MECHANICS OF SEDIMENT ENTRAINMENT

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ABSTRACT

Sediment entrainment mechanisms were studied experimentally involving high-frequency particle image velocimetry (PIV) measurements synchronized with hydrodynamic force measurement and the entrainment of spherical particles. Two experimental series were conducted. The first experimental series termed fixed bed experiments, focussed on the relation between near-bed velocities and forces on a spherical sediment particle. The second series of experiments, termed the entrainment experiments, focussed on the flow structure and magnitude of the critical velocities causing entrainment. High frequency Particle Image Velocimetry (PIV) was used to capture the details of the flow.The study aimed to improve the understanding of sediment transport mechanics, particularly the link between particle entrainment and the velocity causing entrainment, hydrodynamic forces, and turbulent flow structures. A spectral model of drag force based on quasi-steady theory is developed. The model is applied to experiments with different exposures of the target sphere. The performance of the model depends greatly on the choice of appropriate values of C_D and A. In the formulation of drag force the product of coefficient of drag and exposed area ($C_D A$) is found to be a more useful quantity. An improved expression for pdf of lift force based on the normal error law is provided which matches the measured data up to $\pm 3\sigma_{F_L}$ for all exposures. The skewness of the measured lift force is found to increase with increase in exposure indicating that the quasi-steady lift force starts to act with increase in exposure yielding a skewed distribution. The spectral density function of lift force as a function of streamwise and stream-normal velocity is developed and validated using the measured lift force data. The ratio of $C_L A / C_D A$ is found to increase with increase in exposure and the fluctuating

Bernoulli's lift is found to play a dominant role in generating high lift on bed sediment particles. Predominance of fluctuating Bernoulli's lift, over lift due to stream-normal velocity fluctuations, is observed at all particle exposures. The influence of vortices on sediment entrainment was studied in detail using a model vortex. It was found in particular that the streamwise position of the particle with respect to an advecting vortex is important in terms of creating the forces on its surface responsible for entrainment. Experimental investigations using PIV revealed the predominance of clockwise eddies associated with hairpin vortices. However, anticlockwise eddies induced by large scale sweep events were found to be mainly responsible for entrainment. The flow field during entrainment was found to be significantly different from the normal flow field, marked by negatively correlated streamwise and stream-normal velocity fluctuations, indicative of sweep events. For a completely shielded particle, the forces induced by an anticlockwise vortex are found to be the dominant entrainment mechanism. The particle is more likely to entrain by hydrodynamic lift (vortex and Bernoulli's) induced by an advecting anticlockwise vortex directly above it. For particles at higher exposure, the quasi-steady drag is found to be the primary entrainment mechanism aided by Bernoulli's lift. Sweep events were found to be responsible for entrainment of both shielded and exposed particles with lift and drag force being the dominant mechanism respectively. Impulse is found to be an important factor in initiating sediment entrainment. Quadrant analysis and pdf plots of the dominant hydrodynamic force reveal the higher probability of occurrence of high magnitude force induced by sweep events. Ejection events are found to be mainly responsible for extreme forces below the mean. PIV measurements of the velocity flow field for entrainment events revealed that the flow profile at the instant of entrainment is significantly different from the mean flow profile, featuring an increase in velocity. This increase in velocity is due to the occurrence of a large scale sweep event. A non-linear turbulence magnification factor is developed using regression analysis to account

for the role of turbulence and exposure in particle entrainment. The role of turbulence for a given flow depth is found to decrease with increasing exposure of the particle. An expression for the "threshold velocity" based on the mean and the fluctuating velocities at a particular elevation above the bed is developed for estimation of a new Shields type parameter. The new Shields type parameter is found to vary from 18 to 7 with increase in exposure of the particle. The proposed Shields type parameter is found to be dependent on exposure of the particle and considered to be more appropriate in defining the sediment transport threshold, since it closely represents the effect of near-bed turbulence and exposure. The study is extended for field applications by the use of similarity laws relevant to sediment entrainment, rendering the findings relevant to a large number of prototype flow configurations for a range of particle size based on flow depth and slope. The results of this study will be useful in developing new physically based formulation for numerical models of sediment transport based on physics of the particle entrainment.

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LIST OF SYMBOLS

A	Projected area perpendicular to the flow velocity
a	Acceleration of the fluid
C_a	Added mass coefficient
C_D	Drag coefficient
C_L	Lift coefficient
$C_{uw}(f)$	Co-spectrum (real part of the cross-spectrum) of the u and w velocity
$\overline{C_{\lambda u}}$	Time averaged correlation
$C_{\lambda u}\left(r_x, z\right)$	Two point correlation between swirling strength and the instantaneous
D	particle diameter
d_s	Sieve diameter
d_n	Nominal diameter
e	Exposure
f	Frequency
f_{start}, f_{peak} and f_{end}	Start, peak and end frequencies
Fr	Froude number
$F_D(t)$	Instantaneous drag force
$F_L(t)$	Instantaneous lift force
F_{net}	Net force
F_{DN}	Normalised force
$\left\langle f_{pi} \right\rangle$	pressure force
$\left\langle f_{vi} \right\rangle$	viscous force
g_i	Gravity acceleration
H	Flow depth
k_s	equivalent sand grain roughness
k	Vortex of strength
Lz, Lx	Moment arms

n_i is i^{th}	component of the unit vector normal to the surface element dS and directed into the fluid
p	Pressure
$p(F_L)$	Probability density function of lift force
$R_{F_D}(\tau)$	Auto-correlation function at a time lag τ
R_{uu} and R_{ww}	Auto-correlation coefficients of streamwise and stream-normal velocity
R_{uw}	Cross-correlation coefficient
Re	Flow Reynolds number
Re_*	Reynolds number based on shear velocity
R_{k_*}	Roughness Reynolds number
St	Strouhal number
$S_{F_D}(f)$	Auto-spectral density function of drag force at the frequency f
$S_{F_L}(f)$	Auto-spectral density function of lift force at the frequency f
S_{int}	Roughness-fluid surface interface
$S_{ww}(f)$	Power spectral density of w velocity
$S_{uu}(f)$	Power spectral density of u velocity
$S_{uu}(f)$	Power spectral density of u velocity
S_b	Mean bed slope
SF	Shape factor is defined as
std	Standard deviation
T_{DN}	Normalised force
u_t, u_b	Velocities at the top and bottom of the particle
u_i	i^{th} component of the velocity vector
u_p	Particle velocity
u_b	Near bed velocity
u_*	Shear velocity
u'^2	Normal stresses in the longitudinal direction

u_{ent}	Threshold velocity
u'	Velocity fluctuations (streamwise)
U_o	Mean bulk velocity
$\overline{U}$	Depth averaged flow velocity
V_f	Fluid volume within the spatial averaging volume V_o
V_c	Convection velocity of vortex
$\overline{V}$	Time-averaged variable
$\langle\overline{V}\rangle$	Double-averaged variable
V_o	Spatial averaging volume
w'^2	Normal stresses in the vertical direction
w'	Velocity fluctuations (stream-normal)
W_S	Submerged weight of the particle
z	Distance along stream normal direction
z_{ref}	Reference height
z_0	Roughness length

Mathematics and Greek symbols

ρ_{uF_L}	Correlation of lift force with *u*
δ	Delta-Dirac function
θ	Dimensionless shear stress
ρ	Fluid density
ν	Kinematic viscosity
α	Fractional convection rate, Turbulence magnification factor, Angle of the channel bed to a horizontal
Λ_o	Global length scale of the flow
λ_{ci}	Imaginary part of the complex eigenvalues of the velocity gradient tensor
β	Function of the roughness Reynolds number

σ_{F_D}	Standard deviation of drag force
σ_{F_L}	Standard deviation of lift force
σ_u	Standard deviation of the streamwise turbulent velocity fluctuations
δ	Theoretical wall level below the top of the roughness elements
κ	Von-Karman constant
λ	Wavelength
$\rho(\tau)$	Normalised correlation function
Δt	Pulse to pulse time
Π	Protrusion
τ_o	Bed shear stress
$\chi(f)$	Admittance functions
$\phi = V_f / V_o$	Roughness geometry function
$-u'w'$	Fluctuating Reynolds stress
$d\bar{u}/dz$	Streamwise vertical velocity gradient
e / D	Relative exposure

Subscripts

m = model

p = prototype

min = minimum

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