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A numerical study of intermittent sediment concentration under breaking waves in the surf zone

Takayuki Suzuki [a,*], Akio Okayasu [b,1], Tomoya Shibayama [c,2]

[a] *Littoral Drift Division, Marine and Environment and Engineering Department, Port and Airport Research Institute (PARI), 3-1-1, Nagase, Yokosuka, Kanagawa 239-0826, Japan*

[b] *Department of Ocean Sciences, Tokyo University of Marine Science and Technology, 4-5-7, Konan, Minato-ku, Tokyo 108-8477, Japan*

[c] *Department of Civil Engineering, Yokohama National University, 79-5, Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan*

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Abstract

A three-dimensional Large Eddy Simulation (LES) model is presented together with a sediment pickup/advection module for the study of spatial and temporal variation of sediment concentration due to three-dimensional fluid motion under breaking waves on a sloping beach. The LES flow module calculates the turbulent flow due to wave breaking where a large-scale turbulence can be directly solved by the governing flow equations and a small-scale turbulence can be evaluated using a sub-grid-scale (SGS) model. In the sediment pickup/advection module, the sediment pickup rate is estimated by a sediment pickup function using the Shield's number at the bottom of the fluid layer, and suspended sediment particles are assumed to move with the ambient fluid. The numerical results show that the flow field including the wave breaking is represented well by the LES model and the sediment pickup/advection module is able to simulate spatial and temporal intermittency of the sediment suspension. Three noticeable sediment pickup areas are defined, namely around the breaking point, break impact area and run-up zone. In the inner region of the surf zone, the sediment concentration distribution shows strong three-dimensionality. The calculated results of the time-averaged and the equi-phase-averaged sediment concentration distributions are compared to earlier laboratory experiment results. The sediment concentration distribution and advection calculated by the model show general correspondence to the experimental results, but the averaged sediment concentration is approximately 1.5 times greater than the experimental value.

Keywords: Sediment pickup; Advection; Large Eddy Simulation (LES) model; Surf zone; Wave breaking

1. Introduction

Wave breaking in the surf zone generates turbulence and complex fluid motion, which exert shear stress on the sea bottom. This shear stress, especially at the breaking zone and within the swash zone, causes sediment suspension and transport. Previous researchers have pointed out that sediment pickup and suspension (re-suspension) occur locally and intermittently in time and space and have strong three-dimensionality (e.g. Nadaoka et al., 1988; Cox and Kobayashi, 2000; Suzuki et al., 2003). The phenomena can be seen by observing the surf zone from above, such as from a pier or a helicopter.

Several numerical models can simulate the velocity field in the surf zone. For accurate calculation of this velocity field, the effect of complex fluid motion and turbulence dissipation need to be included. However, only a few models can represent the velocity field of complex fluid motion and the effects of high turbulence dissipation, such as wave breaking and organized eddies.

The Direct Numerical Simulation (DNS) model can be used to calculate fluid motions including small scales of turbulence (e.g. Wijayaratna and Okayasu, 2000; Brasseur and Lin, 2005). However, because it requires a fine grid to resolve the turbulence, its application is limited. In contrast, the effect of turbulence can be modeled using the Reynolds-Averaged Numerical

* Corresponding author. Fax: +81 46 841 9812.
E-mail addresses: suzuki-t@pari.go.jp (T. Suzuki), okayasu@kaiyodai.ac.jp (A. Okayasu), tomo@ynu.ac.jp (T. Shibayama).
[1] Fax: +81 3 5463 0517.
[2] Fax: +81 45 348 4565.

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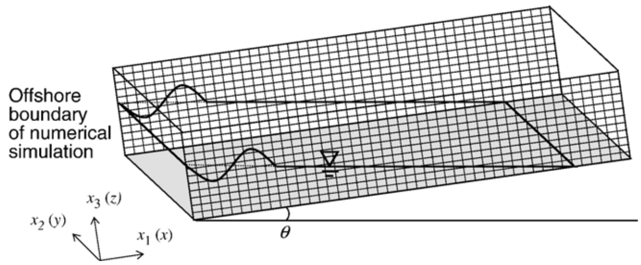

Fig. 1. Computational domain and coordinate system. The x_1 and x_3 axes are tilted $\theta°$ from the horizontal and vertical axes, respectively.

Simulation (RANS) model. Lin and Liu (1998) coupled the RANS equation with a second-order k–ε turbulence model to describe spilling and plunging breaking waves. Chang et al. (2001, 2005) also used a two-dimensional RANS equation with a k–ε closure to study the vortex generation due to flow separation around a submerged reactor obstacle.

The Large Eddy Simulation (LES) model combines these two schemes. The turbulence is separated by its scale length depending upon whether it is larger or smaller than a computational grid size. A larger scale of turbulence is solved directly using Navier–Stokes equations while a smaller scale turbulence can be solved using a turbulence equation. Therefore, the LES model can potentially resolve velocity fluid in the surf zone including all scales of turbulence and also can reduce the computational domain and computational time length in comparison with DNS models.

Watanabe and Saeki (1999) simulated on a laboratory scale the fluid motion due to breaking waves using a three-dimensional LES model. They pointed out that large-scale eddy structures are comprised of horizontal, vertical and helical eddies. Christensen and Deigaard (2001) also applied a LES method to three-dimensional flow. They showed that the model can reproduce complicated flow such as obliquely descending eddies. The turbulence generated at the plunging point is almost immediately distributed over the entire water depth by large organized vortices. Zedler and Street (2002) solved sediment transport patterns over both prototypical topography under idealized wave conditions, and over real topography under real wave conditions, using a LES code. Also, they showed sediment transport patterns over vortex ripples by using van Rijn's (1984) sediment pickup function.

There are several numerical models that can calculate sediment concentration in the surf zone, but most are calculated without the effect of locality and intermittency of sediment suspension.

In the present study, sediment pickup, formation of sediment clouds, and their advection are simulated with a LES flow model together with a sediment pickup/advection module on a laboratory scale. Since the sediment concentration and the diameter of sand particles are small in the calculation, the sediment particles are assumed to be advected by the flow with the effect of the gravity and no interaction is considered between the flow and the particles. The sediment pickup rate is evaluated by the function of shear stress on the bottom, which was proposed by van Rijn (1984) and modified by Nielsen (1992). The sediment concentration distribution caused by the wave breaking was calculated by the LES model, and the outputs were compared with the laboratory experiment results of Sato et al. (1990) for time-averaged and equi-phase-averaged distribution. In this context, pickup is defined as the point at which the applied shear stress causes the sediment particles to move into the fluid. Suspension is slightly different compared to

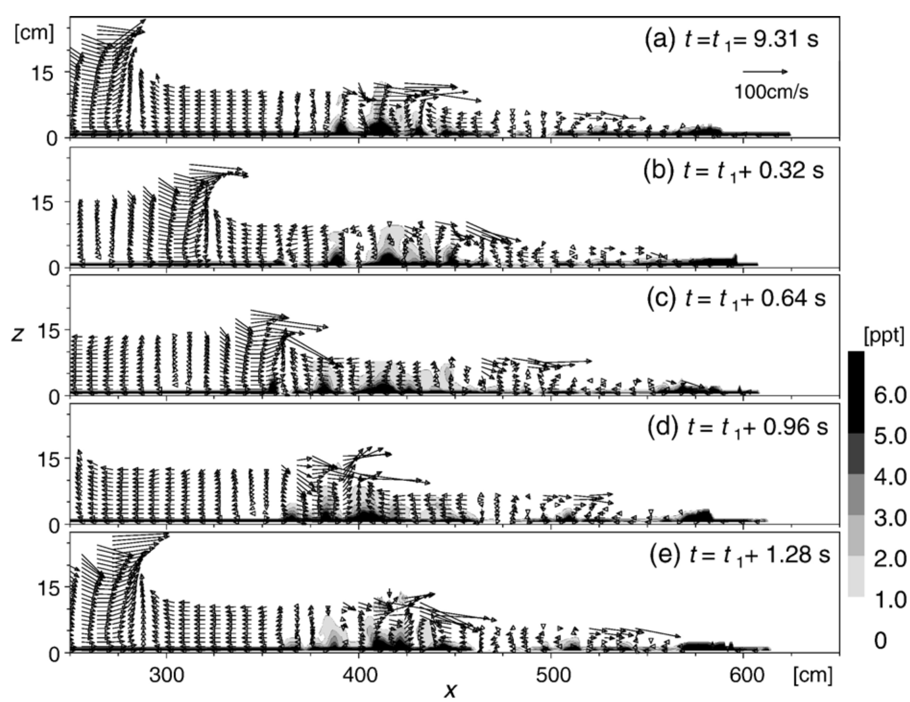

Fig. 2. Snapshot of velocity vectors and sediment concentration distribution in a cross-shore vertical section at the middle of the flume (y = 10 cm).