

Response GMD referee comments

legends:

comments from referee

response to referee comments

modifications

RC1: Gabriel Barajas

The manuscript entitled “sedExnerFoam 2412: A 3D Exner-based sediment transport and morphodynamics model”, presents a numerical model for sediment transport and morphological evolution, with validations and an application.

From the reviewer point of view, this is a very interesting work, as the topic is quite interesting and relevant. However, before recommending this paper for publication I think that the paper needs to be substantially improved in several specific parts. The reviewer adds a detailed review in the hope that the authors will find it useful.

→ response: We would like to thank the reviewer for his positive feedback. In the revision, we did our best to follow the reviewer's recommendation to improve the manuscript. Please find hereafter our point-by-point response.

Major issues:

1.- The abstract is very poor.

→ response: the abstract was extended and improved. It now gives a proper overview of the article content.

2.- All sections need a small introduction.

→ response: Done, each section begins with an introductory paragraph.

3.- Section 2 needs to be checked.

There are wrong namings, variables cited before definition, etc.

→ response: Done, this was checked and modified.

3.- There is not any comment about the computational cost of the different simulations. I would like to know about the computational times and computational resources used for each of the simulations, Y_+ values, etc.

→ response: There are now indications about the computational cost of each simulation in the text. The z_+ values are kept to $z_+ \approx 1$ for most of the simulations to ensure the accurate prediction of the bed shear stress.

“These simulations complete in a few seconds on a single CPU core.” “These suspension development simulations require 10 hours of wall-clock time on 5 CPU cores to compute 50 seconds of physical simulation time.” “These simulations complete in a few seconds on a single CPU core.” “These simulations complete in a few seconds on a single CPU core.”

4.- I would like to see a section highlighting the strengths and limitations of the numerical approach.

→ response: The conclusion has been revised and now includes a description about the strength and limitation of the model.

The model’s main strengths are its open-source availability and extensive validation on idealized benchmarks. From a software development perspective, continuous integration tests are essential for ensuring the long-term maintenance of the code, and these are available on the GitHub repository. Using the proposed avalanche model eliminates the need for the costly and unphysical iterative procedure employed in most existing 3D morphological models. Another novel feature introduced in this work is the near-wall diffusivity for turbulent suspensions, which enables the use of the same mesh for flow hydrodynamics and sediment concentration. To the authors’ knowledge, the application of bedload flux saturation is unique to this subaqueous sediment transport numerical model, and is essential for accurately predicting dune migration. Beyond possible future developments, such as the addition of a free surface, the accounting for multiple grain sizes, or the modeling of cohesive sediments, the following limitations have been identified: (i) the feedback of the suspended sediment concentration on the flow hydrodynamics (e.g. through a Boussinesq term); (ii) the mesh resolution required for the accurate estimation of bed shear stress in regions of non-uniform flow, including bed roughness; (iii) the mesh deformation solver, which may cause the simulation to crash; (iv) the development, validation and implementation of filters for bed evolution; and (v) the formulation, implementation and validation of a multi-dimensional bedload flux saturation model.

5.- I expect to see the units of all variables listed in the manuscript.

6.- There are too many variables defined in the manuscript, a table containing all of them should be added, with the units and the naming.

→ response: a table has been added at the end of the manuscript with the list of variables and their units

7.- Numerical wave tanks are not described by any means, neither the BC's applied or sketches of the meshes. There is no grid analysis in the validation cases.

→ response: There is a grid analysis for one of the validation case. Additionally, an appendix was added which illustrates of the mesh resolution on the bed shear stress.

8.- Section 3.2 and 3.3 should be defined in the order of appearance of Figure 5.

→ response: From our perspective, it is more logical to first explain how the Exner equation is solved before discussing the mesh motion, as the latter is a consequence of the former. Although the mesh is updated at the beginning of each time iteration and thus appears first in the flow chart, it is adjusted to match the new bed position computed from the resolution of the Exner equation at the previous time step. Therefore, it appears to us, that it is conceptually clearer to first present the Exner equation, which drives the bed evolution, before describing the mesh motion procedure that results from its solution.

Notes about the figures:

Figure 2

Is not referred to in the text.

→ response: Done, there is now a reference to Figure 2 in the text

Figure 3 should be next to Table 2a

→ response: the final version of the article being a two column text, the table will span over all page width not allowing to place the Figure next to it.

Figure 4 should be next to Table 2b

→ response: same as previous response, the table will be spanning over the two-column in the final document

Figure 5 should state clearly which variables are in the input and output for each part of the flow chart.

→ response: We chose to retain the previous graph. The flow chart illustrates the sequence of operations performed during a single time step. It is designed to fit within a single column; adding additional elements would make it too large.

Figure 7a is very small, I can not see anything. Figure 7b should be wider, as there is space for doing it in the text.

→ response: The font size has been increased, and the left plot has been zoomed in to improve the visibility of the results. The width of the plot however, was not increased as it should fit in one-column.

Figure 8, legend is missing

→ response: For Figures 8 and 9, a legend is intentionally omitted, as the captions provide sufficient information to interpret the plots, and adding a legend would overlap with the curves due to limited space.

Why figure 10 is referred to in the text before figure 9. Please, correct it.

→ response: Done

Figure 12:

What are the black dots? they are not referred to in the legend.

→ response: Done, they are not referred to in the legend.

Figure 15.

Black crosses are not referred to in the legend.

→ response: Done, the legend now also refers to the black crosses.

Figure 16:

What are the blue and orange zones?

→ response: These color zones represent the sediment and water phases, respectively. The figure caption now provides additional clarification.

Figure 17:

Legend is missing.

→ response: Done, the black crosses have been added to the legend.

Figure 18.

Legend is missing.

→ response: Done, a legend was added on top of the plot.

Notes about the Tables:

Table 2.

Is Phib the bedload flux? In line 128 was defined as q_b ?

→ response: phib is the dimensionless bedload flux also called einstein number. It is written in the paragraph dedicated to the description of bedload formulas. It was added in the Figure caption that phib is the dimensionless bedload.

“formulas to compute the dimensionless bedload flux, also called Einstein number, from the Shields number.”

Notes about the manuscript:

Line 17:

“The twentieth century saw the development of analytical models (Hjelmfelt and Lenau, 1970) and one-dimensional numerical models (Verwey, 1980; Goutal and Maurel, 2002).”

Please, rephrase.

→ response: Done, it was slightly rephrased

line 29: “The twentieth century saw the development of analytical models (Hjelmfelt and Lenau, 1970) and one-dimensional (1D) numerical models (Cunge et al., 1980; Goutal and Maurel, 2002) for the study of hydraulic and morphodynamics phenomena.”

Line 17:

one dimensional (1D)

two-dimensional (2D)

Add it, as well as three-dimensional (3D).

→ response: Done, this was checked throughout the entire manuscript.

Line 33:

“the deformation of the associated volume mesh (ALE)..”

What does ALE stand for?

→ response: the sentence was modified

line 43: “These models are based on the Arbitrary Lagrangian-Eulerian (ALE) approach to handle the evolution of the bed boundary and the deformation of the associated volume mesh.”

Line 38:

“and was developed to meet the needs of hydraulic engineering.”

Please, rephrase.

→ response: the sentence was changed

line 49: “This model, named sedExnerFoam, is an ALE-based numerical model developed to support hydraulic engineering applications and in particular, to provide a relevant tool for studying scour around hydraulic structures.”

Line 39:

“However, the model’s scope extends beyond this to include a wide range of morphodynamics problems”

Please, define which problems.

→ response: some examples of application of the model are now listed:

line 52: “studying the formation and migration of bedforms in channels, assessing sediment deposition and erosion patterns in rivers, and analyzing sediment accumulation in reservoirs”

Line 46:

Please, capital f for Figure 1. Check it through the entire manuscript.

→ response: Done, this was checked throughout the entire manuscript.

Line 49:

Please, summarize correctly all the different sections of the manuscript.

→ response: The final paragraph of the introduction has been modified to provide a more precise and comprehensive overview of the paper's global structure.

line 62: “After presenting the mathematical formulation of sedExnerFoam in Section 2 and the modeling approaches for hydrodynamics, turbulence, and sediment transport closures, several key numerical aspects are discussed in Section 3, with particular emphasis on the treatment of the Exner equation. This is followed, in Section 4, by the model validation

against a series of academic benchmarks consisting of simple test cases designed to isolate individual components of the model and validate them separately against analytical solutions or experimental data. The validation suite includes simulations of idealized dune migration, sediment suspension under steady flow conditions, both in and out of equilibrium, and two sediment deposition scenarios. Finally, in Section 5, the model's capabilities are demonstrated through the simulation of an isolated dune migrating over a rigid bed under steady flow conditions. The numerical results reproduce a stationary migration regime, characterized by the dune moving at a constant velocity while maintaining its shape throughout the migration process. The conclusion provides a summary of the present work and discusses the current limitations of the model and possible future improvements."

Line 54:

"The hydrodynamics is described by the incompressible filtered Navier-Stokes equations."

Please, rephrase.

→ response: Done, this has been rephrased

line 83: "The fluid motion is governed by the incompressible, filtered Navier–Stokes equations"

Line 58:

"It can either be the specific Reynolds stress tensor to run Reynolds Averaged Simulations (RAS), a subgrid scale stress tensor when performing Large Eddies Simulations (LES) or the null tensor in case of laminar simulation or Direct Numerical Simulation (DNS). The model makes use of the vast panel of possibilities offered by OpenFOAM and let the user choose freely the kind of filtering to be applied to equation 1. This is done by changing entries in a file turbulenceProperties. In this work however, the numerical simulations presented are either laminar cases (no filtering of the Navier-Stokes equations) or unsteady RAS simulations"

Please, rephrase.

→ response: Some part of this paragraph have been rephrased. The mention to the file turbulentProperties has been moved to the section dedicated to the model numerical implementation.

line 395: "The turbulence modeling approach (LES, RAS), and the specific model used, is defined in the turbulenceProperties file."

Line 64:

“which is a valid assumption only in the case of dilute suspended sediments”

Please, explain correctly. this statement.

→ response: currently, the model cannot take into account the effects of density or particle drag on the flow, which are not important if the volume fraction of suspended sediment is small. This was added in the text for more clarity.

line 91: “At this stage of model development, no feedback of the suspended load on the hydrodynamics is considered, an assumption appropriate for dilute suspensions where density effects and particle drag are negligible.”

Line 66: Section 2.2

Why a RANS turbulence model and not a LES?

Can it capture correctly all the processes of figure 1?

There is not a clear description of the choice of the turbulent model.

→ response: The model is fully compatible with Large Eddy Simulation (LES). However, the main source of uncertainty in sediment transport simulations arises from the empirical closures used for bedload transport and erosion. These uncertainties are so significant that an error of up to 50% in the bedload flux is often considered acceptable. Consequently, employing a high-resolution approach such as LES may be unnecessary. Moreover, these closures are typically derived from experimental observations in straight channels and are based on averaged quantities, making their validity questionable when flow fluctuations are explicitly resolved with LES. Another important aspect is that the model was developed with the aim of addressing engineering problems, particularly scour around bridge piers, at scales for which LES approaches are generally computationally too expensive to apply.

Line 99:

“It is expressed as the ratio of the turbulent eddy viscosity and the Schmidt number σ_c ”.

Write the relation as an equation,

→ response: Done

line 131: “It is expressed as the ratio of the turbulent eddy viscosity and the Schmidt number σ_c as $\epsilon_s = \nu_t / \sigma_c$ ”

Line 108:

Please, capital t for Table 1. Check it through the entire manuscript.

→ response: Done, this has been checked throughout the entire manuscript

Line 110:

Add “sediment” to the definition of the settling velocity.

→ response: Done

line 147: “a formula to estimate σ_c from the sediment settling velocity and the friction velocity u_* ”

Line 112:

“This yields a Schmidt number smaller than one which corresponds to sediment diffusion being more intense than the turbulent diffusion for the fluid”

Please, justify this statement correctly.

→ response: a few sentence were added to justify the statement

line 149: “This yields a Schmidt number smaller than one which corresponds to suspended sediment being dispersed more effectively than momentum is mixed by turbulence. This can be explained by the fact that turbulent diffusion is not the only mechanism responsible for sediment dispersion, additional processes such as particle collisions, particle inertia, and lift forces can also enhance sediment diffusivity. Because these mechanisms are not accounted for in this classical approach, the Schmidt number is generally treated as a tuning parameter.”

Line 117:

“This topic is covered at the end of the next section in relation to bedload and morphological evolution.”

Please, add the number of the section.

→ response: Done

line 155: “The final key aspect of this approach is how to enforce the bed boundary condition, that is the exchange of mass between the sediment bed and the suspended load. This topic is covered in the Section (2.4.3) relative to erosion and deposition rates.”

Line 23.

“ an Austrian meteorologist and geologist and geophysicist.

Please remove it.

→ response: Done

line 164: “The morphological evolution of a granular bed in a wide range of sediment transport problems is modeled by the so-called Exner equation, which was first proposed by Exner (1920).”

Line 124:

“ In their article, Paola and Voller mention that Felix Exner initially”

Who is Paola? Please, correct.

→ response: the reference was changed from citeauthor to citet

line 165: “In their article, Paola and Voller (2005) mention that Felix Exner initially suggested”

Line 139:

“The bedload flux q_b is the specific flux of sediment transported along the bed per unit width. It is computed from the bed shear stress using an empirical formula”.

Table 2 does not refer to q_b . Please, correct this section.

→ response: ϕb is the dimensionless bedload and is defined in the text. The formula presented in Table 2 express the dimensionless bedload as a function of the Shields and critical Shields.

in Table 2 description: “formulas to compute the dimensionless bedload flux, also called Einstein number, from the Shields number.”

line 194: “Various studies have focused on trying to find relationships between the Shields number and the dimensionless bedload flux ϕb ”

Line 142:

The user can choose between one of those models or manually set a value for θ_c .” How? Which value is appropriate? Please, specify.

→ response: We chose to retain the option of directly specifying the value of the critical Shields number in cases where none of the available models provide a satisfactory estimate. The threshold of motion (critical Shields number) is subject to substantial uncertainty and is often used as a calibration parameter. For this reason, we consider it important to allow users to manually define its value.

Line 152:

“The slope correction can be activated/deactivated in the file bedloadProperties using the entry slopeCorrection.”

This section is the mathematical model, not the numerical model.

Please, add it correctly in its correct section.

→ response: Done, this sentence was removed from the mathematical description section.

new sentences in numerical section, line 404: “In bedloadProperties, the user can enable or disable bedload transport and morphological evolution, choose models for the critical Shields number and for the bedload formulation (see Table 2), activate the critical Shields number slope correction (Eq. 12), set the avalanche coefficient q_{av} , use a morphological acceleration factor, and specify whether a rigid, non-erodible bed exists beneath the sediment layer, which limits the maximum erosion depth.”

Line 154.

What is Phib ?

Correct it.

→ response: phib is the dimensionless bedload also called Einstein number. It is defined in the text.

line 194: “Various studies have focused on trying to find relationships between the Shields number and the dimensionless bedload flux $\phi_b = |q_b| / (s - 1)gd^3$ ”

Line 155:

“A lot of this formulas..”

How many formulas are a lot?

→ response: the sentence was changed to "Many classical formulas" followed by citation of some works who proposed similar formulas.

line 196: “Many classical formulas (Meyer-Peter and Müller, 1948; Nielsen, 1992; Ribberink, 1998) are of the form:”

Line 160:

“Another phenomenon that needs...”

Please, cite explicitly which phenomenon has been already addressed, so readers can easily follow the mathematical models.

→ response: Done, The sentence was changed

line 203: "In addition to transport driven by bed shear stress, sediment can also be mobilized through local avalanche processes when the bed slope exceeds the angle of repose of the granular material."

Line 167:

Is the equation correctly defined?

→ response: yes

Line 173:

Add "and" between the two cited works.

→ response: Done

line 216: "From Charru (2006) and Charru et al. (2013) the saturation can be expressed in a coordinates system aligned with the shear stress as"

Line 177:

"From the file bedloadProperties, the user can activate the saturation and provide values for T_{sat} and L_{sat} . The saturated flux q_{sat} is then computed from the bed shear stress using one of the formula from table 2 and the bedload flux q_b is the solution of equation 14"

Again, this part is the numerical implementation of the mathematical model. Add it to the correct section.

→ response: Done, the sentence was removed and a description of the file bedloadProperties was added to the section relative to the numerical aspects. It has already been detailed in the response to a previous comment.

Line 181:

"As said previously, the modeling of the erosion and deposition fluxes is a hard point of classical sediment transport models"

Please, rephrase it.

→ response: Done, the sentence was changed

line 226: "As mentioned earlier, the modeling of erosion and deposition fluxes represents one of the main challenges in classical sediment transport models."

Line 189:

“Since then, .”

“.. is not appropriate for a lot of situation..”

“The idea is that the ...”

Please, rephrase it.

→ response: Done, the paragraph was rephrased with more formal language

line 234: “This development has been adopted in many sediment transport models, which assume equilibrium at the reference level to define the boundary condition $c_s(\delta z_b^*) = c^*b$. However, this boundary condition is not suitable for cases in which the assumption of local equilibrium at the reference level does not hold. It was adapted by Celik and Rodi (1988) to accommodate non-equilibrium conditions. The erosion rate is written $E = ws c^*b$ and the deposition rate $D = ws c_b$, with c_b a sediment concentration value computed from the values in the neighboring cells which is detailed later on. The erosion rate is assumed equal to its equilibrium value, while deposition depends only on the concentration in the first cells above the bed. If $c_b > c^*b$, then suspended sediment get deposited on the bed and when $c_b < c^*b$, sediment get eroded from the bed and suspended in the water column. The equilibrium occurs when $c_b = c^*b$.”

Line 197:

“One difficulty is then how to impose this reference concentration at the reference level which is above the bed boundary.

→ response: Done, the sentence was changed

line 242: “One difficulty lies in prescribing the reference concentration at the reference level, which is located at some distance above the bed boundary.”

Line 203:

“In sedExnerFoam it was chosen to avoid the use of two different meshes”

Please, specify the solution of one single mesh: pros and cons.

Which physical process is chosen to define the cell size, etc.

→ response: Having two meshes introduce more complexity to couple two solutions on inconsistent meshes but it allows to set directly the reference concentration at a predefined reference level, classically taken as 2 times d . Questions arise when the bed changes and the hydrodynamic mesh is deformed, how to keep the suspended sediment mesh consistent with the hydrodynamic one? The main issue of the single mesh is the sensitivity of the solution to the near bed grid resolution as illustrated in figure X in appendix Y. Indeed, when the grid allows to resolve the viscous sublayer there not enough turbulent diffusivity

to suspend the particles from the first cell centre to the water column above. The additional diffusivity is aimed to compensate this weakness and it allows to ensure a grid convergence property to the solution.

Line 219:

This flux is imposed as a boundary condition for the suspended-load transport (equation 6). With this method the same mesh can be used for both the suspended load and the hydrodynamics with a fine resolution near the sediment bed. It is to be remembered that the various formulas for $c \cdot b$ existing in the literature are all empirical and are based on measurements made in straight channel flow experiments. Their validity out of this configuration, let alone in the vicinity of an obstacle disturbing the flow, is subject to caution

Rephrase this paragraph.

→ response: Done, the paragraph was rephrased

line 266: “This flux is prescribed as a boundary condition for the suspended-load transport (Eq. 7). With this approach, the same computational mesh can be employed for both suspended-load and hydrodynamic calculations, allowing for fine resolution near the sediment bed. It should be noted that the various formulations for $c \cdot b$ found in the literature are empirical in nature and are derived primarily from measurements conducted in straight-channel flow experiments. Their applicability outside of such configurations, particularly in the vicinity of obstacles that disturb the flow, should therefore be treated with caution.”

Line 224:

“The possibility to use an additional diffusivity near the bed for suspended sediments as been introduced in the model after experimenting difficulties to suspend material from the bed to the water column in the case of fine grid resolution and low to medium dimensionless roughness”

Rephrase it.

→ response: Done, it has been rephrased:

line 271: “To address difficulties in suspending material from the bed to the water column under fine grid resolution and low roughness Reynolds number conditions $ks^+ = ks\nu^*$, an additional near-bed diffusivity for suspended sediments ϵ_w , was introduced in the model.”

Line 232:

“The coefficients $\epsilon_0 w$ and ξw are both set to 5 by default but can be modified in the file `bedloadProperties`.”

Again, this part is the numerical implementation of the mathematical model. Add it to the correct section.

→ response: Done, it has been moved to the section relative to the numerical implementation.

in the section relative to numerical aspects, line 401: “In `suspensionProperties`, the user can enable or disable suspended load, select a settling-velocity and/or hindrance model (see Table 1), apply an additional wall diffusivity (see Eq. 19), and adjust the coefficients $\epsilon_0 w$ and ξw , as well as the limiter on the reference concentration $c_{b,max}$ (see Eq. 17).”

Line 244:

“ In the present model, the finite area mesh is mixed with the patch of the volumic mesh corresponding”

What does mixed mean?

→ response: the sentence was changed

line 297: "In the present model, the finite area mesh is coupled with the volumetric mesh patch representing the sediment bed, such that the finite area mesh coincides with the bed boundary of the finite volume mesh. This approach ensures seamless interaction between flow and sediment transport without the need for multiple meshes."

Line 271:

Rephrase “a naive approach...”

→ response: Done, the sentence was changed

line 325: "A straightforward approach would be to linearly interpolate z_b from face centers to vertices. Although this method is mass-conservative for 1D cases on a structured mesh, it fails to preserve mass in the general 3D case with an unstructured mesh."

Line 288:

Please, explain why it is acting as a filter.

→ response: the sentence was changed to the following to give precision on how the interpolation act as a filter for bed displacements

line 341: “This interpolation method is mass conservative and also serves as a filter, the final bed displacement at each face is obtained through two steps first interpolation from

faces to vertices, then from vertices back to faces, with face centers defined as the center of mass of the vertices comprising each face. This filtering effect contributes to maintaining the numerical stability of the Exner equation solution.”

Line 299:

Explain just the mesh motion solver used in the work, not the options.

→ response: Done, it has been modified

“The motion solver is defined in the file constant/dynamicMeshDict, and this study utilizes the displacementLaplacian solver.”

Line 305.

Explain just the mesh diffusivity used in the work, not the options.

→ response: here I am not citing all the possibility offered by OpenFOAM but only the ones which are relevant for the application of the model. That is the ones for which the diffusivity is higher near the bed and diminish far away from it. The sentence has been changed for more clarity.

line 356: “As a general guideline, it is recommended to assign a high mesh diffusivity near the sediment bed interface to preserve mesh quality in this critical region. The following options, which can be selected in the configuration file constant/dynamicMeshDict, ensure this behavior:”

Line 326:

There is no description for sediment bed fields or suspension, please add it in this section.

→ response: Sorry we do not understand what the reviewer is expecting.

Line 331:

Write down a paragraph describing the purpose of each validation and to which part of the flow chart and equations is related. Specify clearly if they are 1D, 2D or 3D validations.

→ response: The number of dimensions for each validation case now appears in the introduction of the model validation section. The two first tests are for the suspended load only, the third one for the Exner equation and the two deposition tests validate the coupling between the suspended load and the Exner equation as well as the behavior of the avalanche module.

line 419: “They are organized as follows: two tests involving suspended load transport only are first presented (1D and 2D). Then the case of an idealized dune transport problem

(1D) for which an analytical solution exists is investigated. At last, the conservation of mass is illustrated by means of two tests on suspended sediment deposition and avalanches (1D and 2D). Most of these tests are part of a continuous integration process available on the GitHub repository.”

Line 338:

Why isolating the physical process at a time is a correct approach in this work?

Please, justify it.

→ response: The idea is to validate the correct implementation of each model components one at a time. According to our experience with sedFoam, this is an efficient method when developing the numerical model. It is also very useful when maintaining a software developed by many contributors.

Line 335:

Please rephrase “The situation is the following”

→ response: we have removed this part of the sentence.

line 426: “A fully developed flow in a channel is considered. The channel is supposed long enough so that the vertical profiles of velocity and turbulent eddy viscosity are stationary.”

Line 350:

Is it four experiments of four tests in the experiment?

If so, update also the naming in Table 3.

→ response: These are probably four tests, table 3 has been corrected.

Table 3: “Parameters of four tests from Lyn (1988) experiment.”

Line 370:

Quantify quantitatively the errors from Figure 7. Do the same for all validations, just a qualitative comparison for the different validations is not correct.

→ response: The error is now qualitatively estimated using the symmetric mean absolute percentage error (SMAPE) to compare numerical results with experimental measurements.

To qualitatively assess the agreement between the numerical and experimental profiles, the symmetric mean absolute percentage error (SMAPE) of the logarithm of the sediment volume fraction is computed as follows:

$$\text{SMAPE} = (2/N) \sum |\log_{10}(c_s^{\text{num}}) - \log_{10}(c_s^{\text{exp}})| / (|\log_{10}(c_s^{\text{num}})| + |\log_{10}(c_s^{\text{exp}})|),$$

where N is the number of measurement available in the experimental test considered, c_s^{exp} is the experimental sediment volume fraction and c_s^{num} is the sediment volume fraction obtained from the numerical simulation and linearly interpolated to the elevations corresponding to the experimental data. The resulting errors are 4.34% for case 1565, 8.29% for case 1965, 6.64% for case 2565, and 2.46% for case 1957.

Line 372.

Why another test? Justify it properly.

→ response: So far we have only tested the erosion/deposition of suspended sediments. In this new test we also validate the streamwise advection of suspended concentration

Line 382:

Why isn't the fourth hypothesis respected? How does it affect the simulation?

→ response: The fourth hypothesis can not be respected in OpenFOAM as it is not possible to easily implement different diffusion coefficients in different directions. Furthermore, the numerical results perfectly fit with the analytical solution even without enforcement of the fourth hypothesis, showing that the effect of x-wise diffusion is indeed negligible.

Line 390:

if just one case is presented in figure 10, then do not write that a series of particle diameter values were selected.

→ response: Done, this has been changed. The text is now:

line 483: "The particle diameter was set to $d = 0.12$ mm, corresponding to a settling velocity of $w_s = 0.773$ cm.s⁻¹ and a Rouse number of $Ro = 0.5$. Although tests were conducted with different Rouse numbers, only the case $Ro = 0.5$ is presented in this work."

Line 409:

Write down again the unrealistic hypothesis assumed for the simulations.

→ response: Done, the sentence has been changed

"As stated previously, the discrepancies with the pseudo-analytical solution arise from the unrealistic assumptions made in its derivation. These include the assumption that suspended sediments are advected by the mean flow, the use of a parabolic eddy viscosity profile, and the assumption of local equilibrium at the reference level."

Line 413:

Please, change it from one-dimensional to 1D.

Check it for 2D and 3D in the entire manuscript.

→ response: Done, it has been checked

line 501: “As a first benchmark for the Exner equation (Eq. 11), an idealized 1D dune transport model for which an analytical solution exists is presented.”

Line 414:

Please rephrase, “a very simple flow”

→ response: The sentence has been changed

line 511: “In this case, a highly simplified flow is considered in order to focus on the behavior of the Exner equation without the added complexity of the hydrodynamics”

Line 424:

Give a reference for the method of characteristics.

→ response: Done, the book from McOwen "Partial differential equations : methods and applications" is now cited.

line 522: “the solution to equation 28 is obtained with the method of characteristics (McOwen, 1996) ...”

Line 431:

Please, rephrase the sentence: “a shock wave will appear somewhere”

→ response: The text has been changed

line 529: “a shock wave will form where the bed slope becomes vertical on the lee side of the dune”

Line 436:

Use the SI for all magnitudes, cm is not correct when referring after to m.

→ response: Done, the unit has been changed.

line 537: “dune properties, $h_d = 0.1 \text{ m}$, $\sigma_d = 0.6 \text{ m}$ ”

Line 453:

Is there any reference for the assumption regarding the avalanche model?

→ response: the reference is the work of Vinent et. al (2019) which is cited in the manuscript.

Line 460:

Specify the number of simulations, multiple is not correct.

→ response: The sentence was changed

line 559: "multiple simulations are performed by varying the grid size and the numerical schemes, and the results are compared with the analytical solution."

Line 470:

I do not see the relation between low courant number and poor mesh quality.

This full paragraph is quite questionable, as there are multiple numerical variables that might affect the stability of the simulations.

Please, justify it properly.'

→ response: In this test case only the Exner equation is solved and therefore only the temporal and flux divergence schemes are involved in the stability of the code. The Courant number is linked to the mesh resolution because the same constant time step is used for all simulations. This information has been added to the text.

line 569: "The simulations were performed using a constant time step. For low Courant numbers, associated with poor mesh quality, all simulations remain stable and exhibit similar errors."

Line 480.

Justify the purpose of this validation.

Is the first validation 1d?

→ response: The first case is 1D as only the Exner equation is involved. The sediment settling allows to validate the mass conservation and the coupling terms between the suspension and the bed.

Line 485.

This paragraph needs to be rewritten.

Where can I see the error?

→ response: the legend of Figure 16 was modified and the error now appears in it. Also the paragraph has been modified

line 587: “During each time iteration, the equation for the concentration of suspended sediments is solved, and the erosion/deposition flux is computed, resulting in an updated sediment bed elevation via the Exner equation (see Figure 5). Since the mesh motion is resolved at the beginning of the time iteration, the bed level increment computed at a given step only affects the mesh geometry in the subsequent time step. Consequently, there is a one-time-step delay in the morphological response of the bed, which introduces a temporary error in the total sediment mass. However, this error vanishes once all suspended sediments have settled.”

Line 492.

Remove black space line.

→ response: Done

Line 493:

What does this 2d case differ from the 1d case? justify this validation case.

→ response: The first case illustrates the consistency of the deposition flux while the second one illustrates the capability of the avalanche model to predict the formation of a heap having a slope corresponding to the angle of repose of the sediments.

Line 508.

How is “mass error” named in figure 17?

→ response: a legend was added to the Figure.

legend of Figure 18 includes “total, suspension, bed, error”

Line 515:

Justify the selection of the application case.

Validations were done for 1D and 2D cases.

→ response: The goal here is to illustrate the full coupling between hydrodynamics, sediment transport and morphodynamics which was not illustrated so far.

The following text has been added to the introduction of section 5, line 614: “Building on the validation of the model components presented in Section 4, this section examines the

transport of an isolated dune under a steady current as an illustrative application of sedExnerFoam.”

Line 526:

“...which differs slightly from values obtained with the models presented in table 2...”

How does it affect the numerical results? Justify it properly.

→ response: All the parameterizations listed in Table 2 are empirical, and slight deviations from directly measured quantities are therefore expected, as observed in these experiments. For parameters whose values are known, such as the settling velocity, the model can be configured to use the measured value directly.

Line 529:

“...large compare to what is expected from the formulas in table 2”.

Again, justify how these values affect the numerical results.

→ response: Same reason as previous point.

Line 542:

Please, specify how Figure 18 is obtained. There is no clear information on the text.

→ response: The text has been changed

line 648: “In order to confirm the capability of the wall friction term to correctly predict the flow velocity in the narrow flume, five simulations corresponding to different discharges as reported in the experiments are performed. Figure 18 shows a summary of these runs with and without the lateral friction term.”

Line 548:

Change two-dimensional to 2D.

→ response: Done

line 653: “The main advantage of taking into account lateral friction as a source term is that it enables the use of a 2D mesh, which significantly reduces the computational cost of the simulation.”

Line 558:

Quantify correctly “after some time”. This type of statement is not acceptable in a paper.

→ response: Done

line 625: “fter the initial transient phase over which the bed porosity evolves”

Line 560:

“...it was verified that the domain upstream “

How was it verified? Please, specify it.

→ response: It was verified through a sensitivity analysis to the upstream domain length that the solution does not change when using a longer domain

line 665: “it was verified through a sensitivity analysis to the upstream domain length that the solution does not change when using a longer domain.”

Line 572:

Which numerical solvers are used for this “new initialization” of the case?

Please, specify them.

→ response: The solver is the same, just the sediment transport and bedMotion are turned off.

Line 577:

Please rephrase the paragraph (“...multiple attempts...”)

→ response: the sentence has been changed as follows:

line 682: “The results presented in Figures 21 and 22 were obtained after multiple simulation attempts and a sensitivity analysis of the various model parameters.”

Line 578:

Please, add in an appendix a graph that illustrates the importance of a grid analysis.

→ response: We have added a grid analysis in appendix. It concerns the effect of mesh resolution on the bed shear stress.

An appendix (Appendix C: Dune migration, supplementary material) has been added

Line 588:

Please, add in an appendix a graph that illustrates the importance of the choice of the numerical schemes.

→ response: a second order scheme for the advection scheme in the momentum equation, a first order scheme shall not be used as it will not accurately capture the position of flow detachment and the recirculation cell.

Line 599:

Please, add in an appendix a graph that illustrates the importance of the choice of the critical Shields number.

→ response: many parameters may be sensitive including the critical Shields number, we decided not incorporate a sensitivity analysis to all of them. According to our experience, the critical Shields number plays a second order role in the morphodynamics and affects the dune migration.

Line 616:

I can not follow how the velocity is better observed in Figure 19 than in Figure 21.

Please, rephrase this paragraph for a better comprehension.

→ response: The text now only mention that the velocity difference is also observed in Figure 19. The Figure referenced was not the correct one, it has been corrected.

line 722: "This velocity difference is also observed in Figure 21 showing the bed elevation profiles at different times."

Line 619.

Please, rephrase the first two sentences correctly.

→ response: Done, it was changed

line 725: "Overall the numerical model is able to reproduce the dune migration and evolution correctly, the remaining discrepancies are the dune's crest shape."

Line 622:

" but it could also be a consequence of the method used to estimate the dune length"

Please, specify why and if it could be solved with a different method.

→ response: An appendix showing how the dune length was estimated has been added. The dune length was estimated from the intersection of two straight lines fitted on the upstream and downstream slopes, respectively. Because the dune upstream slope is not exactly a straight line, this method can slightly underestimate or overestimate the dune's length.

an appendix has been added “Appendix C: Dune migration, supplementary material”

Line 625:

Conclusions are very poor. They should resume the structure of the paper, explain different sections and clearly state the main findings and objectives of the manuscript.

→ response: The conclusion has been almost entirely rewritten and the main findings are now emphasized clearly. In particular two paragraphs are dedicated to the model strength and the current limitations as well as future possible developments.

line 753: “The model’s main strengths are its open-source availability and extensive validation on idealized benchmarks. From a software development perspective, using continuous integration tests on the GitHub repository helps to ensure the long-term maintenance of the code, as well as backward compatibility over time. Using the proposed avalanche model eliminates the need for the costly and unphysical iterative procedure employed in most existing 3D morphological models. Another novel feature introduced in this work is the near-wall diffusivity for turbulent suspensions, which enables the use of the same mesh for flow hydrodynamics and sediment concentration. To the authors’ knowledge, the application of bedload flux saturation is unique to this subaqueous sediment transport numerical model, and is essential for accurately predicting dune migration.

Beyond possible future developments, such as the addition of a free surface, accounting for multiple grain sizes or modeling cohesive sediments, the following limitations have been identified: (i) the feedback of the suspended sediment concentration on the flow hydrodynamics (e.g. through a Boussinesq term); (ii) the mesh resolution required for the accurate estimation of bed shear stress in regions of non-uniform flow, including bed roughness; (iii) the mesh deformation solver, which may cause the simulation to crash; (iv) the development, validation and implementation of filters for bed evolution; and (v) the formulation, implementation and validation of a multi-dimensional bedload flux saturation model.”

RC2: Jennifer Keenahan

General comments: Overall, this is a high-quality paper that presents a coherent, open-source ALE Exner framework in OpenFOAM with clear mathematical formulation, careful numerical implementation, and well-chosen validations that collectively demonstrate capability for complex morphodynamics around structures and steep bedforms. The narrative is logically structured from model description to targeted benchmarks and a realistic dune application, with figures and tables that effectively support the arguments

and trace key design choices such as turbulence modelling, bedload closures, saturation, and avalanche treatment. Reproducibility is bolstered by public code, tutorials, and explicit parameterisation for most tests, although a few tuned constants and boundary-condition specifics in the dune case could be pinned more precisely in the text for one-to-one replication without consulting the repository. The discussion is appropriately balanced - linking observed behaviours to numerical choices and acknowledging limitations like the absence of a free surface, constant porosity, dilute suspension assumption, and RAS grid-sensitivity - while outlining credible extensions that would broaden applicability. Minor editorial issues (e.g., symbol definitions and occasional notation/ordering inconsistencies) do not detract materially from the science or conclusions, which are well supported by the evidence provided. In sum, the paper is rigorous, useful, and timely, meriting a positive evaluation with only small clarifications needed to reach an excellent standard.

→ response: We would like to thank the reviewer for her positive comments and constructive feedbacks. All the points raised have been addressed and our point-by-point response is provided hereafter.

Specific comments:

Slope-corrected critical Shields number formula (eq. 11) has ambiguous powers; the intended factors are likely $\sin^2(\alpha_s)\tan^2(\beta_s)/\mu_s^2$, but it is written as “ $\sin(\alpha_s)^2 \tan(\beta_s)^2/\mu_s^2$ ”; use unambiguous exponent notation to avoid misinterpretation.

→ response: Done, the exponents were modified as suggested

k- ω SST transport equations: in eq. (5) the production term of ω is written “ αS ,” which is not the standard SST form (normally involves production from $P_k/\nu_t P_k/\nu_t$); if this is a deliberate simplification, state it; otherwise, correct the ω equation to the standard SST form or cite the exact implemented variant.

→ response: The explanation about the k-omega SST turbulence model has been corrected and an appendix has been added to detail the blending functions and the different model coefficients. The equations of the model now match the OpenFOAM implementation and it was verified directly in the code.

An appendix was added (Appendix A: RANS k – ω SST model) and the different equations were checked and corrected (section 2.2 turbulence modeling).

Lateral wall source term derivation needs clarity on specific vs absolute quantities and dimensions: τ_{wall} is introduced without density, and the width-based source term $F_{walls} = -f|u|u / (4Wc)$ would benefit from a short derivation to show consistency with the specific (per unit mass) form of the momentum equation used elsewhere (kinematic viscosity, specific pressure gradient)

→ response: An appendix providing a short derivation of this source term has been added to the manuscript. The τ_{wall} is also introduced with the density.

line 637: “The lateral variation of the flow is neglected and the specific shear stress on the lateral walls τ_{wall} is computed with the Darcy-Weissbach equation: $\tau_{wall} = \rho f |u|u / 8$ ”

An appendix (Appendix B: Derivation of Darcy-Weissbach source term) has been added to detail the derivation of the lateral friction to a source term for 2D simulations.

Directionality of bedload flux: the scalar ϕ_b and vector q_b are related via direction along shear or slope; explicitly define how q_b direction is set (e.g., aligned with bed shear stress, corrected for slope via α_s) to avoid ambiguity in eqs. (12) and the Exner divergence.

→ response: the bedload has two components, one aligned with the shear stress q_b and one component related to avalanche, q_{av} . The second one is aligned in the steepest slope direction. The fact that q_b is aligned with the shear stress has been added in the text.

line 219: “In this work, the bedload flux q_b is aligned with the bed shear stress.”

line 212: “This avalanche flux is oriented toward the steepest slope direction.”

Clarify whether τ_f denotes the negative Reynolds stress ($-u'u'$) or the total additional stress; eq. (2) matches the Boussinesq model for $-u'u'$, but the narrative could mislead; a single precise definition early in Section 2.2 would prevent confusion.

→ response: the following precision was added to avoid confusion "is equal to the opposite of the specific Reynolds stress tensor". The filtering tensor is indeed equal to the opposite of the Reynolds stress tensor $\tau_f = -u'u'$ in case of Reynolds Averaged Simulation.

“It can either be the opposite of the specific Reynolds stress tensor to run Reynolds Averaged Simulations (RAS)”

“As stated previously, in the case of RAS filtering, the tensor τ_f in equation 1 is equal to the opposite of the specific Reynolds stress tensor $\tau_f = - \langle u' \otimes u' \rangle$, with $\langle \rangle$ the Reynolds operator and u' the fluctuating velocity field.”

Overstatement: the difference between measured w_0 (7.67 cm s⁻¹) and model estimates (~ 5 cm s⁻¹) is described as “slightly,” but the $\sim 50\%$ gap is not slight; rephrase to “noticeably higher than” or quantify the percentage difference.

→ response: Done, the sentence was changed as suggested.

line 639: “which is noticeably higher than values obtained with the models presented in Table 2”

Suspended-load additional diffusivity (eq. 18): give default values and guidance on when to disable (e.g., rough-wall regimes, $k^+ \gg 1$) and how sensitive results are to $\epsilon_0 w$ and ζ_w , since Section 4.1 notes sensitivity but defaults are only briefly stated.

→ response: Even for rough flow regimes ($k^+ > 90$), the additional diffusivity does not need to be deactivated. As k^+ increases, the turbulent diffusion near the bed eventually becomes much larger than the additional diffusivity, rendering its contribution negligible. Therefore, there is no need to disable it, as it will simply be dominated by the ambient turbulence. The default values for $\epsilon_0 w$ and ζ_w are both 5 and are never adjusted in the presented work.

Bedload saturation (eq. 14): since Section 5 shows saturation is essential to prevent non-physical crest arrest, specify default T_{sat} and L_{sat} and provide a short note on how q_b direction is treated in the 2D finite-area discretisation when aligning with shear.

→ response: Currently, there are no default values for L_{sat} and T_{sat} in the code so that the user must provide the values when using a saturation model. Some guidelines on how to estimate T_{sat} and L_{sat} can be found in the work of Charru et al. (2013) “Sand Ripples and Dunes”. Regarding how q_b direction is treated, the direction of q_b is the results of the saturation equation. The saturated bedload flux is projected on an horizontal planar mesh also used to solve the Exner equation and the saturation equation is solved on this plane.

The following sentence has been added, line 713: “The results presented in this work have been obtained using a saturation length $L_{sat} = 5$ mm and no saturation in time was considered.”

Provide a short derivation or appendix note for converting Darcy–Weisbach wall shear into the 2D source term used, including assumptions (uniformity across width, use of hydraulic diameter D_h , and whether τ_{wall} is per unit mass), to pre-empt reviewer questions on dimensional consistency and calibration of f and k_w .

→ response: Done, a short appendix provides a simple derivation for Darcy-Weissbach source term. The fluid density has been added to τ_{wall} so that it is not per unit mass anymore. There was no calibration of f and k_w , the lateral walls were considered smooth and k_w was taken equal to $1e-6$. Different values of k_w were tested between $1e-6$ and $1e-4$ but the effect on the hydrodynamics was not significant.

An appendix (Appendix B: Derivation of Darcy-Weissbach source term) has been added

Technical corrections:

Convective term notation in the Navier–Stokes equation appears incorrect: “ $\nabla \cdot (u^T u)$ ” should be the divergence of the dyadic product $\nabla \cdot (u u) \nabla \cdot (u u)$, not a vector–vector inner product with a transpose; as written it is dimensionally and notationally inconsistent for convection in vector form.

→ response: The transpose was intended to indicate that the product is made between u in column vector and u in line vector which is the definition of the dyadic product. However to avoid confusion, the notation has been changed and the symbol \otimes is used instead for the dyadic product.

line 84: “where the operator \otimes is the dyadic product ...”

Adams–Bashforth order is misstated: the text says “a first order Adams-Bashforth scheme, which is a second order time scheme,” which is contradictory; AB1 is first-order and AB2 is second-order, so either the method or its order needs correction in Section 3.2 and figure captions/discussion where “Adams Bashforth 1” is presented as second order.

→ response: The confusion comes from the fact that the Adams-Bashforth schemes are derived using a Lagrange polynomial and using a first order polynomial yields a second order Adams-Bashforth scheme. This was changed in the manuscript (text and Figures 16, 18) to avoid confusion, the Adams-Bashforth 2 scheme is a second order scheme.

line 321: “or a second order Adams-Bashforth scheme for temporal discretization”

line 539: “A second order Adams-Bashforth scheme is used for time discretization”

line 548: “using a second order scheme for the temporal term (Adams-Bashforth 2) as the numerical solution no longer oscillates.”

Undefined symbol ϖ (varpi) in bedload formulas and avalanche term: ϖ is used multiplicatively in Table 2, eq. (12), and eq. (13) but is never defined (e.g., Heaviside step function, direction/sign, or scaling factor); define it explicitly or remove if redundant.

→ response: Done, its definition was added in the text just after its first appearance.

line 219: “and ϖ the threshold function so that $\varpi(\vartheta - \vartheta_c) = \vartheta - \vartheta_c$ if $\vartheta > \vartheta_c$ and 0 else.”

Inconsistency for Brownlie: Figure 3 legend shows “Brownlie (1981)” while the references list “Brownlie (1983)”; standardise to the correct year (the widely cited Caltech thesis is 1983) and update the figure legend accordingly.

→ response: Done

Naming consistency in Table 2 and text: “MeyerPeter” vs “Meyer-Peter & Müller (1948)” and “vanRijn” vs “Van Rijn (1984)” are inconsistent; standardise hyphenation, spacing, and capitalisation across tables, figures and prose.

→ response: In Table 2, the left column corresponds to the keywords to which each formula is associated in the code and which need to be selected by the user in the corresponding configuration file. Therefore, MeyerPeter is the keyword associated to the formula from Meyer-Peter & Müller (1948) and vanRijn the one associated to the formula proposed by Van Rijn (1984). It is not inconsistent.

Duplicate heading: “Author contributions. Author contributions.” appears twice; remove duplication.

-> response: Done

line 771: “Author contributions. JC, CB, and OB designed the project”

Spelling: “librairies” → “libraries” in Code and data availability.

→ response: Done

line 768: “sedExnerFoam Renaud et al. (2025) model code, associated libraries, tests and tutorials”

“pimpleFoam” appears only in Conclusions; consider introducing that inheritance explicitly in Section 3.1 for immediate context

→ response: Done, pimpleFoam appear in the introduction of the section dedicated to the numerical implementation.

line 285: “The development originated from the existing solver pimpleFoam, which is designed for incompressible transient flow simulations and employs the PIMPLE algorithm for pressure-velocity coupling.”

RC3: Sem Geerts

Overall, it is a promising paper that is worth publishing as it can be a useful tool for many civil engineers. The manuscript does well in explaining some chosen test cases to explain the model performance. However, I think there are some points worth of attention and major revisions are necessary before final publication.

→ Response: We would like to thank the reviewer for his positive feedback. We did our best to address most of the reviewer's comments and our point-by-point response is provided hereafter.

General comments

The model shows no three-dimensional results and performance while this is computationally different. Especially the introduction talks about processes such as scour (lines 41 – 49 and figure 1), which is then not covered as a complete case for the remainder of the manuscript. I think these three-dimensional cases are worth showing to truly trust the model.

The style of writing of the paper concerns me. To me, it reads like a textbook for students or like an informal review paper describing the history of development of morphodynamic modeling. Overall, the style should be changed and the quality of English should be improved (examples of which are provided in the Technical comments below). Specifically, I recommend to either (1) add the historical framing to the aim of the overall paper, or (2) remove the historical context as it does not contribute scientifically.

→ response: The sketch in figure 1 has been modified to fit with the article's application on dune migration. As the paper is already quite long, we prefer to limit the manuscript to 2D cases. The style of writing has been slightly adjusted but the writer wants to keep the seminal works in the presentation of the sediment transport community.

Some examples:

Lines 76-83 mention all kinds of different turbulence closures, but in the end only one is implemented.

→ response: Only one turbulence model is used but all the turbulence model available in openFOAM, including LES, can be used as well.

Line 122: "...an Austrian meteorologist and geophysicist." Not sure why this is relevant.

→ response: Done, it has been removed

line 164: "The morphological evolution of a granular bed in a wide range of sediment transport problems is modeled by the so-called Exner equation, which was first proposed by Exner (1920)."

Line 135: "In the 1930's, Albert Frank Shields made measurements of the motion threshold already highlighted by Du Boys in 1879." Vague and misses citations

→ response: Done, the original paper from Shields is now cited and the work of du Boys is referenced using the paper from Hager (2005) Journal of Hydraulic Research 43(3):227-233, DOI: 10.1080/00221680509500117

line 178: "In the 1930's, Shields made measurements of the motion threshold already highlighted by Du Boys in 1879 (Hager, 2005)."

Lines 161-165. Unclear why alternatives to modelling avalanches are mentioned when a different implementation is used.

→ response: The most classical way to model avalanches in morphodynamic models is to use the iterative methods while the flux approach that we use is more classical in landscape evolution models. We believe it is important to mention the different options.

Section 2.4.3 provides a lot of context and alternatives, while it seems that only one implementation is done in the end (even mentioning "In sedExnerFoam it was chosen to avoid the use of two different meshes" in line 203). Focus on this formulation and avoid confusion.

→ response: Same as the previous point, we believe it is important to draw the different options before presenting our approach.

Model performance, convergence and computational costs are missing to the manuscript and how this compares to other morphodynamic models. Where should this newly developed model be framed, given the morphodynamic models discussed in the introduction?

→ response: Agreed, in the revised version, the computational costs are reported for the model validation cases at the end of each validation description. An appendix has also been added showing the effect off mesh resolution on the bed shear stress exerted by the flow on the dune.

line 462: “These simulations complete in a few seconds on a single CPU core.”

line 507: “These suspension development simulations require 10 hours of wall-clock time on 5 CPU cores to compute 50 seconds of physical simulation time.”

line 580: “These simulations complete in a few seconds on a single CPU core.”

line 611: “These simulations complete in a few seconds on a single CPU core.”

To me, a separate discussion of the weak points of the developed model is missing. I do notice these kinds of points returning in the main text and the conclusion, and I understand that the migrating-dune case is considered the benchmark, but a separate discussion would be appropriate, such that the conclusion can focus on a fundamental summary.

→ response: We have revised the conclusion and we now emphasize more the strengths and weaknesses of the model

line 753: “The model’s main strengths are its open-source availability and extensive validation on idealized benchmarks. From a software development perspective, using continuous integration tests on the GitHub repository helps to ensure the long-term maintenance of the code, as well as backward compatibility over time. Using the proposed avalanche model eliminates the need for the costly and unphysical iterative procedure employed in most existing 3D morphological models. Another novel feature introduced in this work is the near-wall diffusivity for turbulent suspensions, which enables the use of the same mesh for flow hydrodynamics and sediment concentration. To the authors’ knowledge, the application of bedload flux saturation is unique to this subaqueous sediment transport numerical model, and is essential for accurately predicting dune migration. Beyond possible future developments, such as the addition of a free surface, accounting for multiple grain sizes or modeling cohesive sediments, the following limitations have been identified: (i) the

feedback of the suspended sediment concentration on the flow hydrodynamics (e.g. through a Boussinesq term); (ii) the mesh resolution required for the accurate estimation of bed shear stress in regions of non-uniform flow, including bed roughness; (iii) the mesh deformation solver, which may cause the simulation to crash; (iv) the development, validation and implementation of filters for bed evolution; and (v) the formulation, implementation and validation of a multi-dimensional bedload flux saturation model.”

Specific comments

The abstract should be rephrased, it currently has no conclusion.

→ response: The abstract has been entirely rewritten and now provides a better overview of the content

Line 41: Scour is explicitly covered in the introduction, but later, no reference is made to it, and it's not a use case. Furthermore, it's a 3D process, and it is unclear whether the newly developed model is able to achieve this.

→ response: The reference to scour has been minimized in the introduction. Figure 1 has also been changed and now represents sediment transport in a river with the presence of a subaqueous dune.

Figure 1 has been changed

The introduction misses a clear aim.

The end of the introduction should clearly state the structure of the paper with corresponding sections.

→ response: the outline of the manuscript is now clearly presented at the end of the introduction.

line 62: “After presenting the mathematical formulation of sedExnerFoam in Section 2 and the modeling approaches for hydrodynamics, turbulence, and sediment transport closures, several key numerical aspects are discussed in Section 3, with particular emphasis on the treatment of the Exner equation. This is followed, in Section 4, by the model validation against a series of academic benchmarks consisting of simple test cases designed to isolate individual components of the model and validate them separately against analytical solutions or experimental data. The validation suite includes simulations of idealized dune

migration, sediment suspension under steady flow conditions, both in and out of equilibrium, and two sediment deposition scenarios. Finally, in Section 5, the model's capabilities are demonstrated through the simulation of an isolated dune migrating over a rigid bed under steady flow conditions. The numerical results reproduce a stationary migration regime, characterized by the dune moving at a constant velocity while maintaining its shape throughout the migration process. The conclusion provides a summary of the present work and discusses the current limitations of the model and possible future improvements."

Lines 109 – 114. Not sure why all of this is mentioned while a constant value is assumed in the end.

→ response: the reference to non uniform Schmidt number has been removed, only the equation from van Rijn (1984) remains to serve as an example of guideline to set the value of the Schmidt number.

line 153: "In this model, the Schmidt number is treated as constant and defined by the user, with the preceding equation (Eq. 10) serving as a useful guideline for choosing its value."

Line 130: D and E are not fluxes, but a gradient of fluxes (just like q_b is a flux).

→ response: The terms E and D are not referred to as erosion/deposition rate in the text.

line 173: "D and E are respectively the deposition and erosion rates"

Line 141: Equation 10 has no reference to it and no context or explanation.

→ response: A reference has been added to the equation.

Line 156: Equation 12, and in general, unclear what omega is.

→ response: You were referencing to ϖ which is the threshold function. An explanation has been added to the manuscript.

line 199: " ϖ the threshold function so that $\varpi(\theta - \theta_c) = \theta - \theta_c$ if $\theta > \theta_c$ and 0 else"

Line 156: Equation 12 could be removed, as it is just one of the many sediment transport equations available to the user, listed in Table 2.

→ response: We keep it in its most general form to represent the bedload flux, allowing readers to see the overall structure of a bedload formula directly in the text and to refer to Table 2 for more information on the version implemented in the model.

Line 167, Figure 4: Not sure whether it is worth it to show this figure, as they are not your results.

→ response: All the formula for sediment settling velocity, hindrance effects, critical Shields number and bedload flux were developed by other authors. Figures 2, 3, and 4 serve only to present the range of modelling options offered to users, which we find important to highlight in a manuscript describing an open-source model. Also we believe it is good to show them in the manuscript and we prefer to keep them.

Line 175: Equation 14 is one-dimensional, while bedload q_b is in the text considered a 2D flux.

→ response: This is a good point and we haven't been able to find a 2D version of this equation in the literature. For clarity the following sentence has been added in the manuscript:

line 222: “A clear limitation is that this formulation is 1D, limiting its application to cases limited to one horizontal direction. To the authors’ knowledge, no multidimensional extension of this equation has yet been reported in the literature.”

in the perspectives, line 764: “the formulation, implementation and validation of a multi-dimensional bedload flux saturation model”

Line 354 & 399: unclear what z^+ is.

→ response: $z^+ = z u_* / \nu$ is the dimensionless wall distance for turbulent boundary layers. The definition has been added in the text.

line 447: “Here, $z^+ = u_* z_1 / \nu$ denotes the distance of the first cell center from the bed boundary in wall units, where z_1 is the distance to the sediment bed boundary”

Line 365: “For all 4 simulations, the turbulent Schmidt number was set to values slightly above 1, $\sigma^c \in [1.1, 1.2]$ ” Why is this done? Is this part of a calibration step that is not described?

→ response: The Schmidt number was previously calibrated for two of the cases to improve agreement with the experimental results. However, in this revised version, the figure has

been updated and the results shown are obtained without any calibration, demonstrating that the model already performs satisfactorily. The parameters that could be adjusted for calibration are indicated.

line 460: “a better fit could be obtained by adjusting the turbulent Schmidt number σ_c , the coefficient of the near bed diffusivity ϵ_{0w} and ζ_w (Eq. 19) or even the equivalent sand roughness height k_s .”

Line 369 talks about “adjusting”; is calibration meant by this?

→ response: same as previous response.

Lines 384-385: “Rouse number is equal to 0.5 which corresponds to a highly suspended regime.” Is this still valid concerning the assumption that suspended load does not influence hydrodynamics, as mentioned in line 64?

→ response: Yes, this assumption remains valid, as the analytical solution used for comparison does not account for suspended sediment concentration. Moreover, as shown in Figure 11, except for a thin layer near the bed, the suspended sediment volume fraction is low (<0.01), supporting the assumption that the feedback of the suspended load on the hydrodynamics can be neglected. The term “highly suspended regime” can be misleading; here, it is used to indicate that suspended load is the dominant transport mode compared to bedload, rather than implying that the suspended sediment volume fraction is high. The text was modified to avoid confusion

line 476: “the Rouse number is equal to 0.5 which corresponds to a regime in which suspended load is the dominant sediment transport mode.”

Lines 456-461: I don’t understand which numerical schemes are implemented here. I understand the Euler explicit time scheme, but I’m only familiar to the notion of an upwind scheme when dealing with spatial discretisation of advective terms. In conclusion, I do not understand how a temporal scheme and a spatial scheme are compared here. Could you explain further?

In addition to the point made above; the evaluation of the different numerical schemes is not appropriate within Section 4: Validation.

→ response: The discretization scheme for the divergence flux term can be either centered (i.e. linear), upwind first order or upwind second order (i.e. linear upwind). This is what we want to test here to evaluate which combination of numerical schemes are the most

suitable and what are their convergence properties and stability. We believe this analysis has its place in the validation section of the manuscript.

Line 482: I am not an expert on suspended sediments, but 132 kg/m³ seems like a very high concentration and seems to violate the assumption of dilute sediments only (line 64). Could you comment on this?

→ response: As explained in the text, this value corresponds to 5% of concentration in volume which is substantial but not that huge. This test case is not meant to reproduce a real case but more to verify that the sediment fluxes between the suspended sediment layer and the bed layer are consistent and that mass is conserved.

Section 4.4: The presented cases are all purely deposition cases. The time-step delay in the morphological response (lines 489-491) indicates that mass is not conserved. This is not a problem in the example given, but could you comment on how this influences more realistic cases when hydrodynamic conditions are more complex?

→ response: Mass is indeed conserved; however, due to the one-time-step delay in the morphological response, the mass transferred from the suspended load to the bed during a time step appears in the bed mass only at the beginning of the next time iteration, when the mesh geometry is updated to reflect the morphological change. The mesh motion must occur at the beginning of the time iteration because the updated cell volumes are required to implicitly solve the hydrodynamic and suspended load equations using the finite-volume method. Looking at Figures 16 and 18, the maximum mass delayed is 0.2 and 0.3 % of the total sediment mass. This mass delay is proportional to the time step which is limited by the stability condition for the hydrodynamics (Courant number < 1) so that we do not believe that it could become a problem for more complex hydrodynamic conditions.

Section 5.1: A lot of calibration seems to be necessary to get representative results. Especially, the critical shields parameter and the bedload transport formula need to be greatly adapted to get proper model validation. How do you reflect on the validity of the results? Are the results shown essentially a “model overfit” for the specific experiment examined, or can the same parameters also be used to model different experiments in the same flume from Sandoungout (2019)?

→ response: The same parameters can be used to reproduce other cases of Sandoungout (2019) experiments. In sediment transport the uncertainties in the model parameters can be very large, as large as a factor 10 for bedload fluxes according to Recking (2013) for example. This is one explanation for the tuning of the bedload law, the second one could

be due to the estimation of the bed shear stress which is also sensitive to the model parametrization, boundary conditions and near wall grid resolution.

Section 5.1: The results would become a lot stronger if a validation of the hydrodynamics over the dune is done as well.

→ response: OpenFoam has been validated extensively for the flow hydrodynamics in various configurations. Using RANS k-omega SST model is not the best option but as far as the morphodynamics is concerned we believe this is a relevant modeling approach to start with. The main issue in the present configuration is that the flume is very narrow and therefore a lot affected by the lateral confinement. The author of the experiment did not provided enough data about the flow around the migrating bedform and therefore we can not directly compare the flow with experimental data. The fact that the flume is really narrow might also explain why we had to tune the sediment parametrization.

Technical comments

General technical 1: please use more comments to improve readability. Examples:

408: As stated previously the difference with the pseudo-analytical ... -> As stated previously, the difference with the pseudo-analytical ...

442: Overall, the model fits well with the analytical solution except when the ...-> Overall, the model fits well with the analytical solution, except when the

592: In addition the critical Shields number ...-> In addition, the critical Shields number

→ response: Done

General technical 2: The citation format used (especially the use of first names) is inconsistent and not in line with the journal's expectations.

Line 32: ALE is mentioned but not what it means

→ response: this has been corrected, the first sentence mentioning ALE now gives the full name Arbitrary Lagrangian Eulerian

line 43: "These models are based on the Arbitrary Lagrangian Eulerian (ALE)"

Line 89: Equation 5 has weird formatting

→ response: The final document will be a two-column article in which the equation is too long to fit on one line only which is why it was split. A modification has been made so that it does not appear so weird in the one-column manuscript.

Line 109: "... hot topic today ...", informal -> Rephrase

→ response: Done, the sentence was changed

line 146: "The values adopted for the Schmidt number have remained a topic of debate to this day"

Line 131 – 131: "2 dimensional" -> "two-dimensional"

→ response: It was changed to 2D

line 174: "The Exner equation is a 2D equation and is thus solved after applying a 2D plane projection on all variables."

Line 144: "Accurately measuring the threshold of motion is a difficult task mainly because of the absence of a universal definition of the motion threshold." Vague and unclear -> rephrase

→ response: The sentence was modified to:

line 185: "Accurately measuring the threshold of motion is challenging, primarily because no universal definition exists. Different criteria, such as initial grain displacement, sustained motion, or measurable transport, lead to different threshold values."

Line 167: adimensioned -> dimensionless

→ response: Done

Figure 4: "The dimensionless bedload flux as a function of the relative Shields number"

Line 172: "eolian", unclear what this is.

→ response: We meant aeolian, this has been corrected

line 215: "One last aspect which is often neglected when modeling sediment transport in water but is widely used in aeolian transport is the saturation of the bedload flux."

Line 181: “hard point”, informal and vague -> rephrase

→ response: Done, the sentence has been changed

line 226: “the modeling of erosion and deposition fluxes represents one of the main challenges in classical sediment transport models”

Line 190: “for a lot of situation”, vague and informal -> rephrase

→ response: Done, the sentence was changed

line 235: “this boundary condition is not suitable for cases in which the assumption of local equilibrium at the reference level does not hold”

Line 192: “to handle out of”, unclear -> rephrase

→ response: Done, the sentence was changed

line 236: “It was adapted by Celik and Rodi (1988) to accommodate non-equilibrium conditions.”

Line 238: “split” -> “discretised”

→ response: Done

Line 265-267: “The users have the choice to use either an explicit Euler scheme or a first order Adams-Bashforth scheme, which is a second order time scheme, for temporal discretization.” Confusing -> rephrase

→ response: The confusion comes from the fact that the Adams-Bashforth schemes are derived using a Lagrange polynomial and using a first order polynomial yields a second order Adams-Bashforth scheme. This was changed in the manuscript (text and Figures 16, 18) to avoid confusion, the Adams-Bashforth 2 scheme is a second order scheme.

line 321: “or a second order Adams-Bashforth scheme for temporal discretization”

line 539: “A second order Adams-Bashforth scheme is used for time discretization”

line 548: “using a second order scheme for the temporal term (Adams-Bashforth 2) as the numerical solution no longer oscillates.”

Line 273-275: “Jacobsen (2015) made a detailed review of the different possible methods to solve the Exner equation and analysed their benefits and shortcomings. He proposed a mass conservative interpolation scheme which is the one implemented in the current model.” Informal, rephrase

→ response: Done, it has been rephrased in a more formal way.

line 327: “Jacobsen (2015) provided a detailed review of the various methods available for solving the Exner equation and analyzed their respective advantages and limitations. He proposed a mass-conservative interpolation scheme, which is the one implemented in the present model.”

Lines 314-325: Rephrase, informal use of English and many redundant words.

→ response: Done, those paragraphs have been rephrased.

line 370: “In their work, Jasak and Tukovic (2006) examined in greater detail the issues that arise when mesh motion is computed using a finite-volume based approach. They proposed a vertex-based method that avoids cell-collapse problems during mesh deformation. To apply this method to meshes composed of arbitrary polyhedra, each polyhedron is decomposed into a set of tetrahedra. The drawback of this approach is that Eq. 22 must then be solved on a significantly refined tetrahedral mesh, which contains many more cells than the original. For example, decomposing a hexahedral mesh increases the number of cells by a factor of six. For this reason, and because the classical finite-volume formulation has provided satisfactory results in practice, the vertex-based method is not currently implemented in sedExnerFoam. Nevertheless, it could be introduced in the future should the need arise for more demanding applications.”

Line 375 & 381: “hypothesis” -> hypotheses

→ response: Done

Line 398: vary -> varies

→ response: Done

Line 440: “looked for”, rephrase

→ response: Done

Line 442: get -> gets

→ response: Done

Line 464: deltax -> Δx

→ response: Done

Line 470: “all simulation are stables” -> “all simulations are stable”

→ response: Done

Line 485: “ the sediment bed slopes get important on the extremity of the deposition mound” -> rephrase

→ response: Done, it has been rephrased

line 596: “Because the settling is not spatially uniform, pronounced slopes form at the margins of the deposition mound, where avalanching occurs, producing a conical shape similar to that seen in an hourglass.”