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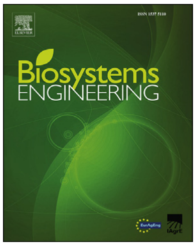

Research Paper

Analysis of the incipient motion of spherical particles in an open channel bed, using a coupled computational fluid dynamics–discrete element method model

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The measurement of liquid-induced erosion using CFD–DEM (computational fluid dynamics–discrete element method) models has been studied in detail, particularly in rough pipes. Some studies have provided measurements of the erosion rate in open liquid–solid systems, but there is less information on the incipient motion of individual particles since it is difficult to design test beds that can provide reliable results. This work compares the fluid flow velocity required to initiate incipient motion of a particle predicted by a coupled CFD–DEM model with measurements obtained during an experiment in an open channel under laboratory conditions. The experiment was designed to obtain a continuous flow with a slow and gradual increase in water velocity. The bed was made using two rows of spheres fixed in staggered positions, and a test sphere resting on top of the three neighbouring fixed spheres (i.e. nestling in the space between the surfaces of the fixed spheres). A 50 mm-high spillway gate was located downstream of the test sphere in order to obtain deeper water upstream, and provide more easily monitored and controllable water flows. The critical flow velocity required to initiate incipient motion in the five test spheres of different dimensions was measured by acoustic Doppler velocimetry. The difference in the results provided by the two methods was <5% (i.e. no significant difference). The coupled CFD–DEM model could therefore predict this variable and could be useful for investigating incipient erosion under other conditions.

1. Introduction

Soil erosion is commonly quantified in terms of an ‘erosion rate’, the value of which is a function of the shearing force, the critical shearing force, and a coefficient of erodibility (Elliot, Liebenow, Laflen, & Kohl, 1989). For many years, soil conservation technicians have used the Universal Soil Loss Equation (USLE) system to select the erosion-control practices required

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Nomenclature

AGNPS	Agricultural Non-Point-Source Pollution Model
CFD–DEM	Computational Fluid Dynamics–Discrete Element Method
GUEST	Griffith University Erosion System Template
LISEM	Limburg Soil Erosion Model
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
n'_c	Number of sampling points within the mesh cell occupied by a particle
C_D	Drag coefficient
F_D	Lifting force
F_L	Drag force
K_a	Area constant for a spherical particle
K_f	Projected area of the drag and lifting forces
M_C	Combined moment of cohesive forces
U_D	Time-averaged drag velocity
V_p	Volume of the particle
W_S	Submerged weight of a particle
l_i	Moment length for each contact location
u_t	Friction velocity
y^+	Dimensional parameter to differentiate sublayers
N	Number of sampling points that define a particle
S	Transmission of the momentum
T	Temperature
U	Time-averaged velocity
V	Volume of the cell in the CFD mesh
d	Diameter of the particle
g	Acceleration due to gravity
y	Depth of the channel

Greek Symbols

ε_s	Fraction of sampling points within a cell
ρ_w	Density of the fluid (Wilson Model)
ρ_s	Density of the particle (Wilson Model)
τ_c	Critical shearing strain
γ	Specific mass
ε	Additional volume fraction
μ	Dynamic viscosity of the fluid
ρ	Density of the fluid (Continuous Model)

to protect farmers' fields. However, Foster, Lane, Nowlin, Laflen, and Young (1981) pointed out that changes during the season and storm types impose limitations on the usefulness of this method. Physically-based models are therefore needed to predict erosion. Nearly all physically-based models rely on empirical equations and have their origin in the relatively simple diagram developed by Meyer and Wischmeier (1969) for testing whether a mathematical approximation of erosion is possible.

The best known physically-based models are the Water Erosion Prediction Project (WEPP) (Flanagan, Gilley, & Franti, 2007), Limburg Soil Erosion Model (LISEM) (Takken et al., 1999), Griffith University Erosion System Template (GUEST) (Yu, Rose, Ciesiolka, Coughlan, & Fentie, 1997) or Agricultural Non-Point-Source Pollution Model (AGNPS) (Abdelwahab, Bingner, Milillo, & Gentile, 2014) types, although there are many others, each with their advantages and drawbacks (Merritt, Letcher, & Jakeman, 2003). One of the scientific fundamentals underlying all these models is an equation or submodel describing the detachment of particles caused by the action of flowing water and how well this reflects reality strongly influences the results obtained. Any improvement made to these equations/sub-models used may have important repercussions for the results of simulations.

Wilson (1993a, 1993b) developed and tested an early analytical model of particle detachment in which the drag force required to detach a particle from its bed was understood to be a function of the mean velocity of the water flow over time and the diameter of that particle. The analytical model was calibrated via experiments involving systems that measure the rate of erosion, e.g., the jet erosion test for river courses (Clark & Wynn, 2007; Hanson & Cook, 2004) and the mini jet device for laboratory work (Al-Madhhachi, Hanson, Fox, Tyagi, & Bulut, 2013), but the bed was assumed to be a continuous medium.

The incipient motion of particles in fluidised environments is of great interest in the analysis of sediment transport in alluvial streams. Since the pioneering work of Shields (1936), who attempted to provide a theoretical-experimental solution to the problem of the motion threshold of sediments, many authors have examined incipient motion - the term commonly used to describe the start of movement by sedimentary particles (Dey & Papanicolaou, 2008). Other authors (Buffintong & Montgomery 1997; Miller, McCave, & Komar, 1977; Paphitis, 2001) gradually modified the results of Shields, or incorporated new variables such as the Archimedes' number (Rabinovich & Kalman, 2008, 2009) and the movability number (Simões, 2014). Experiments to improve the underlying theory have involved a range of materials (Rabinovich & Kalman, 2007; Simões, 2014) and have provided abundant information.

However, the lack of a basic quantitative understanding of large scale erosion impairs the development of a general, reliably scalable method for describing erosion processes (Zhu, Zhou, Yang, & Yu, 2007). The problem lies in the difficulty of describing the threshold at which sediments begin to move when these are considered as individual particles. Visual criteria have been proposed (Tsuji, Kawaguchi, & Tanaka, 1993) involving qualitative comparisons of the results of simulations and experimentation, but these introduce discrepancies and comparisons are not easy to make (Beheshti & Ataie-Ashtiani, 2008).

Advances in the development of analytical and computational models have allowed better approximations to experimental results. The discrete elements method (DEM) of Cundall and Strack (1979) has undergone much development for use in the mining, mineral processing (Cleary, 2009) and pharmaceutical industries (Ketterhagen, am Ende, & Hancock, 2009), and in biosystems engineering scenarios (Ayuga, 2015; Horabik & Molenda, 2016), but it has been less used to examine erosion. Models coupling computational fluid dynamics (CFD) and DEM software were developed in gas–solid fluidised bed environments for use in applications in the chemical industry (Ebrahimi & Crapper, 2016; Karimi, Mostoufi, Zarghami, & Sotudeh-Gharebagh, 2012; Li, Gopalakrishnan, Garg, & Shahnam, 2012; Lim, Wang, & Yu, 2006;