Wave-induced particle kinematics in the nearshore zone: measurements and simulations

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We report on a measurement campaign conducted at a beach on the island of Sylt, located off the German North Sea Coast with the goal of understanding particle dynamics in the surf zone. Using oranges as particle tracers in connection with a dual two-camera stereo imaging system, we were able to track individual tracers as they cycle through the waves approaching the beach. Supporting measurements were provided using ADV, wave staffs, pressure gauges and drones. The tracer positions are computed from the pixel positions, and the trajectories and velocities are analyzed with focus on wave-by-wave behavior, pre-breaking behavior and nearshore circulation.

Wave-by-wave dynamics in non-breaking waves

Pressure measurements show strong variation in mean-water level between consecutive waves due to the infragravity wave signal. It is shown that elevated or depressed local mean water level correlates with amplified or reversed Stokes drift. For example in Figure 1, it can be seen that the wave has a slight set-down of 0.02 meters, and there is no apparent Stokes drift. Indeed, the tracer drifts slightly seawards in one wave cycle.

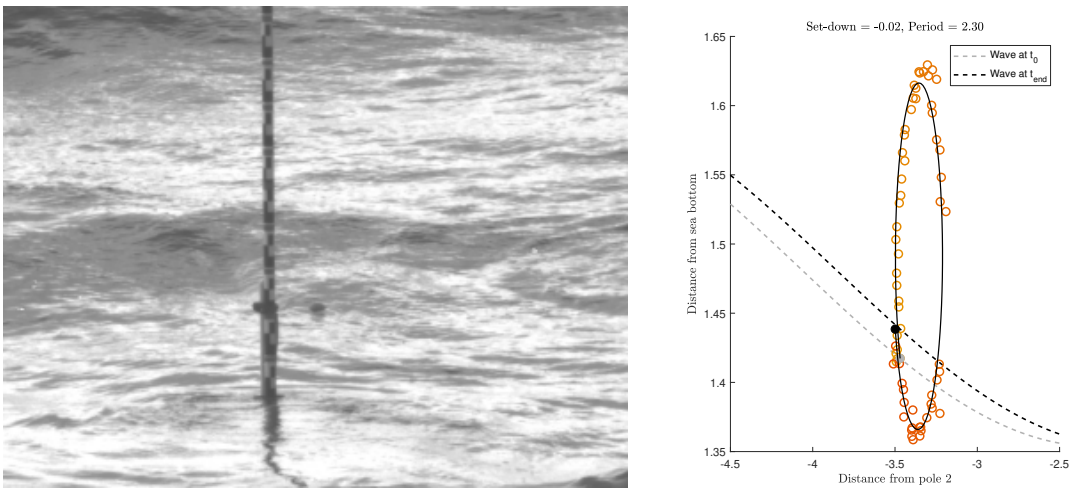

Figure 1: Left: Raw image of south cam showing sea surface, orange tracer and wave staff. Right: Tracer positions (orange circles) and numerical approximation of particle trajectory (solid line) for a wave with zero-crosssing period of $T = 2.30$s. All other measurements in meters. The gray circle shows the initial position, and the black dot shows the final position. For the numerical approximation, the KdV equation is used [6]. The right panel shows the projection onto the $x - z$ plane (x for cross-shore direction, z for depth).

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Particle dynamics in pre-breaking waves
Tracking individual tracers in pre-breaking waves allows the testing of common wave-breaking criteria such as the the kinematic criterion [4, 9, 10, 13] and other criteria [8, 14].

Time-averaged particle dynamics and nearshore circulation
There are a number of recent field campaigns and numerical simulations of wave-driven nearshore circulations (see [2, 12] and references therein). Using a Boussinesq model, the nearshore wavefield at the measurement site can be simulated, and velocity fields can be extracted. Numerical tracer trajectories can be computed and compared to measurement data from the field campaign. Fair agreement is obtained (see Figure 2).

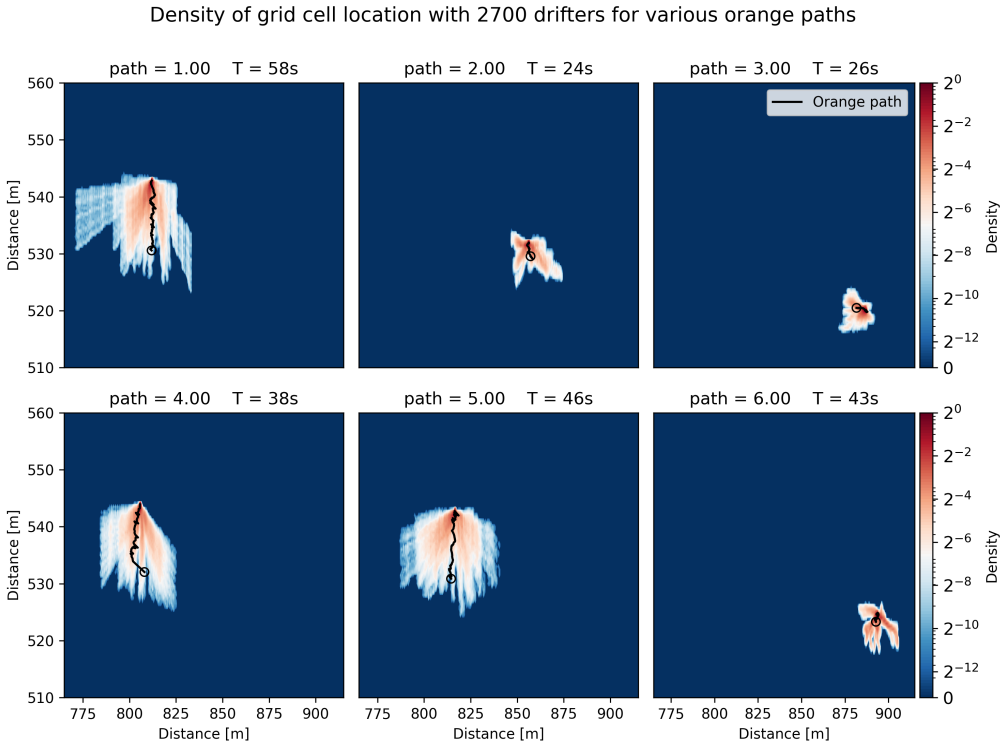

Figure 2: Comparison between tracer paths (black curves) and Boussinesq simulations with a variety of parameters defining tide level and spectrum of incoming wave field (likelihood of tracer in a given position is given by the color bar). The plot shows a projection into the horizontal (cross-shore longshore plane).

References

[1] Bacigaluppi, P., Ricchiuto, M. and Bonneton, P. 2020 *Implementation and evaluation of breaking detection criteria for a hybrid Boussinesq model*, Water Waves **2** 207–241.

[2] Baker, C.M., Moulton, M., Raubenheimer, B., Elgar, S. and Kumar, N. 2021. *Modeled three-timensional currents and eddies on an alongshore-variable barred beach*, J. Geophys. Res.: Oceans **126**, p.e2020JC016899.

[3] Bertin, X., de Bakker, A., Van Dongeren, A., Coco, G., André, G., Ardhuin, F., Bonneton, P., Bouchette, F., Castelle, B., Crawford, W.C., Davidson, M. et al. 2018 *Infragravity waves: From driving mechanisms to impacts*. Earth-Science Reviews **177**, 774–799.

[4] Bjørkavåg, M. and Kalisch, H. *Wave breaking in Boussinesq models for undular bores*, Phys. Lett. A **375** (2011), 1570–1578.

[5] Bjørnestad, M., Buckley, M., Kalisch, H., Streßer, M., Horstmann, J., Frøysa, H.G., Ige, O.E., Cysewski, M. and Carrasco-Alvarez, R. *Lagrangian measurements of orbital velocities in the surf zone*. Geophysical Research Letters **48** (2021), e2021GL095722.

[6] Borluk, H. and Kalisch, H. *Particle dynamics in the KdV approximation.* Wave Motion **49** (2012), 691–709.

[7] Calvert, R., Whittaker, C., Raby, A., Taylor, P.H., Borthwick, A.G.L. and Van Den Bremer, T.S. *Laboratory study of the wave-induced mean flow and set-down in unidirectional surface gravity wave packets on finite water depth*, Physical Review Fluids **4** (2019), 114801.

[8] Derakhti, M., Kirby, J.T., Banner, M.L., Grilli, S.T. and Thomson, J. *A unified breaking onset criterion for surface gravity water waves in arbitrary depth*, J. Geophys. Research: Oceans **125** (2020), p.e2019JC015886.

[9] Itay, U. and Liberzon, D. *Lagrangian kinematic criterion for the breaking of shoaling waves*, J. Phys. Oceanography **47** (2017), 827-833.

[10] New, A.L., McIver, P. and Peregrine, D.H. *Computations of overturning waves*, J. Fluid Mech. **150** (1985), 233–251.

[11] Roeber, V., Cheung, K.F. and Kobayashi, M.H. *Shock-capturing Boussinesq-type model for nearshore wave processes*, Coastal Engineering **57** (2010), 407–433.

[12] Scott, T., Masselink, G., Austin, M.J. and Russell, P. *Controls on macrotidal rip current circulation and hazard*, Geomorphology **214** (2014), 198–215.

[13] Vinje, T. and Brevig, P. *Numerical simulation of breaking waves*, Adv. Water Resour. **4** (1981) , 77–82.

[14] Zhang, S. and Yuan, Y. *Energy and momentum dissipation through wave breaking*, J. Geophys. Res.: Oceans **110** (2005), C09021