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Numerical modeling of sand transport using Lagrangian particle tracking

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SUMMARY:
Sand transport is a significant concern in various fields, such as railway industry, environmental and wind engineering. Accurate modeling of aeolian sand movement can help engineers design effective systems for managing sand and preventing damage to equipment. In this study, a numerical model is implemented to simulate the transport of sand particles using CFD and Lagrangian Particle Tracking (LPT). The main goal of this work is to obtain a good balance between accuracy and computational efficiency, as existing models in literature are extremely accurate but too heavy to be used in full scale problems. The model was validated by comparing the simulated results with measurements taken from the experimental campaign done by Saipem on the sand mitigation system of the Etihad Rail Stage 1, located in the UAE.

Keywords: CFD, Lagrangian Particle Tracking, sand transport

1. INTRODUCTION

Wind-blown sand is a growing concern that impacts not only structures such as individual buildings, cities, and transportation infrastructure, but also human endeavors like farming and industrial operations, in particular in desert region the sand accumulation on railway tracks can cause disruption of operations, safety and maintenance issues. An accurate model for simulating sand movement can help engineers design effective systems for preventing sand buildup and protecting equipment from damage. The goal of this study is to develop a computationally efficient numerical model capable of accurately simulating the behavior of sand particles in desert environments. To simulate wind-blown sand transport different approaches are possible, such as multiphase flow (Ariyaratne et al., 2016; X. Chen and Yu, 2022; H. Zhang et al., 2021; X. Zhang et al., 2023; Y. Zhang et al., 2020), lagrangian (Liqiang and Liejin, 2006; Nino and Garcìa, 1998; Sarafrazi and Talaee, 2019; Z. Zhang and Q. Chen, 2007) and CFD-DEM (Plenker and Grabe, 2016; Yang et al., 2010). The physics of the aeolian sand movement is complex and expensive to simulate for full-scale problems, as it involves collisions between particles, friction, and other variables (Bagnold, 1936; Huang et al., 2019). Therefore, the approach used in this work is to simplify the physics of the problem by ignoring the more complex phenomena and artificially reproducing the sand transport by directly injecting particles in order to reproduce the desired behavior. The numerical model is validated using experimental data taken from the experimental campaign done by Saipem on the sand mitigation system of the Etihad Rail Stage 1. In this work we present the implementation of the numerical model of sand transport on a railway infrastructure using the LPT. The experimental setup and equipment, is described first; then the aerodynamic and numerical setup are discussed followed by an explanation of the underlying physics and solutions in modeling the problem. Finally the last section will collect a general view of the work.

2. EXPERIMENTAL DATA

The experimental data provided by Saipem are represented by the monitoring database of Field Trials (FT) and Wheather Stations (WS) created for the study of the Sand Mitigation System of Etihad Rail Stage 1. Each FT and WS was collocated in predetermined points along the railway line and was equipped with the following instrumentation:

- Ultrasonic anemometers, for the measurement of wind velocity, wind direction and humidity.
- Big Spring Number Eight (BSNE) sand traps, to measure the amount of sand carried by the wind.
- Impact counter sensor (or saltation sensor), to evaluate the number of flying sand particles carried by the wind impacting on the sensor.

3. NUMERICAL MODEL

The numerical model consists of an aerodynamic solver, able to simulate the wind profile, and a particle tracking solver, capable of simulating the phenomenon of transport of sand particles under the action of the wind. Both solvers belong to the open-source framework OpenFOAM. The entire model was calibrated and validated using the experimental data of the FT provided by Saipem. Data from different geometries of mitigation are available, enabling the use of one of them for the calibration of the model and the others for the validation of the results.

3.1. Aerodynamic model

To simulate the sand transport a Lagrangian Particle Tracking approach is used: this method represents particles as discrete points and their path is solved by applying Newton's Laws. In order to reduce the simulation time a decoupled approach is used, so the solid phase doesn't influences the flow field. To obtain the velocity field a steady-state RANS approach with a k-ε turbulence model is used while a LPT is used to inject and track the particles. The mesh is hexaedral structured in the whole domain and polyhedral close to the terrain surface. The input velocity profile for this study is based on the theory of turbulent boundary layer explained in the Eurocode 1 (Eurocode, 2005), standard EN 1991-1-4: 2005.

3.2. Sand transportation

A preliminary literature review on the aeolian sand movement (Bagnold, 1941; Huang et al., 2019; Kok et al., 2012; Sørensen, 1991), allowed to identify two main types of sand motion:

- Suspension, characterized by constant sand flux with height (Fig.1 in red). It involves smaller particles that can remain suspended for long distances.
- Saltation, which accounts for the majority of the mass flux (Fig.1 in green). It involves particles that are too large and heavy to remain suspended in the air and fall or jump onto the terrain at a height of 50 cm or less.

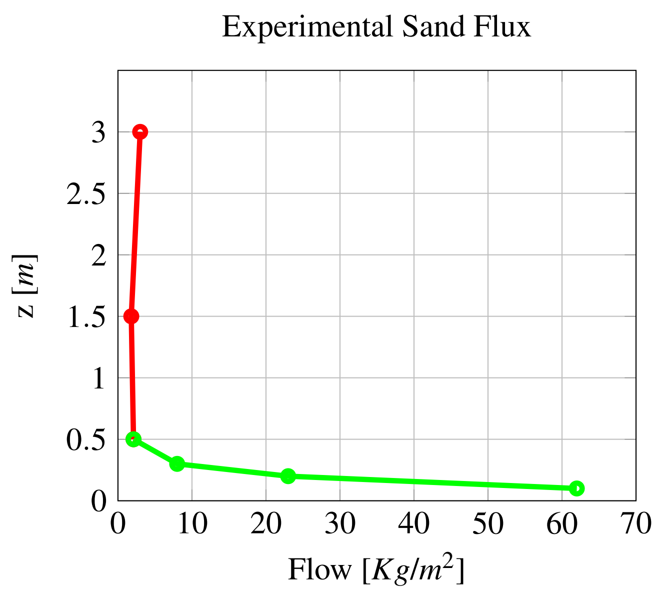

Figure 1. Sand flux at different height measured at the trial site.

4. INJECTION MODELS

In this section the injection models (Fig.2) that replicate the main behaviours of the sand particles, adopted in the numerical simulations, are described.

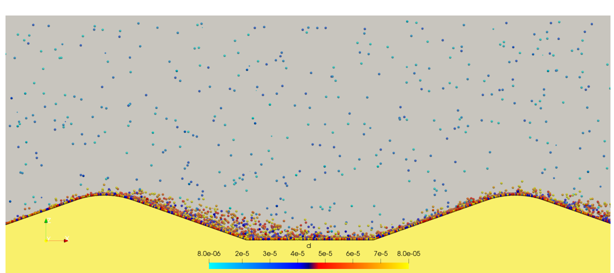

Figure 2. Suspension and saltation.

4.0.1. Suspension

The sand transported by suspension has a smaller size and is injected directly from the inlet face, where the wind comes from. Spherical particles are used with a dimensions of 8, 12, 20, 25 and 30 microns and a density of 2600 Kg/m^3. On this particle acts the aerodynamic drag force and the gravitational force g.

4.0.2. Saltation

The sand that is transported by saltation has a larger size and is injected directly from the ground at different velocities in order to catch the experimental heights registered from the traps. The particles injected have a dimensions of 40, 50, 60, 70 and 80 microns with density equal to the ones in suspension.

5. CONCLUSIONS

This study demonstrates that the numerical model presented is able to accurately simulate the primary modes of sand transportation in the target desert region: saltation and suspension. The numerical results show a very good correspondence with the experimental data both in terms of flow velocity and sand transport. It will be also noted that the experimental data must be carefully analyzed, since the meteorological uncertainties affect the experimental data.

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