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EXPERIMENTAL STUDY ON THE INCIPIENT MOTION OF MICROPLASTIC PARTICLES WITH DIFFERENT SHAPES, SIZES, AND DENSITIES ON A LIVE SEDIMENT BED

K. D. Goral[1], H. G. Guler[1, 2], B. E. Larsen[1], S. Carstensen[1], E. D. Christensen[1], N. B. Kerpen[3], T. Schlurmann[3] and D. R. Fuhrman[1]

1. *Department of Civil and Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Building 403, 2800 Kgs. Lyngby, Denmark.* kdego@dtu.dk.
2. *Department of Civil Engineering, Middle East Technical University, K5 Building, Üniversiteler Mah. Dumlupınar Blv. No: 1, 06800 Çankaya/Ankara, Turkey.* goguler@metu.edu.tr.
3. *Ludwig-Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Faculty of Civil Engineering and Geodetic Sciences, Leibniz University Hannover, Nienburger Str. 4, 30167 Hannover, Germany.* schlurmann@lufi.uni-hannover.de.

Abstract: The incipient motion of 65 microplastic particle groups, having both regular (57) and irregular (eight) shapes, are investigated experimentally in a circular flume. Regular shapes considered include spheres, circular cylinders, circular disks, square plates, cubes, square prisms, rectangular prisms, tetrahedrons, and fibers. The present data set is combined with another from the literature, and the incipient motion conditions of the collective particles are systematically analyzed. After accounting for (1) differences in static friction as well as (2) hiding-exposure effects, reasonable agreement with the classical Shields curve for the incipient motion of sediments is achieved.

Introduction

Microplastic particles are plastic fractions of any kind having length scales less than 5 mm, constituting a significant portion of plastic litter. Once released as pollutants, due to natural run-off processes, the long-term destination of microplastics is often the sea (beaches, oceans, coastal areas, reefs, etc.), where they can pose a threat to the marine environment, marine organisms, and consequently human health. Therefore, the fundamental transport properties and patterns of microplastic particles must be better understood as a prerequisite to developing any successful management strategies.

Studies considering the incipient motion of microplastic particles are limited. Waldschläger and Schüttrumpf (2019, hereafter WS19) conducted experiments with 14 different microplastic particles placed on different sediment beds to find their critical bed shear stress (τ_{bc}) for incipient motion. Yu et. al. (2022) investigated the incipient motion of 19 different microplastic particles considering different bed roughness using both a smooth glass bed and a bed comprised of glass beads to simulate smooth and rough bed conditions, respectively.

The present study aims to add a novel data set on the incipient motion of a broader array of microplastic particles, on a live sediment bed comprised of finer sediment grains than those used by WS19. This will thus cover a wider range of hiding-exposure effects, known to be important in analogous incipient motion and transport of mixed grain sediments.

Experimental Setup and Procedure

The present incipient motion experiments were performed with 65 different microplastic particle groups. The microplastic particle groups considered have variable size (1 to 5 mm), density, and shape. Regular shapes considered include: spheres, circular cylinders, circular disks, square plates, cubes, square prisms, rectangular prisms, tetrahedrons, and fibers. Additionally, eight groups were comprised of irregularly shaped particles (F, G, H, J, L, M, N, and P), taken from the wave flume experiments of Kerpen et al. (2020). Note that 18 of the regularly shaped particle groups used in the present experiments were also used in separate wave flume experiments of Guler et al. (2022).

The experiments were conducted using the circular flume at the Technical University of Denmark (DTU), depicted in Fig. 1a. An example snapshot of a cube having a 5 mm side length near incipient motion is depicted in Fig. 1b.

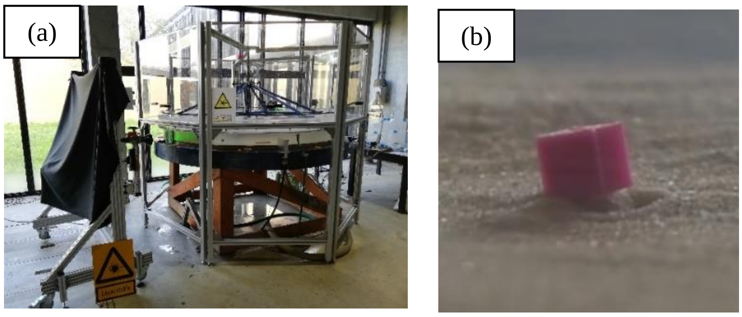

Figure 1: (a) The circular flume and (b) a snapshot just prior to the incipient motion of a cube with a 5 mm side length

Sediment with a median grain size d_{50}=0.18 mm and a density of 2560 kg/m^3 was placed inside the circular flume to create a live sediment bed, which was manually flattened prior to each test. The water column height between the lid and sediment bed was 0.12 m. Eight particles were selected from each group for testing. These particles were individually released from the middle of the water column to eight different locations equidistant from one another. The release angle (in plan, relative to the main streamwise direction) was varied by 45° for each successive particle release, in an attempt to avoid any alignment bias. The lid velocity then was gradually increased (and continuously recorded) until the incipient motion of each particle was observed.

The critical friction velocities ($U_{fc} = \sqrt{\tau_{bc}/\rho}$) were assessed, based on prior tests using Laser Doppler Velocimetry (LDV). In these tests a false bottom having the same thickness as the sediment bed was placed in the flume, enabling the measurement of flow velocities very near the bed. These were then reconciled with well-known theory for the viscous sub-layer region, such that the (linear) variation of the friction velocity versus lid velocity could be determined. These results were then confirmed with subsequent LDV measurements above the sediment-covered bed. (It is emphasized that the sediment used in the present experiments is sufficiently fine to yield hydraulically smooth conditions over the range tested, as was confirmed by these subsequent measurements.) For the present purposes, the critical Shields parameter, as commonly used for natural sediments, has been generalized from the first principles (similar to that presented in Section 7.3 of Fredsøe and Deigaard, 1992) to

$$\theta_c = \frac{2}{3}\frac{U_{fc}^2 A}{g(s-1)\text{Ꝟ}}, \tag{1}$$

where g=9.81 m/s^2 is the acceleration of gravity, $s=\rho_p/\rho$ is the relative particle density, ρ=998 kg/m^3 is the density of water, ρ_p is the density of the particle, Ꝟ is the particle volume, and, $A \sim c\sqrt{ab}$ is the characteristic projected area (where $a \geq b \geq c$ are the three characteristic particle dimensions). Note that in the case of spheres Eq. 1 simplifies to the classical definition

$$\theta_{c,\text{spheres}} = \frac{U_{fc}^2}{g(s-1)d}, \tag{2}$$

where d is the diameter. In addition, the Reynolds number is defined as

$$Re = \frac{U_{fc} d_p}{\upsilon}, \tag{3}$$

where $d_p = \sqrt{A}$ is a characteristic length scale of the microplastic particle and ν=1.01×10^{-6} m^2/s is the kinematic viscosity of water.

Analysis and Results

On dimensional grounds, we expect the critical Shields parameter for foreign microplastic particles to have the following functional dependence:

$$\theta_c = \varphi \cdot f\left(Re, \frac{d_n}{d}, \text{shape}\right), \qquad (4)$$

where $\varphi=\mu_{s,p}/\mu_s$ is the static friction coefficient of plastic ($\mu_{s,p}$) relative to that of pure sand (μ_s) and $d_n = \sqrt{6\cancel{V}/\pi}$ is the nominal diameter. Inspired by Eq. 4, we propose the following formulation for predicting the critical Shields parameter for foreign microplastic particles lying on a sediment bed:

$$\theta_c = \varphi \cdot \psi(Re) \cdot \Lambda\left(\frac{d_n}{d}\right), \qquad (5)$$

where an analytical approximation of the Shields curve for natural sediments is taken from Sui et. al. (2021):

$$\psi(Re) = 0.165(Re + 0.6)^{-0.8} + 0.045\exp(-40\mathrm{Re}^{-1.3}) \qquad (6)$$

and $\Lambda(d_n/d)$ is a function to be determined that accounts for hiding-exposure effects. Note that at the classical limit where the particle in question matches the properties of the native sediment bed $\varphi=\Lambda(d_n/d)=1$, Eq. 5 naturally reduces to: $\theta_c=\psi(Re)$.

Results for the present microplastic particles, as well as data from WS19, are shown on the classical Shields plane (θ_c versus Re) in Fig. 2, with the Shields curve for sediments (Eq. 6, black line) provided as a baseline.

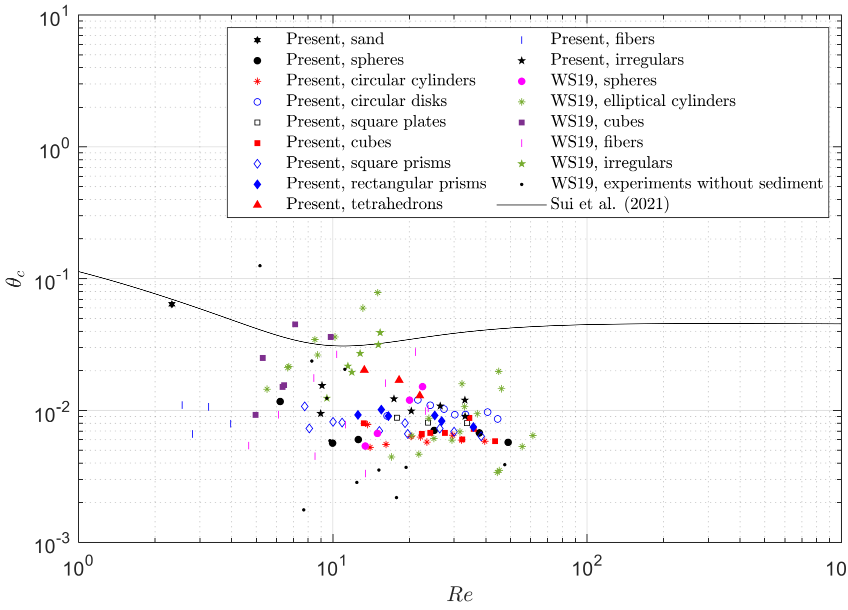

Figure 2: θ_c versus *Re* results for the present data combined with that of WS19.

It can be seen from Fig. 2 that using Eq. 6 alone is not sufficient to represent the θ_c of the microplastic particles, as nearly all the Shields parameters of the microplastic particles are below the classical Shields curve. Therefore, to consider the physics properly as summarized in Eq. 5, we first take φ=0.45, to account for the lower static friction between the plastic and sand particles. Additionally, based on the comparison of the combined data we find that the hiding-exposure effect may be reasonably calculated according to:

$$\Lambda\left(\frac{d_n}{d}\right) = \max\left[\left(\frac{d_n}{d}\right)^{-0.75}, 0.50\right]. \tag{7}$$

Inspired by Eq. 5, we now plot the normalized Shields parameters $\theta_c/(\varphi\cdot\Lambda(d_n/d))$ versus *Re* in Fig. 3. As can be seen, while there is considerable scatter, after taking into account the differences in static friction as well as hiding-exposure effects, the normalized Shields parameter for the microplastic particles cluster reasonably around the classical Shields curve. This thus marks the first time that the incipient motion conditions for microplastic particles have been properly reconciled with those of natural sediment grains.

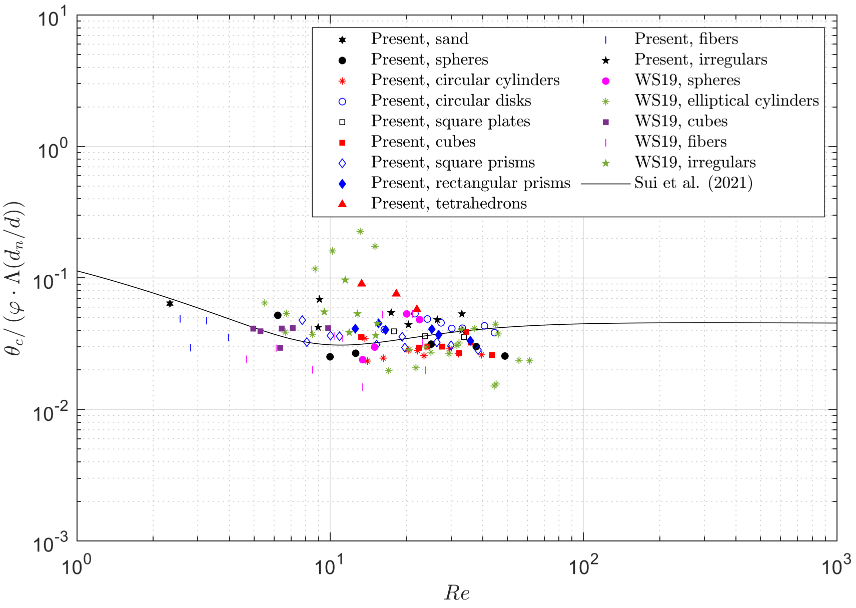

Figure 3: Normalized θ_c versus *Re* results for the present data combined with that of WS19.

Conclusions

The incipient motion of 65 different microplastic particle groups having both regular (57) and irregular (eight) shapes have been experimentally investigated within a circular flume located at the Technical University of Denmark. Regular shapes considered include spheres, circular cylinders, circular disks, square plates, cubes, square prisms, rectangular prisms, tetrahedrons, and fibers. The present data set is analyzed together with that of Waldschläger and Schüttrumpf (2019). The results show that if the Shields parameter is normalized to account for (1) differences in static friction between plastic and sand and (2) hiding-exposure effects, the classical Shields curve used widely for natural sediments can likewise be used to reasonably predict incipient motion conditions for foreign microplastic particles.

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References

Fredsøe, J. and Deigaard, R. (1992). "*Mechanics of Coastal Sediment Transport*," World Scientific, 369 p.

Guler, H. G., Larsen, B. E., Quintana, O., Goral, K. D., Carstensen, S., Christensen, E. D., Kerpen, N. B., Schlurmann, T. and Fuhrman, D. R. (2022). "Experimental study of non-buoyant microplastic transport beneath breaking irregular waves on a live sediment bed," *Marine Pollution Bulletin*. 181, article no. 113902.

Kerpen, N. B., Schlurmann, T., Schendel, A., Gundlach, J., Marquard, D. and Hüpgen, M. (2020). "Wave-induced distribution of microplastic in the surf zone," *Frontiers in Marine Science,* 7, article no. 590565.

Sui, T., Staunstrup, L. H., Carstensen, S. and Fuhrman, D. R. (2021). "Span shoulder migration in three-dimensional current-induced scour beneath submerged pipelines," *Coastal Engineering*, 164, article no. 103776.

Waldschläger, K. and Schüttrumpf, H. (2019). "Erosion behavior of different microplastic particles in comparison to natural sediments," *Environmental Science & Technology,* 53(22), 13219–13227.

Yu, Z., Yao, W., Loewen, M., Li, X. and Zhang, W. (2022). "Incipient motion of exposed microplastics in an open-channel flow," *Environmental Science & Technology* 56, 14498–14506.