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Estimation of settling velocity of sediment particles in estuarine and coastal waters

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A B S T R A C T

A model for estimating the settling velocity of sediment particles (spherical and non-spherical) in estuarine and coastal waters is developed and validated using experimental data. The model combines the physical, optical and hydrodynamic properties of the particles and medium to estimate the sediment settling velocity. The well-known Stokes law is broadened to account for the influencing factors of settling velocity such as particle size, shape and density. To derive the model parameters, laboratory experiments were conducted using natural flaky seashells, spherical beach sands and ball-milled seashell powders. Spectral light backscattering measurements of settling particles in a water tank were made showing a distinct optical feature with a peak shifting from 470-490 nm to 500–520 nm for particle populations from spherical to flaky grains. This significant optical feature was used as a proxy to make a shape determination in the present model. Other parameters experimentally determined included specific gravity (Δ_{SG}), Corey shape factor (*CSF*), median grain diameter (D_{50}), drag coefficient (C_d) and Reynolds number (*Re*). The *CSF* values considered ranged from 0.2 for flaky to 1.0 for perfectly spherical grains and Reynolds numbers from 2.0 to 10^5 for the laminar to turbulent flow regimes. The specific gravity of submerged particles was optically derived and used along with these parameters to estimate the sediment settling velocity. Comparison with the experiment data showed that the present model estimated settling velocities of spherical and non-spherical particles that were closely consistent with the measured values. Findings revealed that for a given D_{50}, the flaky particles caused a greater decrease in settling velocity than the spherical particles which suggests that the particle shape factor has a profound role in influencing the sediment settling velocity and drag coefficients, especially in transitional and turbulent flow regimes. The present model can be easily adopted for various scientific and operational applications since the required parameters are readily measurable with the commercially available instrumentations.

1. Introduction

The settling velocity — also known as terminal or fall velocity — which refers to the rate at which suspended solids subside and are deposited in a fluid medium depending on the dynamic viscosity of the fluid, grain size, shape and density, and the difference between grain specific gravity and the settling medium (Dietrich, 1982) — is an important aspect in geological oceanography and is essential for various theoretical analyses and engineering applications, such as sediment transport, suspension (Zhang et al., 2017), deposition, mixing and exchange processes (Zhiyao et al., 2008), wetland reclamation and restoration, dredging, waterways navigation, harbor design, construction and monitoring the stability of coastal and offshore structures (Engelund and Hansen, 1967; Komar and Reimers, 1978; Khelifa and Hill, 2006). The well-known Stokes law expression is often employed to compute settling velocity of a particle in creeping flow, with the assumptions such as infinite medium, rigid sphere and no slip at the surface of the sphere. Stokes' law analysis is accurate for the forces exerted by the air, but begins to break down with increasing Reynolds numbers (for transitional and turbulent flow regimes) and grain sizes due to the increasing importance of fluid inertia and viscosity and grain physico-chemical characteristics. This has eventually led to the development and use of several empirical formulations to calculate the factors and forces affecting the settling velocity of sediment particles (Rubey, 1933; Dietrich, 1982; Cheng, 1997; Zhiyao et al.,

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2008).

In the absence of the theoretical basis of fluid flow around non-spherical and irregular grains, the settling velocity of a smooth sphere as a function of the grain size has been studied experimentally and theoretically by numerous researchers. For example, the settling velocity of natural sediment particles was characterized with a single curve of settling velocity as a function of the grain size (Baba and Komar, 1981) or sets of curves that account for the particle characteristics within a limited range of particle and fluid properties and with the identification of few factors affecting their settling velocities (Komar and Reimers, 1978; Haider and Levenspiel, 1989; Cheng, 2009). A large number of the published work have provided a simple formula to predict the settling velocity of fine and medium grains as a function of the particle diameter and Reynolds numbers. For instance, some studies have used the particle diameter with a set of constants for the determination of the settling velocity (Zhu and Cheng, 1993; Ahrens, 2000; Guo, 2002; She et al., 2005). Estimations of the settling velocity based on such inadequate data were inevitably overestimated with large errors (Ahrens, 2000; She et al., 2005). Numerous studies have derived the empirical formulations based on measurement data to predict the settling velocity as a function of assumed spherical particle diameter without regard to density and viscosity of the fluid and non-sphericity (Engelund and Hansen, 1967; Batchelor, 1972; Dietrich, 1982; Brown and Lawler, 2003; Cheng, 2009). The experimental work conducted by Baba and Komar (1981) provided evidence that the asymmetrical shape of settling grains needs to be accounted or else it will lead to too much of scatter in the settling velocity estimation results. Few studies have examined the various measures of sphericity and their ability to predict the drag coefficient and settling velocity of a non-spherical grain based on different experimental data that used quartz-silt, Quartz-sand, gravels and pebbles with different geometrical shapes including cylindrical, isometric, axisymmetric, orthotropic, and elongated/irregular conglomerates (Krumbein, 1942; McNown and Malaika, 1950; Komar and Reimers, 1978; Haider and Levenspiel, 1989). Empirical analyses of these results based on the pebble settling data extended to much larger Reynolds numbers (i.e., $Re = 5 \times 10^4$), yielded an expression which was found to be a better descriptor of the drag coefficient of the settling particles from its Corey shape factors (*CSF*) and Reynolds number. Pettyjohn and Christiansen (1948) and Graf and Acaroglu (1966) were among other researchers to emphasize the importance of considering the shape factor for determination of the settling velocity of any natural grains. Haider and Levenspiel (1989) proposed a design chart for settling velocity with the different sphericity factors. In other studies, a systematic analysis of several experimental data combined from different resources provided an empirical formulation which accounts for the effects of size, shape and density on the settling velocity of naturally occurring sediment grains (Graf and Acaroglu, 1966; Hallermeier, 1981; Dietrich, 1982; Khelifa and Hill, 2006; Law et al., 2014).

Despite substantial efforts devoted by many researchers to overcome the limitations associated with the Stokes law expression, the gross effects of these factors on settling velocity and their functional relationships have been poorly quantified in the previous studies. In addition to these known deficiencies, the empirical and semi-empirical methods reported in the literature have less advantageous since they are not readily usable with commercially available instrumentations. In this paper, a new model is developed to estimate the settling velocity of spherical and non-spherical sediment grains based on the characterisitcs of the particles and medium. Data from the previous experimental studies are used to serve as a base for establishing the model parameters and comparing the settling velocity results for spherical and non-spherical grains. These are combined with the new data sets established through our laboratory experiments on particulate scattering, backscattering and attenuation coefficients, turbidity, and sediment concentration with natural flaky seashells, spherical beach sands and ball-milled seashell powders (to nullify the material signature with shape). The Stokes law is subsequently extended with new parametrizations to estimate the settling velocity of spherical and non-spherical (flakey) grains. Results from the new model are evaluated by using various experimental data and comparison with results from the existing models.

2. Controlling factors for the grain settling velocity

2.1. Nominal or median particle size

The most important sediment properties are related to their grain size, shape, and specific gravity/density. Setting velocities of the sediment particles are often determined based on their size distribution (Guo, 2002; Zhiyao et al., 2008) or in-situ measurement techniques (Agrawal and Pottsmith, 2000; Law et al., 2014). In estuaries and coastal waters, the most significant particles are those of lithogenic (inorganic) and detrital (organic) particles with sizes in the range from clay to gravel (0.0039–200 mm) according to the classification on Udden–Wentworth scale (40–42) (Udden, 1914; Wentworth, 1922). In coastal hydraulic theory, the grain size analysis is performed for either individual particles or its hydraulic equivalents and the mean diameter (median) corresponding to 50pct finer (denoted by D_{50}) is widely utilized to describe the sediment size distribution curve without taking into account the shape of sediment grains. In this study, laboratory experiments were conducted for grain size and shape measurements on the lithogenic and sea shell particles using a Tri-Laser Particle Sizer (Microtrac S3500). This instrument provides a better resolution at lower particle sizes with a measurement capability of 0.02–2800 μm and the modified Mie algorithms for non-spherical particles. The Microtrac S3500 uses a unique detector geometry with logarithmic array that produces signal proportional to the volume of the particulate material, with the output size of sample being the median particle size (D_{50}). For these experiments, two sets of samples were prepared – sea shell powders obtained from the ball milling and mechanical hammering process (Fig. 1). The particle size range obtained includes the most significant particles present in coastal and estuarine waters (Sheldon et al., 1972; Jonasz, 1983; Buonassissi and Dierssen, 2010; Zhang et al., 2011).

The ball milled sea shell powders in dry state were taken in a sample delivery controller equipped with a built-in ultrasonic probe which was used to disperse the particles as they flew through the system. The fluid handler enabled uniform mixing of sample grains in the solvent before measurement. The filtered sea water was used as solvent in the analysis. The ensued particle sizes were analyzed in order to undertake an appropriate ball milling procedure in the sample preparation. Finally, samples were prepared with diameter (D_{50}) of 5.54 μm (Type I) and 100.68 μm (Type II). The Type I samples with 5.54 μm diameter were produced from the ball milling method and the Type II samples with 100.68 μm diameter resulted from the mechanical hammering method. These methods enabled to characterize the grain shape with different sizes corresponding to spherical and non-spherical particles. The previous studies provided evidence that organic particles are often larger in the size range of 3–100 μm (Sheldon et al., 1972; McCAVE, 1975; Zhang et al., 2011) compared to the inorganic particles in the size range of 5–6 μm in North Atlantic surface waters (Krey, 1967; Gordon, 1970; Raymond and Bauer, 2001).