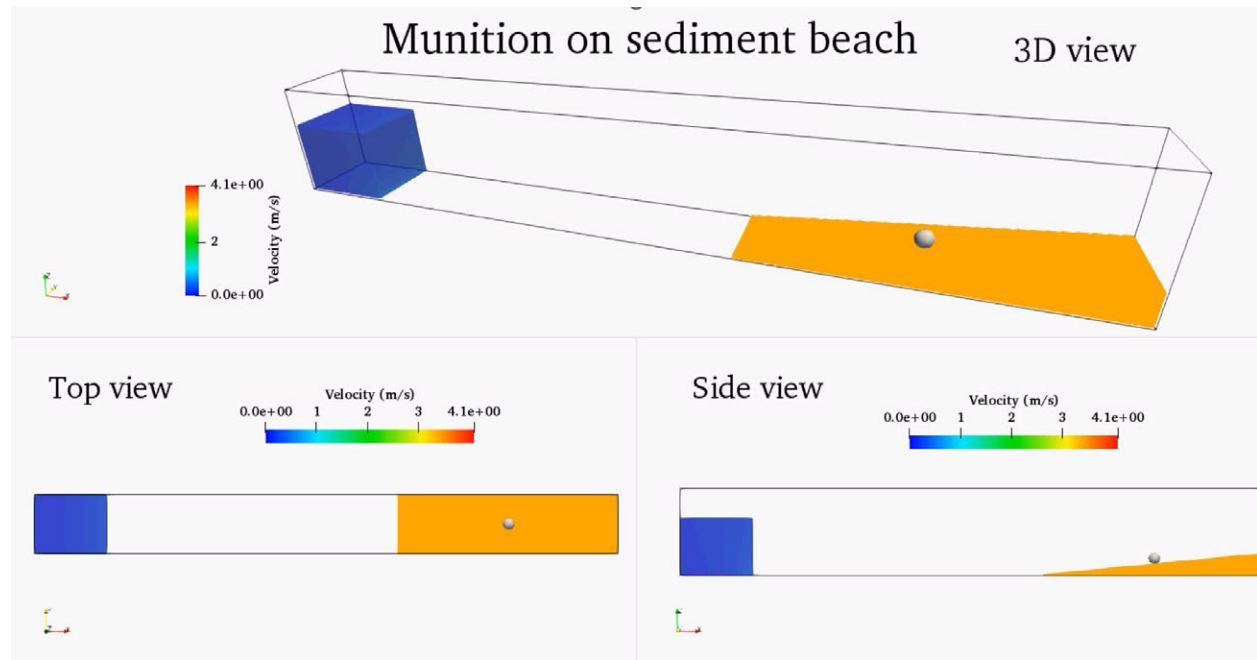


Figure 5.37: Munition on beach face subjecting to dam break wave (initial moment).

The value of the 3D SPH model is also reflected in the detailed force history on the munition. Figure 5.41 shows the simulated forces. In this plot, x is along the flume direction, y is the spanwise direction, and z is the vertical direction. The four representative moments shown in previous figures and their corresponding positions are also shown. Due to symmetry, the force along the spanwise direct F_y is almost zero. The motion of the sphere is mainly driven by the force in the x direction. From the figure, it is clear there are three spikes corresponding to the moments of initial wave impact, maximum wave force, and the impact against the end wall. Force analysis, in conjunction with simulated flow, helps us understand the whole process of munition movement.

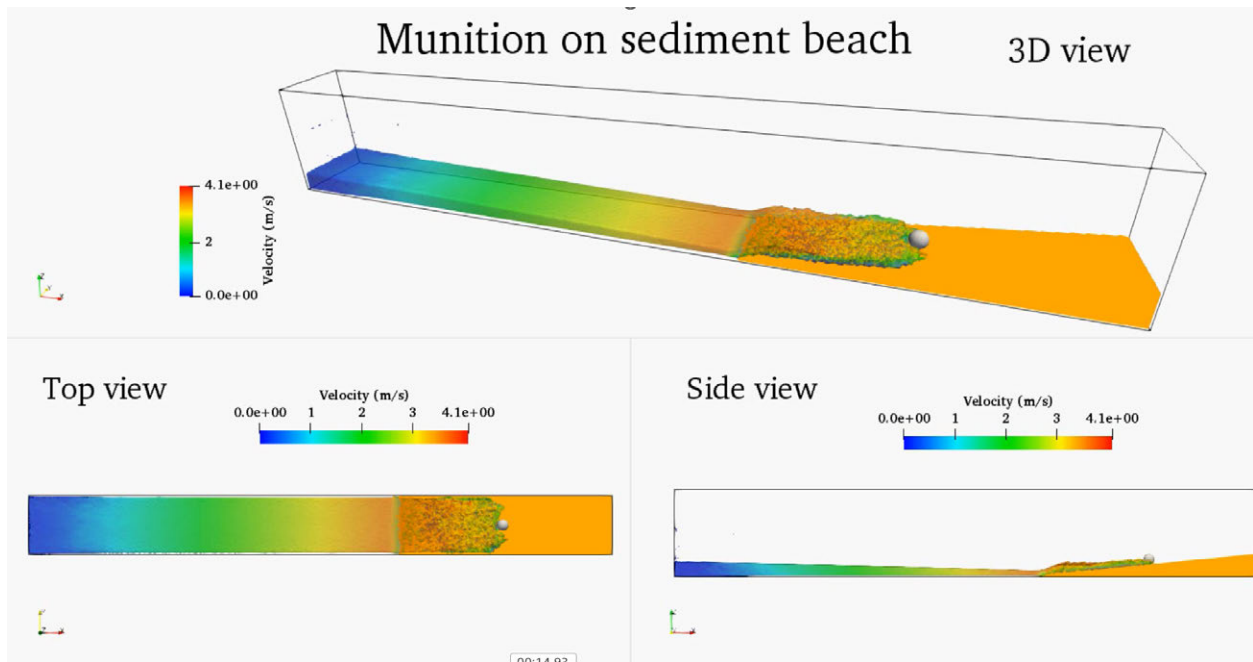


Figure 5.38: Munition on beach face subjecting to dam break wave (the moment when wave touches the sphere).

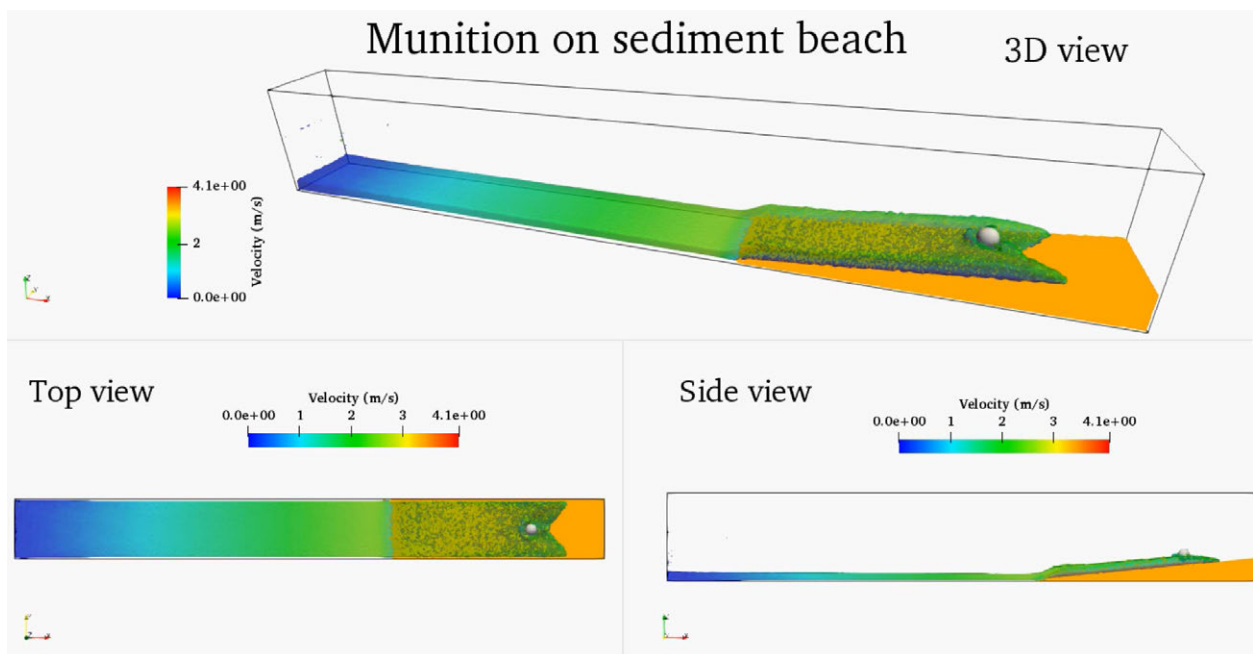


Figure 5.39: Munition on beach face subjecting to dam break wave (the moment when the sphere has already started to move).

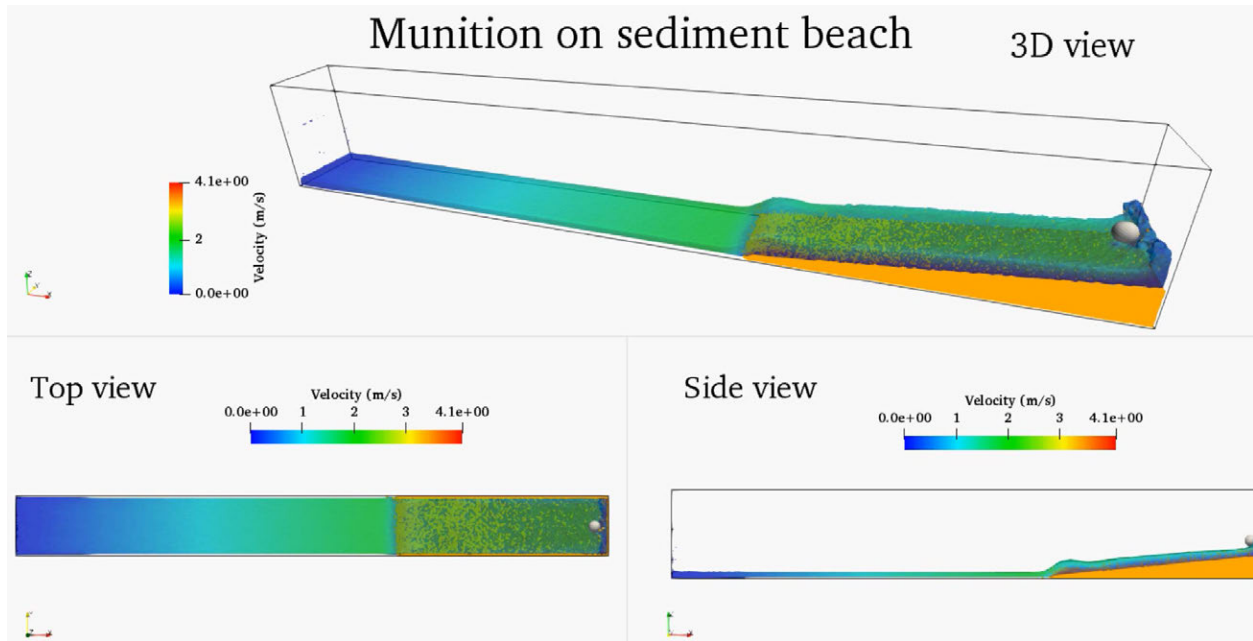


Figure 5.40: Muniton on beach face subjecting to dam break wave (the moment when the sphere has reached the end wall).

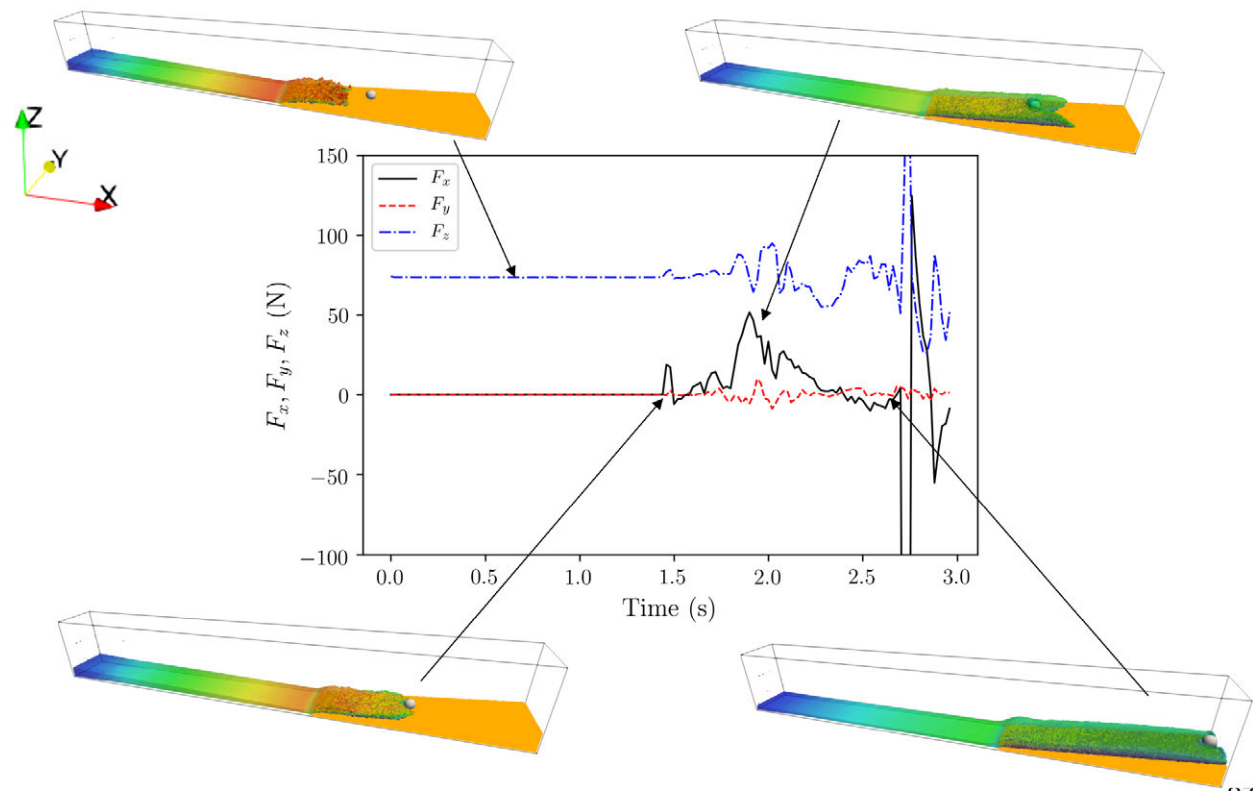


Figure 5.41: Force history on the munition placed on beach face subjecting to dam break wave. The four representative moments are also shown.

5.3.4 Effect of munition shape (fins)

This is another hypothetical case to show the capability of the 3D SPH model to capture the effect of fins on anchoring the munition and thus its mobility. Some UXOs has fins as part of its geometry. Geometry and shape of UXOs generally have great impact on their mobility because of their effects on hydrodynamics and sediment transport. In addition, the extruding part of UXOs, such as fins, can act as anchors and help reduce their mobility.

The setup of the simulation is similar to the previous case. A dam-break type wave was generated in a rectangular box where water is filled above the sediment bed. A munition with a tapered head and fins on the tail was placed on the sediment bed. The munition was initial slightly buried and part of the fins were anchored into the sediment. Figure 5.42 shows the initial setup of the case and Fig. 5.43 shows the moment when the dam-break wave overtops the munition. In addition to the water phase, the sediment phase is also plotted. It is clear from the figures that the wave not only mobilizes the munition but also the sediment. In addition, because of the anchoring effect, the tail part of the munition does not move while the tapered head part is pushed forward, resulting in a rotational motion of the munition. Similar behavior has been observed in flume experiments in other Munition Response Program sponsored researches.

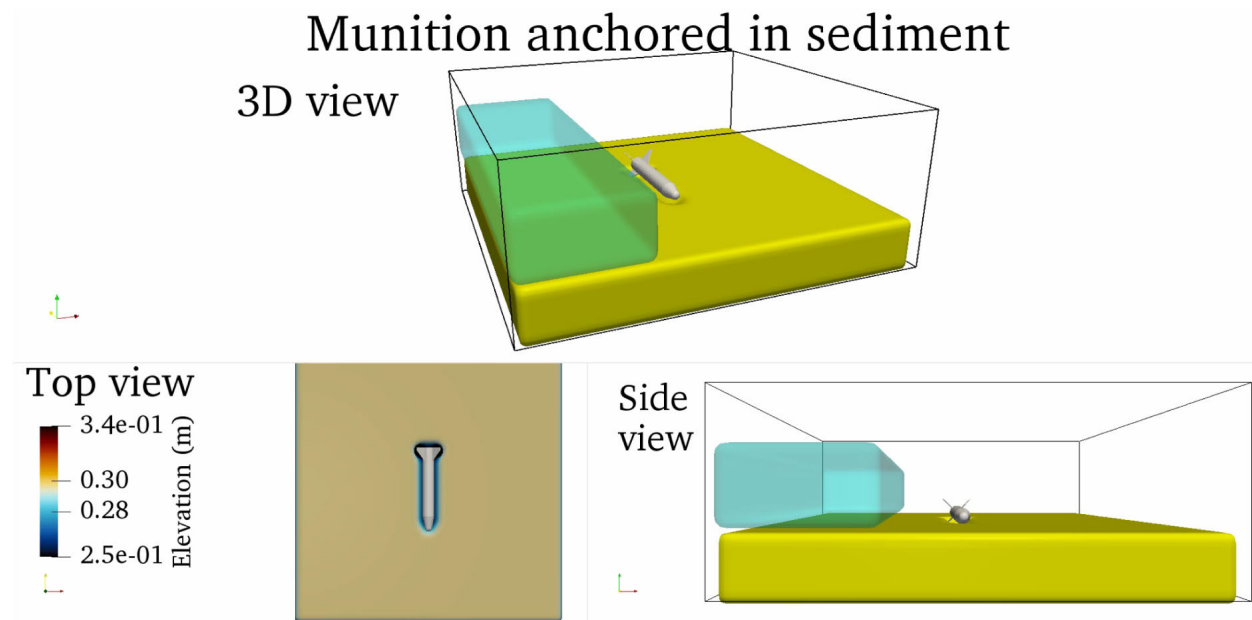


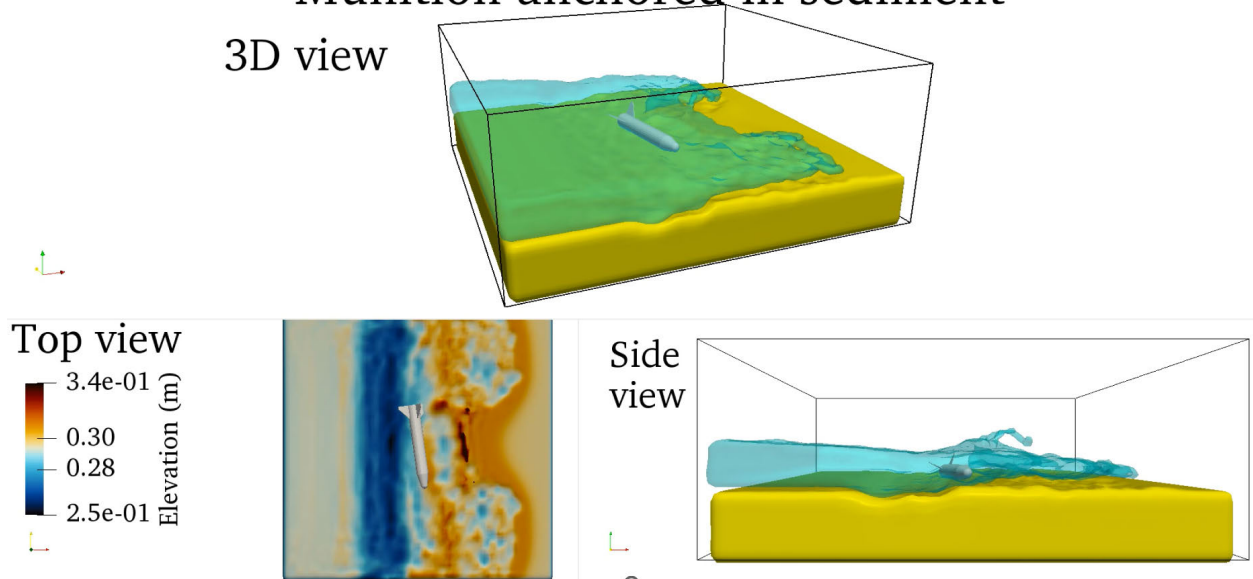
Figure 5.42: Anchoring effect of munition fins. Munition is subjected to dam break wave. The figure shows the initial setup.

5.3.5 Munition motion on hard substrate

The 3D SPH model does not need to have both fluid and sediment. Indeed, when munition is placed on hard substrate, such as bed rocks, the bed is not deformable. Thus, the system only contains flow and munition. To show the capability of the 3D SPH model for such scenarios, a hypothetical case was simulated which is similar to the previous case, except there is no sediment. The simulated results at three representative moments are shown in Figures 5.44 to 5.46.

Munition anchored in sediment

3D view



Top view

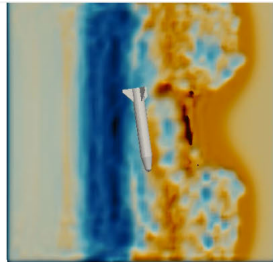
Elevation (m)

3.4e-01

0.30

0.28

2.5e-01



Side view

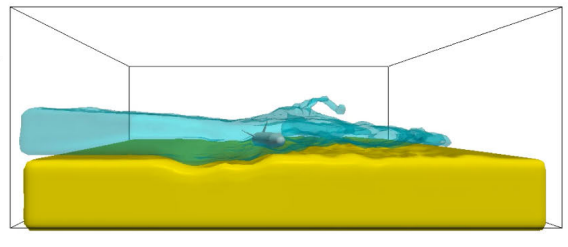


Figure 5.43: Anchoring effect of munition fins. Munition is subjected to dam break wave. The figure shows the rotation and anchoring of the munition due to the fins buried inside the sediment.

Munition on hard substrate

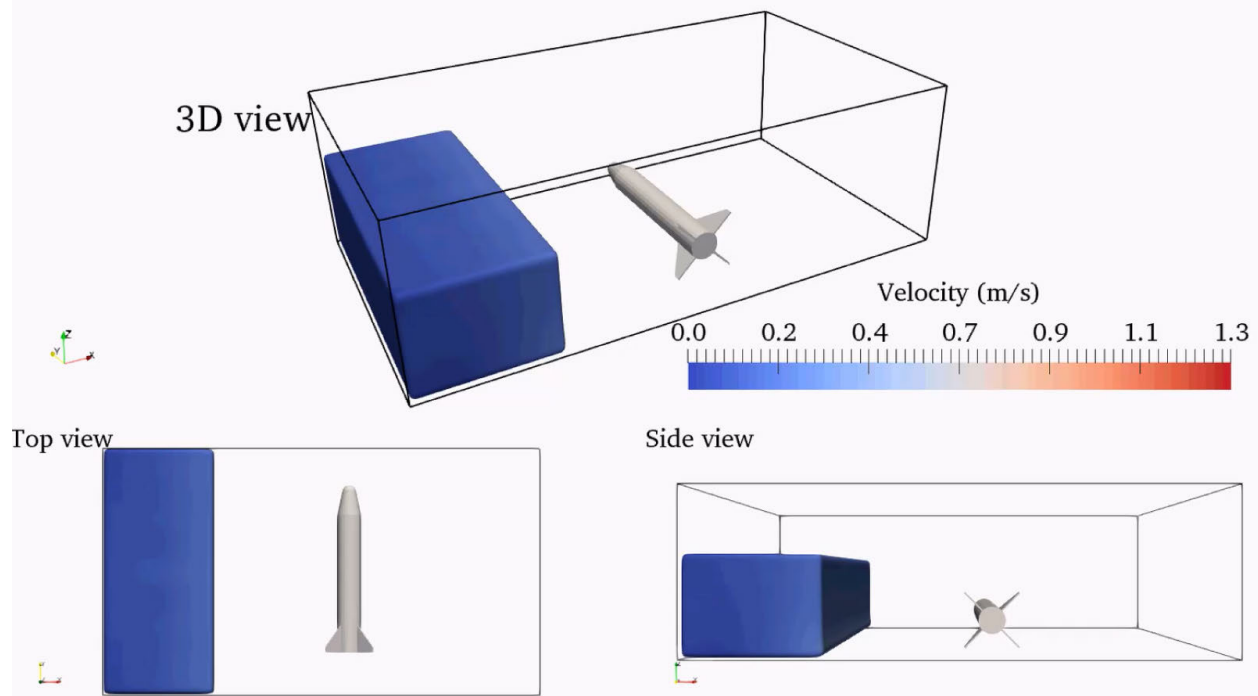


Figure 5.44: Munition motion on hard substrate (initial moment).

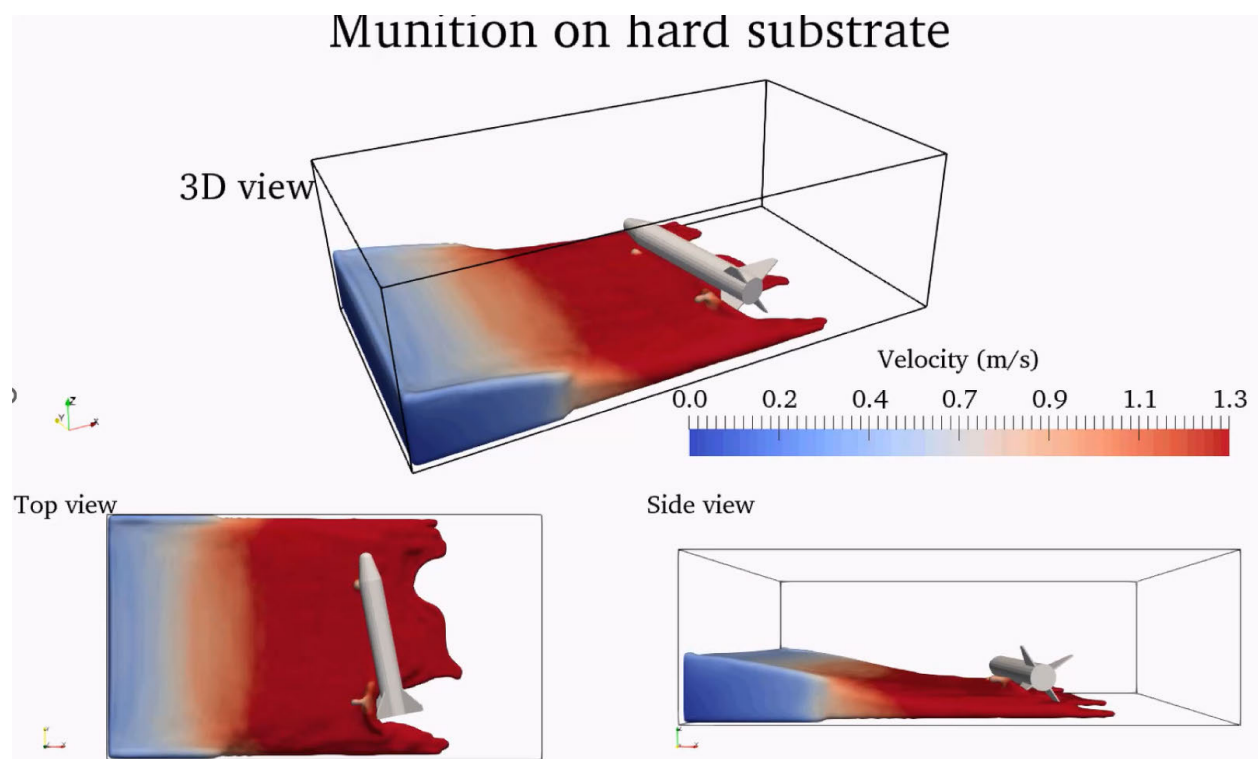


Figure 5.45: Munition motion on hard substrate (the moment when munition has already started to move).

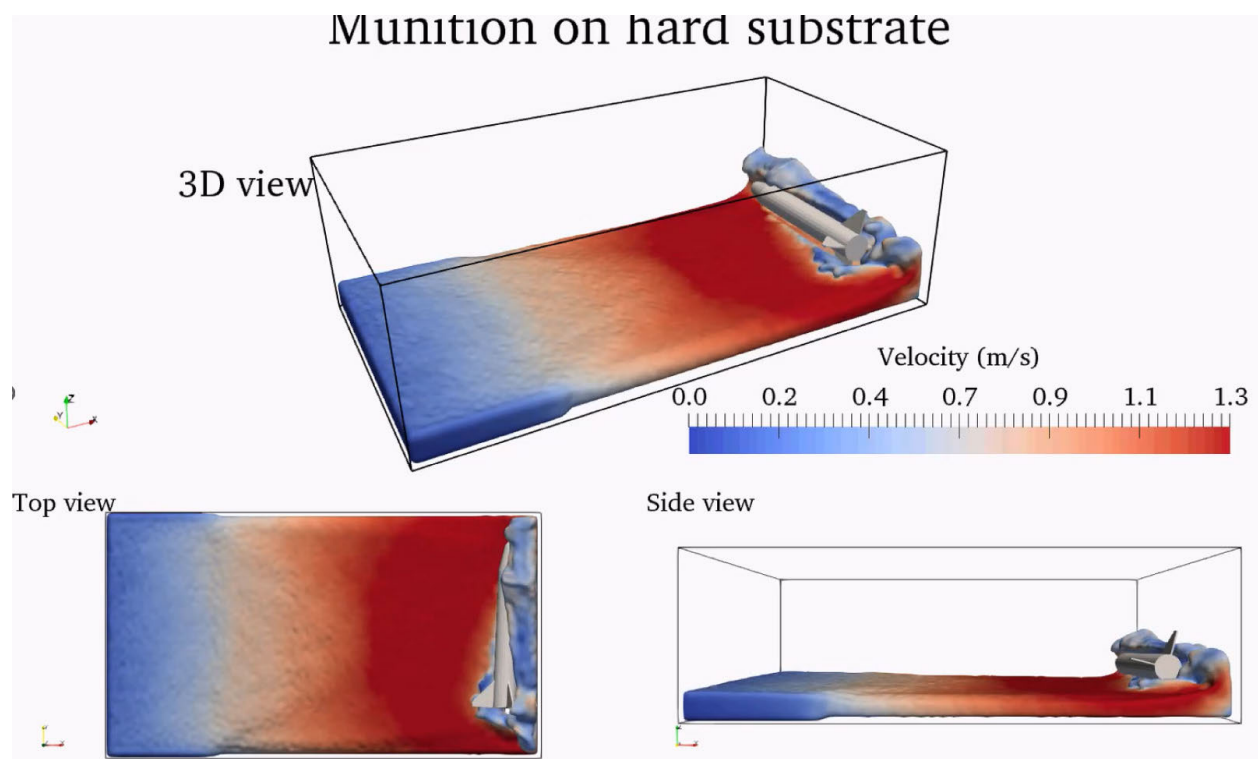


Figure 5.46: Munition motion on hard substrate (the moment when munition has been pushed to the end wall).

6 Conclusions and Implications for Future Research and Implementation

6.1 *Summary of results and conclusions*

This project started to develop and utilize high-fidelity computer models to capture the physical processes involved in underwater munition dynamics. Very little computational modeling work has been done before. The products of this project fill this gap. Specifically, two computer models, one for 3D scour and another for coupled fluid-munition-sediment dynamics, have been produced. With proper calibration, they can be used to investigate and reveal important physics that are critical for the fate of underwater UXOs.

During the development of the computer models, some new computing techniques have to be invented to overcome some weaknesses of existing methods. In particular, a new sand slide method was developed to correct the scour hole bed where the slope exceeds the angle of repose. This is because the physics and governing equations in traditional sediment transport theories do not fully respect the granular material dynamics. The second important invention is the use of a new immersed boundary method for scour modeling. Previous methods suffer from several drawbacks. For example, they may produce spiky and nonsmooth bed shear stress, which makes it almost useless for sediment transport modeling. The new immersed boundary method uses an adaptive strategy to produce accurate and smooth wall shear.

With the two new computer models, this project also investigated several aspects of munitions dynamics. Valuable physical insights and knowledge have been gained. With the 3D scour model, the effects of munition shape and flow angle of attack were studied. The results show that both play very important role. Dimensional analysis were performed and a new time scale for scour development was proposed to collapse the simulated data. The scaling analysis is useful to up-scale the results and make them useful for operational forecast. With the 3D SPH model, two application cases were studied. One is the penetrometer experiments where the dynamics of a penetrometer dropping into water and sediment was simulated. Key model parameters for the saturated sediment and their physical meanings were found. The second case is the movement of munition on beach face subjecting to dam-break type waves. Among many results, one key contribution is that the model can produce the force history on munitions. The force can be further decomposed into contributions by water and sediment. The force information is critical for the prediction of munition movement.

In conclusion, high-fidelity computer models are very valuable tools to our understanding of

the complex dynamics of underwater UXOs. With proper calibration, they can produce high quality results, which are hard to obtain otherwise. These computer models complement all other research efforts in the MR program.

6.2 *Implications for Future Research/Implementation*

Based on the current status of the two computer models and the results they produced, there are many areas for future work. These future researches should focus on improving the two computer models, adding more functionalities, and using them to investigate many other aspects of munitions dynamics which have not been studied in this project. These two models may also be used for selected field sites where data are available.

One important future work is for model improvement. The two computer models developed are very powerful. However, they have their limitations. For the 3D scour model, only bedload is currently considered and suspended sediment transport needs to be added. For the 3D SPH model, more reliable constitutive model for sediment should be added in future. Currently, the visco-elastoplastic multi-phase model for saturated sediment cannot correctly capture the full granular material dynamics. For example, the parameters have to be fine tuned case-by-case for the penetrometer and dam-break cases to match with experimental data. In addition, the visco-elastoplastic multi-phase model cannot properly capture the pore-pressure response and thus liquefaction is not possible to be modeled correctly. More advanced granular material model should be used in the future.

Munition mobility and movement involve many processes and variables. In addition to the variables studied in this project, there are many other important aspects that should be investigated in future:

- How do the bottom conditions (e.g., roughness and bedforms) affect the munition stability? In this project, the bed is assumed to be flat before scour hole develops. In natural environments, bedforms such as ripples may exist. How the bottom topography affects the whole process is worth studying both numerically and experimentally.
- This project already showed that the force acting on a munition changes dramatically over time. The force depends on munition shape, angle of attach, and degree of burial, among many others. It is definitely not correct to use constant drag and lift coefficients in large scale and long term models. However, it is not feasible to perform detailed 3D simulations in large scale models. This is very common in multiscale problems. One way to address this might be parameterization with many pre-simulated 3D cases.
- Another way to address the scale problem and quantify the uncertainties associated with the parameters is to combine deterministic and stochastic approaches. All the work in this project is deterministic. However, there are substantial uncertainties due to our limited knowledge on the UXO dynamics and our model limitations. Deterministic models can provide reasonable range of parameters and the general trend on how these parameters affect local and short-term response of the system. Stochastic approaches can utilize these information to improve their probabilistic predictions. A risk-based decision-making is

probably more meaningful for such a complex problem. For example, the prediction of munition movement should be an ensemble of trajectories like the hurricane prediction in weather models.

The computer models developed in this project can be very useful to leverage and collaborate with other researchers supported by the MR program. Indeed, although not in the scope of this project, we already collaborated with some of other PIs on for example penetrometer and munition mobility on beach faces. There are many possibilities for future researches. It is important that PIs in the MR program communicate more frequently and effectively. Both experimentalists and modelers have data and tools that may be useful to others.

From the perspective of “modelers”, there is a urgent need for high-quality data from experiments and field measurements carefully designed for model calibration. Previous researches have produced tremendous amount of data and they served their purpose. However, much of those data are hard to be used for modeling purpose. Without data, computer models cannot fully realize their values.

During the project, the PI was asked frequently about what the data needs are. The following is a partial list of what could be ideal purely from the point of view of a modeler. Some of them may be difficult or even impossible to do in the lab or the field. However, it is hoped that this list can generate ideas for additional future research.

- Munition object in oscillatory channel or wave tank. The munition can be fixed on a supporting structure or free to move. In this project, we have performed some preliminary experiments in an unidirectional flume where the munitions were fixed on a supporting structure. Similar work can be done in oscillatory channel or wave tank. It will be very valuable to measure flow and sediment movement, scour hole evolution, and force on object (using a load cell fixed to the supporting structure). Pressure sensors can also be embedded in sediment to measure pore-pressure as the system evolves.
- Munition shape effect. In this project, we have done simple comparison between a munition and an equivalent cylinder. The differences are quite big. More representative shapes can be selected to perform similar studies and build a library of munitions information for operational use.
- Measurement of lift and drag forces on different munitions with different orientation, percentage of burial, and scour hole development. Currently, constant lift and drag coefficients are used in large scale models, which is obviously not right.
- Munition object in combined wave and current. It seems that no previous work has been done on this. Previous work either focused on unidirectional flow or oscillatory flow. But in reality, munition could be subject to both wave and current. The flow and sediment dynamics, and the corresponding munition movement, may be significantly different.
- Interaction of a munition with a single sand dune wave. Sand dunes exist in many coastal environments and they migrate. Sand dune movement may bury or expose a munition object. One can imagine that munition could be carried forward by a dune as it migrates, or the munition may stay. A hypothesis is whether a munition will be carried by a migrating dune depends on its density and length scale in comparison with dune height and length.

Appendices

A Supporting Data

The following computer code and data are produced from this project. They are archived, made available online or upon reasonable request from the PI.

- 3D scour model *ibScourFoam* - <https://github.com/psu-efd/ibScourFoam>:
 - source code developed using the open source platform OpenFOAM
 - all scour simulation cases
- 3D SPH model
 - source code modified from the open source code DualSPHysics
 - all simulation cases

B Results for the New Sand Slide Method

This section demonstrates the use of the slope-limited diffusive sand slide method with two cases: one is the collapse of a sand column under no flow condition and the other is the scour around a cylinder in unidirectional flow.

B.1 Collapse of sand column under no flow condition

Numerous factors, such as flow condition, boundary condition, grain size and density, sand slide, can affect the result of a scour simulation. To separate the effect of sand slide, the diffusive sand slide model was used to study the collapse of a sand column without flow as shown in Fig. B.1. The column had a radius of $r_0 = 5$ cm and a height of $h_0 = 6$ cm. The angle of repose was set at 35° ($\tan \phi_0 = 0.7$). Under the influence of gravity, the sand column will collapse and form a cone-shaped pile. The resulting bottom angle of the pile should be approximately equal to the angle of repose.

To show the sensitivity of the method to mesh types, this case was tested with four different meshes as shown in Fig. B.2 (a), (b), (c), and (d). The average cell size for all meshes was $\Delta x \approx 0.5$ cm. The first mesh consists of equal size squares (named “Square mesh”). The rest three meshes are all made of triangles (named Triangle mesh “1”, “2”, and “3”). And the triangles in the three meshes are of similar size. However, “Triangle mesh 1” is more “unstructured” with irregularly paved triangles. In contrast, “Triangle mesh 2” and “Triangle mesh 3” are more “structured” with equal-size triangles. The main difference between “Triangle mesh 2” and “3” is the orientation of the triangles. The purpose of such arrangement is to show the mesh dependence of the sand-slide algorithm if the gradient scheme is not suitable. The time step was set as $\Delta t = 0.001$ s. This time step size was set arbitrarily small to ensure numerical stability ($\Delta t / \Delta x^2 \leq 1 / (2K_0)$). Because there was no flow and thus no sediment transport, the diffusivity constant K_0 cannot be determined with the scaling equation in Eq. 4.7. Instead, K_0 and Δt should satisfy the constraints on numerical stability and efficiency. For this case, the K_0 value was set as $0.001 \text{ m}^2/\text{s}$. This sand slide method is not sensitive to the values of K_0 and Δt such that other combinations satisfying the numerical constrain also produce similar results.

Figure B.3 (a), (b), (c), and (d) show the final contours of piles after the sand column collapses with the LGS scheme on four different meshes. The horizontal coordinate x and y are made dimensionless with the initial radius r_0 . The bed elevation z_b is made dimensionless with the initial height h_0 . Except for “Triangle mesh 1”, the sand piles with all other three meshes are distorted. Fig. B.4 presents the dimensionless profiles and mean slopes S_0 of these sand piles.

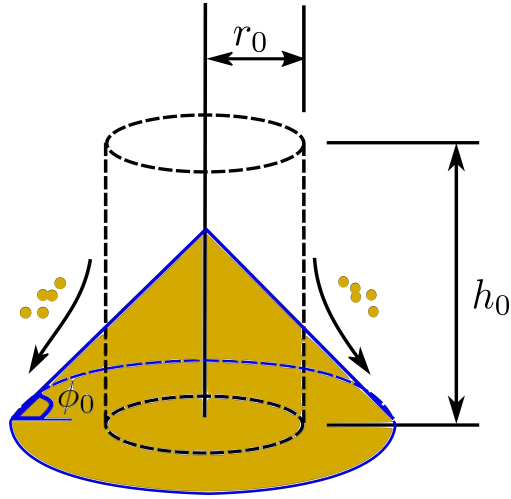


Figure B.1: Schematic view of the collapsing sand column case.

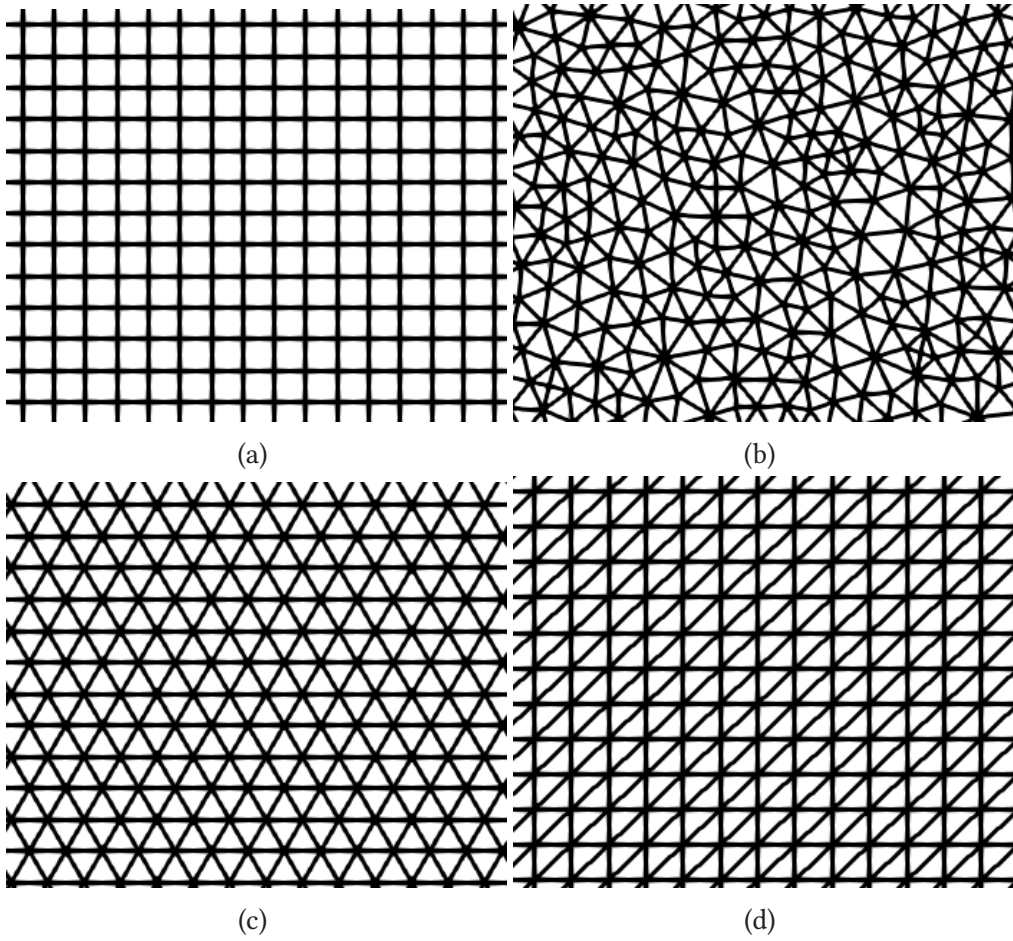


Figure B.2: Four meshes used in the collapsing sand column case: (a) Square mesh, (b) Triangle mesh 1, (c) Triangle mesh 2, (d) Triangle mesh 3.

Because of the distortion, the profiles depend on where the slice is cut. Here, the plotted profiles in Fig. B.4 are sliced at $y = 0$ cm.

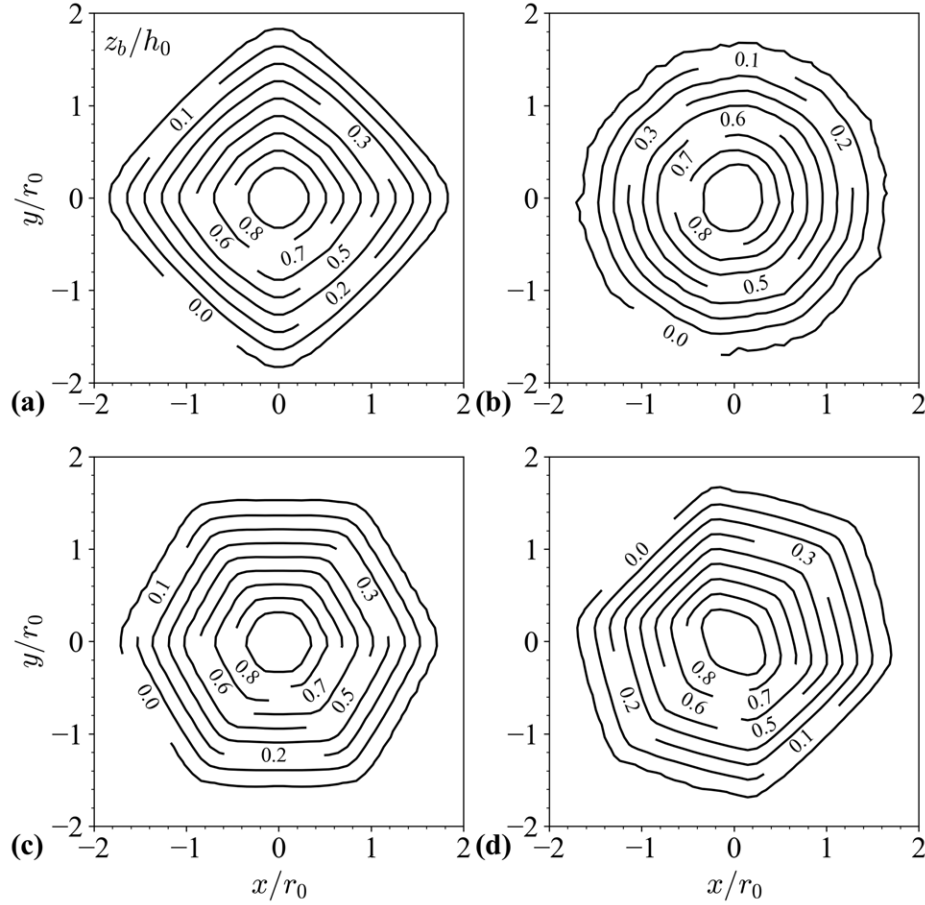


Figure B.3: Final contours of the sand piles with different meshes. LGS was used. (a) Square mesh, (b) Triangle mesh 1, (c) Triangle mesh 2, and (d) Triangle mesh 3.

The problematic distortion shown in Fig. B.3 is caused by the use of LGS in the conditional function of Eq. 4.4 for the calculation of diffusivity K . Assuming the bed angle in the neighborhood around cell P exceeds the angle of repose, then sand slide will be triggered (Fig. B.5). In reality, the sand slide flux will be axisymmetric with no preferential directions for this sand column case. However, on a discrete mesh, the axisymmetric sand slide process will be broken with LGS. This is explained as follows. The cell P has two types of neighbors. One is those sharing one common edge, denoted as N_i in Fig. B.5. The other is those sharing one node, denoted as D_i . In real axisymmetric sand slide process, there should be no difference between the two types of neighbors in terms of receiving sand from cell P . However, in the finite-volume discretization, the direct sand slide flux exchange only happens between cell P and the neighbors N_i , not D_i . The sand movement between cell P and the neighbors D_i is indirect through the neighbors N_i . For example, sand will slide from cell P to its neighbor N_1 . As a result, the elevation of N_1 will increase and consequently increase the bed slope between cells N_1 and D_1 . The sand slide flux between cells N_1 and D_1 will not happen until the bed slope between them exceeds the angle of repose. Thus, there is a time lag between when the real sand slide starts and when the diagonal cell D_1

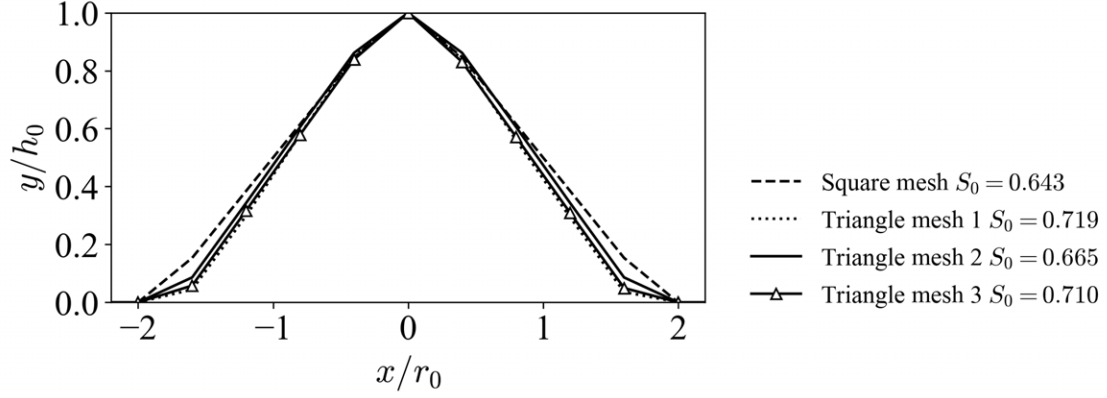


Figure B.4: Final profiles of the sand piles with different meshes. LGS was used. S_0 is the mean slope of each profile.

can receive any sand flux. As a result, the axisymmetry of the sand pile cannot be maintained. This is the reason that severe distortion is observed in the results. The distortion is less severe in results with “Triangle mesh 1”. This is because the cells are randomly paved with no preferential direction. So on average, the sand pile develops in approximately axisymmetrical fashion.

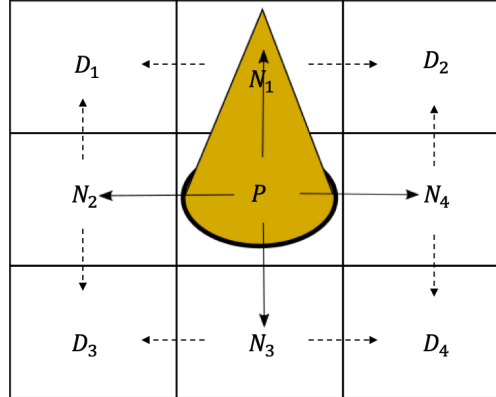


Figure B.5: Illustrative sketch of sand slide process. Sand will slide firstly from cell P to its neighbouring cells N_i following the solid-line arrows. This increases the elevation of N_i . Then, sand will slide from cells N_i to diagonal cells D_i if their elevation difference is such that the bed angle exceeds the angle of repose.

To solve the distortion problem caused by the numerical time lag, this work proposes the use of GNGS to calculate the bed slope in Eq. 4.4. This scheme utilizes the elevation information on an expanded stencil as shown in Fig. 4.3. Specifically, when calculating the elevation gradient on the edges between cells N_i and the diagonal cells D_i , the elevation of cell P is also used. In this way, the higher elevation of P will result in higher gradient at these edges and then trigger the sand slide through them earlier. As a result, the process of sand slide toward the diagonal cells D_i will be accelerated and thus it is closer to reality.

Using GNGS, Fig. B.6 (a)(b)(c), and (d) show the resulted elevation contours with the four different meshes. The final profiles and slopes S_0 of the sand piles are shown in Fig. B.7. It can be observed

that the resulted contours on all meshes are similar and they keep the symmetry without distortion. The fitted final slopes are in the range of 0.62 to 0.68, which are all close to but below the slope of repose.

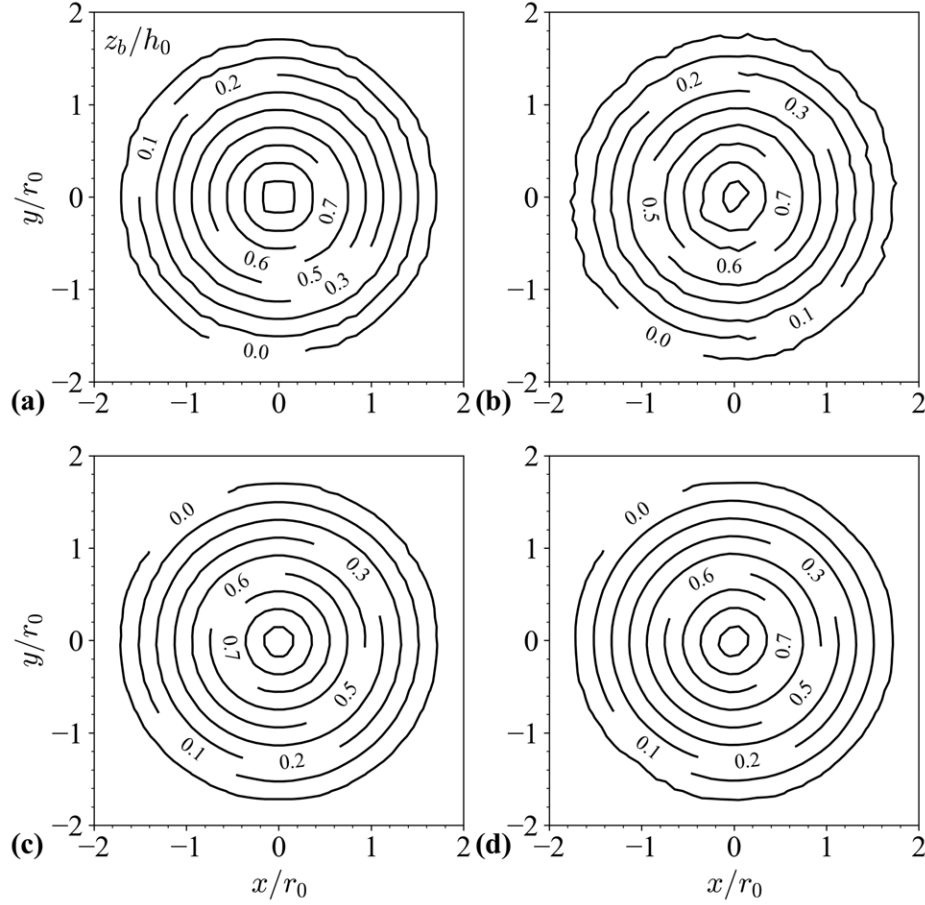


Figure B.6: Final contours of the sand piles with different meshes. GNGS was used: (a) Square mesh, (b) Triangle mesh 1, (c) Triangle mesh 2, (d) Triangle mesh 3.

Although GNGS can greatly alleviate the distortion caused by LGS, it has some limitations. With GNGS, some residual faces may still have slopes larger than the angle of repose. This is mainly because of the inconsistency between GNGS for bed slope evaluation in Eq. 4.4 and the linear discretization of bed elevation gradient when solving Eq. 4.6. As a remedy, the combined use of GNGS and LGS is proposed, which combines the benefits of GNGS and LGS. In this combined method, GNGS is used as the main scheme and LGS is only used at the end to remove residual faces.

Table B.1 shows the comparison among different sand slide schemes, which include LGS, GNGS, and the combined GNGS+LGS. In addition, the geometric sand slide method in Khosronejad et al. (2012) is also compared. A convergence criterion of 10^{-9} m for bed elevation change was used. The sand column collapse case was simulated. The simulations were performed on a Dell Precision Tower 5810 with an Intel Xeon CPU ES-1620. Overall, the comparison shows that the diffusive sand slide method runs faster than the geometric method, especially with GNGS and

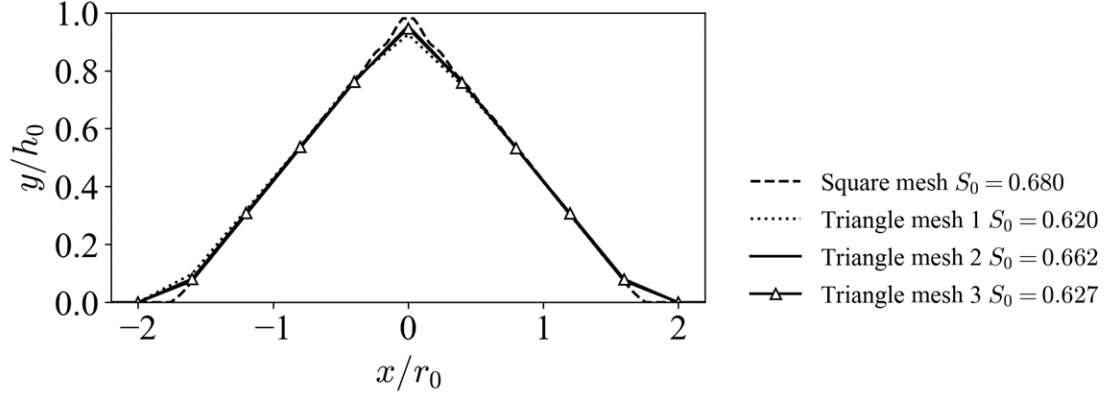


Figure B.7: Final profiles of the sand piles with different meshes. GNGS was used.

GNGS+LGS. In addition, the geometric method can not totally get rid of the residual faces. Despite the severe distortion, LGS has no residual face problems. On the other hand, GNGS has some small number of residual faces, which can be totally rid of with the combined GNGS+LGS scheme.

Table B.1: Efficiency and residual faces of sand slide methods. Here, t is computing time, N is total face number, p is the percentage of faces whose slopes are larger than the angle of repose.

Mesh type	t & p	Geometric method			
		(Khosronejad et al., 2012)	LGS	GNGS	GNGS+LGS
Square mesh	t	1.4 s	2.66s	5.6 s	2.77s
$N = 50880$	p	1.2%	0%	0.09%	0%
Triangle mesh 1	t	2.38s	1.7s	3.34s	2.23s
$N = 29840$	p	2.47%	0%	0.09%	0%
Triangle mesh 2	t	7.89s	4.24s	5.16s	5.38s
$N = 78236$	p	2.43%	0%	0.01%	0.01%
Triangle mesh 3	t	6.42s	5.47s	5.7s	5.49s
$N = 81779$	p	2.37%	0%	0.005%	0%

B.2 Scour around a cylinder in unidirectional flow

The scour around a cylinder case in Roulund et al. (2005) is a popular case for scour model validation. It is also used in this work. The turbulent flow was simulated with the Reynolds-Averaged Navier-Stokes (RANS) model. In particular, the $k-\omega$ SST (Shear-Stress Transport)-based Scale-Adaptive Simulation (SST-SAS) model was used and the details can be found in Egorov and Menter (2008). For the simulation case, although the sediment transport is in the live-bed regime, the suspended load is insignificant. Similar to Roulund et al. (2005), only the bedload transport was considered in the simulation and the bedload transport formula in Engelund and Fredsøe (1976) was used.

For this case, GNGS+LGS was utilized where GNGS was used at the beginning of each sand slide step until semi-equilibrium. Then, LGS was used if there were remaining bed faces exceeding the angle of repose. The case was also simulated with only LGS in the sand slide model and its results were compared with those from the combined GNGS+LGS scheme. The case was simulated for about 100 minutes after which the bed remained unchanged.

The channel had a water depth H of 20 cm and the mean velocity U of 46 cm/s. The cylinder's diameter D was 10 cm. Figure B.8 shows the setup of the simulation. The simulation domain's length, width, and height were 230 cm, 120 cm, and 20 cm, respectively. The mesh was refined near the surfaces of cylinder and bed. The resulted mesh size ranged from 0.6 cm to about 4 cm with a total of about 1 million cells. All parameters of the case are listed in Table B.2. In the scour experiment reported in Roulund et al. (2005), the measured skin friction velocity u_τ is about 2.8 cm/s. Thus, the corresponding roughness height is estimated to be about 0.5 cm based on the flow resistance estimator in Chen et al. (2019).

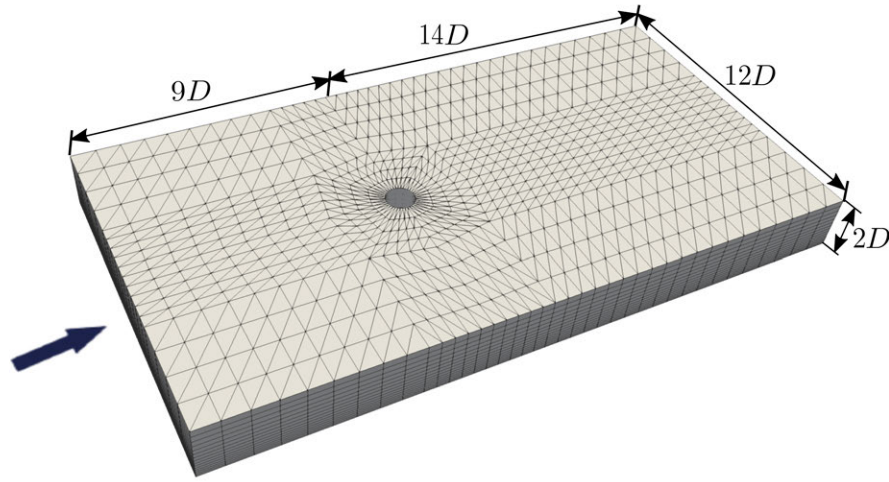


Figure B.8: Mesh for the simulation of 3D scour around a pile. Approximately every fifth cell is shown for clarity.

Figure B.9 (a) and (b) show the evolution of the scour depth at the upstream side and the downstream side of the cylinder. The scour depth z_b is made dimensionless with the cylinder diameter D . Both LGS and GNGS+LGS produced similar scour processes which agree with the experiment. In particular, the equilibrium depths on both upstream and downstream sides were well predicted. There is some difference between the two schemes during the scour process, especially at the downstream side. Nevertheless, both schemes show slight overprediction of the scour rate at the beginning. And then there was a sudden large sand slide event at about $t = 20$ minutes. From the analysis of the scour result, this was induced by the accumulation of sediment at the edge of the scour hole. With time, the accumulation induced large bed slope and consequently triggered the massive sand slide. This sudden failure of bed within a scour hole has been observed in many lab experiments (Ettema et al., 2011). Further deepening of the scour hole undermines the slope within and causes episodic avalanches of sediment to the bottom. Then, the flow gradually sweeps sand away from the bottom of scour hole and the cycle continues. Even though the nu-

Table B.2: Simulation parameters for scour around a cylinder

Water depth H (cm)	20
Mean flow velocity U (cm/s)	46
Cylinder diameter D (cm)	10
Skin friction velocity u_τ (cm/s)	2.8
Roughness height k_s (cm)	0.5
Grain size d_{50} (mm)	0.26
Critical Shields number θ_{cr}	0.05
Angle of repose ϕ_0	32°
Diffusivity K	0.0005
Mesh resolution (cm)	$0.6 \sim 4$
Mesh size	1.08 millions

merical results from Roulund et al. (2005) well predicted the scour process at the initial stage, the final scour depths at both upstream side and downstream side are underestimated compared with numerical results from this work and the experiment, especially at the downstream side.

Figure B.10 compares the scour hole profiles from numerical simulations and experiment. A perturbation was added in Roulund's model to trigger the bed ripples such that their profile has waves at upstream and downstream of the cylinder. Overall, the shapes from all numerical results agree well within the scour hole. The agreement for the upstream part is excellent except a slight underestimation of scour depth in Roulund's numerical result. The simulated upstream scour hole profiles have slopes of about 29° , which are close to the angle of repose (32°). The predicted downstream side of the scour hole is slightly flatter than that in experiment. This might be due to a number of factors, including the turbulence model used to resolve the wake. Further improvement can be made to use a more advanced turbulence model suitable to capture the wake dynamics, especially the wall shear in the wake zone behind the cylinder. In general, it can be concluded that the 3D scour model with the new sand slide method can capture the overall process of the scour around a cylinder.

For this case, the maximum bedload transport rate $|\mathbf{q}_0|_{max}$ was in the range of $10^{-4} \text{ m}^2/\text{s} \sim 10^{-3} \text{ m}^2/\text{s}$. Thus, the constant K_0 in the conditional Eq. 4.4 should have the same order of magnitude as $|\mathbf{q}_0|_{max}$ and was set to be $0.0005 \text{ m}^2/\text{s}$. This constant was used during the whole simulation. In comparison with the sand column collapse case in the previous section where massive sand slide happens everywhere in the domain, the sand slide process only happens sporadically. On average, these locations with sand slide occurrence are concentrated near the scour hole. For example, Fig. B.11(a) shows a snapshot of the bed elevation adjustment δz_b due to sand slide at the early stage of the scour process. It is observed that the sand slide induced bed change is mainly within the scour hole. For each face on the bed, the total occurrence of sand slide during the whole simulation was recorded and shown in Fig. B.11(b). Again, the result shows that the most active region of sand slide is within the scour hole where the morphodynamics is most active. There are other regions on the bed where sand slide seems to be activated frequently, such as the inlet. This is due to the fact that at the inlet the bed elevation was fixed in order to stabilize the entrance (similar to Roulund et al. (2005)). This imposed fixation created some

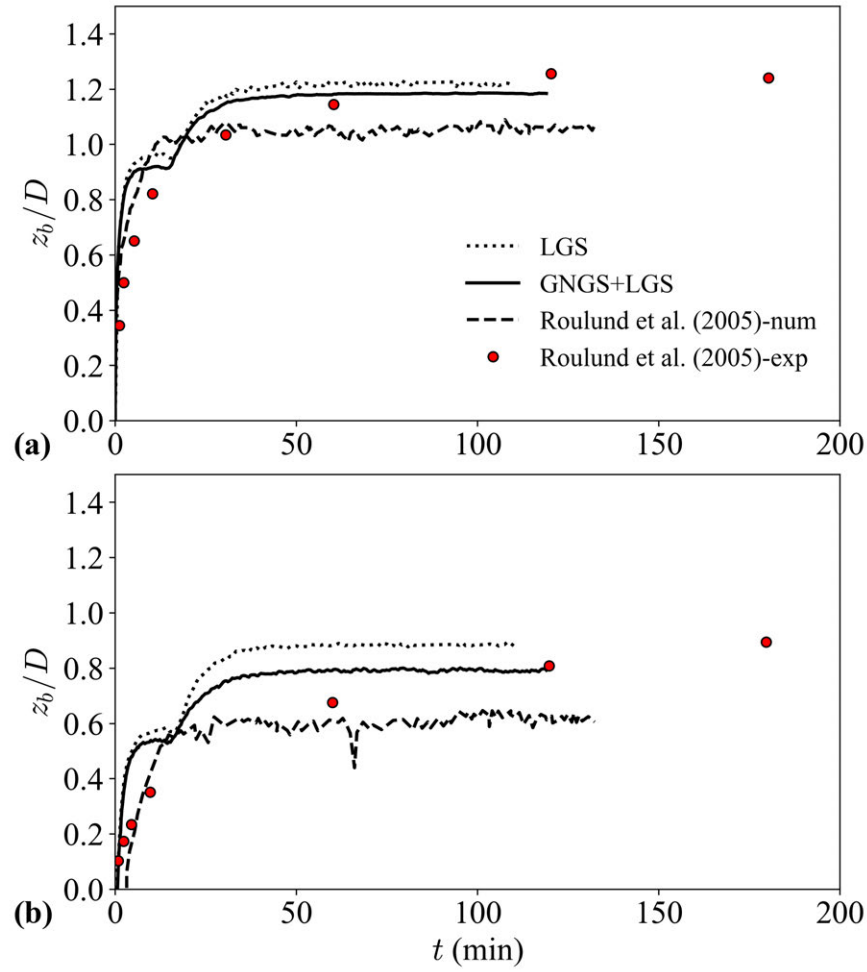


Figure B.9: Scour depth evolution around a cylinder in unidirectional flow: (a) Scour depth at the upstream side of cylinder. (b) Scour depth at the downstream side of cylinder.

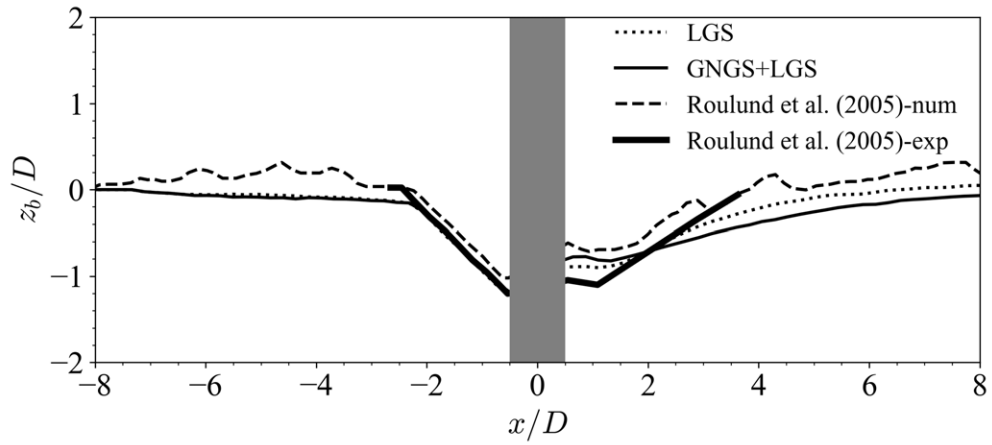


Figure B.10: Equilibrium scour profile on the vertical slice of the domain.

artificial disturbance to the sediment dynamics and thus sand slide was triggered to smooth out the disturbance.

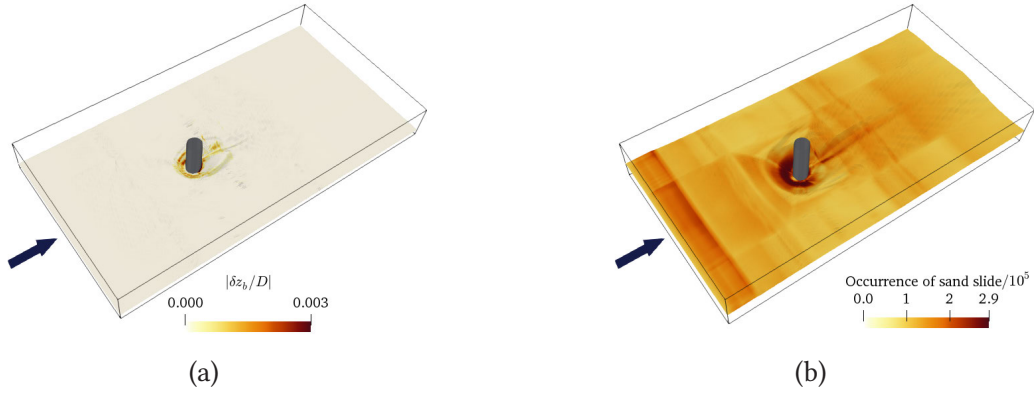


Figure B.11: Sand slide in the 3D scour model: (a) A snapshot of the bed adjustment due to sand slide showing the active region within the scour hole. (b) Total occurrence of sand slide on each face of the bed mesh.

The contours of the final bed elevation simulated with both LGS and GNGS+LGS are shown in Fig. B.12. As expected, the final bed with LGS is asymmetric due to the distortion, especially in the wake region. In addition, the bed contours upstream of the cylinder are not smooth. In contrast, the resulted bed with the combination scheme is symmetric and the contour lines are much smoother. This shows that the scheme for the calculation of gradient in the sand slide model is of great importance. It affects the scour process and the final hole morphology.

It is worth to note that the sand slide flux in this case is less significant than the massive slide flux in the previous sand column collapse case. Therefore, the use of LGS may be acceptable if one compares Fig. B.12(a) and (b). The difference between the two is not significant. However, if frequent sand slide happens with large magnitude during the simulation, the combination scheme should be used.

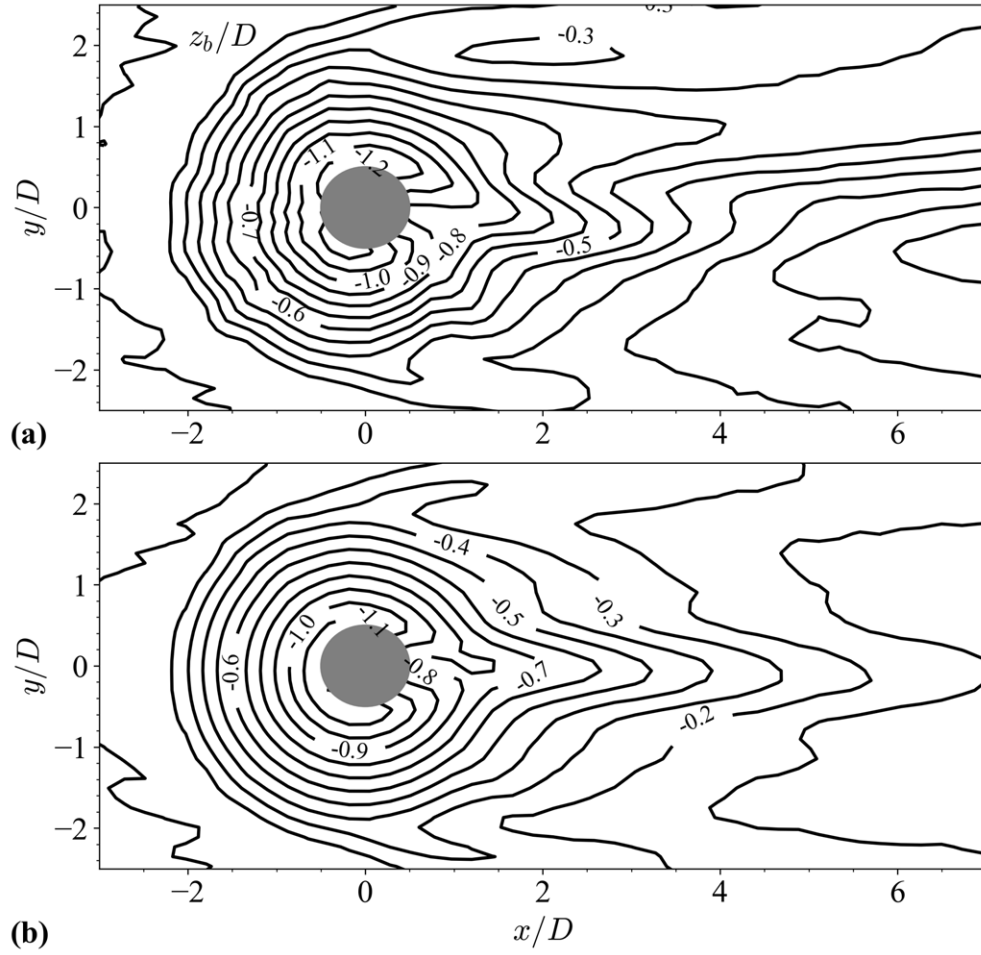


Figure B.12: Contours of bed elevation (z_b/D) at equilibrium for the scour around cylinder case:(a) with LGS. (b) with GNGS+LGS.

B.3 Discussion on the sand slide method

Based on the physics of sand slide during scour process, a new sand slide treatment method in scour models was proposed in this work. The foundation of the new method is that the sand slide process is of diffusive nature, which has been long recognized in geomorphology. The sand slide flux is proportional to elevation gradient when the bed slope exceeds the angle of repose, which results in a slope-limited diffusion equation for bed elevation. The key to the new method is a proper numerical scheme for the calculation of bed elevation gradient which is used to evaluate the conditional function of the diffusivity K . Two schemes, LGS and GNGS, were tested. LGS has severe limitations because of the resulted distortion in bed elevation. This distortion is caused by the time lag between the physical time and numerical time for a sliding sand particle to travel from a computational cell to its diagonal neighbors. The distortion is also mesh dependent. GNGS can greatly alleviate this problem by using a larger stencil for the gradient evaluation such that the resulted bed slope is more accurate and contains the information of the computational cell where the sliding sand is originated from. In addition, the redistribution of sliding sand using GNGS is mesh independent.

The new sand slide method and the schemes were implemented in a 3D scour model (which is similar to the 3D scour model developed in this project, but not using the immersed boundary method) and applied to two simulation cases. One case was the collapse of a sand column where massive sand slide happened. The other case was the scour around a cylinder where sand slide happened but was much less significant. For the first case, four different types of meshes were used. The result showed that LGS greatly distorted the final sand pile shape and did not preserve the symmetry of the pile. GNGS improved the result and kept the symmetry of the pile during the collapsing process but some residual faces may still have slopes larger than the angle of repose. The combined use of GNGS and LGS is proposed to improve the efficiency and accuracy of sand slide, and to remove the residual faces. The symmetry of the pile is still preserved because GNGS is used as the main scheme. For the second case, the simulated 3D scour hole development process agreed well with experiment. For this case, since the sand slide was not significant, both LGS and GNGS+LGS gave reasonable final scour depth. However, the scour hole shape from LGS was slightly distorted and not symmetric. Thus, it is recommended to use GNGS+LGS in practice.

Finally, the comparison with previous methods does not suggest any criticism. It is merely for the sake of scientific investigation and shedding some light on the strength and weakness of each method. The comparison results were based on our implementation of geometric method, which may not capture its full details.

C Validation, Verification and Demonstration of the 3D Scour Model

This section will show the validation, verification, and demonstration of the new 3D scour model based on the immersed boundary method, *ibScourFoam*, which can capture the scour process around objects with complex geometries.

C.1 Validation case

This section shows a 3D validation case of flow and scour around a vertical circular pile reported in Roulund et al. (2005). The flow and scour parts are validated separately in the following. The cases shown in this chapter are small-scale problems. Due to the parallel computing capability, large scale applications are feasible given sufficient computing power.

C.1.1 Flow around a vertical pile mounted on a rigid bed

A vertical circular pile is placed on a rigid and flat bed in steady flow as shown in Figure C.1. The bed is modeled as an immersed boundary. The validation is mainly focused on whether the model can capture the main flow features which are responsible for scour. The main features are the horseshoe vortex upstream of the pile and the lee-wake vortex downstream. Two cases were validated. The first is with a smooth bed and the second is with a rough bed. Experimental conditions are listed in Table C.1.

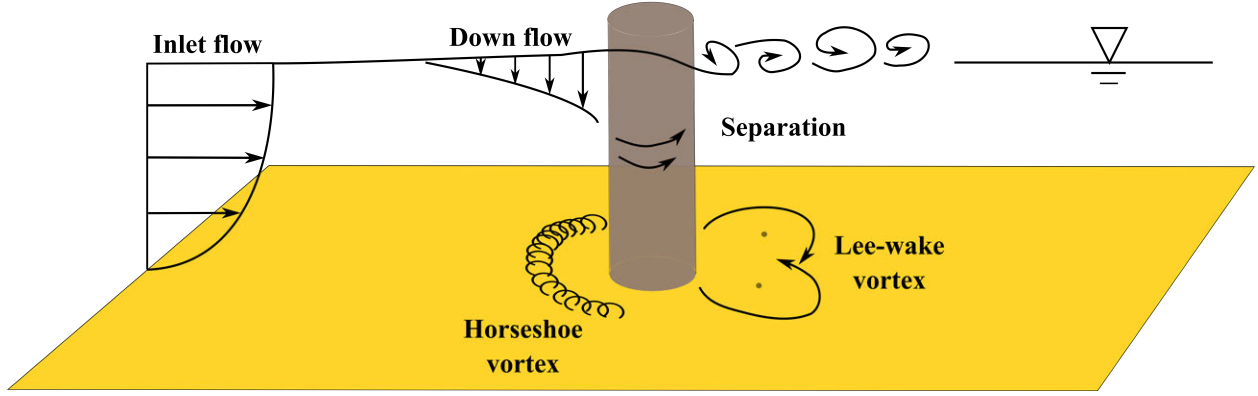


Figure C.1: Schematic view of flow around a vertical circular pile.

Table C.1: Simulation conditions for flow around a vertical circular pile on a rigid bed reported in Roulund et al. (2005).

Parameters	Values
Water depth H (cm)	54
Mean flow velocity U (cm/s)	32.6
Pile diameter D (cm)	53.6
Roughness height k_s (cm)	0, 1.0
Hydrodynamic time step Δt_h (s)	0.005

Figure C.2 shows the mesh used. The mesh conforms to the pile, i.e., the pile is part of the background mesh boundary. On the other hand, the bed is modeled as an immersed boundary. This arrangement is optimal because the pile is stationary thus not necessary to be modeled as an immersed boundary which is computationally more expensive. The length, width, and height of the domain are $9D$, $5D$, and $1D$, respectively. Here, D is the pile diameter. The mesh has about 7 million cells and is refined near the cylinder, bed, and in the downstream region to better capture the flow structure. The smallest cell size is approximately 1 mm near the cylinder and bed. The largest cell is approximately 50 mm in size near the inlet and outlet. The maximum dimensionless wall distance for the IB cells, $y_{IB_{\max}}^+$, is approximately 13 and 30 for the smooth and rough bed cases, respectively.

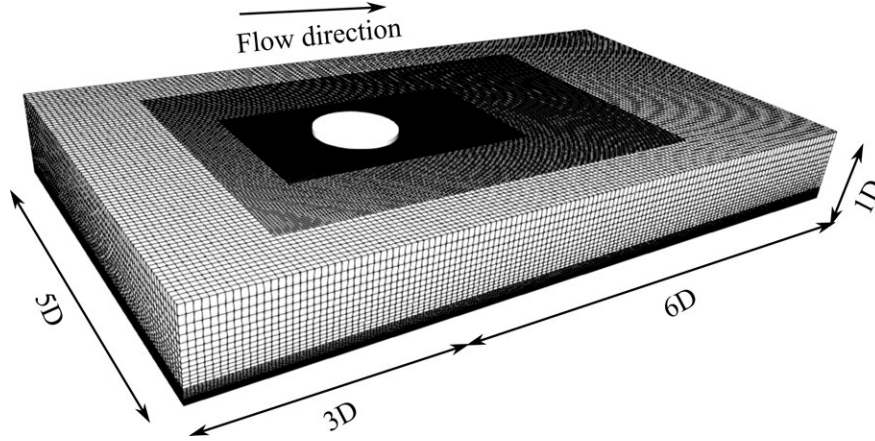


Figure C.2: Schematic view of mesh used for flow around a vertical circular pile on a rigid bed.

In addition to the immersed bed, the boundary conditions are as follows for the rest of the domain, which include inlet, outlet, two sides of the channel, top surface, and the pile surface:

1. At the inlet, profiles for velocity, k , and ω were mapped from a pre-simulated channel flow with no pile.
2. At the outlet, the Neumann boundary conditions were used for all flow variables except the pressure, which was set to zero.
3. The two sides were treated as symmetry boundaries.
4. The shear-free rigid-lid approximation was used for the free surface.
5. The pile surface was modeled as a smooth, rigid wall.

Figures C.3 and C.4 show the streamwise velocity at different elevations in the plane of symmetry. The red dots and green dashed lines in the figures represent the experimental measurements and numerical results, respectively, from Roulund et al. (2005). The blue lines represent the results of this work. All the simulations ran for at least 300 s. This is equivalent to approximately 20 flow through time which is defined as the domain length divided by the average velocity. This ensured the simulations reached steady state. Then, the simulations were run for more than 100 s (about 7 flow through time) to calculate the mean flow variables. The horseshoe vortex manifests itself as the negative value of the streamwise velocity (pointed to the upstream direction) near the bed (see Figures C.3 and C.4). The comparison is satisfactory and the immersed boundary method captures main flow dynamics well.

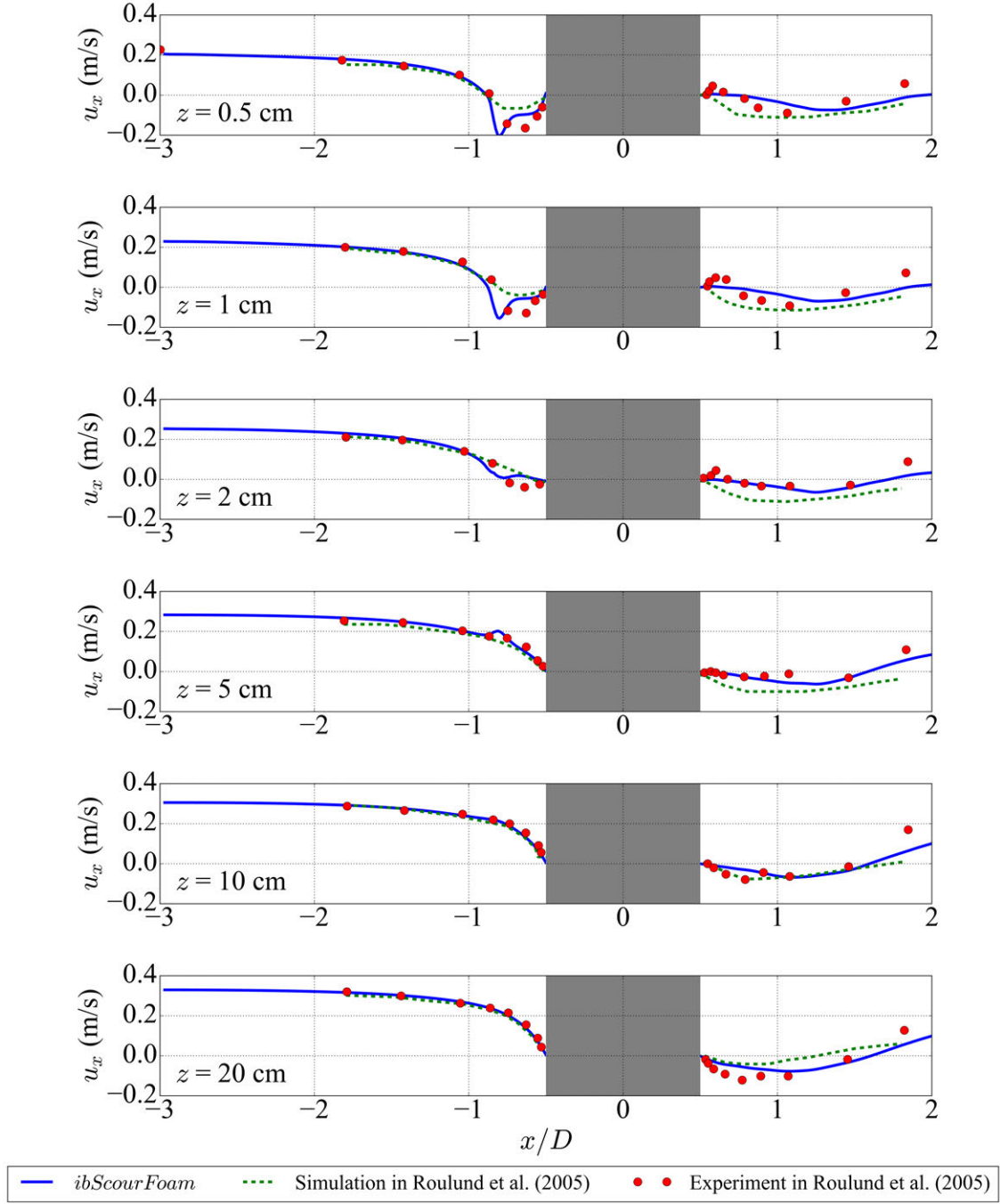


Figure C.3: Streamwise velocity, u_x , in the plane of symmetry at different elevations for the smooth, rigid bed case.

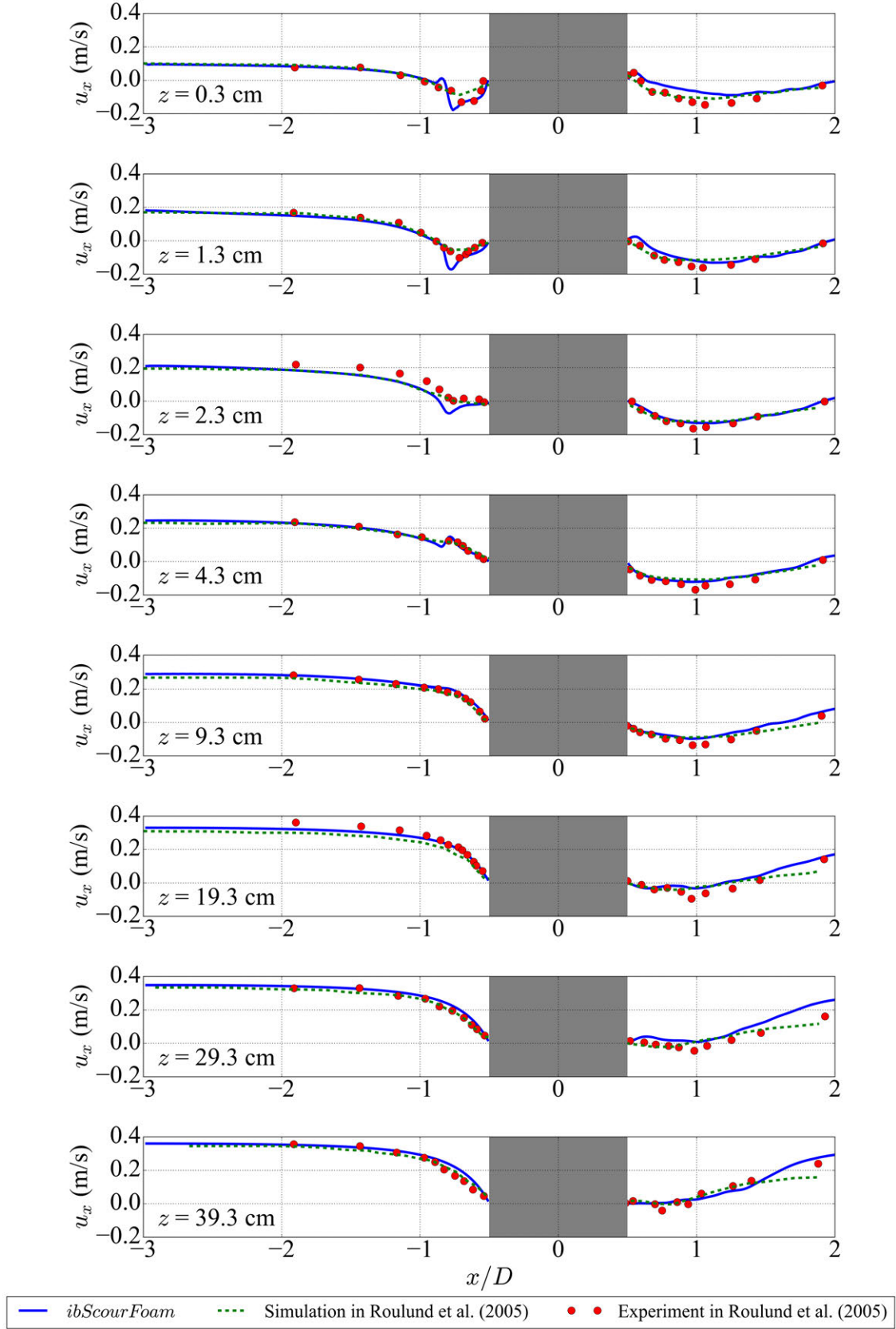


Figure C.4: Streamwise velocity, u_x , in the plane of symmetry at different elevations for the rough, rigid bed case.

On the downstream side of the pile, the experimental measurement in Roulund et al. (2005) showed an anticlockwise circulation in the smooth bed case, and a clockwise circulation in the rough bed case. These circulations are relatively weak and are difficult to capture by numerical models. For example, the simulated circulation in Roulund et al. (2005) was clockwise for the smooth bed case. In our work, the immersed boundary method correctly captured the circulation directions for both smooth and rough bed cases as shown in Figure C.5 (a) and (b). In addition, the prediction of the downstream velocity was improved in this work (see Figure C.3). One possible reason is that a more refined mesh was used in this work, in comparison with only 0.2 million cells used in Roulund et al. (2005).

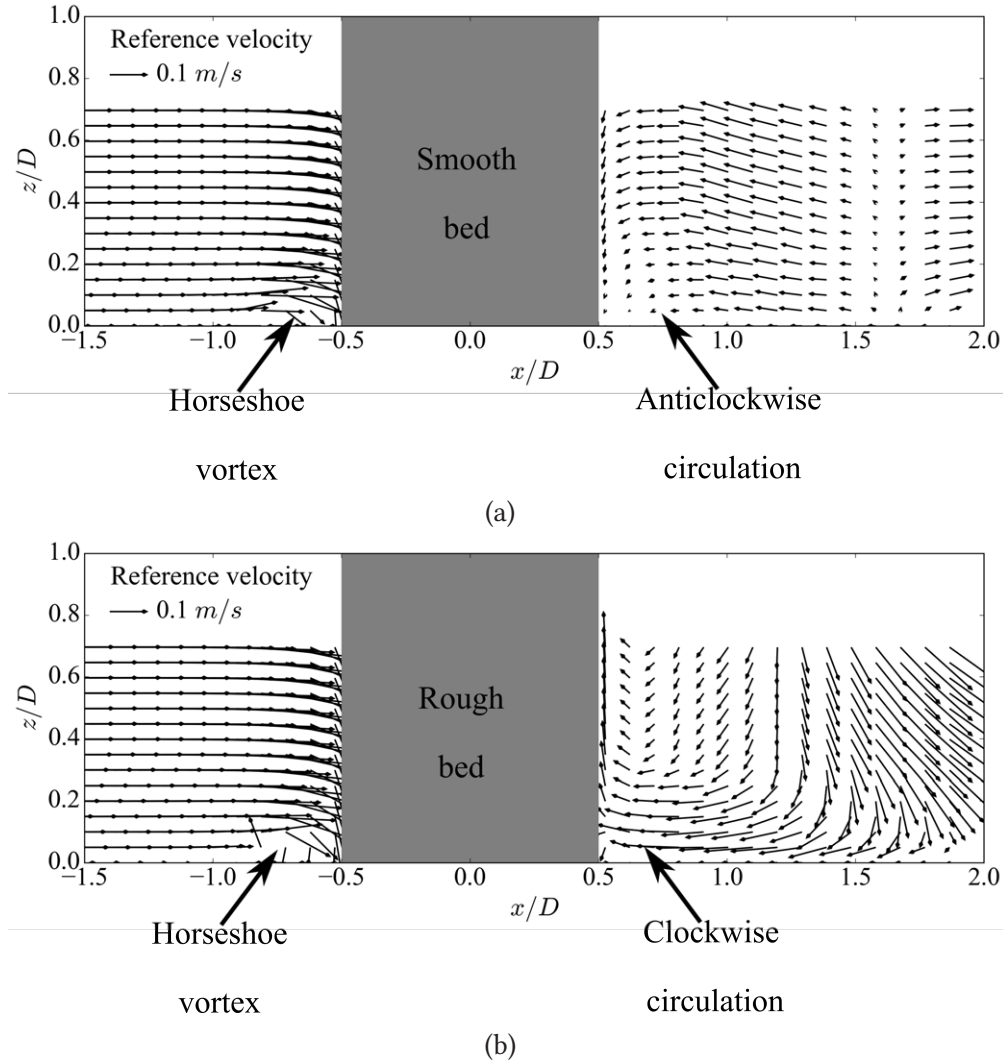


Figure C.5: Velocity field in the plane of symmetry: (a) Smooth bed (b) Rough bed.

Figure C.6 shows the comparison of the bed shear stress amplification τ/τ_0 along the x -axis in front of the pile between simulations and the experiment for the smooth bed case. The negative value is due to the horseshoe vortex which makes the shear pointing upstream. In general, the comparison is acceptable given the dynamic nature of the horseshoe vortex and uncertainties in

measurement data. Both simulations in this work and Roulund et al. (2005) under-predicted the magnitude of the bed shear stress by about 30%. The discrepancy may result from the implementation of two-equation turbulence model in RANS equations that underestimates the effect of horseshoe vortex system (Khosronejad et al., 2012). It also may be caused by a relatively low order numerical scheme used for the advection terms.

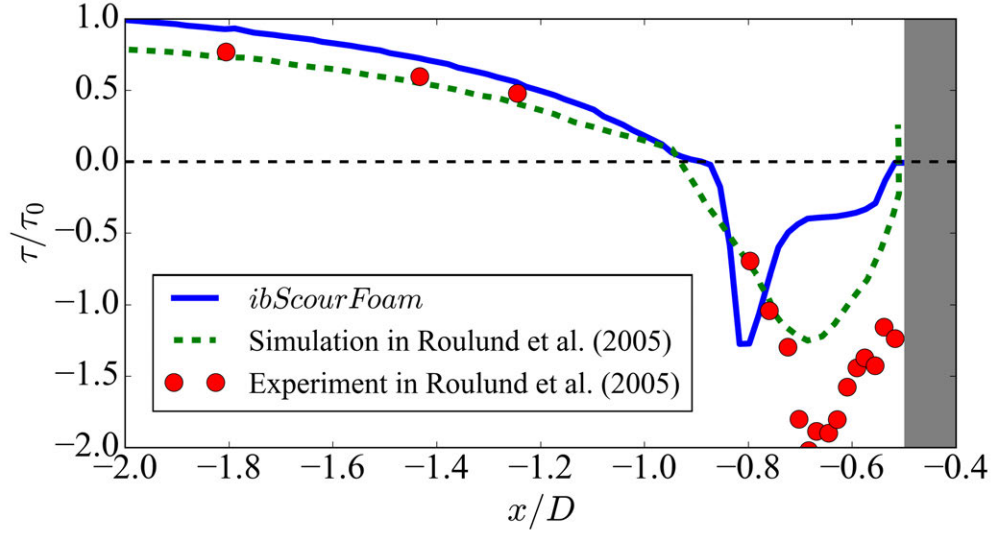


Figure C.6: Bed shear stress amplification along the symmetry line upstream of the pile

C.1.2 Scour around a vertical circular pile

In this section, the scour model was validated with the experimental case where a pile is mounted on erodible sediment bed (Roulund et al., 2005). The flow resistance estimator in Chen et al. (2019) was used to estimate the roughness height based on the shear velocity measured in the experiment. The diffusivity for the sand slide model used the same value as in Song et al. (2020). The morphological factor α was adjusted during the simulation because the scour process happens much faster during the early stage than the later stage. Thus, α had a value 0.2 at the beginning and then was reduced to 0.05 to accelerate the simulation. The simulation ran for 45 mins of real time and took approximately 330 h (14 days) on 80 processors Intel(R) Xeon(R) CPU E5-2680 v3 @ 2.50GHz. The flow condition and sediment properties are shown in Table C.2.

Figure C.7 shows the domain and mesh used for the scour simulation. The domain's length, width, and height are $16D$, $10D$, and $3.3D$, respectively. The upper part with a height of $2D$ is the initial fluid domain, and the lower part with a height of $1.3D$ is the initial sediment domain. The mesh has about 10 million cells and is refined near the cylinder, bed, and the downstream part. The smallest cell size is approximately 1 mm in the vicinity of the cylinder and the sediment bed. The largest cell is approximately 50 mm in size near the inlet and outlet. The maximum dimensionless wall distance for IB cells, $y_{IB\max}^+$, is approximately 130. The immersed bed surface mesh has about 60,000 triangles. The boundary conditions are similar to the flow validation case.

Table C.2: Parameters for the scour around a vertical circular pile case.

Parameters	Values
Water depth H (cm)	40
Mean flow velocity U (cm/s)	46
Pile diameter D (cm)	10
Shear velocity u_τ (cm/s)	2.8
Roughness height k_s (cm)	0.5
Grain size d_{50} (mm)	0.26
Critical Shields number for flat bed	0.022
Static friction coefficient μ_s	0.63
Diffusivity for sand slide (m^2/s)	0.0005
Hydrodynamic time step Δt_h (s)	0.002
Time scale factor α	0.05 $\sim$ 0.2

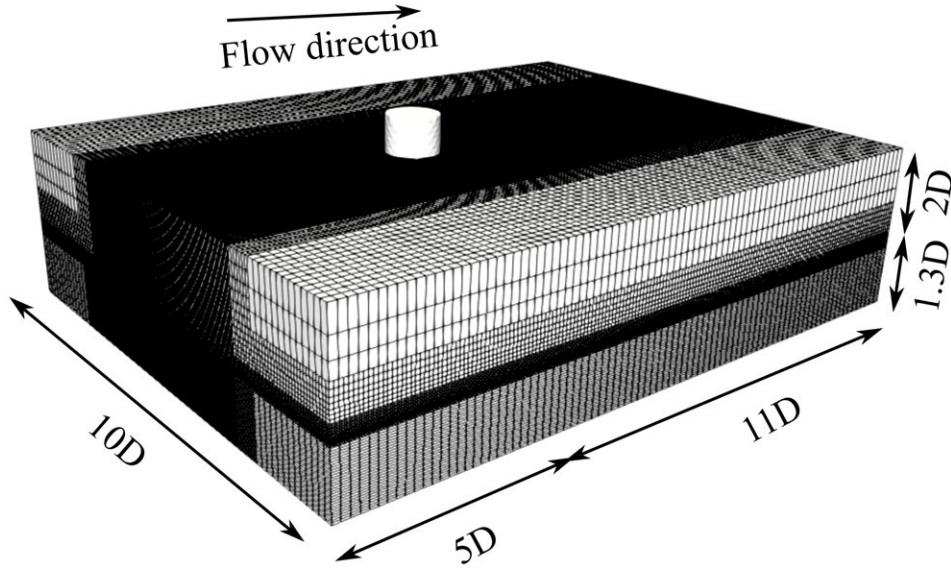


Figure C.7: Mesh used for scour around a vertical circular pile.

Figure C.8 (a)(b)(c), and (d) show the contours of bed elevation at four representative times during the scour process ($t = 10$ s, 60 s, 150 s, and 600 s). The elevation is made dimensionless with the pile diameter, D . The arrows show the direction of the wall shear stress, as well as the direction of the bed-load flux. The reference value of the arrow is the wall shear stress at the inlet, $|\tau_0| (= \rho u_\tau^2)$.

The four representative scour stages revealed by our model are as follows. First, the scour occurs on the two sides of the pile due to flow contraction and the horseshoe vortex. Second, the scour hole starts to expand in the upstream direction where the horseshoe vortex strengthens because water flows into the scour hole (Ettema et al., 2011). During this stage, eroded sediment accumulates at the immediate downstream side of the pile. Third, the scour expands to downstream

to form a complete hole around the pile. The sediment accumulation downstream of the pile is further washed away due to vortex shedding in the wake. And lastly, the erosion gradually slows down to equilibrium as the scour hole enlarges. Within the scour hole, sediment still moves. However, sediment cannot escape the hole due to sand slide (Song et al., 2020).

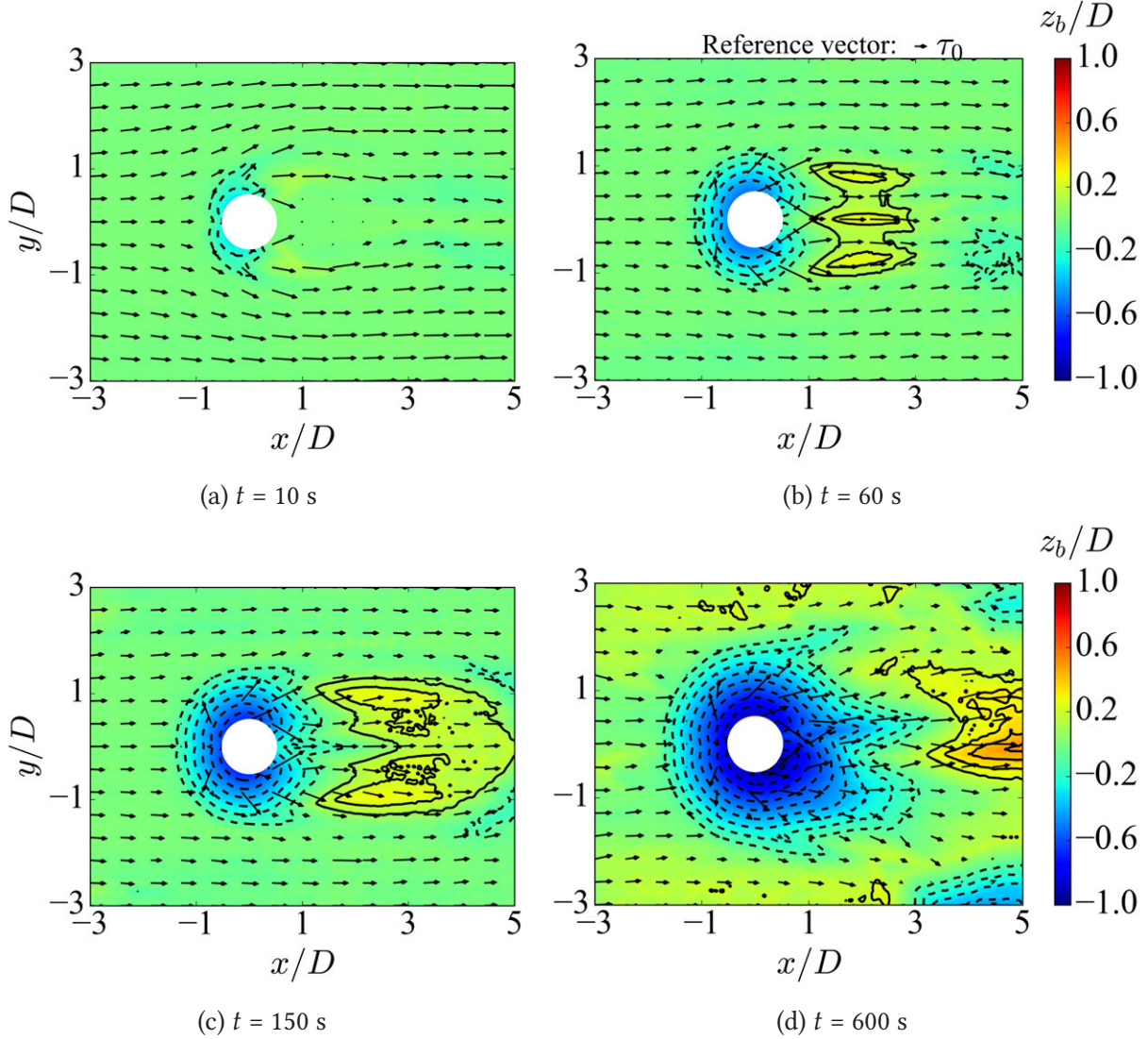


Figure C.8: Four representative stages of simulated scour hole development. It shows the bed elevation made dimensionless with the pile diameter D at (a) 10 s, (b) 60 s, (c) 150 s, and (d) 600 s. The arrows show the direction of wall shear stress and the bed-load flux.

Figures C.9a and C.9b show the time evolution of the scour depth at the upstream and downstream side of the pile, respectively. For comparison, the experimental and numerical results from Roulund et al. (2005), as well as the simulation results by *sedFoam* in Nagel et al. (2020) are also plotted. All the numerical models perform well at the initial scour stage up to 5 mins. The erosion rate of the two-phase flow simulation is smaller than the other simulations and the experiment from 5 to 10 mins. All simulations reach equilibrium at around 10 mins. On the upstream

side, the two-phase flow simulation gives the maximum $z_b = 0.63D$, whereas the predicted maximum scour depths in Roulund et al. (2005) and *ibScourFoam* are $0.91D$ and $1.06D$, respectively. The measured maximum scour depth from the experiment is $1.25D$. On the downstream side, the two-phase flow shows the maximum $z_b = 0.18D$. Simulations in Roulund et al. (2005) and *ibScourFoam* both give the maximum $z_b = 0.6D$. The measured maximum scour depth from the experiment is $0.89D$. As a result, even though all the numerical models underestimate the maximum scour depths at both upstream and downstream sides, the results in Roulund et al. (2005) and *ibScourFoam* are similar and close to the measured scour depth. One explanation of the underestimation is that two-equation isotropic eddy viscosity turbulence models used to close RANS equations underpredict the effect of the horseshoe vortex system, the main factor of scour around a vertical pile (Khosronejad et al., 2012). The other reason is that the contribution of suspended load to the equilibrium scour depth is not included in these two models (Baykal et al., 2015). In addition, a perturbation was added in the simulation of Roulund et al. (2005) to trigger the development of ripples. However, the impact of ripples was not included in our simulation. This could be another reason that the predicted scour depth in *ibScourFoam* is slightly less than that in Roulund et al. (2005). In general, our model captures the scour depth time history relatively well.

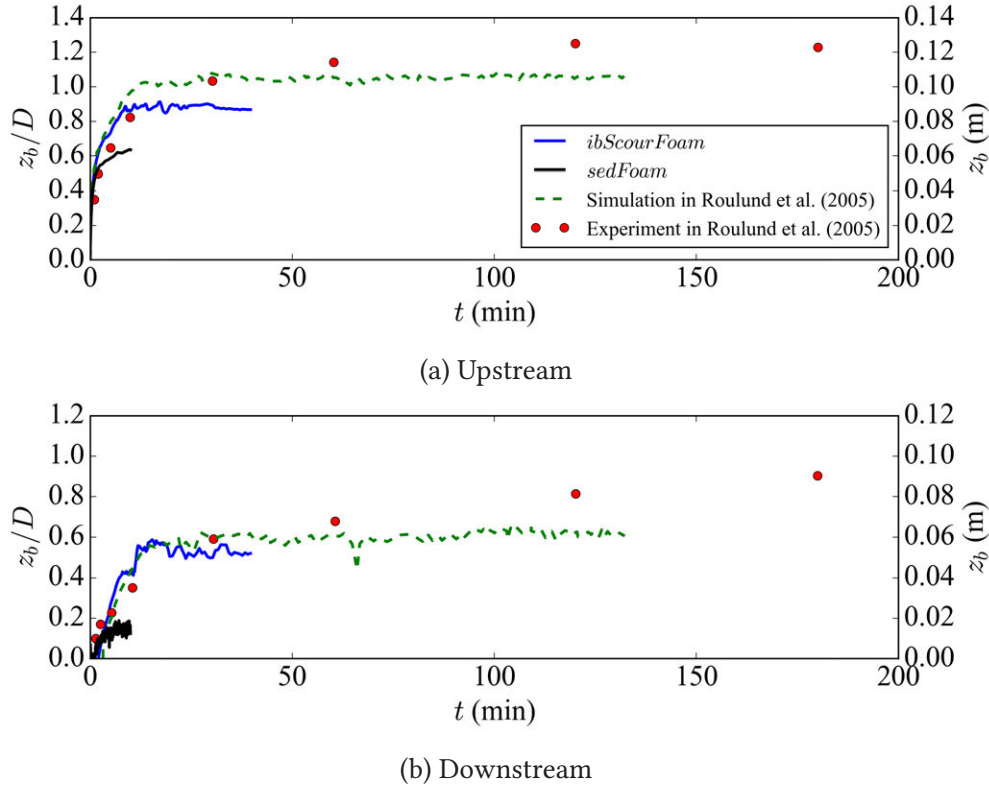


Figure C.9: Time history of scour depth at (a) the upstream and (b) the downstream side of pile.

C.2 *Demonstration case*

To demonstrate the capabilities of the model in dealing with scour around complex structures, a flume experiment was carried out to obtain detailed flow and scour information for comparison purpose. In the experiment, flow and scour were measured around a horizontal cylinder with finite length placed on a foundation (cradle) as shown in Figure C.10a. The foundation was fully buried in the sand initially. The cylinder, measuring 0.514 m long and 0.089 m in diameter, was placed onto the foundation. The position of the cylinder is fixed by the two crosses of the cradle. To prevent excessive undercutting of the cylinder and to ensure it engages with the cradle, the cylinder was partially buried initially to a depth of 14.5 mm. It was oriented such that the long axis of the cylinder was perpendicular to the primary flow direction. With the development of scour, the bed gradually lowered. As a result, the scour exposed the initially buried part of the cylinder and the cradle. Figure C.10b shows the computational mesh. It also shows that as the scour hole develops, the simulated bed (shown as red solid lines) evolves and interacts with the solid boundaries at $x = 0$ m, where x is the streamwise position with $x = 0$ at the center of the cylinder (shown as red dash lines in Figure C.10a). The mesh marked with blue is the initial fluid and the mesh marked with yellow is the initial sediment.

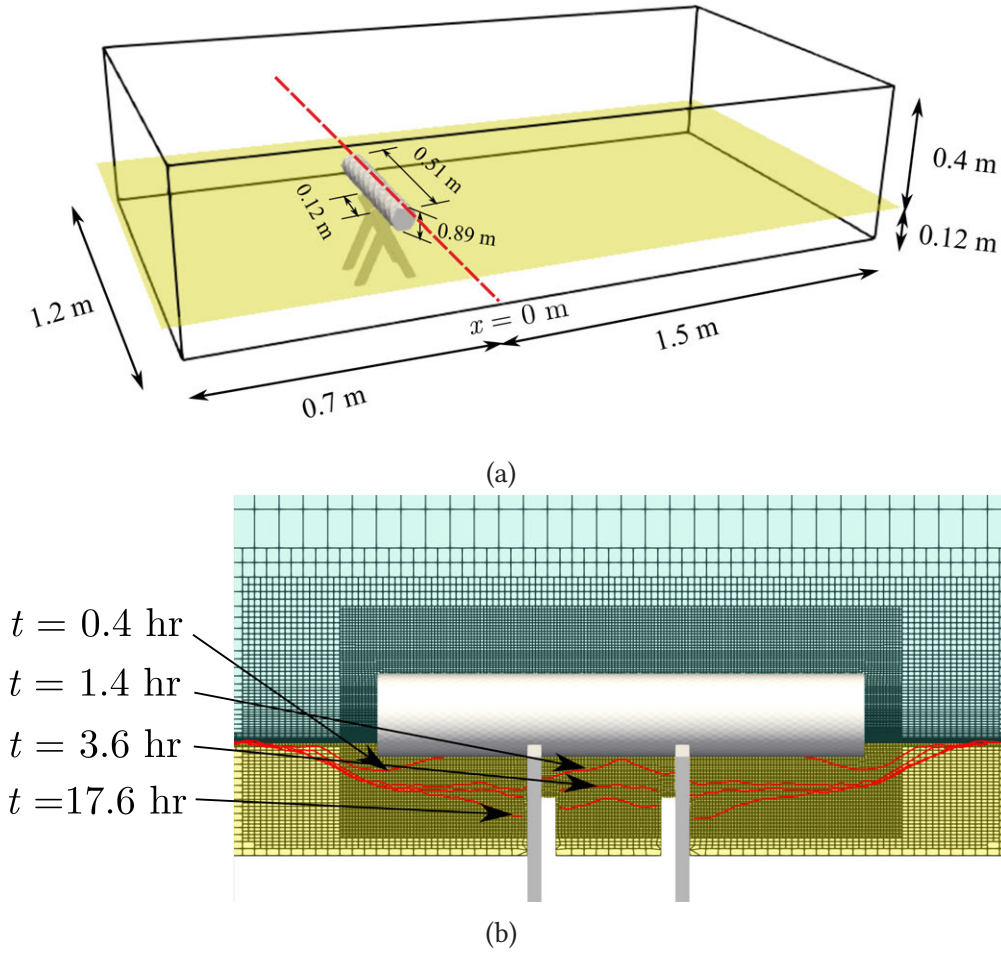


Figure C.10: Demonstration case setup: (a) schematic view of the domain for scour around a horizontal cylinder placed on a foundation. (b) interaction of the bed with solid boundaries in the background mesh. The red lines are the simulated bed at different times on the vertical slice of the domain at $x = 0$ m.

Laboratory experiments were conducted in a re-circulating, tilting flume measuring 15.24 m in length, 1.52 m in width, and 0.91 m in depth. The test reach of the flume, extending from 3.048 m to 7.621 m from the inlet, was covered to a depth of 0.12 m with sand having a median grain size of 0.67 mm. Water circulated through the system via a horizontal pump capable of delivering a maximum flow rate of 240 l/s. Before the test, the sand bed was planed using a scraper attached to an instrument carriage. Once the bed was prepared, the initial bed surface including the cylinder and cradle was measured using a handheld 3D scanner (Artec EVA). The same scanner was used to measure the final, eroded bed surface.

The flume was slowly filled to a depth of 0.40 m above the sand bed surface, and the pump was turned on. The targeted flow rate was selected by limiting the flow conditions to remain within the clear water scour regime. This meant that the free-stream flow conditions did not significantly transport bed sediment, and any erosion was caused by local accelerations. This threshold was first determined using an estimated Chezy coefficient, then confirmed through

preliminary testing. A description of the methodology can be found in Ismail et al. (2021). The flow condition and sediment properties are summarized in Table C.3.

Table C.3: Test conditions for scour around a horizontal cylinder placed on a cradle foundation.

Parameters	Values
Water depth H (cm)	40
Mean flow velocity U (cm/s)	22.2
Cylinder diameter D (cm)	8.9
Cylinder length L (cm)	51.4
Shear velocity u_τ (cm/s)	1.5
Roughness height k_s (cm)	1
Grain size d_{50} (mm)	0.67
Critical Shields number for flat bed	0.016
Static friction coefficient μ_s	0.63
Diffusivity for sand slide (m^2/s)	0.0005
Hydrodynamic time step Δt_h (s)	0.005
Time scale factor α	0.002 $\sim$ 0.02

Once the flow began, the sand bed started to be eroded near the cylinder and cradle and formed a deposit downstream. The flow continued until the bed reached equilibrium at which time there was no noticeable change in the bed surface. Then, measurements of the velocity field were obtained. These include two sets of velocity data: 1) the free-stream inlet velocity far upstream from the structure, and 2) the velocity field in a streamwise, vertical transect extending from $x = [-1.03, 1.03]$. The streamwise transect measurements were spaced 0.04 m in the streamwise direction and at five elevations from the initial plane bed (15, 30, 45, 60, and 75 mm). Note that the streamwise transect did not include data collection immediately above the cylinder.

In our experiment, the upstream of the flume was a transitional section filled with large cobblestones to ensure a gradual flow adjustment from the lower rigid bed to the higher sand bed. The existing of the cobblestones increases the flow resistance of the bed, as well as the Nikuradse equivalent roughness at the upstream region of the sand bed. Thus, the hydraulic roughness is related to not only sediment sizes, but also incoming flow state. In this work, we adapted the value of roughness k_s by fitting the inlet velocity profile measured from the experiment, instead of only using the sediment size d_{50} . Figure C.11 shows the mean velocity profiles upstream of the test section. The red dots are the measured velocity. The blue dots are the pre-simulated profile in the channel with no object. The black line is the velocity profile fitted with the general log-law

$$u^+ = \frac{1}{\kappa} \ln(y^+) + B - \Delta B(k_s^+), \quad u^+ = \frac{u}{u_\tau}, \quad y^+ = \frac{u_\tau y}{\nu} \quad (C.1)$$

where B is 5.2. The roughness function ΔB depends on $k_s^+ = k_s u_\tau / \nu$ and represents the downward shift of the logarithmic velocity profile due to roughness. The functional form of ΔB in

Cebeci and Bradshaw (1977) was used:

$$\Delta B = \begin{cases} 0 & \text{if } k_s^+ < 2.25 \\ [B - 8.5 + \frac{1}{\kappa} \ln k_s^+] \sin[0.4258(\ln k_s^+ - 0.811)] & \text{if } 2.25 \leq k_s^+ < 90 \\ B - 8.5 + \frac{1}{\kappa} \ln k_s^+ & \text{if } k_s^+ \geq 90 \end{cases} \quad (\text{C.2})$$

The fitted shear velocity u_τ is 0.015 m/s and the Nikuradse equivalent sand roughness k_s is 0.01 m.

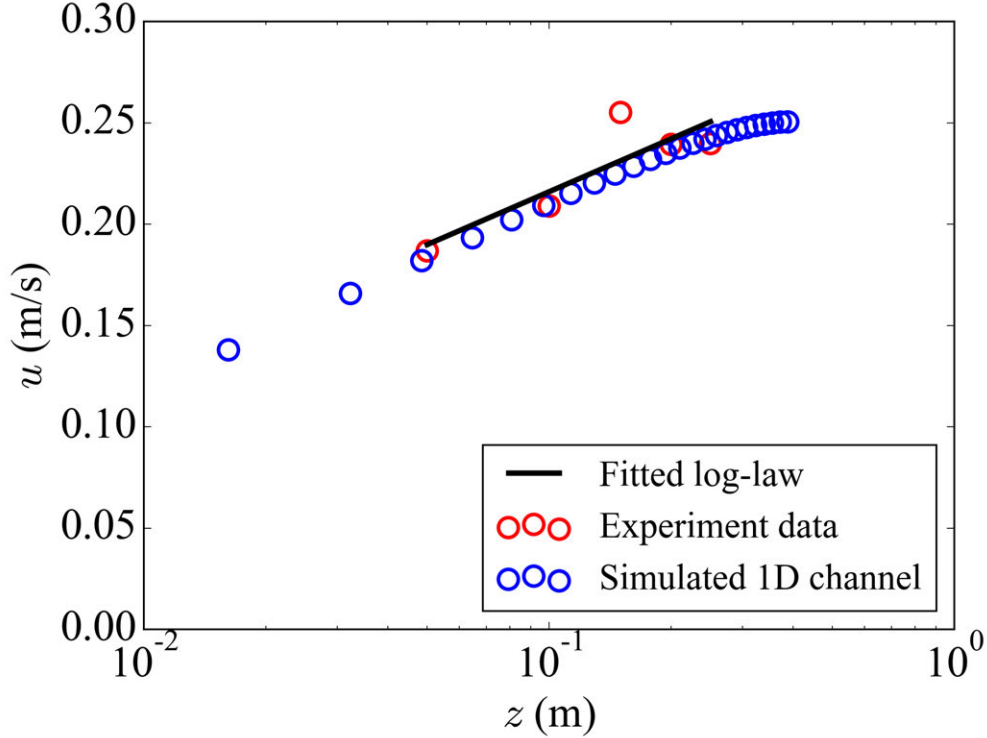


Figure C.11: Mean velocity profile measured at the undisturbed inlet of flume

In the model, the inlet condition mapped from the uniform-channel flow calculation with the fitted roughness k_s is a standard logarithmic profile. Even though the measured velocity profile deviates from the log law in the upper region, the effect of different inlet conditions used in the model and the experiment is not significant since the scour is induced by flow contraction near the object.

The simulation domain has a length, width, and height of 2.2 m, 1.2 m, and 5.2 m, respectively. The mesh has approximately 8 million cells and the smallest cell is approximately 1.6 mm in size. The maximum dimensionless wall distance for IB cells, $y_{IB\max}^+$, is approximately 40. The immersed bed surface has 60,000 triangles. The simulation ran for 17 hours of real time and took approximately 170 h (about 7 days) on 200 processors (Intel(R) Xeon(R) CPU E5-2680 v3 @ 2.50GHz).

Figure C.12 shows four stages of scour from the initial to equilibrium in four rows. The columns, in their order, show the following: slices of bed at $x = 0$ m (column a), scour depth patterns (column b), streamlines (column c), wall shear stress amplification factors (column d), dimensionless sediment flux (column e), and photos from experiment (column f). Arrows in column d show the direction of wall shear stress. The reference value of the arrow is the wall shear stress at the inlet $|\tau_0| (= \rho u_\tau^2)$.

With the details revealed by the computational model, the four stages of erosion observed in the laboratory experiment and laid out in Figure C.12 can be further examined:

1. Wake flow stage (Figure C.12, row 1): water flows over the cylinder and contracts when passing around the two ends of the cylinder. The approaching flow decelerates in front of the cylinder. Most of the incoming water flows up and over the cylinder. A small portion of incoming water flow down and forms a weak vortex that erodes the sand at the upstream side the cylinder. In this stage, most sediment movement and erosion happen at the two ends of the cylinder where flow contracts. As sediment moves away, the two ends are undermined and the underside of the cylinder starts to be exposed.
2. First jet flow stage (Figure C.12, row 2): In this stage, the dominant flow is the two jet flows under the two ends of the cylinder. Once the scour holes there are developed, the incoming flow is split when it encounters the cylinder. The downward flow into the scour holes contracts and accelerates to form two jet flows under the cylinder. The sediment in the scour holes is pushed out and deposited in the adjacent downstream side. It is also observed that some sediment near the two ends of the cylinder slides down to the deep part of scour hole and then is washed away by the jet flow. Gradually, the scour holes on the two ends expand toward the center.
3. Second jet flow stage (Figure C.12, row 3): The two scour holes merge at the center and expose the two crosses of the cradle. More incoming flow goes under the cylinder and contracts at the center due to the existence of two crosses. At this stage, the dominant flow is the one single jet under the whole cylinder. The sediment flux is maximum and thus the scour rate is the largest under the center of the cylinder because of the cradle's blocking effect. As a result, more sediment is being moved out from the center and then deposited downstream. The newly deposited sediment merges with the sediment from previous two stages and form a ridge downstream. With time, the bed under the cylinder slightly flattens.
4. Pier-like flow stage (Figure C.12, row 4): In this stage, undermining under the cylinder continues but mainly happens around the two crosses of the supporting cradle. The two crosses act like bridge piers and two local scour holes around them start to form. The scour pattern around the two crosses bears some resemblance to the vertical pile scour shown in Figure C.8. Scour continues near the cradle until equilibrium and the deepest part of the scour hole is around the two crosses. During the process, the sediment that moved out of the center region deposited in the bar downstream and forms the highest point in the middle.

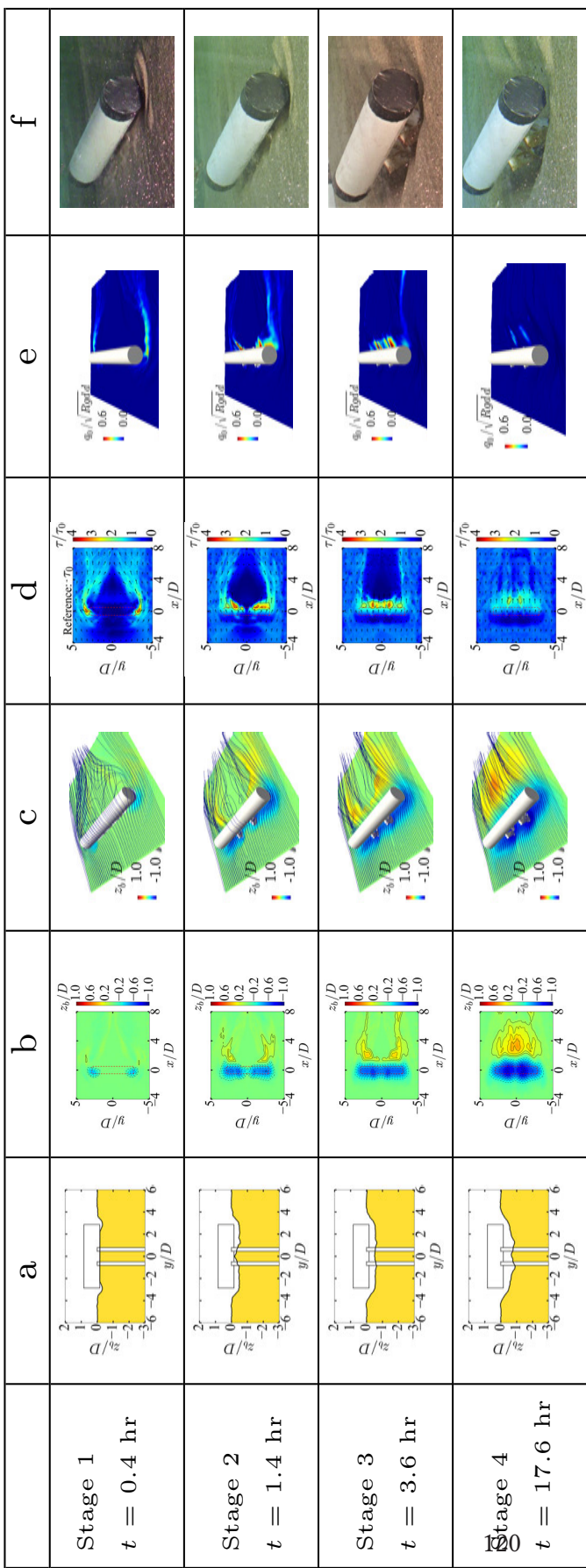


Figure C.12: Different stages of the simulated scour process around a horizontal cylinder supported by a cradle foundation. Rows corresponds to different stages. Columns a, b, c, d, e, and f are bed profile, scour depth contour, flow streamlines, wall shear amplification, sediment flux, and photos from experiment, respectively.

It should be noted that the wall shear stress distribution in Figure C.12 (column d) is smooth, which enables a successful scour simulation. This demonstrates the capability of the immersed boundary method and the associated wall model proposed in this work.

Figure C.13 shows a good comparison of the scour profile on the vertical slice at $x = 0$ m. The maximum scour depth is well captured near the crosses of the cradle. Bed slope of the scour hole is also consistent with the experimental data. The main discrepancy is that the scour hole on the right side is slightly deeper than that on left side in the experiment. It may result from the slight asymmetry of experimental setup. For comparison, the simulated result is symmetric along the symmetry plane of the flume. In this case, the driving flow of scour is dominated by flow contraction, rather than the horseshoe vortex that is underestimated by the RANS model. Thus, a better agreement between the simulation and experiment is produced by our model than that of the previous scour case.

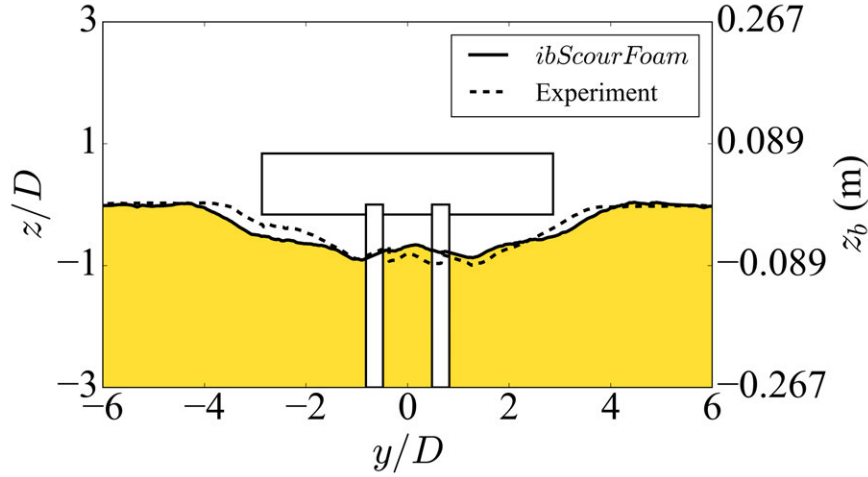


Figure C.13: Equilibrium scour profile on the vertical slice at $x = 0$ m.

C.3 Limitations of current 3D scour model

Despite the success shown in this chapter, the current model still has limitations. The major one is it is computationally more demanding than previous methods, such as the ALE method. In the current model, the simulation domain has to be larger to include the sediment part. In addition, the mesh in the sediment part has to be refined to have accurate results of flow and wall shear stress. As the Reynolds number increases, the required mesh resolution of the immersed boundary method increases much faster than the ALE method (Mittal and Iaccarino, 2005). The other limitation is the numerical instability caused by the switch among the IB, fluid, and solid cells when the boundary moves. Our background mesh is very stretched in the vertical direction to increase the mesh resolution and decrease the total mesh size, which also increases the instability of our model. Therefore, we used a relatively low order numerical scheme for the advection terms in Table 4.1. This scheme adds more numerical diffusion into the model and decreases its capability to capture finer flow features downstream. In addition, scour models solving RANS equations with two-equation turbulence models underestimate the wall shear, as well as

the scour depth induced by the horseshoe vortex system (Khosronejad et al., 2012). To alleviate this problem, a conservative modification of Brownlie’s (Brownlie, 1981) curve from Parker et al. (2003) was used to calculate the critical shields number, which amplifies the bed-load transport rate and increases the estimated maximum scour depth. The current model also lacks the suspended sediment component. Suspended sediment transport within the framework of immersed boundary method, especially how entrainment and deposition can be modeled, is currently under development.

C.4 Conclusions

A 3D scour model, *ibScourFoam*, has been developed based on a sharp-interface immersed boundary method. It can simulate the scour process around complex structures, a difficult task for many previous scour models. This chapter describes the details of the model and its implementation. In particular, the wall model proposed here produces accurate and smooth wall shear stress, a prerequisite for scour simulations.

The model was validated by simulating the flow and scour cases in Roulund et al. (2005). The flow structures and the temporal evolution of scour depth were well predicted. The model was further validated with a more complicated flume experiment case where a short cylinder sits on a cradle. The cylinder is initially partially buried and the cradle is fully buried. The model successfully simulated the undermining process starting at the two ends of the cylinder, the progressive enlargement of the scour holes, the merging of the two scour holes, and the subsequent scour around the fully exposed crosses of the cradle. With the 3D scour simulation results, it is now possible to analyze the details of the process and different stages of the scour development.

The 3D scour model developed in this work provides a viable path for scour modeling to be used in engineering practice. It helps us go beyond the “scour around simple geometry” phase in this field. With ever increasing computing power, the relatively high computational cost required by the immersed boundary method will soon become more affordable.

D List of Scientific/Technical Publications

With the support of this project, the following publications were produced:

D.1 *Published*

1. Y. Song, Y. Xu, and X. Liu (2020). A gradient-limited diffusive sand slide method in scour models. *Journal of Hydraulic Engineering*. 146(11): 04020074
2. Y. Xu and X. Liu (2021). An immersed boundary method with y^+ -adaptation wall function for smooth wall shear. *International Journal of Numerical Methods in Fluids*. 93: 1929-1946
3. Y. Song, Y. Xu, H. Ismail, and X. Liu (2022). Three-dimensional modeling of scour around complex structures with immersed boundary method. *Coastal Engineering*. 171, 104037
4. Y. Song, H. Ismail, and X. Liu (2020). Numerical modelling of scour around mobile objects with prescribed motion. In *Proceedings of 2020 International Conferences on Scour and Erosion*, Washington, DC.

D.2 *In revision/In progress*

1. Y. Song, A. Darzikolaei, X. Liu. Scour and burial of underwater unexploded ordnances (UXOs): An experimental and computational investigation. *Ocean Engineering*. In revision for resubmission.
2. Z. Li, X. Liu, G. Fourtakas, N. Stark, and T. Qiu. Dynamics of coupled fluid-object-sediment systems with smoothed particle hydrodynamics (SPH) simulations. In progress.

E Other Supporting Materials

N/A

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