Entrainment of Sediment Particles in Protection Layers

Mandviwalla, Xerxes; Christensen, Erik Damgaard

Published in:
Journal of Hydraulic Engineering

Link to article, DOI:
[10.1061/\(ASCE\)HY.1943-7900.0001898](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001898)

Publication date:
2021

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Mandviwalla, X., & Christensen, E. D. (2021). Entrainment of Sediment Particles in Protection Layers. *Journal of Hydraulic Engineering*, 147(10), [04021040]. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001898](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001898)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Entrainment of sediment particles in protection layers.

Xerxes Mandviwalla¹, Erik Damgaard Christensen²

Abstract

Protection layers are often used to prevent scour and erosion, e.g. prevention of scour around wind turbine foundations. However, several cases exist where installed scour protection has settled, where loss of sediment through the armour layer can explain the failure. This paper presents the use of a detailed LES-DEM model to study sediment particles in porous media. Firstly, a simple idealised case was setup of the removal of sediment from an idealised cavity beneath a smooth turbulent boundary layer. The model showed the penetration of turbulence, mainly in the form of sweep events, into the cavity. This high momentum would at times reach the bottom and entrain the fine sediments. The sediment would subsequently roll over and form a pile and at times be suspended from the return flow of the penetrating turbulence. Finally, a more realistic armour layer was set up with a series of closely packed spheres. Fine sediments were seeded at the bed. A hydraulically rough boundary layer was developed over the armour layer, where turbulent statistics from the model compared well against experiments. Turbulent structures characteristic to the bursting process were identified in the rough wall case. The penetration of sweep events entrain and suspending the finer sediments was detailed. The flushing of cavities from passing ejection events was also presented.

Introduction

Large porous structures are used in for instance stone covers for pipelines, scour protection, armour- and filter layers in rubble mound breakwaters. They present an area where currents, waves and turbulence often have a large influence on the structural design. Studies of porous structures are generic in nature as porous structures often are an

¹ Senior Research Engineer, DHI, Port and Offshore Department, Agern Alle' 5, DK-2970 Hørsholm, Denmark. E-mail: xem@dhigroup.com

² Professor, Head of Section, Technical University of Denmark, DTU-MEK, Nils Koppels Alle', Building 403, DK-2800 Kgs. Lyngby, Denmark, (Corresponding Author), E-mail: edch@mek.dtu.dk

important part of common hydraulic, coastal and offshore structures. New protection measures such as artificial reefs that apart from acting as coastal protection also support recreational activities such as surfing, fishing, and diving activities might increase the use of porous structures. Porous structures can also be seen in other structures such as fish cages, (Chen and Christensen 2018), floating breakwaters (Christensen et al. 2018) and in studies of porous bed as in (Corvaro et al. 2010), and (Nielsen et al. 2013). The failure of scour protection due to winnowing of sediment was studied in (Nielsen et al. 2011).

In order to mitigate against scour, a scour protection can be installed. This typically comprises of dumped stones around the structure. The protection works to armour the finer sediment grains from the enhanced bed stresses applied from the hydrodynamic mechanisms mentioned in the previous section. Design of the scour protection is site specific depending on the hydrodynamic conditions. The protection layer can failure in three ways; loss or movement of the protection stones, winnowing or suction removal of finer, and edge scour. Edge scour occurs at the perimeter of the protection layer, wherein the event of a scour hole development can cause stones of the protection layer to be become unstable, (Petersen et al. 2012, 2015). Such a loss of material can result in sinking of the armour stones. Winnowing between armour layers has been studied experimentally for current, waves and breaking waves (Dixen et al. 2008; Nielsen et al. 2013; Sumer et al. 2001). The loss of cover stones occurs when the critical Shields parameter for the rocks in the protective layer is exceeded, causing the material to displace. One can design a static scour protection using the critical Shields criteria, a ratio of agitation force of the shear stress over the stabilizing immersed weight of the protective stones. In the case of a monopile, the amplification of the shear stress around the pile has been studied extensively, in both experimental and numerical tests (Baykal et al. 2015; Roulund et al. 2005; Sumer et al. 1997). Another design approach was presented in (De Vos et al. 2012). This criterion allows for some movement or allowable damage of the protection layer in order to be less conservative than a design that would be derived based on a critical Shields parameter (i.e. ensuring no movement).

During recent years studies of flow in porous media with large eddy simulations have enlightened detailed flow features over an inside the porous media as the following examples show. (Liu and Prosperetti 2011) studied the finite-Reynolds-number three-dimensional flow in a channel bounded by one and two parallel porous walls. The porous

medium was modelled by spheres in a cubic arrangement. The results showed that lift force acts on the spheres. Further, slip velocity at the surface of the porous layers was analysed. In (Liu et al. 2017) the results of a large eddy simulation of the flow over an array of wall-mounted boulders placed on a rough, permeable bed was studied. First- and second-order turbulence statistics obtained through laboratory data validated the numerical simulations. (Mazzuoli and Uhlmann 2017) conducted direct numerical simulation of open-channel flow over a bed of spheres arranged in a regular pattern. Bulk Reynolds number and roughness Reynolds number (based on sphere diameter) were approximately 6900 and 120, respectively, for which the flow regime was fully rough. (Kuwata and Suga 2017) investigated components of the anisotropic permeability tensor of porous media to understand what influences turbulence over porous walls. (Fang et al. 2018) investigated the effects of bed permeability on the turbulent characteristics of macro-rough flow at a high Reynolds number. Large-eddy simulation (LES) of flows over three cases with different permeability values having the identical structure of surface elements was conducted.

The removal of sediment from a cavity in a hydraulically rough current boundary layer was described by (Sumer et al., 2001) from experimental observations. Here the rough boundary layer was created from a stone cover placed on the bed of a hydraulic flume. For visualizing the removal mechanism, a single particle was placed in between a stone cavity and the subsequent removal into the main flow was described from simultaneous flow visualization and Laser Doppler Anemometry (LDA) velocity measurements of both stream-wise and vertical velocity. The described mechanism for the removal of the particle was due to initial entrainment from a vortex formed within the cavity, followed by an ejection for the vortex and the particle. Experiments using sand instead of a single particle were also performed and provided in the paper where the same process was visualized. The accompanying LDA measurements revealed a correlation of the streamwise and vertical fluctuations in the cavity, following the removal of the vortex. (Zhao et al. 2020) investigated the influence of particle shapes on the characteristics of particle saltation and, thereby, to improve the accuracy of existing bedload transport formulas, the numerical simulation results concerning saltation characteristics of variously shaped particles over a flatbed were analyzed. The study (Sumer et al. 2001) gave fundamental insights to suction of particle between armour blocks. Still, the reason

for the ejection of the vortex remained unclear. This was partly the motivation for the following CFD analysis. Further, the present studies is expected to shed light over the possibilities of using a coupled Computational Fluid Dynamics – Discrete Element Method (CFD-DEM) model CFD-DEM model to analyse basic sediment transport processes inside large porous media as for instance armour protection layers.

The following chapter outlines the CFD-DEM model to gain insight into the transport of sediment particles from their interaction with turbulent eddies. This is followed with a case of an idealized cavity under a turbulent boundary layer where sediment particles are placed initially at the bottom of the cavity. Then, a more realistic application is presented where a turbulent rough boundary layer is modelled over the closely packed arrangement of armour spheres on a bed. Finally, the study is summarized and concluded.

Numerical Methodology

The model meshing and numerical calculations were performed using the C++ CFD toolbox OpenFOAM® (OF) (“OpenFOAM, The open source CFD toolbox” 2018). The following section outlines the implemented turbulence model, boundary conditions and sediment transport models within the OpenFOAM framework.

Flow equations

The CFD model is a Large Eddy Simulation (LES) model solving the spatially filtered Navier Stokes Equations as presented in eqs. (1), and (2):

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{\partial \overline{u'_i u'_j}}{\partial x_j} + F_{BF} \quad (1)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2)$$

where u_i is the filtered or resolved component of velocity, u'_i is the component of the unresolved subgrid velocity, p is the filtered pressure and ν is the kinematic viscosity of the fluid. The term F_{BF} in eq. (1) represents a body force term, which in the case of a steady current can be equated to the friction velocity u_f as follows:

$$F_{BF} = u_f^2 / h \quad (3)$$

where h is the height of the channel.

Closure for the third term on the right hand side of eq. (1) which accounts for the unresolved subgrid stresses (SGS) was approximated by the Boussinesq approximation, which is analogous to Newtons' law of friction:

$$\overline{-u'_i u'_j} = \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (4)$$

Where ν_t is the subgrid eddy viscosity, which accounts for the turbulence which is unresolved by the numerical grid. The eddy viscosity ν_t is modelled by the Smagorinsky Model (Smagorinsky 1963), which is derived from the Prandtl's mixing length model as follows:

$$\nu_t = C_s^2 \Delta^2 s \quad (5)$$

Where Δ is the filter width, defined in this model by the dimensions of the grid cells as:

$$\Delta = (\Delta x \Delta y \Delta z)^{\frac{1}{3}} \quad (6)$$

The parameter s in eq. (6) is defined as:

$$s = (2S_{ij}S_{ij})^{\frac{1}{2}} \quad (7)$$

Where S_{ij} is the strain rate tensor:

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (8)$$

C_s is the Smagorinsky constant. This is evaluated dynamically at each grid cell by the method of (Lilly 1992), which improves the original dynamic method of (Germano et al. 1991).

The solution is based on a finite volume discretization, where pressure-velocity coupling was solved using the Pressure Implicit with Splitting Operator (PISO) ((Ferziger and Peric' 2002)) algorithm. The time-integration was the 2nd order upwind Euler (called backward in OpenFOAM), see (Lee 2017). The Gauss linear Upwind (LUD) resolved the convective terms, while central differences was used for diffusive terms. This leads to a spatial resolution close to second order. The pressure equation that can be derived from the continuity equation was solved using Geometric-Algebraic Multi-Grid solver (GAMG), while the momentum equations, eq. (1), were solved using preconditioned bi-conjugate gradient solver (PBICG). As preconditioner the incomplete LU (DILU) was used for the momentum equations eq. (1). More details on temporal discretization and time integration is available in (Moukalled et al. 2016).

DEM equations

The DEM equations solve Newton's second law for each spherical particle to calculate the translation and rotation. For every i^{th} particle eqs. (9), and (10) are solved.

$$m_i \frac{d\mathbf{u}_{p_i}}{dt} = \mathbf{F}_{F_i} + \sum_{j=1}^n \mathbf{F}_{G_{i,j}} + m_i \mathbf{g} \quad (9)$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^n \mathbf{M}_{T_{i,j}} \quad (10)$$

Where $\mathbf{u}_p$, $\boldsymbol{\omega}_i$ are the particle translational and rotational velocity respectively, I_i is the rotational inertia, m_i is the particle mass and $\mathbf{M}_{T_{i,j}}$ is the torque applied from the tangential contact of the neighbouring j^{th} particle or wall (Zhu et al. 2007)

The second term on the right hand side of eq. (9) is the force on the i^{th} particle from the collisions of the neighbouring n particles, while the contribution from gravity is represented by the third term.

The force from the fluid on the particles $\mathbf{F}_{F_i}$ in eq. (9) was modelled as the combined contribution of drag force, pressure gradient force and buoyancy force in eq. (11). Other forces such as the inertia and Basset force are neglected, similar to other investigators using similar models as these contributions were considered small for finer sediments (Liu et al. 2016), (Pedinotti et al. 1992) and difficult to correctly compute (Schmeeckle 2014).

$$\mathbf{F}_{F_i} = \mathbf{F}_{D_i} + \mathbf{F}_{PG_i} + \mathbf{F}_{B_i} \quad (11)$$

The drag force contribution F_{D_i} is modelled as:

$$\mathbf{F}_{D_i} = \frac{1}{8} \pi \rho C_d d^2 |\mathbf{u} - \mathbf{u}_p| (\mathbf{u} - \mathbf{u}_p) \quad (12)$$

Where d is the diameter of the particle, ρ is the density of water, $\mathbf{u}$ is the resolved velocity vector and $\mathbf{u}_p$ is the velocity vector of the particle. C_d is the drag coefficient defined by a modified Schiller-Naumann model presented in (Schmeeckle 2014) for application in sediment transport defined as:

$$C_d = \left(0.9 + \frac{4.8}{\sqrt{Re_p}} \right)^2 \quad (13)$$

Where Re_p is the particle Reynolds number:

$$Re_p = \frac{|\mathbf{u} - \mathbf{u}_p| d}{\nu} \quad (14)$$

A force balance was set-up for, gravity, buoyancy and the specified drag force that estimated the fall velocity. With the specified sediment grain, this gave a fall velocity of 0.008 m/s. Using Soulsbys empirical formula, (Soulsby 1997), gave 0.009 m/s. This made us confident that the method described in (Schmeeckle 2014) well represented the drag force.

From eq. (11) F_{PG_i} is the pressure gradient force contribution:

$$\mathbf{F}_{PG_i} = -V_{p_i} \nabla p \quad (15)$$

Where V_{p_i} is the volume of the i^{th} particle and p is the pressure linearly interpolated to the particle centre from the CFD grid. Lastly, the buoyancy force contribution $\mathbf{F}_{B_i}$ in eq. (11) is:

$$\mathbf{F}_{B_i} = -V_{p_i}(\rho_s - \rho)\mathbf{g} \quad (16)$$

Where ρ_s is the particle density and $\mathbf{g}$ is the gravity vector.

The force contribution from collisions between other particles and walls are modelled with a spring and dashpot type model accounting for the normal and tangential components. Details of the Hertz–Mindlin formulation used can be found in (Zhu et al. 2007). The basset force was not included in eq. (11). However it should be emphasized that research, (Bombardelli et al. 2008), indicate that it can have a significant effect on particle paths.

The purpose of the model is to use the particles more like tracer to highlight the sediment transport mechanisms. Therefore, the model is very basic in this respect and does not go into details of comprehensive modelling of for instance particle-particle and particle-wall interactions.

Boundary conditions

The applied boundary conditions on the geometry presented include cyclic conditions which pair the ‘IN’ and ‘OUT’ boundaries as well the ‘SIDE 1’ and ‘SIDE 2’ boundaries for all hydrodynamic variables. The ‘TOP’ boundary is modelled with a slip condition that models the surface as a solid frictionless boundary, while the ‘BOTTOM’ boundary is modelled as a solid no-slip boundary, see Figure 1.

Refinement in the vertical direction was geometrically graded with finer cells towards the friction no-slip boundary BOTTOM and WALL, where the cell centre of the

first cell was positioned within the viscous sub-layer. As the viscous sub-layer was resolved the dynamic LES Model does not need the use of ad hoc damping functions.

Boundary conditions for DEM

Boundary conditions for the DEM model apply 'periodic' conditions on the 'IN', 'OUT', 'SIDE 1' and 'SIDE 2' boundaries, this means that for example, a particle leaving the 'OUT' boundary will re-enter the domain via the 'IN' boundary. The 'BOTTOM' boundary is applied as a solid wall to the particles. The grain diameter of the particles was set to $d = 0.14 \text{ mm}$, resembling fine sand sediment, with a density of 2000 kg/m^3 . Other parameters were based on values provided by (Schmeeckle 2014).

Computational domain and meshing strategy

Cavity tests

To initiate the study of removal of sediment from an armour layer, a simple cavity geometry was set up as presented in Figure 2. The hydraulically smooth boundary layer was applied with the addition of a square cavity in the centre of the bottom. Sediment particles were placed at the bottom of the cavity, in order to observe the removal and identify the responsible fluid mechanisms. The figure illustrates the main mean flow structures within the cavity. Similar to the classical cavity flow problem, a clockwise vortex is formed from the shear of the passing boundary layer overhead. Due to the depth of the channel, a secondary (weaker) vortex is formed which makes contact to the bottom of the cavity.

The depth of the cavity, D_{cavity} , as presented in Figure 2 was calculated as $D_{cavity} = 0.7D$ relating to the height of a theoretical wall of a layer comprising of stones of diameter $D = 0.0385 \text{ m}$. Stones of this size were used in the study (Test14 - (Sumer et al. 2001)) to study suction removal of sediment between armour stones in a current. The width was selected as a quarter of the total diameter of the stone, this was based on the work of (Dixen et al. 2008), where the ratio $G/D = 0.25$ of gap width to depth of an arrangement of square blocks gave equivalent protection to a layer comprising of real stones. It should be noted that this was attained from experiments under oscillating conditions; however, these dimensions were used as a starting point for the cavity geometry.

The water depth was 0.06 m and also 0.06 in the transverse direction. The length in the flow direction was 0.116 m. The cavity was 0.027 m deep and 0.00963m wide. The Reynolds number was $Re = 20000$. The cavity was resolved with $23 \times 69 \times 91 = 144417$ cells. A total number of computational hexagonal cells of 1376481 resolved the total domain. The grid was stretched towards the channel bottom where the $\Delta z = 0.0002$ m. 15000 sediment particles were placed in the bottom of the cavity.

Spherical Armour Layer

The spherical elements were placed in a closely packed configuration as presented in Figure 3, similar to the experimental setup of (Defina 1996), where the low-speed wall streaks were investigated over a rough bed.

Dimensions for the channel are $7D \times 4D \times 3D$ in the stream wise, lateral and vertical directions respectively. The diameter of the cross-section of the diameter of the spheres is $D = 0.0385$ m. These dimensions are inadequate to resolve several low-speed wall streaks, where the distance between the streaks $k_s^+ \sim (1000)$ for a hydraulically rough wall, of roughness height (k) is roughly equal to (Grass et al. 1991):

$$\lambda/k \approx 3 \quad (17)$$

The small domain was constructed due to limited computing resources, required to solve the large domain that would accommodate a few low-speed streaks. Despite this, the present small model was still able to reproduce reasonable turbulence statistics as presented in the results chapter.

The computational mesh was constructed using OpenFOAM's automatic mesh generator snappyHexMesh. This produces a mesh with predominantly hexahedral elements. The surface of the roughness elements is input to snappyHexMesh as a CAD Stereolithography (.stl) file.

Figure 4 shows a close-up of the mesh from the side, where the grading of the elements in the vertical direction have the smallest elements in the vicinity of the theoretical wall ($\Delta y = 0.7D$). This meshing strategy was adopted in order to resolve the steep gradient of the mean velocity profile. Conforming of the elements to the rounded surface of the sphere by 'snapping' was avoided as to not reduce the quality of the overall mesh, the jagged surface of the individual spherical elements was deemed accepted for the present model investigation. The immersed boundary model as used in for instance (Jensen et al. 2017), could have alternatively been used for the description of the stone

spheres. However, due to the large computational resource of the LES runs, and the potential further optimisation of the immersed boundary method in parallel, we decided that the initial investigations to be carried out using established and standard methods readily implemented in OpenFOAM.

The mesh used for the current model comprised of 5 million cells which were distributed over 64 computational cores on a high performance cluster. The Reynolds number was 60000 and 22000 based on depth h , mean velocity and viscosity. The finest grid with smallest cells located around the spheres had grid resolution of $\Delta z^+ = 2.0$ for the low speed flow and $\Delta z^+ = 14.0$. In the two horizontal directions grid spacing was the double. Further away from the spheres the grid size was twice as large in each direction.

The DEM mesh also used periodic conditions for the channel sides, with bed and stone geometry as solid walls. The fluid flow was simulated without coupling to the DEM model until converged turbulent statistics were attained. The time step was 0.0003 s. The total simulation time with fully developed flow was 400 s for the low flow case and around 20 s for the high flow case. Through autocorrelation analyses, this was found sufficient, and even considered to the safe side. The statistics of turbulent fluctuations were used as the final documentation.

Results

Driven cavity

Figure 5 shows a sequence of vertical slices of the channel and cavity where vectors showing velocity fluctuation, derived from Reynolds decomposition are presented. Sweep and ejection events are highlighted by light and dark contours respectively from the shear flow above the cavity. Surface-bound streamlines show the flow pattern within the cavity with the direction arrows. The figure plots instances of successive penetrating sweep events into the upstream end of the cavity. The snapshots show the development of the flow within the cavity, especially the lower anti-clockwise rotating bottom vortex. Frame C) of the sequence shows a direct path from the entrance point of the fluid at the top of the cavity to the bottom.

Figure 6 shows a snapshot of Figure 5 after C), where the developed flow formation starts to entrain the bottom particles into the bottom anti-clockwise vortex. The particles

are transported toward the wall, and as they interact and roll over each other are more exposed to the bottom vortex, where they are transported towards the downstream end of the cavity. Figure 7 shows the sediment transported from the bottom vortex to the upper vortex of the cavity. Particles are ‘sucked’ out of the cavity by a passing ejection event, marked by the dark contours.

The experiments of (Sumer et al. 2001) provided a criteria for the initiation of suction removal of sediment between armour stones exposed to current only flow conditions. Figure 8 plots the data from the experiments with respect to the Shields parameter, $\theta = \frac{u_f^2}{\rho(s-1)d}$, for the sediment grains, and the ratio of sediment grains to armour stone diameter, d/D . Cases for the cavity outlined in this section are plotted for a scenario where sediment grains were removed from the cavity, fulling the ‘suction’ criteria and a case where no grains were removed (‘no suction’). The case of a flatbed where the ratio, $d/D = 1$, equivalent to sediment transport of a flat bed with no armouring effect.

Spherical Armour Layer

Model Setup and Validation

A body force was used to drive the flow and was calculated by eq. (3), where the flow depth ($h = 0.08855 \text{ m}$) was determined by taking the total channel height ($3 D$) away from the estimated theoretical bed level ($0.7D$), as used in (Sumer et al. 2001) for stones of similar size. Two flows were simulated one of a very rough hydraulic roughness where $k_s^+ \cong 1600$ and one of moderate roughness $k_s^+ \cong 230$, where $k_s^+ = \frac{k_s u_f}{\nu}$. Due to the non-uniform geometry, the flow was sampled over seven evenly spaced probes, such that a spatial and temporal average could be performed.

The fit of the spatially and temporal averaged velocity profile to the following rough logarithmic law:

$$\frac{u}{u_f} = \frac{1}{\kappa} \ln \left(\frac{30(y' + \Delta y)}{k_s} \right) \quad (18)$$

where Δy is the shift of the vertical axis from the bed to the theoretical wall, where the shift is determined to form the largest logarithmic layer and y' is the vertical coordinate from the bed and $y = y' + \Delta y$ is the distance from the theoretical wall. The Nikuradse sand equivalent roughness k_s was also determined from the logarithmic fit, where the value $\frac{k_s}{D} = 0.78$ was determined for $k_s^+ = 230$, (intercept from Figure 10), values from

other investigators for spherical layers include $\frac{k_s}{D} = 0.82$ (Grass et al. 1991), $\frac{k_s}{k} = 0.77$ (Singh et al. 2007), and $\frac{k_s}{D} = 0.67$ (Defina 1996).

Figure 9 compares the mean turbulent flow statistics against (Grass 1971) and (Sumer et al. 2001), for the turbulent quantities. The plot shows two sets of results from the LES model, one for a non-dimensional roughness height of moderate roughness, $k_s^+ = 230$, and the other for a high roughness of $k_s^+ = 1600$. A reasonable agreement is attained from the calculations. Figure 10 shows a comparison of the simulated mean flow to a logarithmic fit, which is in good agreement.

Figure 11 shows one dimensional energy spectra at approximately $\frac{y}{h} = 0.2$. The spectra were elaborated from time-series in one position above the bed. Other positions have also been analysed and showed basically the trends in the area where we expected to be in the logarithmic layer. In this area an inertial subrange is expected to be a part of the spectrum. According to Kolmogorov's theory, (Kolmogorov 1991), (original from 1941 in Russian), the slope of the spectrum should be $\sim k^{-5/3}$, which in the frequency space under the assumption of the Taylors frozen turbulence approximation corresponds to $\sim f^{-5/3}$. In both cases this range can be identified in the figure. This indicated that the computational set-up including the grid-resolution was sufficient to resolve the main characteristics of the flow.

Flow Features

As in a case with a smooth wall, the bursting process is evident in the hydraulically rough wall case where alternating low and high-speed streaks are features in the near wall region. Figure 12 plots a contour of instantaneous velocity magnitude positioned above the spherical elements at $\frac{y}{D} = 0.58$, which in accordance with (Sumer and Deigaard 1981) is within the region of fluid ejections for a rough wall, $0.5 < \frac{y}{D} < 2$, , again noting that in the rough wall case y is the distance from the theoretical wall. From Figure 12 we observed the presence of a low speed streak by the blue coloured contours between two higher speed streaks.

Vortices

For a fully rough turbulent boundary layer, turbulence is produced from the gradient in the mean velocity profile, as well as additional turbulence from the vorticity created around the roughness elements.

Vortices created from the fluid interaction with the spherical elements are visualised using contours of the Q-criterion, (Hunt et al. 1988) in Figure 13 for the flow case of non-dimensional roughness $k_s^+ = 230$. The figure presents an instance in time, where coherent structures such as a horseshoe, elongated, and a hairpin vortices are visible. The horseshoe vortex much like the rolled up shear layer observed in front of bottom mounted monopile exposed to a current, is presented in the figure with label ‘A’. The vortex spans around the spherical element from the upstream end of the flow. Growth of the vortex and the ultimate shedding of its legs occur on all the spheres at various instances of time. The shed legs can be advected downstream and grow to form the elongated vortices labelled ‘C’ in the figure. A hairpin vortex, which is a common feature of turbulent boundary layers in the near wall region, is also presented with label ‘B’.

These vortex structures were also identified by the work of (Bomminayuni and Stoesser 2011), where LES modelling of rough boundary layers was also performed. It should be noted that the structures presented were harder to identify in the case of the higher roughness flow, $k_s^+ = 1600$, where the vorticity appeared to be more homogenous in shape, possibly due to the larger coherent structures breaking apart from the increased flow velocities.

Sweep and ejection events

At the near wall region of a turbulent boundary layer, the so-called bursting process takes place (Grass 1971; Offen and Kline 1975), which describes the near wall exchange of momentum with bursts of low-speed wall streaks up to the upper layers of the boundary layer preceded by downward directed sweep events. Turbulent events were identified via quadrant analysis. (Willmarth and Lu 1972) showed that you can categorise these turbulent events into four categories or quadrants (Q1-Q4) based upon the correlation of the fluctuations. The methodology can be used to highlight such structures in the flow integral to the Reynolds Stresses.

Figure 14 a) plots an instantaneous velocity slice at $\frac{y}{D} = 0.5$, where the mean flow is going from left to right for the flow conditions $k_s^+ = 1600$. The armour spheres underneath the contour are visible by dashed grey lines. A streak of relatively high momentum is indicated in the upper part of the plot with the yellow contours above a streak of low momentum plotted in blue.

Figure 14 *b*) plots the contours for fluid that is correlated with a sweep event ($u' > 0$ & $v' < 0$), where high momentum is directed towards the stone cover. This, as expected is mainly in the region of the yellow contours presented in Figure 14 A) and C), in contrast, plots contours highlighting the fluid which is correlated to an ejection event ($u' < 0$ & $v' > 0$), where low momentum fluid from the near wall is ejected to the upper layers of the flow. Similarly, the contours from Figure 14 C), are aligned to the low-speed streaks presented in Figure 14 A). This provides evidence that the bursting process is still present at very high roughness flows where $k_s^+ > 1000$.

PIV measurements of flow over stone cover by (Detert et al. 2010), also show the existence of streaks at roughness values above 1000. These streaks are however more clearly defined in the lower roughness range $k_s^+ \cong 200 - 300$. Therefore, the existence of these turbulent structures will result in the exchange of fluid within the stones cover, as was presented in the previous section of turbulent flow above a cavity. This would also have expected implications to the entrainment, suspension and re-deposition of finer sediments of which the spherical armour is used to shield. (Singh et al. 2007) showed from their DNS simulations over a rough bed a high level of mixing below the midplane of the roughness element and the fluid flow above.

Penetration of Turbulence

The following section will detail the penetration of turbulent events into the stone cover layer. It earlier was shown that entrainment of the sediments at the bottom of a square cavity was from the penetration of sweep events from the turbulent flow above. Sweep events were able to penetrate the cavity where it coincided with the mean flow at the upstream end of the cavity. Similarly, in the case of the spherical armour layer, we first identify the time-averaged flow patterns around the roughness elements. Figure 15 shows a stream-wise cross-section slice with projected streamlines onto the contour surface. The figure highlights the point of stagnation 'A' in the front of the spherical element, separation of the flow towards the back 'B' and 'C' a circulating flow field. Red arrows are used to highlight the direction of the flow, showing the parting of the flow from the stagnation point. The density of the streamlines indicate the speeding up of fluid which is visible above the spheres.

Figure 16 shows lateral cross sections in front of and behind spherical elements, plotting streamlines of the time-averaged mean flow, where the streamwise direction is

into the page. From Figure 16 a) the flow pattern upstream of a sphere is presented, shedding light on the flow pattern within the cavity in front of it. The location of the stagnation point labelled 'A' in Figure 15 is shown again in the figure, as well as the circulating feature from Figure 15 labelled 'C'. It can be observed from the highlighted red arrows a downward directed path towards the bed of the mean flow from the edges around the sides of the cavity. This feature is labelled 'D' in the figure. Similarly, Figure 16 b) plots contours for the mean flow downstream of the spheres. Label 'E' on the figure denotes the mean edge of the separating shear layer identified in Figure 15 with label 'B'. The red arrows highlight the direction of the mean circulating flow patterns in the back of the sphere.

With regard to potential entry points for downward directed turbulence into the cavities between the spheres, could most likely occur at points coinciding with downward directed mean flow patterns. Such points could be around the stagnation point denoted by 'A' in Figure 16 a), enhancing the downwards directed flow denoted 'D'. From Figure 16 b), in the downstream cavity downwards directed turbulence could enter via the sides forcing a downwards directed flow pattern.

Figure 17 demonstrates the penetration of high momentum into a cavity. This plot is for the high roughness flow of $k_s^+ = 1600$, at the same time instance as Figure 14, plotting a lateral slice along the stream wise direction $x=0.08m$ (Figure 14). The figure shows contours of instantaneous velocity magnitude, illustrating a clear path from the sweep event (Figure 14 B)), entering the cavity to the left hand side of Figure 16. The injection of fluid into the cavity shows a clear path coinciding with the mean flow presented in Figure 16 a), where the flow enters around point 'A' and reaches the bed by enhancing the flow from fluid structure 'D' labelled in Figure 16 a). The cavity to the right in Figure 17, shows the ejection of fluid linking to the ejection event. It can be observed from the projected streamlines that the sweep event reaches the bottom, having the potential to entrain fine sediments resting at the bed.

Figure 18 plots 3D streamlines showing the penetration of fluid into the downstream cavity, of which the mean flow was depicted in Figure 16 b). The figure shows the same time instance of the instantaneous velocity as in the previous Figure 14 and Figure 17. Here the fluid enters to the side of the cavity and is then pulled out in correspondence to the ejection event overhead. This has also been illustrated on the right

hand side of Figure 17. As opposed to the penetrating event depicted in the upstream cavity in Figure 17, the penetration in the downstream cavity in Figure 18 does not appear to reach the bed, as shown in the side view of the 3D streamlines in the figure. The implication to sediment transport is that such a flow field could eject suspended sediments from the stone cover, however, may less likely entrain the sediment from the bed into suspension.

Sediment Transport

Spherical particles of size, $d = 0.2 \text{ mm}$, were seeded on the bottom of the bed between the armour layers spheres of size, $D = 0.0385 \text{ m}$. These particles were applied to fully developed high roughness flow where $k_s^+ = 1600$. The sediment grains have a Shields parameter of, $\theta = 1.2$, which in accordance to the suction criteria presented in (Sumer et al. 2001) is a state where suction of the finer sediment does not occur but movement does.

Figure 19 shows a sequence of entrainment of the particles (shown in black) from the time instance of the flow depicted previously in Figure 14, Figure 17 and Figure 18. Contours are plotting vertical instantaneous velocity, where downward directed fluid is highlighted in blue. It can be observed from the figure that the sediment starts to spread in circular patterns around downward directed fluid. From the first figure of the sequence it is evident that these penetrative events are in spatial correspondence to the sweep event passing over the stones in Figure 14, and are as illustrated on the right hand side of the lateral cross section in Figure 17. The sequence shows the penetrating events growing in size and spreading the sediment in circular patterns. The final plot in the sequence shows the sediment in piles along the bed. No suspension of the sediments from the bed occurred in this simulation as expected. It should be noted that for the Shields parameter of $\theta = 1.2$, suspension of grains would occur on a flat bed without the presence of armouring.

Figure 20 plots results from a simulation using the same flow field as the previous figure, with particles of size, $d = 0.2 \text{ mm}$, with a Shields parameter of $\theta = 8.2$, where suction removal would be expected according to (Sumer et al. 2001). The figure shows a close-up of a cavity, where similar to the previous figure velocity contours show vertical instantaneous velocity 1 mm above the bed. The size of the sediments in the plot have been exaggerated for better viewing, and are colours according to their vertical height. From Figure 20 A) we can see the penetrating turbulent events in the blue contours

sweeping sediment to the sides in a circular manner. From the edges of these circular contours, one can observe red contour border indicating an upwards directed flow. Between the two penetrating events in front of the armour stone (illustrated partially transparent), suspension is evident from the lighter coloured particles, labelled 'A' in the figure.

These particles are suspended from the return flows from the two events, which will be applying an upward direct force which exceeds the particles submerged weight. Figure 20 B) reveals the interaction of a third event which penetrated and advected from upstream. Sediment is also shown to start to suspend in the interacting area labelled 'B' in this figure. It should be noted that this location of suspension corresponds to the location of the sediment pile formed in the case where suction did not occur (labelled 'B' in Figure 19).

A lateral cross section of the suspending particles in Figure 20 (label 'A'), is shown in Figure 21. Instantaneous velocity shows the penetrating turbulent events and the resulting upward directed return flow in between, where the particles are brought into suspension.

Suction Criteria

The current model shows the removal of sediment (albeit very small amount) at the Shields parameter of $\theta = 3.25$, which is well below the suction criteria outlined from the experiments of (Sumer et al. 2001) of $\theta = 6.65$ for the ratio of sediment to armour size $\frac{d}{D} = 0.005$ used in the present simulations. The reasons for this could be due to the fact that the experiments use a bed of fine sediment, which act as a porous media. Impact of the penetrating turbulent events, which initialise suspension from the bed, would partially penetrate the porous media providing a less pronounced return flow than in the case of a solid wall in the simulations.

Summary and conclusions

The coupled LES-DEM model presented in this study produced detailed descriptions of the interaction between turbulent structures and sediment particles. The analysis started by modelled a deep cavity under a turbulent hydraulically smooth boundary layer. This model is highly idealised and simplification of flow around armours layers, but served as a good 'stepping stone' to the more complex problem. The

mechanism of the suspension and removal of the sediment placed at the bottom of the cavity was observed. Sweep events (downward directed high moment turbulence) was able to penetrate the cavity at its downstream edge from the turbulent boundary layer. This entry point is where the cavity aligns with the mean flow cavity vortex, familiar in the classic lid-driven cavity flow problem. It was shown that successive sweep events, occurring at this entry point forced a flow path well into the cavity, resulting in the entrainment of the bottom laden sediments. The sediments were transported to the downstream edge of the cavity, where they collided and rolled to form an elevated pile. Removal of particles occurred when the elevated particles were swept into mean fluid flow within the cavity. Once the particle was close to the shear interface of the cavity and the boundary layer, it could either be suspended into the boundary layer by a passing turbulent ejection event or flushed out by the return flow of an incoming sweep event. The numerical results were in agreement with the criteria of suction removal of sediment between the armour layer in a current flow defined by the experiments of (Sumer et al. 2001).

The final part of the study dealt with the more realistic situation of a modelling a hydraulically rough boundary layer of which the geometric roughness comprised of packed spheres of diameter $D = 0.0385m$. Turbulent quantities and the Reynolds stresses were determined and compared well against experimental data. Wall streaks of low and high speed streaks were identified even at very high non-dimensional roughness's $k_s^+ = 1600$, indicating the existence of the bursting process. The spacing between the streaks was increased in comparison to the smooth wall as expected from experimental observations (Defina 1996). Despite the extents of our computational domain not being large enough to accommodate multiple sets of streaks, reasonable turbulent statistics were still attained. Vortex structure formation and shedding was visualised around the spherical elements using contours plotting the Q-criterion, and observed to be an additional source of turbulence in a rough wall flow. Mean flow structures between the cavities of the spheres were identified and instances of sweep structures penetrating into the cavities were presented. The flushing out of cavities where flow was upward directed and their relation to low speed streaks above was also presented.

DEM spheres representative of sediment particles were placed on the bottom of the bed between the armour spheres, in an already developed rough boundary layer flow. The

initial entrainment of the sediments occurred in circular patches and were associated to penetrating turbulence which at locations of the cavities where a downward flow aligned to a mean velocity flow. Grains could be swept into piles between the impinging events, resulting in greater exposure to the internal flow in the cavity, and potentially suspend from the bed from the counter rotating vortices observed between two impinging events. Removal of the suspended sediment from the cavity can then occur from the flushing of the cavity from a passing ejection event above. Particles can also be transported out of the sphere layer by transport from the mean flow paths within the cavities, as also demonstrated in the simpler cavity model described earlier. It was observed from projected streamlines that the sweep event reached the bottom, having the potential to entrain fine sediments resting at the bed. Depending on penetration depth of sweep events, the flow field could eject suspended sediments from the stone cover even for weaker events. However, strong sweep events might be necessary to entrain the sediment from the bed into suspension. In the tests with sediment particles where suction was not expected to occur the sediment piled up along the bed. When increasing the shields parameter entrainment of particles did occur, which was in line with the literature.

Future work would extend the computational domain in order to resolve more pairs of low and high-speed wall streaks in the case of a rough wall. The effect of waves would be also of interest, this could be simulated in the current model with an oscillatory body force. In an oscillatory flow, larger accelerations and free vorticity shed from the roughness elements due to flow reversal, which has a more agitating effect on the bottom sediments. Suction removal of sediments between armour layers in waves was studied extensively in experiments by (Dixen et al. 2008).

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgement

The authors gratefully acknowledge financial support from Energinet.dk (ForskEL project 2013-1-68012: “Management of seabed and wind farm interaction”).

566 **Notation**

- 567 C_d = drag coefficient for sediment particles;
- 568 C_s = Smagorinsky constant;
- 569 D = mean stone size;
- 570 D_{cavity} = depth of cavity;
- 571 d = single particle size;
- 572 $\mathbf{F}_{Fi}$ = fluid force on sediment particle;
- 573 $\mathbf{F}_{Di}$ = drag part of fluid force on sediment particle;
- 574 $\mathbf{F}_{PGi}$ = pressure gradient contribution to fluid force on sediment particle;
- 575 $\mathbf{F}_{Bi}$ = buoyancy contribution to fluid force on sediment particle;
- 576 $F_{ii}(f)$ = One-dimensional energy spectrum in frequency space for the velocity
- 577 components u , v , and w ;
- 578 G = gap width;
- 579 $\mathbf{g}$ = gravitational vector;
- 580 h = height of channel;
- 581 k_s = Nikuradse's equivalent sand roughness;
- 582 k_s^+ = dimensionless roughness: $k_s^+ = \frac{k_s u_f}{\nu}$;
- 583 $\mathbf{M}_{Ti,j}$ = torque from the tangential contact of the neighbouring j^{th} particle or wall;
- 584 m_i = mass of particle i ;
- 585 p = pressure;
- 586 Re_p = particle Reynolds number;
- 587 t = time;
- 588 s = modulus of rate of strain tensor;
- 589 S_{ij} = strain rate tensor;
- 590 u_f = friction velocity;
- 591 u' , v' = fluctuating streamwise and vertical velocities; y = distance from bed;
- 592 u_i = the filtered or resolved velocity component;
- 593 u'_i = unresolved subgrid velocity component;
- 594 $\mathbf{u}_{pi}$ = particle i translation velocity;
- 595 V_{pi} = volume of particle i ;
- 596 $\boldsymbol{\omega}_{pi}$ = particle i rotational velocity;

- 597 $\Delta =$ filter width;
 598 $\kappa =$ von Kármán constant;
 599 $\nu =$ kinematic viscosity;
 600 $\nu_t =$ eddy viscosity;
 601 $\rho =$ density of water;
 602 $\theta =$ Shields parameter: $\frac{u_f^2}{\rho(s-1)d}$, where s is the specific density, $s = \rho_s/\rho$;

603 References

- 604 Baykal, C., Sumer, B. M., Fuhrman, D. R., Jacobsen, N. G., and Fredsøe, J. (2015).
 605 “Numerical investigation of flow and scour around a vertical circular cylinder.”
 606 *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*
 607 *Engineering Sciences*, 373(2033), 20140104 1–21.
- 608 Bombardelli, F. A., González, A. E., and Niño, Y. I. (2008). “Computation of the Particle
 609 Basset Force with a Fractional-Derivative Approach.” *Journal of Hydraulic*
 610 *Engineering*, 134(10), 1513–1520.
- 611 Bomminayuni, S., and Stoesser, T. (2011). “Turbulence Statistics in an Open-Channel
 612 Flow over a Rough Bed.” *Journal of Hydraulic Engineering*, 137(11), 1347–1358.
- 613 Chen, H., and Christensen, E. D. (2018). “Simulating the hydrodynamic response of a
 614 floater – net system in current and waves.” *Journal of Fluids and Structures*, Elsevier
 615 Inc., 79, 50–75.
- 616 Christensen, E. D., Bingham, H. B., Skou Friis, A. P., Larsen, A. K., and Jensen, K. L.
 617 (2018). “An experimental and numerical study of floating breakwaters.” *Coastal*
 618 *Engineering*, 137.
- 619 Corvaro, S., Mancinelli, A., Brocchini, M., Seta, E., and Lorenzoni, C. (2010). “On the
 620 wave damping due to a permeable seabed.” *Coastal Engineering*, Elsevier B.V.,
 621 57(11–12), 1029–1041.
- 622 Defina, A. (1996). “Transverse spacing of low-speed streaks in a channel flow over rough
 623 bed.” *Coherent flow structures in open channels*, P. Ashworth, S. J. Bennett, J. L.
 624 Best, and S. McLelland, eds., Wiley, New York, 87–99.
- 625 Detert, M., Nikora, V., and Jirka, G. H. (2010). “Synoptic velocity and pressure fields at
 626 the water-sediment interface of streambeds.” *Journal of Fluid Mechanics*, 660, 55–
 627 86.

- Dixen, F. H., Sumer, B. M., and Fredsøe, J. (2008). "Suction Removal of Sediment from between Armor Blocks. II: Waves." *Journal of Hydraulic Engineering*, 134(10), 1405–1420.
- Fang, H., Han, X., He, G., and Dey, S. (2018). "Influence of permeable beds on hydraulically macro-rough flow." *Journal of Fluid Mechanics*, 847, 552–590.
- Ferziger, J. H., and Peric', M. (2002). *Computational Methods for Fluid Dynamics*. Springer-Verlag, Berlin Heidelberg New York.
- Germano, M., Piomelli, U., Moin, P., and Cabot, W. H. (1991). "A dynamic subgrid-scale eddy viscosity model." *Physics of Fluids A*, AIP Publishing, 3(7), 1760–1765.
- Grass, A. J. (1971). "Structural features of turbulent flow over smooth and rough boundaries." *Journal of Fluid Mechanics*, 50(2), 233–255.
- Grass, A. J., Stuart, R. J., and Mansour-Tehrani, M. (1991). "Vortical structures and coherent motion in turbulent flow over smooth and rough boundaries." *Philosophical Transactions of the Royal Society of London. Series A: Physical and Engineering Sciences*, 336(1640), 35–65.
- Hunt, J. R. C., Wray, A. A., and Moin, P. (1988). "Eddies, streams and convergence zones in turbulent flows." *Proceedings of the Summer Program 1988*, Center for Turbulence Research, 193–208.
- Jensen, B., Liu, X., Christensen, E. D., and Rønby, J. (2017). "Porous Media and Immersed Boundary Hybrid - Modelling for Simulating Flow in Stone Cover-Layers." *Coastal Dynamics*, T. Aagaard, R. Deigaard, and D. Fuhrman, eds., ASCE, Helsingør, Denmark, 1312–1323.
- Kolmogorov, A. N. (1991). "Local Structure Of Turbulence in an Incompressible Viscous Fluid at Very Large Reynolds Numbers." *English translation reprinted in Proc. Roy. Soc. Lond. A*, 434(1890), 9–13.
- Kuwata, Y., and Suga, K. (2017). "Direct numerical simulation of turbulence over anisotropic porous media." *Journal of Fluid Mechanics*, 831, 41–71.
- Lee, S. B. (2017). "A study on temporal accuracy of OpenFOAM." *International Journal of Naval Architecture and Ocean Engineering*, Elsevier Ltd, 9(4), 429–438.
- Lilly, D. K. (1992). "A proposed modification of the Germano subgrid-scale closure method." *Physics of Fluids A*, 4(3), 633–635.
- Liu, D., Liu, X., Fu, X., and Wang, G. (2016). "Quantification of the bed load effects on

- turbulent open-channel flows.” *Journal of Geophysical Research: Earth Surface*, 121, 767–789.
- Liu, Q., and Prosperetti, A. (2011). “Pressure-driven flow in a channel with porous walls.” *Journal of Fluid Mechanics*, 679, 77–100.
- Liu, Y., Stoesser, T., Fang, H., Papanicolaou, A., and Tsakiris, A. G. (2017). “Turbulent flow over an array of boulders placed on a rough, permeable bed.” *Computers and Fluids*, Elsevier Ltd, 158, 120–132.
- Mazzuoli, M., and Uhlmann, M. (2017). “Direct numerical simulation of open-channel flow over a fully rough wall at moderate relative submergence.” *Journal of Fluid Mechanics*, 824, 722–765.
- Moukalled, F., Mangani, L., and Darwish, M. (2016). *The finite volume method in computational fluid dynamics :Fluid Mechanics and Its Applications*. Springer.
- Nielsen, A. W., Liu, X., Sumer, B. M., and Fredsøe, J. (2013). “Flow and bed shear stresses in scour protections around a pile in a current.” *Coastal Engineering*, 72, 20–38.
- Nielsen, A. W., Sumer, B. M., Fredsøe, J., and Christensen, E. D. (2011). “Sinking of armour layer around a cylinder exposed to a current.” *Proceedings of the ICE - Maritime Engineering*, Thomas Telford, 164(4), 159–172.
- Offen, G. R., and Kline, S. J. (1975). “A proposed model of the bursting process in turbulent boundary layers.” *Journal of Fluid Mechanics*, 70(2), 209–228.
- “OpenFOAM, The open source CFD toolbox.” (2018). <<https://www.openfoam.com/>>.
- Pedinotti, S., Mariotti, G., and Banerjee, S. (1992). “Direct numerical simulation of particle behaviour in the wall region of turbulent flows in horizontal channels.” *International Journal of Multiphase Flow*, 18(6), 927–941.
- Petersen, T. U., Sumer, B. M., Bøgelund, J., Yazici, A., Fredsøe, J., and Meyer, K. E. (2015). “Flow and Edge Scour in Current Adjacent to Stone Covers.” *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 141(4), 04014044 1–14.
- Petersen, T. U., Sumer, B. M., Meyer, K. E., Fredsøe, J., and Christensen, E. D. (2012). “Edge scour in current adjacent to stone covers Key words.” *ICSE-6 – 6th International Conference on Scour and Erosion*, 739–746.
- Roulund, A., Sumer, B. M., Fredsøe, J., and Michelsen, J. (2005). “Numerical and experimental investigation of flow and scour around a circular pile.” *Journal of*

- 692 *Fluid Mechanics*, Cambridge University Press, 534, 351–401.
- 693 Schmeeckle, M. W. (2014). “Numerical simulation of turbulence and sediment transport
694 of medium sand.” *Journal of Geophysical Research: Earth Surface*, 119(6), 1240–
695 1262.
- 696 Singh, K. M., Sandham, N. D., and Williams, J. J. R. (2007). “Numerical Simulation of
697 Flow over a Rough Bed.” *Journal of Hydraulic Engineering*, 133(4), 386–398.
- 698 Smagorinsky, J. (1963). “General Circulation Experiments with the Primitive Equations,
699 I. The basic experiment.” *Monthly Weather Review*, 91(3), 99–164.
- 700 Soulsby, R. (1997). *Dynamics of marine sands, A manual for practical applications*.
701 Thomas Telford, London.
- 702 Sumer, B. M., Christiansen, N., and Fredsøe, J. (1997). “The horseshoe vortex and vortex
703 shedding around a vertical wall-mounted cylinder exposed to waves.” *Journal of*
704 *Fluid Mechanics*, 332, 41–70.
- 705 Sumer, B. M., Cokgor, S., and Fredsøe, J. (2001). “Suction Removal of Sediment from
706 between Armor Blocks.” *Journal of Hydraulic Engineering*, 127(4), 293–306.
- 707 Sumer, B. M., and Deigaard, R. (1981). “Particle motions near the bottom in turbulent
708 flow in an open channel. Part 2.” *Journal of Fluid Mechanics*, 109, 311–337.
- 709 De Vos, L., De Rouck, J., Troch, P., and Frigaard, P. (2012). “Empirical design of scour
710 protections around monopile foundations. Part 2: Dynamic approach.” *Coastal*
711 *Engineering*, Elsevier B.V., 60(1), 286–298.
- 712 Willmarth, W. W., and Lu, S. S. (1972). “Structures of Reynolds stress near the wall.”
713 *Journal of Fluid Mechanics*, 55(1), 65–92.
- 714 Zhao, C., Fang, H., Liu, Y., Dey, S., and He, G. (2020). “Impact of Particle Shape on
715 Saltating Mode of Bedload Transport Sheared by Turbulent Flow.” *Journal of*
716 *Hydraulic Engineering*, 146(5), 1–13.
- 717 Zhu, H. P., Zhou, Z. Y., Yang, R. Y., and Yu, A. B. (2007). “Discrete particle simulation
718 of particulate systems: Theoretical developments.” *Chemical Engineering Science*,
719 62, 3378–3396.

1
 2 *Figure 1 Sketch of the computational domain with specification of boundary faces. The*
 3 *surface of a sphere is treated as a Bottom, and dented wall*
 4

5

6 *Figure 2 Illustration of a turbulent smooth boundary layer over an idealised cavity.*

7 *Sediment particles are placed at the bottom of the cavity*

8

9

10 *Figure 3 3D view of a channel with a bed of packed spheres*

11

12

13 *Figure 4 Side view of mesh for the channel with spherical bed roughness.*

14

15

16 *Figure 5 Sequence of successive penetration of sweep events (grey contours) into the*

17 *upstream end of the cavity. C) Shows development of a clear pathway for penetrating*

18 *high momentum from the sweep event directed to the bottom of the cavity.*

19

20

21 *Figure 6 Shows entrainment of the bottom sediment (black dots) swept into bottom cavity*
 22 *vortex after the formation of flow configuration in the cavity in Figure 5 C).*

23

Figure 7 Shows transport of the sediment particles to the upper vortex of the cavity and ejected out into the main body of the flow by a passing ejection event (darker contours).

29

30 *Figure 8 Criteria for suction where d is particle diameter, D is the diameter of the armour*
 31 *stones and θ is the Shields parameter of the sediment.*

32

33

34 *Figure 9 Turbulent quantities for a hydraulically rough boundary layer from (Grass*
 35 *1971; Sumer et al. 2001) and the current LES results for non-dimensional*
 36 *roughness, $ks^+ = 230$ and $ks^+ = 1600$.*

37

38

39 *Figure 10 Velocity plots of time-averaged streamwise velocity u and the vertical*
 40 *coordinate, y from the theoretical wall. A) Moderate roughness $ks^+ = 230$ B) High*
 41 *roughness $ks^+ = 1600$.*

42

43

44 *Figure 11 Examples of one-dimensional energy spectra for, left: $k_+ = 230$, , right:*

45 *$k_+ = 1600$ at approximately $y/h = 0.2$.*

46

47
 48 *Figure 12 Slice of instantaneous velocity magnitude above the spherical cover positioned*
 49 *at $yD = 0.58$ for $ks^+ = 1600$.*
 50

Figure 13 A time instance of vorticity around the spherical elements using the Q -criterion (Hunt *et al.* 1988) for $ks^+ = 230$. Key structures labelled in the figure are A) Horseshoe vortex B) Hair Pin vortex C) Elongated vortex.

56

57 *Figure 14 Horizontal slices across the channel. A) Plotting instantaneous velocity*
 58 *magnitude. B) Contour with sweep event correlation C) Contour with ejection event*
 59 *correlation.*

60

Figure 15 Stream wise contour slice with projected streamlines (black), plotting the time averaged mean flow. Red lines with arrows highlight the direction of the flow. A) Stagnation point. B) Flow separation from the sphere. C) Circulating flow feature. The non-dimensional roughness was $ks^+ = 1600$.

Figure 16 Lateral slices with projected streamlines plotting the mean flow, viewed in the stream wise direction. a) View in front of the spheres b) View in the cavity from the downstream end of a sphere. Red lines and arrows highlight the direction of the mean flow. Figures to the right show the position of the lateral slice on the left in relation to the spheres. The red dashed box on the right hand figures related to the highlighted cavity in the right hand figure. Label A shows the location of the stagnation point as presented in stream wise plot Figure 15.

Figure 17 Lateral slice at the same position as Figure 16 a), plotting instantaneous velocity magnitude, with projected streamlines. Flow paths from the sweep like structure presented in Figure 14, penetrating the cavity where the mean flow was presented in Figure 16 a) and flow path of the ejection of fluid from the cavity to the corresponding ejection event are highlighted by the red lines and arrows.

Figure 18 Streamlines showing the penetration of fluid into the cavity, where the mean flow is illustrated in Figure 16 b) and the 'suction' of the streamlines out of the cavity. The penetration and suction from the cavity is associated to the sweep and ejection structures presented in Figure 14.

89

90

91
92

93 *Figure 19 Two panels of a sequence of entrainment of sediment particles (black) under*
 94 *the armour stones in a developed channel flow. The view is from the top viewing*
 95 *through the transparent stones. Velocity contours of vertical velocity, 1mm above*
 96 *the bed. A) $t=0.02s$, B) $t=0.06s$. The Shields parameter for the sediment is $\theta = 1.2$.*
 97

B
 Figure 20 Close up of suspending particles near a cavity, viewed from above the flow looking down. Contours are of near-bed instantaneous velocity in the vertical direction, (blue indicates wall ward directed flow, red upward directed. The size of the sediments in the figure are exaggerated for illustrative purposes and are coloured with regard to their vertical position (black is on the bed, lighter colour to yellow is suspending. The armour layer of spheres is set to be transparent. Snapshot B) is 0.2 seconds after snapshot A).

111
 112 *Figure 21 A lateral slice taken at the point of suspending particles presented in Figure*
 113 *20 A). Contours of instantaneous vertical velocity. Yellow arrows highlight the*
 114 *upward directed flow from the two downward directed events and the suspending*
 115 *sediments. The mean flow is directed into the page.*