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Published in:
The Proceedings of the Coastal Sediments 2023

Link to article, DOI:
10.1142/9789811275135_0105

Publication date:
2023

Document Version
Peer reviewed version

LABORATORY STUDY OF NON-BUOYANT MICROPLASTIC TRANSPORT BENEATH BREAKING IRREGULAR WAVES ON A LIVE SEDIMENT BED

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Abstract: Wave flume experiments investigating the cross-shore transport and accumulation patterns of non-buoyant microplastic particles under irregular waves propagating, shoaling and breaking on a live sediment bed are considered. Eighteen microplastic particle groups having variable shape, density and size are tested. The experiments considered a pre-developed singly-barred profile, reasonably representative of field conditions. Four different microplastic accumulation hotspots are identified: (1) the offshore toe of the breaker bar, (2) at the breaker bar, (3) the plateau region between the breaker bar and beach, and (4) the beach. The accumulation patterns primarily fall within three different particle Dean number regimes (ratio of the characteristic wave height to the product of the settling velocity and characteristic wave period). For the parameter space tested, the dominant transport direction generally depends on the importance of offshore-driving gravitational effects and onshore-driving effects associated with nonlinear wave shapes. Particle position relative to the jet of plunging breaking waves likewise plays a key role in determining the net transport direction, especially near the breaker bar.

Introduction

Microplastic particles (length scales ≤5 mm) are increasingly recognized as a harmful pollutant in natural environments, including the sea. Improved understanding of their transport mechanisms and accumulation patterns in e.g. nearshore coastal environments is required, as a prerequisite to any successful management or mitigation strategies. Towards enhancing this understanding, the present work utilizes a state-of-the-art wave flume facility, commonly used for studying coastal sediment transport and morphology, to study related nearshore transport and accumulation patterns of non-buoyant microplastic particles. The present work considers such transport beneath irregular breaking waves on a live sediment bed. This builds on prior experimental work of Forsberg et al. (2020), who considered short-term accumulation beneath breaking regular waves on a fixed (no sediment) bed and Kerpen et al. (2020), who utilized regular waves on a live sediment bed. Full results of the present study can be found in Guler et al. (2022), which includes additional investigations on the effects of the initial cross-shore profile (initially plane bed versus the initially singly-barred profile specifically considered herein).

Dimensional Analysis and Experimental Set Up

Experiments have been conducted in a wave flume in the Hydraulic Engineering Laboratory at the Technical University of Denmark, with a predeveloped sediment coastal profile and a far-field water depth of 0.5 m. On dimensional grounds, the cross-shore transport and accumulation patterns of foreign microplastic particles ought to depend on the following dimensionless numbers, in addition to their shape and the coastal profile:

$$\frac{H_0}{L_0},\ \frac{d}{H_0},\ \frac{d_p}{d},\ Re = \frac{H_0^2}{T\nu},\ \Omega = \frac{H_0}{Tw_s},\ \Omega_p = \frac{H_0}{Tw_{sp}} \qquad (1)$$

In the above H_0 = deep-water significant wave height; L_0=$gT^2/(2\pi)$ = deep-water peak wave length; d = median sediment grain size; d_p = characteristic microplastic size, T = peak wave period; ν = 0.988×10^{-6} m^2/s = kinematic water viscosity; w_s = sediment settling velocity; w_{sp} = settling velocity of microplastic particles; and g=9.81 m/s^2 = gravitational acceleration. The experiments use fixed H_0=0.16 m, T=1.6 s, d=0.18 mm, w_s=0.0173 m/s (hence H_0/L_0=0.041, d/H_0=0.0011, Reynolds number Re=17,000 and Ω=6.0).

The sediment settling velocity has been estimated based on the method of Fredsøe and Deigaard (1992). Microplastic settling velocities have been experimentally determined in separate tests, utilizing a clear plastic graduated beaker cylinder. The motion of the settling particles was recorded using a digital camera. The recordings were analyzed to obtain settling position versus time using an image processing algorithm, based on color tracking, similar to Goral et al. (2021). From these the terminal settling velocities (mean and standard deviation) have been obtained, based on results from several repeated tests for particles comprising each group.

Eighteen microplastic particle groups (90 particles each) having various shapes (spheres, cubes, circular disks, square plates and cylinders), sizes and densities have been considered. Photographs representing each particle group can be seen in Fig. 1. For a complete description of particle characteristics, see Guler et al. (2022). The initial sediment bed profile in the wave flume was manually shaped to a singly-barred profile (see Fig. 2a, largely governed by the sediment Dean number Ω), which was found to be close to equilibrium in a prior study on profile nourishment (Larsen et al. 2022, using the same flume, wave conditions and bottom sediment). Particles were initially released at the beach (x≈21 m), plateau (x≈17 m), and breaker bar regions (x≈12 m; see Fig. 2a), with 30 particles from each group released at each position. Experiments spanning long durations (up to 88 hr) have been considered, which were stopped every few hours such that particle positions could be counted and their temporal evolution monitored. Experiments were stopped once the particle counts from successive countings were very similar, such that near equilibrium accumulation patterns were believed to have been reached.

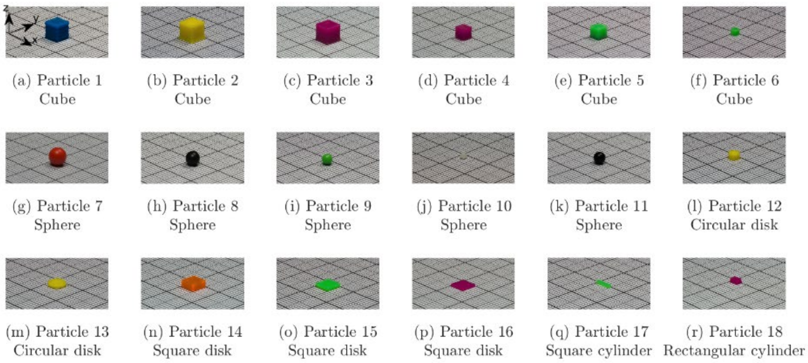

Fig. 1. Photographs depicting the microplastic particles used in the wave flume experiments on top of millimetric paper. This figure is reproduced from Guler et al. (2022).

Results and Discussion

Histograms depicting the final distribution of all 18 microplastic particle groups are presented in Fig. 2b-s. Note also the arrows on this figure, depicting the direction of net transport across regions (with numbers in text indicating the approximate net number of particles transported). From this figure four clear cross-shore accumulation regions can be identified: (1) the beach, (2) plateau, (3) breaker bar, and (4) the offshore toe of the breaker bar. Of the dimensionless numbers varied, the Dean number (Ω_p) has been identified as the most important governing the observed transport and accumulation patterns of the microplastic particles. Patterns largely fall into three microplastic particle Dean number Ω_p regimes. There are likewise additional shape effects, though these will not be specifically discussed in much detail herein, for the sake of brevity (see again Guler et al. 2022 for more detailed discussions).

The Dean number can be generally interpreted as the ratio of the characteristic wave height to the vertical distance a particle will fall over a characteristic wave period. Thus, larger values indicate smaller settling velocity and greater particle mobility, for fixed wave conditions. That Ω_p is important for governing transport and accumulation patterns of foreign microplastics is not altogether surprising, as Ω is commonly utilized to predict beach profile types (Wright and Short, 1984) and is important for the formation of breaker bars (Jacobsen and Fredsøe, 2014). In the present experiments, the sediment Dean number ($\Omega = 6.0$) is actually larger than those of the microplastic particles ($0.46 \leq \Omega_p \leq 2.51$). The microplastic particles in the present experiments may therefore be analogous to those of coarser sediment grains.

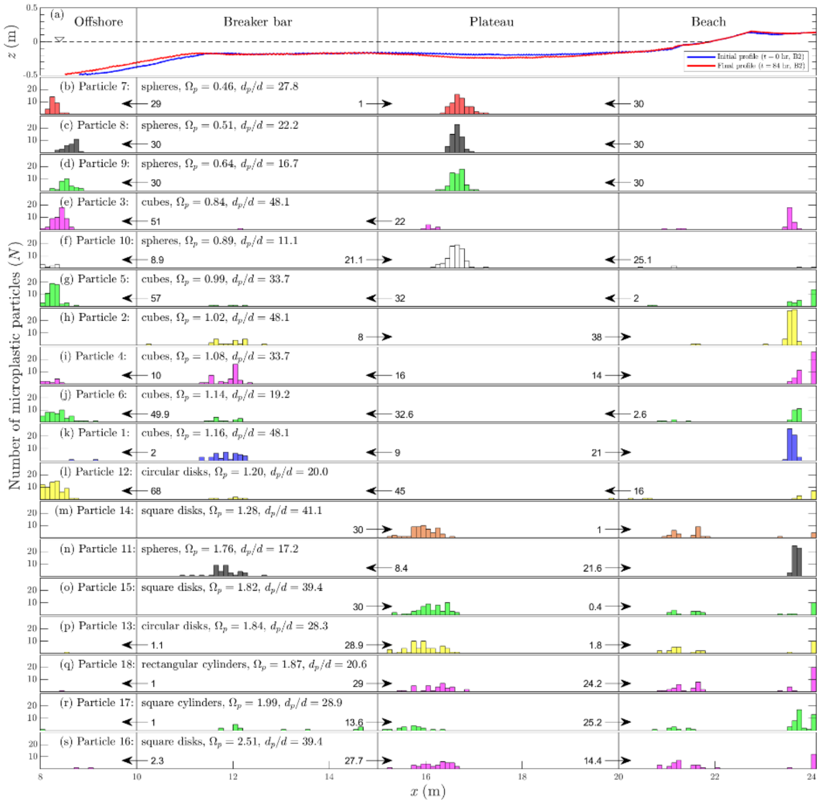

Fig. 2. Plots showing (a) initial (blue line) and final live (red line) sediment bed profiles and (b-s) final cross-shore distribution of microplastic particles, in ascending order based on the particle Dean number Ω_p. This figure is reproduced from Guler et al. (2022).

When viewed in this context, particles in the high particle Dean number regime (identified as $\Omega_p > 1.2$, Fig. 2m-s) generally behaved as expected. These particles will spend less time in suspension than the underlying sediment, and will therefore be less exposed to the offshore-directed near-bed undertow. They will therefore tend to be transported onshore as bed load, due to the combined effects of nonlinear wave shapes (wave skewness and asymmetry) and boundary layer streaming. Particles initially dropped near the breaker bar tended to be transported onshore, accumulating on the plateau. Very few were transported offshore of the breaker bar. Particles initially dropped on the plateau either stayed there or were transported further shoreward to the beach region. Particles initially dropped near the beach tended to remain there, with many being deposited on the berm (the deposition of sand onshore of the shoreline). Similar findings as these have been observed for cross-shore sediment transport when lowering the Dean number, by changing the wave conditions (e.g. Baldock et al., 2011, 2017). These trends are likewise generally consistent with observations that coarser sediment grains tend to accumulate at the shoreline (e.g. Guillen and Hoekstra 1996).

Conversely, microplastic particles in the low particle Dean number regime (identified as $\Omega_p \leq 0.9$, Fig. 2b-f) generally experienced offshore transport. Those initially placed near the beach tended to accumulate on the plateau. Particles initially dropped on the plateau generally remained there (with the exception of Particle 3, cube, Fig. 2e), such that this region clearly acts as a particle sink. Particles initially dropped on the breaker bar were uniformly flushed to the offshore toe in this regime. In this regime the foreign microplastic particles are relatively large and heavy, and hence tend to be dominated by gravitational forces. As a result, any onshore driving mechanisms, either at the sloping beach or near the breaker bar, were insufficient to overcome gravitational forces pulling them downslope.

Finally, experiments involving microplastics in the intermediate particle Dean number regime (identified as $0.9 < \Omega_p \leq 1.2$, Fig. 2g-l) demonstrate that they may be transported in either on- or offshore directions. This is due to the combination / competition of the driving forces discussed above, with the net transport direction largely depending on their initial drop position (also somewhat on their shape). Particles initially dropped on the plateau region were either transported further onshore to the beach or further offshore to the breaker bar (or beyond). In stark contrast to the high Ω_p regime, no particles in the intermediate regime accumulated on the plateau. Particles initially dropped on the breaker bar either remained there or were transported further offshore. Observations based on video analysis have indicated that their position relative to the jet of plunging breakers played a key role in determining whether particles either remained at the bar or were flushed further offshore (for further discussion of these effects, see Section 6.5 of Guler et al. 2022).

Particles initially dropped near the beach tended to remain there, with the clear exception of circular disks (Particle 12, Fig. 2l).

Conclusions

Experiments have been conducted in a small-scale wave flume investigating the cross-shore transport and accumulation of microplastic particles on a singly-barred profile subject to irregular waves propagating, shoaling and breaking on a live sediment bed. Eighteen microplastic particle groups have been considered, having variable shapes (spheres, cubes, circular disks, square plates and cylinders). Four different microplastic accumulation hotspots have been identified: (1) the offshore toe of the breaker bar, (2) at the breaker bar, (3) the plateau region between the breaker bar and beach, and (4) the beach. The observed transport and accumulation patterns generally fall within three particle Dean number regimes, though there are additional effects associated with particle shape. Within the parameter range tested, particles having high Dean number (relatively mobile particles, but not as mobile as the sediment utilized in the experiment) tended to be transported onshore as bed load due e.g. to effects associated with nonlinear wave shapes (skewness and asymmetry). Analogy has been made to prior observations involving coarse grained sediments. Conversely, particles having low Dean number (relatively large, heavy particles) tended to be transported offshore, due to gravitational effects combined with the locally sloping bed. Particles in the intermediate Dean number regime were transported either on- or offshore, largely depending on their initial drop position. Especially near the breaker bar, their position relative to the jet of plunging breakers played a key role in determining the net direction of transport.

Data availability

The full experimental data set from the present study is available at the DOI: https://doi.org/10.11583/DTU.19298669. The dataset includes the particle descriptions and properties, the full set of counted particle locations over time, selected experimental videos, as well as animations demonstrating the observed microplastic particle migrations.

Acknowledgments

This work is financially supported by the Independent Research Fund Denmark (MPCOAST, grant no. 0136-00227B). The second author also acknowledges support from The Scientific & Tech. Research Council of Turkey (TUBITAK), 2219 Int. Postdoctoral Research Fellowship Programme.

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