EXPERIMENTAL VALIDATION OF A CONSTANT SURFACE SHEAR STRESS IN PARTICLE SALTATION LAYERS

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Abstract Owens second hypothesis [1] states that the surface shear stress induced by the fluid on the stationary sediment on the ground in a particle saltation layer equals the threshold for particle entrainment. Despite the fact that most numerical models describing sediment entrainment and particle mass fluxes in turbulent boundary layer flows make use of Owens second hypothesis, no direct experimental validation of this assumption has been presented to date. We present direct measurements of the fluid shear stress on the ground in sand saltation layers to validate this hypothesis. The shear stress was measured for different wind velocities with various particle concentrations in the saltation layer using Irwin sensors. Additionally, particle concentrations in the saltation layers were estimated from shadowgraphic images taken with a high speed camera.

INTRODUCTION

In his paper on saltation of uniform grains in air, Owen [1] stated that "*the concentration of particles within the saltation layer is governed by the condition that the shearing stress born by the fluid falls, as the surface is approached, to a value just sufficient to ensure that the surface grains are in a mobile state*". In other words: In saltation layers, the fluid stress τ_f on the stationary sediment on the ground is equal to the threshold shear stress τ_{th} for particle erosion. The fact that particles extract momentum from the flow and thus getting accelerated results in a deceleration of the air flow within the saltation layer. The more particles get entrained and transported within the saltation layer, the more momentum is extracted by the particles from the wind resulting in a reduced fluid shear stress on the ground. However, to maintain the saltation layer and the particles in a mobile state, a minimum of fluid shear stress on the ground, which has to be equal to the threshold τ_{th}, is necessary. This self-balancing mechanism is what Owen [1] described in his second hypothesis. Generally, Owens second hypothesis is physically plausible and it is widely accepted to use these assumptions in numerical models, however, to our best knowledge, a direct validation was still missing.

METHODS

We performed wind tunnel measurements of the air induced skin friction velocity $u_\tau = (\tau_f /\rho)^{1/2}$ (where ρ is the air density) in sand saltation layers using 11 Irwin sensors [2,3]. Irwin sensors can be used to measure a small pressure difference close to the surface that can be calibrated against skin friction velocities. For the experiments, commercial quartz sand was glued on wooden boards that covered the test section of the wind tunnel (Fig. 1), providing a sand-rough reference case without saltation. For the saltation experiment, a 1.5 cm layer of the quartz sand was distributed on the sand rough wooden boards 6 meter upstream of the Irwin sensors. The loose sand was then slowly discontinued so that the area around the sensors was completely without loose sand (Fig. 1). This setup guarantees that the Irwin sensors are always at the same level with the sand surface during the erosion experiment. Furthermore, it was found that the few particles that get caught by the sensors during an erosion experiment do not influence their performance. For the experiments, the free stream velocity U_δ of the wind tunnel was continually increased from 0 to about 16 m s^{-1} during the first 330 s, then kept constant at this speed for another 70 s and afterwards continually decreased to zero. One experiment was performed with, and one without saltating sand.

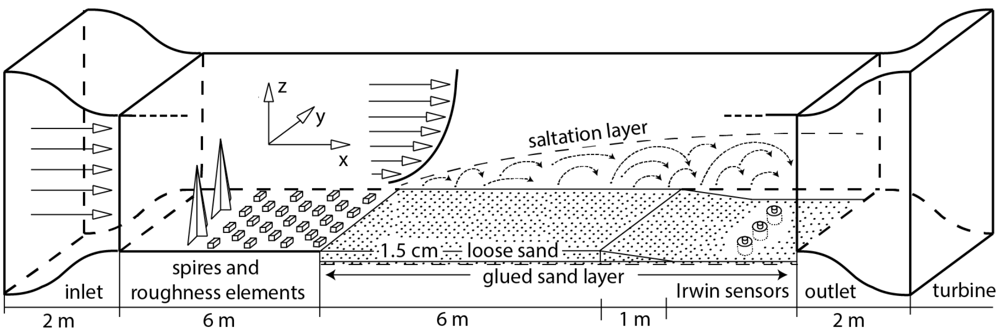

Figure 1. Sketch of the wind tunnel setup with a 1.5 cm thick loose sand layer above a thin layer (≈ 2 mm) of glued sand on the ground. Spires and artificial roughness elements were used for preconditioning the boundary layer flow.

RESULTS

Fig. 2 shows the shadowgraphic images of the lowest 80 mm of the sand saltation layer taken with a high speed camera at t = 250, 300 and 350 s during the erosion experiment. It clearly shows the strong increase in the particle mass flux in the saltation layer due to the increase in U_δ. The images were taken at a frame rate of 2000 Hz. Unfortunately, the high particle densities at high wind velocities makes particle tracking and the determination of particle sizes impossible. Nevertheless, the images provide very useful data to get an idea of the magnitude of the particle mass flux in the saltation layer.

Figure 2. Shadowgraphic images taken with the high speed camera during the sand saltation experiment.

Fig. 3 shows the averaged skin friction velocities u_τ measured with the 11 Irwin sensors as a function of time. Each data point is an average of 23.3 s and 11 Irwin sensors. The error bars give one standard deviation of the variations of the time averaged u_τ –values of the 11 Irwin sensors. The strong variations between the different sensors are mainly a result of their location in the wind tunnel, the sensor calibration procedure [3], how well they are flush mounted with the sand surface and the rather short averaging period of 23.3 s at a non-stationary flow. Nevertheless, the averaging procedure results in a nice linear increase of u_τ with increasing U_δ validating the accuracy of the measurements.

Both, the skin friction velocities for the experiment with and without saltation increased equally with increasing U_δ during the first 200 s (Fig. 3). Then, from t = 200 s on ($U_\delta \approx 11$ m s^{-1}), the threshold for particle entrainment was reached resulting in the development of a sand saltation layer. From there on, u_τ remained constant at around 0.3 m s^{-1} and did not increase with increasing wind velocities and particle mass fluxes. Contrary, in case without particle saltation, u_τ continued increasing for $t > 200$s. When decreasing U_δ below the threshold for erosion around t = 500 s, the saltation layer collapsed and u_τ began to decrease with the same rate as it did for the experiment without particle saltation. These results suggest that the threshold skin friction velocity $(\tau_{th}/\rho)^{1/2}$ is about 0.3 m s^{-1} for the here investigated sand surface. However, most interestingly and important, the constant skin friction velocities found during particle saltation of various magnitudes in between t = 200 – 500 s validates Owens second hypothesis.

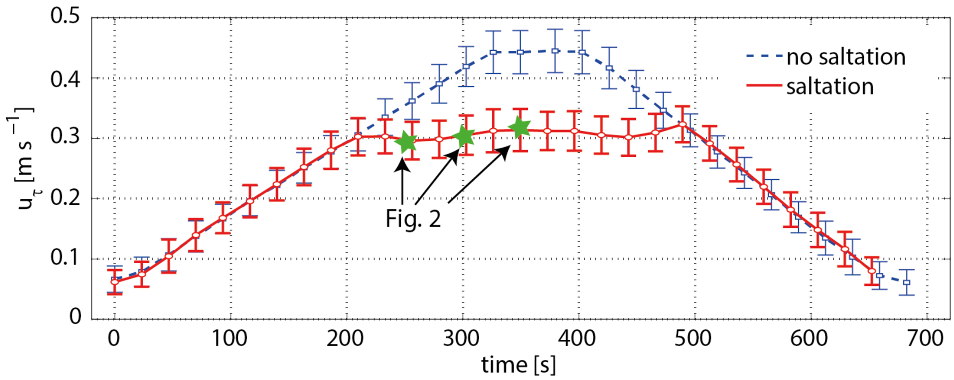

Figure 3. Temporal evolution of the skin friction velocity u_τ in case of an immobile sand surface (no saltation) and in case of a mobile sand surface (saltation).

References

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