



Sediment transport analysis under combined action of waves and current using a novel semi-coupled computational fluid dynamics solver

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Abstract

Development of a numerical model to study the hydrodynamics and sediment transport phenomenon is essential in venturing into the field of coastal engineering applications. In the framework of OpenFOAM, a solver which can simulate simultaneously waves and current and its impact on sediment transport is nonexistent. Here, a semi-coupled sediment transport solver has been developed using open source framework OpenFOAM. Initially a new hydrodynamics solver (hereafter named hydroFOAM) has been developed to study the flow dynamics in coastal engineering applications. A set of Navier–Stokes equations including the continuity, momentum and inter-phase equations are solved using the finite volume method. Volume of fluid method has been employed to track the free surface. Later, different mathematical formulations are solved in a newly written solver (hereafter named sedimentTransportFOAM) to simulate the sediment transport phenomenon. Bed load and suspended load transport theories are being used while developing the solver. Precise descriptions of the two solver as well as the employed algorithm has been presented in this paper. Towards the end, the developed mathematical model has been validated with earlier experimental investigations and same has been presented using graphical figures and tables.

Keywords OpenFOAM · hydroFOAM · SedimentTransportFOAM · Volume of fluid · Sediment transport

1 Introduction

Studying and analysing the sediment transport phenomenon and hydrodynamics in different flow regimes (Afzal et al., 2021; Dutta et al., 2022, 2023; Gautam et al., 2021; Kumar & Afzal, 2023a, b, c; Prasad and Kumar, 2014; Pradhan et al., 2022; Priyadarsan and Afzal, 2023; Ranasinghe & Turner, 2006) around a structure plays an important role in several coastal engineering applications which includes bridge pier construction, oil and gas

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pipeline transmission, low Reynolds number applications and many more. The key point in sediment transport phenomenon in coastal areas is the presence of both waves and current. Earlier several researchers have studied the sediment transport phenomenon in detail using computational fluid dynamics (CFD) which was mainly due to effect of steady current (Chauchat et al. 2017) in OpenFOAM framework. Some of the other researchers have studied hydrodynamics beneath both waves and current in OpenFOAM framework but lacked the presence of sediment transport in the module (<https://openfoamwiki.net/index.php/Contrib/sedfoam>). Development of a solver (that can take into account presence of both waves and current along with sediment transport) which caters to the need to coastal and ocean engineers is very rare but essential. The development of a new solver is paramount in diving deep into the intriguing physics of the sediment transport phenomenon and hydrodynamics around the bridge piers. An attempt has been made in this paper to develop a new computational solver for studying the sediment transport phenomenon and complex hydrodynamics in coastal engineering applications.

Sukhinov et al. (2014) has developed a mathematical model to study the sediment transport phenomenon for a non-stationary spatial 2D model in the coastal zone of water reservoirs. They have considered the soil porosity, the critical shear stress, turbulent exchange, wind currents and friction on the bottom. Lai and Wu (2019) have developed a new 3D hydrostatic pressure model to study the open channel flows. The proposed model works well for flow and sediment transport phenomenon with flexible meshes. Yoyrurob and Liengcharernsit (2011) has developed a finite element solver to study the sediment transport considering the bedload and suspended load transport. Singh (2005) has developed a two-dimensional sediment transport model to study the sediment transport phenomenon.

Jian and Chen (2019) have numerically simulated sediment transport to study the sediment movement and the evolution law of the estuary bed for studying the estuary sediment deposition, sea water intrusion prevention treatment scheme and solve the problems of engineering. Benkhaldoun et al. (2009) have presented a one- and two-dimensional finite volume method to study the sediment transport. It has been found that the numerical simulations are well able to capture the complex physics sediment transport under flow regimes with high shocks. Kitsikoudis et al. (2015) has used artificial neural networks, symbolic regression based on generic programming and adaptive-network-based fuzzy inference system for the derivation of sediment transport formulae. Chauchat et al. (2017) have developed a two-phase solver for sediment transport application. The developed solver was an extension to the already existing in-built *twoPhaseEulerFoam* solver. Since the proposed solver by Chauchat et al. (2017) is a two phase solver, the effect of waves can not be studied. The solver OLAFOAM (<https://openfoamwiki.net/index.php/Contrib/sedfoam>) developed in OpenFOAM environment to study the hydrodynamics in an open channel due to the combined action of waves and current. The hydroFOAM solver developed in this work is different from the OLAFOAM (<https://openfoamwiki.net/index.php/Contrib/sedfoam>), where the wave module is not completely numerical, rather it is a combination of both analytical and numerical approaches. To work with the sedimentTransportFOAM solver, the output from the hydroFOAM solver needs to be solved and formatted in a particular manner. Thus, the need to create a customized hydrodynamics solver named hydroFOAM is created in this work.

Wu (2004) has proposed a two-dimensional depth averaged model to study the sediment transport in open channel flow using the finite volume method. He has computed the flow and sediment transport formulations in a decoupled manner. Hung et al. (2009) have used an orthogonal curvilinear coordinate system to develop a depth averaged two-dimensional non-equilibrium cohesive and non-cohesive transport model. Jacobsen

et al. (2012) have developed a wave generation toolbox in OpenFOAM (<https://www.openfoam.org/>) for solving open channel flows using the Reynolds averaged Navier–Stokes (RANS) equations.

As per the author's knowledge, there is no computational tool available that integrates the advanced capabilities of OpenFOAM for high-performance finite volume simulation with established and accurate analytical expressions encompassing free surface flows, wave dynamics, and flow current mechanics. This paper signifies a pioneering effort in this direction. What sets this paper apart is its fusion of numerical and analytical methods to forecast scour and flow properties. This tool will find widespread applications in sediment transport, scour prediction, and bridge pier modeling. Conversely, solvers such as IHFOAM and OLAFOAM lack the speed and comprehensive solution provided by analytical methods. In our approach, we've harnessed the strengths of both analytical methods and numerical simulation to create hydroFOAM and sedimentTransportFOAM as two distinct modules. The decision to maintain them as separate modules is rooted in software development standards, specifically to maintain modularity in the code. This design choice allows for future expansions without entangling or interlinking with the existing code.

In this paper, the flow dynamics and sediment transport computational models are developed for the open channel coastal engineering applications, this will help the engineers to design the structures more safely leading to environmental sustainability (Abdelzaher, 2022; Abdelzaher & Shehata, 2022; Elkhoully et al., 2021). The numerical modeling has been carried out using the open source C++ framework OpenFOAM (<https://www.openfoam.org/>). The developed semi-coupled code has been validated with the data from literature. To the best of authors' knowledge, this work is idiosyncratic in its own. The development of solver for the open channel coastal engineering applications in sediment transport has not been done earlier in OpenFOAM framework. With the aid of OpenFOAM parallel computing classes, the developed solver can be used to run in parallel threads. Thus, the proposed module can work in serial as well as parallel computing mode. The paper is structured as follows: A brief introduction has been presented in Sect. 1. The mathematical model has been presented in Sect. 2. The validation of the developed model is presented in Sect. 3. A concluding remark has been presented in Sect. 4.

2 Mathematical modeling

The solver developed in this module to study the sediment transport phenomenon due to the combined action of waves and current is a combination of two solvers, i.e., hydroFOAM and sedimentTransportFOAM. The proposed mathematical model in this article is a semi-coupled solver. The proposed mathematical framework has been implemented using the free and open source OpenFOAM framework. hydroFOAM solver is used to study the hydrodynamic parameters of the flow behaviour in coastal engineering applications without taking consideration of the effect of sediment transport. Later the parameters resulted out from the hydroFOAM solver is used as an input to the sedimentTransportFOAM solver. The sedimentTransportFOAM solver solves the differential equations to calculate the sediment transport parameters. hydroFOAM solver solves the three-dimensional volume averaged Reynolds averaged Navier–Stokes (VARANS) equations for two in-compressible phases using a finite volume discretization and the volume of fluid (VOF) method.

2.1 hydroFOAM solver

The volume averaged Reynolds averaged Navier–Stokes (VARANS) equations include continuity and momentum conservation equations to solve the pressure and velocity field in the flow domain. The continuity equation is as follows:

$$\frac{\partial \langle u_i \rangle}{\partial x_i} = 0 \quad (1)$$

The momentum equation can be expressed as follows:

$$\begin{aligned} \frac{\partial \rho \langle u_i \rangle}{\partial t} + \frac{\partial}{\partial x_j} \left[\frac{1}{\phi} \rho \langle u_i \rangle \langle u_j \rangle \right] = & -\phi \frac{\partial \langle p^* \rangle}{\partial x_i} + \phi g_j \mathbf{X}_j \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu_{eff} \frac{\partial \langle u_i \rangle}{\partial x_j} \right] \\ & - \left[A \langle u_i \rangle + B \langle u \rangle | \langle u_i \rangle + C \frac{\partial u_i}{\partial t} \right] \end{aligned} \quad (2)$$

The friction coefficients are calculated according to the formula proposed by Engelund (1953). The coefficients are calculated as follows:

$$A = \alpha \frac{(1 - \phi)^3 \mu}{\phi^2 D_{50}^2} \quad (3)$$

$$B = \beta \left(1 + \frac{7.5}{KC} \right) \frac{\rho(1 - \phi)}{\phi^2 D_{50}} \quad (4)$$

To track the fluid movement and interface the following interphase equation is used.

$$\frac{\partial \alpha}{\partial t} + \frac{1}{\phi} \frac{\partial (\alpha \langle u_i \rangle)}{\partial x_i} = 0 \quad (5)$$

In this solver the two phases are assumed as water and air. In computation these two phases can be substituted by denser media and lighter media respectively. Thus, the two phases presented here can be generalized for any fluids. Here α is the volume fraction of water (or the denser medium). α is defined as follows:

$$\alpha = \text{volume of water per cell} = \frac{V_{water}}{V_{total}} \quad (6)$$

where V_{water} and V_{total} are volume of water in cell and total volume of cell respectively.

From Eq. (6), it can be concluded that the value of $\alpha = 1$ corresponds to the cells where the complete cell is filled with water. Similarly, $\alpha = 0$ corresponds to the cell having air only. All other values corresponds to the interface. Any hydrodynamic parameter, Y for any given cell can be calculated from the following formula:

$$Y = \alpha Y_{water} + (1 - \alpha) Y_{air} \quad (7)$$

For example the density in any particular cell can be calculated using the Eq. (7). This is shown in the following Eq. (8):

$$\rho = \alpha \rho_{water} + (1 - \alpha) \rho_{air} \quad (8)$$

The values of α for each and every cell in the domain can be calculated using the Eq. (5). But for physical interpretation there should be sharp interface. Thus to maintain the physical continuity and sharp interface, α must be conservative and lie between 0 and 1. Thus an artificial compression term $[\nabla \cdot \mathbf{U}_c \alpha(1 - \alpha)]$. This is a standard procedure used in OpenFOAM (Weller et al., 1998). This approach is conservative and takes only non-zero values only at the interface. Thus the Eq. (5) can be written as presented in Eq. (9). The boundedness of the equation is achieved by using the MULES solver (presented in Appendix A). The MULES solver is an already existing solver in OpenFOAM. A limiter factor on the fluxes of the discretized divergence term is used to ensure the value lies between 0 and 1.

$$\frac{\partial \alpha}{\partial t} + \frac{1}{\phi} \frac{\partial(\alpha \langle u_i \rangle)}{\partial x_i} + \frac{\partial \langle u_{ci} \rangle \alpha(1 - \alpha)}{\phi \partial x_i} = 0 \quad (9)$$

Freely available wave generation toolbox developed by Jacobsen et al. (2012) is being used in the hydroFOAM solver for the purpose of generation of wave boundary conditions. The module incorporates generation and absorption of waves at inlet and outlet boundaries. The wave generation toolkit (Jacobsen et al., 2012) is being released under the GNU public license through the extended community. Table 1 presents the list of wave theories included in this study. A brief discussion on the turbulence modeling has been presented in Appendix B.

2.2 sedimentTransportFOAM

The sediment transport mechanism depends on the shape and size of sediment particles. There are two modes of sediment transport, i.e. suspended load transport and bed load transport. The mode in which sediment transport will occur depends not on the settling velocity of the sediment to the critical bed shear stress (Kraft et al., 2011). There is also a good way to approximate the chance of which mode of sediment transport on the basis of the ratio of settling velocity to the shear velocity. In suspended load transport, sediment particles move without staying in contact with the bed, whereas in bed load transport, the particles maintain continuous contact with the bed as they move. The larger sediment particles move downstream due to the bed load transport mechanism. There is a rough estimation of 5–25% of the suspended load is transported as bed load. The developed solver sedimentTransportFOAM is a semi-analytical solver. The calculation of bed shear stress in the combined action of waves and current is challenging. Earlier several researchers have

Table 1 List of “wave type” and “wave theory” available in hydroFOAM

Wave type	Wave theory
Regular	cnoidal
Regular	StokesI
Regular	StokesII
Regular	StokesV
Regular	streamFunction
Solitary	Boussinesq
Wavemaker	tveta
Irregular	–

worked on calculating bed shear stress and developed a couple of equations. The sediment-TransportFOAM has six models to calculate the bed shear stress. The end-user can choose among these equations as per the need. Babaeyan-Koopaei et al. (2002) has developed the following equation to calculate the bed shear stress:

$$\tau = \rho g R S_f \quad (10)$$

Schlichting and Gersten (1979) has proposed the following equation to calculate bed shear stress:

$$\tau = \rho C_D U^2 \quad (11)$$

The friction-based approach takes into account the bed friction in calculation of bed shear stress. The following equation is derived by considering the frictional force.

$$\tau = \frac{1}{2} \rho f U^2 \quad (12)$$

where $f = 0.06 / \log\left(\frac{12h_s}{\frac{3.3\nu}{u^*}}\right)^2$ if $u^*k_s/\nu < 5.0$, otherwise if $u^*k_s/\nu > 70.0$, then $f = 0.06 / \log\left(\frac{12h_s}{k_s}\right)^2$. Here f is the coefficient of friction, k_s is bed roughness parameter. Rijn (1984) has suggested that the value of $k_s = 3d_{90}$.

Schlichting and Gersten (1979) has used a logarithmic relationship to calculate the bed shear stress.

$$\tau = \rho u^{*2} \quad (13)$$

where, $u^* = u \left(\frac{1}{k} \ln \left(\frac{z}{z_0} \right) \right)^{-1}$

where u^* is the shear velocity, z is the height above the bed and z_0 is the characteristic roughness length and is calculated as $k_s/30$.

Simulations carried with keeping the turbulence models turned on can be used to calculate bed shear stress τ using the following definition.

$$\tau = -\rho(\nu_t + \nu) \frac{\partial u}{\partial z} \quad (14)$$

Another formulation that can be used whenever a turbulence model is in place for carrying out the simulation, is presented here. The total kinetic energy, k is defined as:

$$k = \frac{1}{2} (\langle \tilde{u}^2 \rangle + \langle \tilde{v}^2 \rangle + \langle \tilde{w}^2 \rangle) \quad (15)$$

The $\langle \rangle$ is the averaging operator. Then the bed shear stress can be calculated as follows:

$$\tau = k \sqrt{c_\mu} \quad (16)$$

Generally, the value of c_μ is taken as 0.09.

Above section discusses the methodology to calculate the bed shear stress using different mathematical proposed earlier. Table 2 lists down the keywords available in sedimentTransportFOAM for calculating the bed shear stresses. Three different formulations are there in sedimentTransportFOAM to calculate the bed load transport rate. The

Table 2 Different formulations available in sedimentTransportFOAM for calculation of bed shear stress

Name of the model	Keywords in
Babaeyan-Koopaei et al. (2002)	<i>babaeyan</i>
Schlichting and Gersten (1979) linear formulation friction based approach	<i>schlichtingLinear</i> <i>frictionBased</i>
Schlichting and Gersten (1979) log formulation	<i>schlichtingLog</i>
Turbulence formulation	<i>turbulenceFormulation</i>
Total kinetic energy formulation	<i>tkcFormulation</i>

different models are discussed here. Before that three non-dimensional numbers are formulated below to ease out the discussions. The non-dimensional formula of bed shear stress, critical bed shear stress and bed load transport rate are described below:

$$\begin{aligned}\tau^* &= \frac{\tau}{(\rho_s - \rho)gd_i} \\ \tau_{c,i}^* &= \frac{\tau_{c,i}}{(\rho_s - \rho)gd_i} \\ q_{b,i}^* &= \frac{q_{b,i}}{\sqrt{\frac{(\rho_s - \rho)g}{\rho}}d_i}\end{aligned}\quad (17)$$

The formulation given by Rijn (1984) is presented below:

$$\frac{q_{b,i}}{d_i^{1.5} \sqrt{\frac{(\rho_s - \rho)g}{\rho_s}}} = 0.053 \frac{\left(\frac{\tau - \tau_{c,i}}{\tau_{c,i}}\right)^{2.1}}{\left(d_i \left(\frac{\rho_s / (\rho - 1)g}{v^2}\right)^{\frac{1}{3}}\right)^{0.3}} \quad (18)$$

The critical bed shear stress $\tau_{c,i}^*$ is calculated from the Shields diagram (Dustegir et al., 2018). According to Van Rijn (1984) this equation fits well for the small diameter particles in a range of 100–500 μm . When modeling suspended sediment numerically, the computed bed-load movement can be utilized as a boundary condition i.e. reference concentration. Meyer-Peter and Müller (1948) proposed the following formula to calculate the bed load transport rate:

$$\begin{aligned}q_{b,i}^* &= 0; & \text{if } \tau^* < \tau_{c,i}^* \\ q_{b,i}^* &= \alpha_s \left(\tau^* - \tau_{c,i}^*\right)^n; & \text{if } \tau^* > \tau_{c,i}^*\end{aligned}\quad (19)$$

where

$$\alpha_s = 1.6 \ln \tau^* + 9.8$$

Engelund and Fredsøe (1976) has given the following model in 1976 to calculate the bed load transport rate:

$$\begin{aligned}
 q_{b,i}^* &= 0 : & \text{if } \tau^* < \tau_{c,i}^* \\
 q_{b,i}^* &= 18.74 \left(\tau^* - \tau_{c,i}^* \right) \left(\tau^{*0.5} - 0.7 \tau_{c,i}^{*0.5} \right) : & \text{if } \tau^* > \tau_{c,i}^*
 \end{aligned}
 \tag{20}$$

A convection diffusion transport equation is used for predicting the suspended load transport in sedimentTransportFOAM.

$$\frac{\partial c}{\partial t} + U_i \frac{\partial c}{\partial x_j} + w_s \frac{\partial c}{\partial z} = \frac{\partial}{\partial x_i} \left(\Gamma \frac{\partial c}{\partial x_i} \right)
 \tag{21}$$

The deposition rate is calculated from the following formulation:

$$D = w_s c_b
 \tag{22}$$

The sediment concentration rate is calculated from the following equation:

$$c_{bed,sus.load,i} = 0.015 \frac{d_i}{a} \frac{\left(\frac{\tau - \tau_{c,i}}{\tau_{c,i}} \right)^{1.5}}{\left(d_i \left(\frac{\rho_s / (\rho_w - 1) g}{\nu^2} \right)^{\frac{1}{3}} \right)^{0.3}}
 \tag{23}$$

The equivalent roughness height of Nikuradse was considered as reference level above bed (a), with a minimum value 0.01d. According to Rijn (1984) the equation is the "best" agreement between measured and calculated concentration profiles for a flow depth of 0.1–0.25 m, with a flow velocity varied from 0.4 to 1.6 m/s and sediment size in the range of 180–700 μm. The above section discusses the mathematical model used in the sediment-TransportFOAM solver in a concise manner. In the next section some differential equation solving algorithms are presented.

2.3 Algorithm

hydroFOAM solver is coded using the PIMPLE algorithm which is a combination of PISO and SIMPLE algorithm. PISO stands for pressure implicit with splitting of operators, whereas SIMPLE stands for semi-implicit method for pressure linked equation. The non linearity terms in the equations explained in hydroFOAM is handled using an iterative technique. For example the non-linear term in the momentum equation $\nabla \cdot (\mathbf{U}\mathbf{U})$ is approximated as $\nabla \cdot (\mathbf{U}^n \mathbf{U}^{n+1})$. Here, \mathbf{U}^n and \mathbf{U}^{n+1} are the solution at present and next step respectively. As there is no pressure equation in the governing Navier–Stokes equation, the continuity equation imposes a constraint on the momentum equation. At low Courant number, the coupling between the pressure and velocity is very strong. Therefore a pressure corrector term is repeated without updating the same in the momentum equation. In in-compressible flows, the momentum equation is discretized as:

$$a_p^u \mathbf{U}_p + \sum_N a_N^u \mathbf{U}_N = r - \nabla p
 \tag{24}$$

Writing a new term $\mathbf{H}(\mathbf{u})$, which is defined as follows:

$$\mathbf{H}(\mathbf{U}) = r - \sum_N a_N^u \mathbf{U}_N
 \tag{25}$$

Applying Eq. 25 in Eq. 24 gives:

$$\begin{aligned} a_p^u + \mathbf{U}_p &= \mathbf{H}(\mathbf{U}) - \nabla p \\ \mathbf{U}_p &= (a_p^u)^{-1}(\mathbf{H}(\mathbf{U}) - \nabla p) \end{aligned} \quad (26)$$

Substituting the Eq. 26 in continuity equation ($\nabla \cdot \mathbf{U} = 0$) will result in the following equation:

$$\nabla \cdot [(a_p^u)^{-1} \nabla p] = \nabla [(a_p^u)^{-1} \mathbf{H}(\mathbf{U})] \quad (27)$$

The differential equations used in sedimentTransportFOAM are solved by using the finite volume discretization. All the terms of the equation are solved implicitly.

The variables used in the earlier equations of bed shear stress calculation are presented in Table 3.

3 Validation

The hydroFOAM solver has been validated with the works of Umeyama (2011) for combined wave-current flows without the presence of any structure. The flow condition used are presented in Table 4. The validation plot comprising of z versus *velocity* at four different time steps are presented in Fig. 1 which shows very good agreement between the simulated velocity profile obtained using the developed code and the experimental results of Umeyama (2011).

The numerical model (hydroFOAM and sedimentTransportFOAM solver) has also been validated with the work of Sumer et al. (2003) for steady current condition. The bed load transport rate computed from the numerical model is compared with the work of Sumer et al. (2003) and is presented in Table 6. The flow conditions used in this validation are

Table 3 List of symbols used

Symbol	Description
τ	Bed shear stress
ρ	Density of water
R	Hydraulic radius
S_f	Energy slope
C_D	Drag coefficient
U	Average fluid velocity
f	Coefficient of friction
k_s	Bed roughness parameter
u^*	Shear velocity
ν	Viscosity of water
ν_t	Eddy viscosity
τ^*	Non-dimensional bed shear stress
$\tau_{c,i}^*$	Non-dimensional critical shear stress
$q_{b,i}$	Bed load transport rate
$q_{b,i}^*$	Non-dimensional bed-load transport rate

Table 4 Flow conditions used for the results presented in Fig. 1

Name of the model	Keyword in sedimentTransport-FOAM
Density of water	998.2
Kinematic viscosity of water	1.004e-06
Density of air	1.205
Kinematic viscosity of air	1.41e-05
Wave theory	cnoidal
Wave height	0.0309
Wave period	1.0
Wave direction	0.0
Wave phase	1.57079633
U	0.08

All dimensions are in SI unit

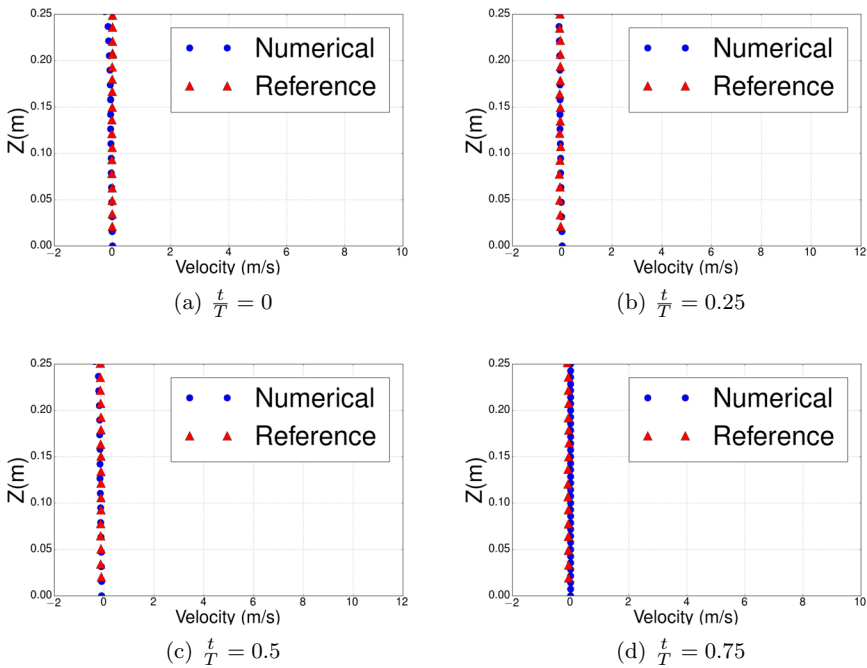


Fig. 1 Validation of z versus velocity plot at four different t/T ratio

mentioned below (Table 5). The validations shows excellent agreement between the experimental results and to that obtained using the developed numerical model.

Further, the developed numerical model has been validated with the work of Ribberink and Al-Salem (1994) for oscillatory flow conditions. The domain dimensions are taken as 14 m × 0.3 m × 1.1 m. Second order Stokes wave formulation has been used here for wave

Table 5 Flow conditions used in the validation with the works of Sumer et al. (2003)

Parameter	Value
Flow rate, $Q(Ltr/s)$	18.4
Mean velocity, $U(cm/s)$	30.67
Bed friction velocity, U_{fb} (cm/s)	1.74
Shields parameter, θ_b	0.085

Table 6 Comparison of the rate of bed load transported in volume per unit time per unit width, q cm³/cm s) with the works of Sumer et al. (2003)

Sumer et al. (2003)	Present computation
0.065×10^{-2}	0.06359×10^{-2}

Table 7 Flow conditions used for the results presented in Fig. 2

Cases	Water depth (m)	Wave period (s)	Net transportation rate (m ² /s)	U_{rms} (m/s)
Case1	0.8	6.5	107.2×10^{-6}	0.5
Case2	0.8	6.5	107.2×10^{-6}	0.9

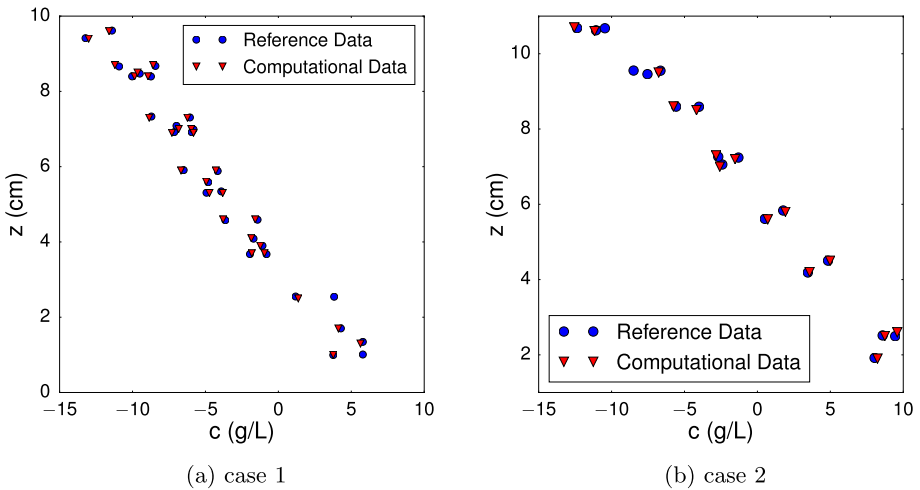


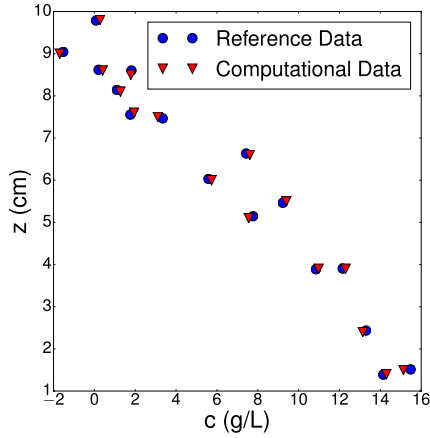
Fig. 2 z versus c plot for two considered cases

generation. Figure 2 present the plots of the validation showing the variation of suspended sediment concentration at different distances from the bed. The flow conditions used in the simulation are presented in Table 7.

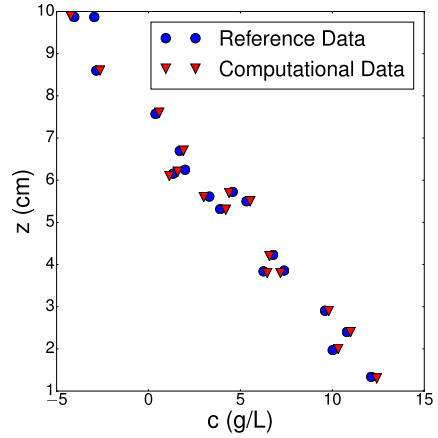
Furthermore, the present computational model has been validated with the work of Li and Davies (1996) for combined wave-current flows. The flow conditions used here are

Table 8 Flow conditions for the plots presented in Fig. 3

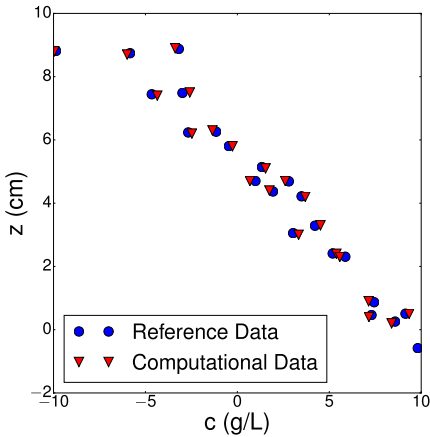
Cases	Net current (m/s)	Wave velocity amplitude (m/s)	Wave period	Net transportation rate ($\times 10^{-6}$)(m ² /s)
Case 1	0.15	1.60	7.2	107.2
Case 2	0.20	1.35	7.2	111.8
Case 3	0.30	1.10	7.2	80.8
Case 4	0.45	0.90	7.2	84.4



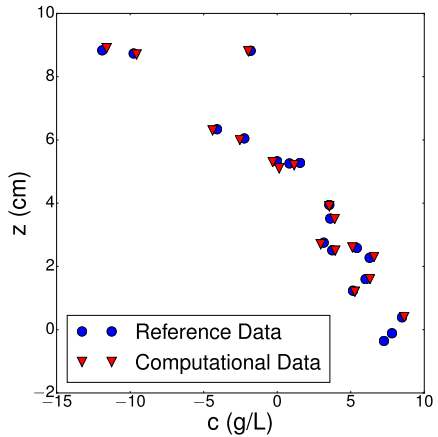
(a) case1



(b) case2



(c) case3



(d) case4

Fig. 3 Validation of z versus c plot with the work of Li and Davies (1996)

presented in Table 8. Figure 3 shows the plots of the validation showing the variation of suspended sediment concentration at different distances from the bed. The Fig. 3 shows that the present computational model is able to satisfactorily predict the experimental results obtained by Li and Davies (1996).

4 Conclusion

The continuity, momentum and interphase equations are solved using the finite volume method. The volume of fluid method is being employed to track the interface. The solver is developed with the aid of the PIMPLE algorithm. The simulation data computed from the hydroFOAM solver is used for the simulation of the sedimentTransportFOAM solver. The resulted data from the sedimentTransportFOAM is used to analyze the sediment transport phenomenon.

4.1 Key lessons learnt

The hydroFOAM solver successfully captures the wave-current phenomenon, the code has been validated with the works of Umeyama (2011) for combined wave-current flows without the presence of any structure. The sediment transport cases are successfully validated with the works of Sumer et al. (2003) for steady current condition, Ribberink and Al-Salem (1994) for wave only flow conditions and Li and Davies (1996) for combined wave-current flows. The developed model predicts very well the hydrodynamics and sediment transport phenomenon in river and coastal engineering applications.

4.2 Future work

The code will be further employed to investigate hydrodynamic scour and design bridge piers resistant to flow-induced vibrations, instabilities, and erosion. In the future, there are plans to incorporate smoothed particle hydrodynamics (SPH) into the current framework for analyzing particle-level scour predictions and also develop a coupled three-phase sediment transport module.

Appendix A: MULES

The multidimensional universal limiter for explicit solution (MULES) technique as described in Sect. 2.1 is presented here. The Eq. (5) can be written in the following form:

$$\frac{\partial A}{\partial t} + \nabla \cdot \mathbf{B} = 0 \quad (28)$$

The Eq. (28) can be discretized and written in the following form:

$$\frac{A_i^{n+1} - A_i^n}{\Delta t} V + \sum_f (\mathbf{B}^n \cdot \mathbf{S})_f = 0 \quad (29)$$

The Eq. (29) can be expressed with flux-corrected transport schemes. A sample one-dimensional simple flux-corrected transport scheme is presented below for the reference of the reader.

$$A_i^{n+1} = A_i^n - \frac{\Delta t}{V} \left(B_{i+\frac{1}{2}}^L - B_{i-\frac{1}{2}}^L \right) - \frac{\Delta t}{V} \left(\lambda_{i+\frac{1}{2}} C_{i+\frac{1}{2}} - \lambda_{i-\frac{1}{2}} C_{i-\frac{1}{2}} \right) \quad (30)$$

A sample MULES function used in OpenFOAM is presented below:

```
MULES::correct
(
  alpha1,
  alphaPhi,
  talphaPhiCorr0.ref(),
  1,
  0
)
```

Appendix B: Turbulence modeling

The OpenFOAM framework has three different types of turbulence modeling provided with the package which are being rendered in the hydroFOAM and sedimentTransportFoam solver. These are Reynolds averaged simulation (RAS), detached eddy simulation (DES), and large eddy simulation (LES). The details of the implementation of all these models are presented in the OpenFOAM documentation (<https://www.openfoam.org/>). $k - \epsilon$ turbulence model is being presented here for the reference of readers. Two transport-equation for linear-eddy-viscosity turbulence closure model are as follows:

$$\frac{D}{Dt}(\rho k) = \nabla \cdot (\rho D_k \nabla k) + P - \rho \epsilon \quad (31)$$

where D_k is effective diffusivity of k , P is turbulent kinetic energy production rate, ϵ is turbulent kinetic energy dissipation energy rate.

$$\frac{D}{Dt}(\rho \epsilon) = \nabla \cdot (\rho D_\epsilon \nabla \epsilon) + \frac{C_1 \epsilon}{k} \left(P + C_3 \frac{2}{3} k \nabla \cdot \mathbf{u} \right) - C_2 \rho \frac{\epsilon^2}{k} \quad (32)$$

where D_ϵ is effective diffusivity for ϵ and C_1 , C_2 , and C_3 are model coefficients.

The above Eqs. (31) and (32) are solved using numerical methods. The $k - \epsilon$ model is extensively used to predict the turbulence modeling influence in the flow domain.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

- Abdelzaher, M. A. (2022). Performance and hydration characteristic of dark white evolution (DWE) cement composites blended with clay brick powder. *Egyptian Journal of Chemistry*, 65(8), 419–427.
- Abdelzaher, M. A., & Shehata, N. (2022). Hydration and synergistic features of nanosilica-blended high alkaline white cement pastes composites. *Applied Nanoscience*, 12(5), 1731–1746.
- Afzal, M. S., Holmedal, L. E., & Myrhaug, D. (2021). Sediment transport in combined wave-current seabed boundary layers due to streaming. *Journal of Hydraulic Engineering*, 147(4), 04021007.
- Babaeyan-Koopaei, K., Ervine, D., Carling, P., & Cao, Z. (2002). Velocity and turbulence measurements for two overbank flow events in river Severn. *Journal of Hydraulic Engineering*, 128(10), 891–900.
- Benkhaldoun, F., Sahmim, S., & Seaid, M. (2009). Solution of the sediment transport equations using a finite volume method based on sign matrix. *SIAM Journal on Scientific Computing*, 31(4), 2866–2889.
- Chauchat, J., Cheng, Z., Nagel, T., Bonamy, C., & Hsu, T.-J. (2017). SedFoam-2.0: A 3-D two-phase flow numerical model for sediment transport. *Geoscientific Model Development*, 10(12), 4367–4392.
- Dustegir, M.M., Rahman, M.M., Haque, A., Rahman, A., Nakagawa, H., Takebayashi, H., & Hao, Z. (2018). Morphodynamic responses of the jamuna against long term stabilization.
- Dutta, D., Afzal, M. S., & Alhaddad, S. (2023). 3D CFD study of scour in combined wave-current flows around rectangular piles with varying aspect ratios. *Water*, 15(8), 1541.
- Dutta, D., Bihs, H., & Afzal, M. S. (2022). Computational fluid dynamics modelling of hydrodynamic characteristics of oscillatory flow past a square cylinder using the level set method. *Ocean Engineering*, 253, 111211.
- Elkhouly, H. I., Abdelzaher, M., & El-Kattan, I. M. (2021). Experimental and modeling investigation of physicochemical properties and firing resistivity of cement pastes incorporation of micro-date seed waste. *Iranian Journal of Science and Technology Transactions of Civil Engineering*. <https://doi.org/10.1007/s40996-021-00760-2>
- Engelund, F. (1953). On the laminar and turbulent flows of ground water through homogeneous sand. Akad. for de Tekniske Videnskaber
- Engelund, F., & Fredsøe, J. (1976). A sediment transport model for straight alluvial channels. *Hydrology Research*, 7(5), 293–306.
- Gautam, S., Dutta, D., Bihs, H., & Afzal, M. S. (2021). Three-dimensional computational fluid dynamics modelling of scour around a single pile due to combined action of the waves and current using level-set method. *Coastal Engineering*, 170, 104002.
- Hung, M., Hsieh, T., Wu, C., & Yang, J. (2009). Two-dimensional nonequilibrium noncohesive and cohesive sediment transport model. *Journal of Hydraulic Engineering*, 135(5), 369–382.
- Jacobsen, N. G., Fuhrman, D. R., & Fredsøe, J. (2012). A wave generation toolbox for the open-source CFD library: Openfoam®. *International Journal for Numerical Methods in Fluids*, 70(9), 1073–1088.
- Jian, J., & Chen, H. (2019). Advance of research on the numerical simulation of sediment transport in the Yellow River estuary. *Earth Sciences Research Journal*, 23(4), 379–383.
- Kitsikoudis, V., Sidiropoulos, E., & Hrisanthis, V. (2015). Assessment of sediment transport approaches for sand-bed rivers by means of machine learning. *Hydrological Sciences Journal*, 60(9), 1566–1586.
- Kraft, S., Wang, Y., & Oberlack, M. (2011). Large eddy simulation of sediment deformation in a turbulent flow by means of level-set method. *Journal of Hydraulic Engineering*, 137(11), 1394–1405.
- Kumar, L., & Afzal, M. S. (2023). Numerical simulations of scour around vertical wall abutments with varying aspect ratios under combined waves and current flows. *Journal of Marine Science and Engineering*, 11(10), 1886.
- Kumar, L., & Afzal, M. S. (2023). Experimental and numerical modelling of scour at vertical wall abutment under combined wave-current flow in low KC regime. *Ocean Engineering*, 285, 115394.
- Kumar, L., & Afzal, M. S. (2023). A review of the state of research on bridge pier scour under combined action of waves and current. *Acta Geophysica*, 71(5), 2359–2379.
- Lai, Y. G., & Wu, K. (2019). A three-dimensional flow and sediment transport model for free-surface open channel flows on unstructured flexible meshes. *Fluids*, 4(1), 18.

- Li, Z., & Davies, A. G. (1996). Towards predicting sediment transport in combined wave-current flow. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 122(4), 157–164.
- Meyer-Peter, E., Müller, R. (1948). Formulas for bed-load transport. In: IAHSR 2nd Meeting, Stockholm, Appendix 2. IAHR
- OLAFOAM: olafow solver. <https://openfoamwiki.net/index.php/Contrib/sedfoam>
- Pradhan, A., Arif, M. R., Afzal, M. S., & Gazi, A. H. (2022). On the origin of forces in the wake of an elliptical cylinder at low Reynolds number. *Environmental Fluid Mechanics*, 22(6), 1307–1331.
- Prasad, D. H., & Kumar, N. D. (2014). Coastal erosion studies-a review. *International Journal of Geosciences*. <https://doi.org/10.4236/ijg.2014.53033>
- Priyadarsan, A., & Afzal, M. S. (2023). Numerical investigation of flow past a circular cylinder modified with a single groove at low Reynolds number. *Physics of Fluids*. <https://doi.org/10.1063/5.0137530>
- Ranasinghe, R., & Turner, I. L. (2006). Shoreline response to submerged structures: A review. *Coastal Engineering*, 53(1), 65–79.
- Ribberink, J. S., & Al-Salem, A. A. (1994). Sediment transport in oscillatory boundary layers in cases of rippled beds and sheet flow. *Journal of Geophysical Research: Oceans*, 99(C6), 12707–12727.
- Rijn, L. C. V. (1984). Sediment transport, part ii: Suspended load transport. *Journal of Hydraulic Engineering*, 110(11), 1613–1641.
- Schlichting, H., & Gersten, K. (1979). *Boundary-layer theory*. New York: McGraw Hill.
- Singh, V. (2005). Two dimensional sediment transport model using parallel computers.
- Sukhinov, A., Chistyakov, A., & Protsenko, E. (2014). Mathematical modeling of sediment transport in the coastal zone of shallow reservoirs. *Mathematical Models and Computer Simulations*, 6(4), 351–363.
- Sumer, B. M., Chua, L. H., Cheng, N.-S., & Fredsøe, J. (2003). Influence of turbulence on bed load sediment transport. *Journal of Hydraulic Engineering*, 129(8), 585–596.
- The OpenFOAM Foundation: OpenFOAM Documentation. <https://www.openfoam.org/>
- Umeyama, M. (2011). Coupled piv and ptv measurements of particle velocities and trajectories for surface waves following a steady current. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 137(2), 85–94.
- Van Rijn, L. C. (1984). Sediment transport, part i: Bed load transport. *Journal of Hydraulic Engineering*, 110(10), 1431–1456.
- Weller, H. G., Tabor, G., Jasak, H., & Fureby, C. (1998). A tensorial approach to computational continuum mechanics using object-oriented techniques. *Computers in Physics*, 12(6), 620–631.
- Wu, W. (2004). Depth-averaged two-dimensional numerical modeling of unsteady flow and nonuniform sediment transport in open channels. *Journal of Hydraulic Engineering*, 130(10), 1013–1024.
- Yoyurob, S., & Liengcharernsit, W. (2011). Development of sediment transport model and its application to Songkhla lake basin. *Lowland Technology International*, 13(2), 25–34.

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