

Numerical Modelling of Bed Shear Stress in OpenFOAM



Nandakumar Visuvamithiran, V. Sriram and Jaya Kumar Seelam

Abstract In coastal zones, erosion is the major threat to the livelihood as it leads to the water inundation into the human premises. Sediment transport results in erosions causes morphological changes and also affects the coastal ecosystem. The sediment transport processes are primarily driven by bed shear stress induced by waves and currents. As bed shear stress plays a major role in the determining sediment transport rates, the accuracy of sediment transport models mainly rely on the basis of bed shear stress measurements. So, there is a need to measure the reliable bed shear stress to improve the effectiveness of sediment transport models. In coastal zones when the waves enter into the low water depth, it starts to feel the bottom and the effect of shear stress at the bottom will be high. In this paper, bed shear stress is estimated from the numerical simulations using OpenFOAM. In OpenFOAM, bed shear stress is calculated from viscous force on the bed by integrating the pressure and the skin frictional forces. Surface elevation and flow velocity were measured using the numerical gauges. This bed shear stress can be directly incorporated into the shields parameter. In this study, numerical simulations in OpenFOAM were carried out for the regular sinusoidal waves with a time step of 0.001 s for a total duration of 16 s. OpenFOAM uses the waves2Foam toolbox for wave generation in the numerical wave tank.

Keywords Bed shear stress · OpenFOAM · Waves2Foam · Friction factor
Sediment transport

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K. Murali et al. (eds.), *Proceedings of the Fourth International Conference in Ocean Engineering (ICOE2018)*, Lecture Notes in Civil Engineering 22,
https://doi.org/10.1007/978-981-13-3119-0_41

1 Introduction

Fluvial processes due to water waves are important reason for the morphological changes in the coastal environments. Sediment instability in the sea floor occurs when the sea bed's shear resistance is exceeded by bed shear stresses, and dynamic pressure results in the propagation of waves. Prediction of erosion and sediment transport rate is important in the conservation and development of coastal ecosystem. When a wave enters the shallow water regions, it starts to feel the bottom and the effect of bed shear stress on the sea bed will be greater. Bottom shear stress induced by the water waves is important in the coastal sediment transport modelling. So, the accuracy of sediment transport modelling can be improved by the calculating reliable bed shear stress value. Bed shear stress also has the impacts on coastal structures, as well as during cyclonic events, storm surge and in wave-structure modelling. In boundary layer, bed shear stress is usually measured from the following four methods viz., log law fit, momentum integral method, Reynolds stress and shear plate method. The measurements of the bottom shear stress under regular waves may be classified as direct and indirect methods [1]. The indirect method includes the pressure difference method, hot film sensors [2] and velocity measurements method [3]. But there are some difficulties in indirect method like the direction of shear stress is not measured by hot film, and it is difficult to measure the boundary layer velocity accurately in the turbulent conditions in experiments. These uncertainties in the bed shear stress measurements affect the accuracy of the sediment transport modelling. Ippen and Mitchell [4] measured the bed shear stress by using shear plate method and relate it with the damping of wave height. Jonsson [5] found the empirical friction factor from the relationship between the bed shear stress and the near bottom velocity for an oscillatory flow. Kamphuis [6] measured the bed shear stress directly by using the shear plate method. Rankin and Hires [7] related the bed shear stress with friction factor by measuring the energy dissipation in the ripple geometry. Sleath [8] analysed the boundary layer by the velocity measurements with a laser Doppler anemometer. Recently, Barnes et al. [9], Pujara and Liu [10], Lin et al. [11] directly measured the bed shear stress from force–displacement relationship of the shear plate. Barnes and Baldock [12] developed the new Lagrangian boundary layer model for analysing the friction coefficient in the boundary layer for the swash zone. Although many experimental and theoretical studies are carried out for direct measurement of bed shear stress, there is a need of feasible numerical modelling for direct bed shear stress measurement. In this study, numerical modelling of bed shear stress is simulated using open-source CFD solver OpenFOAM.

Computational fluid dynamics is the tool for solving the real world fluid flow problems by a set of algebraic equations using the digital computers. Open Field Operation and Manipulation, known as OpenFOAM, is an open-source CFD solver with the package of C++ libraries and codes that are created to simulate the numerical modelling of continuum mechanics problems. OpenFOAM consists of large number of solvers, libraries and utilities to solve a wide range of problems. It is also possible for users to create their own codes and solvers for their specific problems or to

modify the existing solvers [13]. Waves2Foam is a toolbox recently developed by OpenFOAM users to simulate free surface wave generation and absorption [14]. It uses the relaxation method to generate and adsorb the waves. OpenFOAM uses Navier–Stokes equation which were given below

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \rho g_x + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (1)$$

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + \rho g_y + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (2)$$

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \rho g_z + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (3)$$

The objective of this paper is to simulate the periodic waves in an OpenFOAM numerical wave tank and to investigate the characteristics of bed shear stress under laminar conditions and to analyse the relationship between wave friction factors with the Reynolds number.

2 Numerical Modelling of Bed Shear Stress

Numerical modelling of bed shear stress is done in OpenFOAM using waves2Foam solver. In this numerical model, numerical wave tank shown in Fig. 1 and meshing created by using blockMesh utility in OpenFOAM. Geometry was divided into five hexagonal blocks with each block has eight vertices. Cell size in the y direction is 0.003 m, and in the wave propagation direction, it was 0.02 m. Bed shear stress measured in the plate created in the tank numerical tank using patches to measure the bed shear stress. Patches were created for 0.1 m length and 0.02 m width at 7.5 m from the paddle. Bed shear stress at the plate (patches) were measured by integrating the pressure and skin frictional force at the bed. Mesh near the patches where the bed shear stress measured, were made finer cells than the remaining cells to increase the accuracy of the results. OpenFOAM uses volume of fraction method (VOF) for tracking and locating free surface in the interface of air and water. VOF will calculate the fraction of each fluid (air and water) in each cell [15]. Physical properties used in this numerical study are presented in Table 1.

Using waves2Foam toolbox, periodic waves of time period 1.5, 1 s and wave height of 1.8–6.6 cm were simulated and the wave elevation, flow velocity and viscous force were measured at every time step of 0.001 s in the duration of 16 s. Schematic view of wave propagation was shown in Fig. 2. In this study, Stokes second-order wave theory used for regular wave generation. WaveGaugesNprobes utility is used to define the type and orientation of the numerical probes. SetWaveParameter and setWaveField utilities were used to compute the required wave parameters and to set the initial condition according to the defined theory. The meshing of numerical wave tank created from blockMesh utility was shown in Fig. 3. Horizontal (u) and vertical (v)

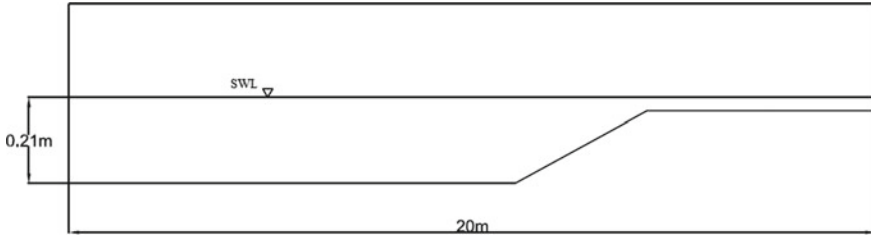


Fig. 1 Schematic view of numerical wave tank

Table 1 Physical properties

Property	Value
Acceleration gravity (g) (m/s ²)	9.81
Density (kg/m ³)	1000 (water) 1.2 (air)
Kinematic viscosity (m/s ²)	10 ⁻⁶ (water) 1.48 × 10 ⁻⁵ (air)
Surface tension (N/m)	0.07

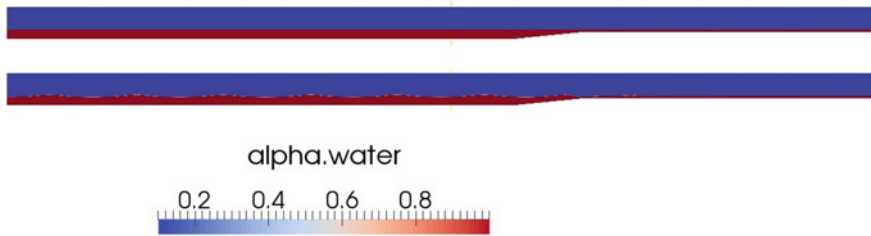


Fig. 2 Wave propagation in OpenFOAM

components of particle velocity which are partial derivatives of the velocity potential Φ in the model use the Stokes second-order wave theory given below

$$u = \frac{H}{2} \frac{gh}{\omega} \frac{\cosh k(h+y)}{\cosh kh} \cos(kx - \omega t) + \frac{3}{16} \frac{H^2 \omega k}{\sinh^4 kh} \frac{\cosh 2k(h+y)}{\sinh^4 kh} \cos 2(kx - \omega t) \tag{4}$$

$$v = \frac{H}{2} \frac{gh}{\omega} \frac{\sinh k(h+y)}{\cosh kh} \cos(kx - \omega t) + \frac{3}{16} \frac{H^2 \omega k}{\sinh^4 kh} \frac{\sinh 2k(h+y)}{\sinh^4 kh} \sin 2(kx - \omega t) \tag{5}$$

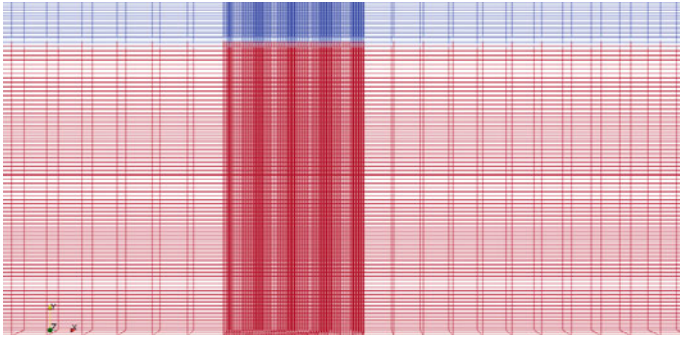


Fig. 3 Meshing of the numerical wave tank

3 Experimental Setup

Experiments were carried out in the wave flume in Gordon McKay hydraulics laboratory at the University of Queensland by Seelam and Baldock [16]. In the experiments of Seelam et al. [17], the shear cell developed by Barnes et al. [9] was used for direct bed shear stress measurement. The shear cell consists of the 1.21 mm thick plate with the length and breadth of 0.1 and 0.25 m. The shear cell was supported by four flexible legs. Displacement of the leg due to shear stress was measured by eddy current sensor. From the displacement, shear force can be calculated by force–stiffness relationship. Shear cell was placed at 7.8 m from the paddle. Pressure in the gap between shear cell edges was measured by the pressure sensors, flow velocity at the centre of shear cell was measured by ADV, and surface elevation at the cell edges was measured by the ultrasonic gauges. Schematic view of experimental setup was shown in Fig. 4.

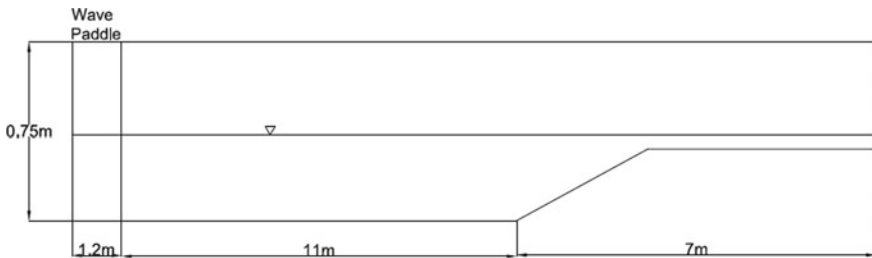


Fig. 4 Schematic view of experimental setup

4 Results and Discussion

The typical time series of experimental and numerical wave height was shown in Fig. 5, and the typical time series of bed shear stress for the water depth (d) of 0.21 m, the wave height of 0.05 m and the wave period = 1.5 s was shown in Fig. 6. Surface elevation was measured at both upstream and downstream edges of the plate. Surface elevation measured using volume of fraction method which tracks and locates the air water fraction at free surface. Bed shear stress calculated from the dividing bed's viscous force with the area of the plate (patches). Bed shear stress value varies from 0.034 to 0.134 Pa. Velocity obtained from the numerical study was compared with experimental results. Velocities were measured at the 6 mm above the centre of the plate. Experimental and numerical velocity comparison time series were shown in Fig. 7, from that plot it knows that numerical results were very well match with the experimental results.

From the velocity and shear stress measurements, wave friction factor can be back calculated using the quadratic drag law given in Eq. 6. Numerical friction factor and Reynolds number results were compared with theoretical and experimental results [16]. Theoretical friction factor was calculated from Eq. 7. The relationship between the wave friction factor and Reynolds number shows in Fig. 8. It can be seen that numerical results were in good agreement with the theoretical and experimental results. Numerical results were slightly lower than the theoretical results because of smooth bed conditions. Friction factor decreased with increase in Reynolds number as the flow transition happens from laminar to transition flow. The friction factor decreases with increase in Reynolds number because skin frictional drag gets minimum in the boundary layer. In this study, friction factor varies from 0.03 to 0.14.

$$\tau_b = \frac{1}{2} \rho f_w u^2 \tag{6}$$

$$f_w = \frac{2}{\sqrt{Re}} \tag{7}$$

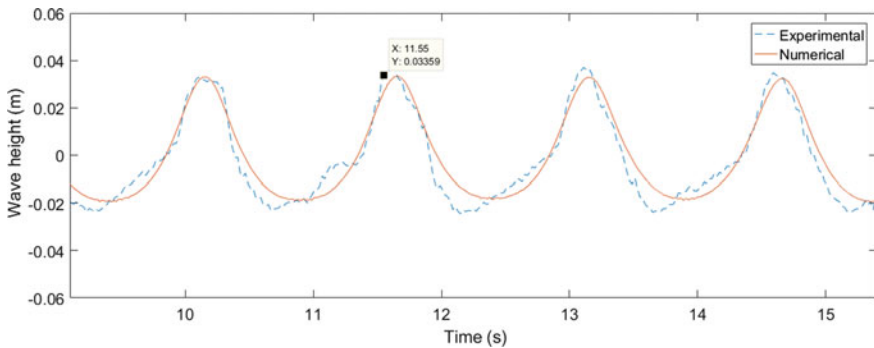


Fig. 5 Typical time series of wave elevation ($T = 1.5$ s, $H = 5$ cm, $d = 0.21$ m)

Fig. 6 Typical time series of bed shear stress ($T = 1.5$ s, $H = 5$ cm, $d = 0.21$ m)

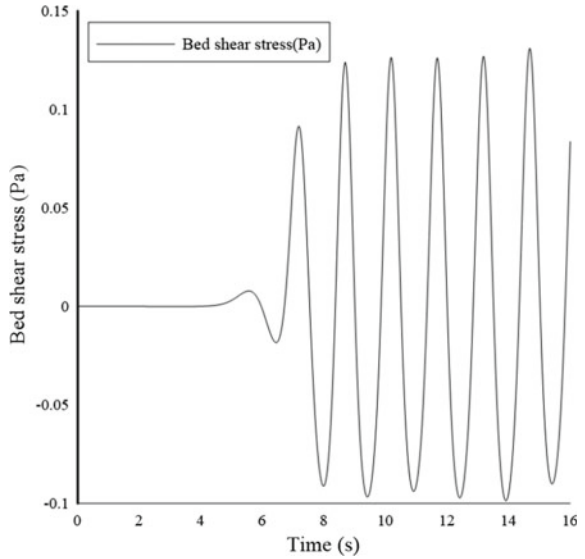
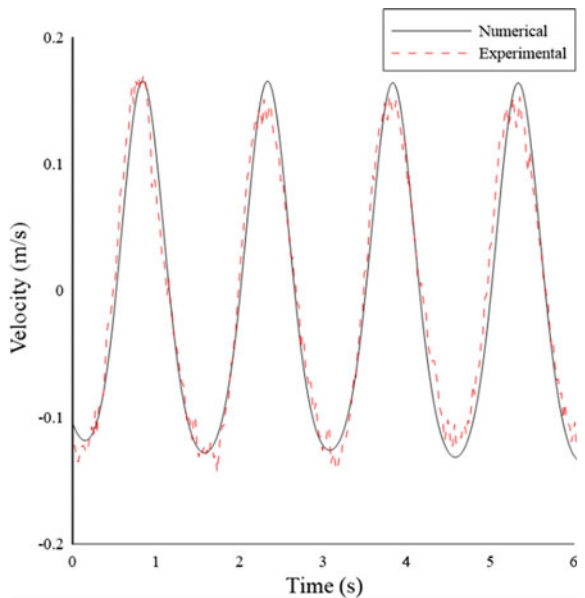


Fig. 7 Typical time series of experimental and numerical velocity results at 6 mm above the bed ($T = 1.5$ s, $H = 5$ cm, $d = 0.21$ m)



where τ_b is bed shear stress, ρ is density, f_w is the wave friction factor, u is flow velocity, and R_e is Reynolds number. The relationship between the bed shear stress and the relative wave height was shown in Fig. 8. In this study, the relative wave height was in the range of 0.05–0.35. Figure 9 shows the bed shear stress increases linearly with increase in wave height.

Fig. 8 Friction factor and reynolds number comparison

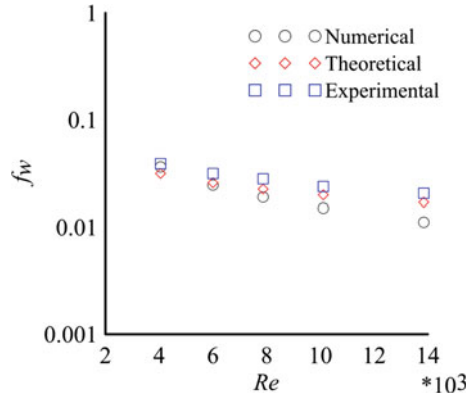
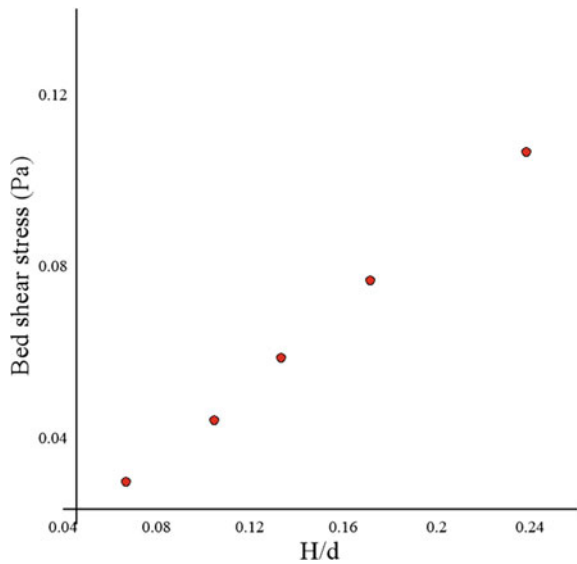


Fig. 9 Bed shear stress versus relative wave height



5 Conclusions

In this paper, bed shear stress due to periodic waves was modelled in OpenFOAM using waves2Foam toolbox. Wave friction factors were found from the velocity and shear stress measurements using quadratic drag law. Numerical results from this study were compared with the theoretical and experimental results. Wave friction factors were decreasing with increase in Reynolds number because of flow transition from laminar flow to transitional flow. From the results obtained from this study, it is seen that OpenFOAM model results match very well with the theoretical and experimental results. Wave friction factor back calculated using the bed shear stress

and velocity measurements can also be related to the wave energy dissipation factor [7]. These numerical studies can also be extended to solitary waves.

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