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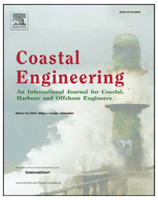

A partial cell technique for modeling the morphological change and scour

Zhong Peng [a], Qing-Ping Zou [b,c,*], Pengzhi Lin [c]

[a] *Metocean Modelling and Analysis, Fugro GB Marine Ltd., Wallingford, OX10 9RB, UK*
[b] *The Lyell Centre for Earth and Marine Science and Technology, Institute for Infrastructure and Environment, Heriot-Watt University, Edinburgh, UK*
[c] *State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, 610065, Chengdu, China*

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ABSTRACT

A novel partial cell technique applied on structured grids is developed to track the deformation of water-soil interface associated with beach morphological change and toe scour in front of coastal structures. It allows the use of the same orthogonal structured grids for morphological, sediment transport and hydrodynamic models therefore, has the advantage of consuming less CPU and without the need to adapt grids to the evolving beach morphology. An improved sand-slide model with better mass conservation is introduced to resolve the avalanche behaviour of the sediment motion. The RANS-VOF hydrodynamic model has been extended to cope with complex bathymetry. The newly developed numerical model suite, coupling the RANS-VOF model, a bedload sediment transport model and a morphological model using the partial cell technique, are validated against the analytical solutions and laboratory measurements for different incoming wave conditions, local water depths and bottom slopes. This study reveals the key processes that govern the behaviour of beach morphology change in front of a vertical coastal structure during storms. The model-data comparisons demonstrate the robustness of partial cell technique to capture the movement of the water-soil interface.

1. Introduction

Coastal flooding occurs when a flood defence fails. This happens when the storm conditions surpass what the defence was designed for (functional failure) or the defence is damaged and therefore does not function as expected (structural failure). Structural failures are unexpected, therefore, more dangerous and have been the cause of recent major flooding events (CIRIA 1986; Zou et al., 2013). During severe storms, excessive overflow or wave overtopping and toe scour at the costal defence are the two leading causes of structural failure. The former occurs in the presence of high water level due to surge and wave set-up, therefore low freeboard (vertical distance from the crest of the defence to the water level) and large waves and may erode the leeward face and crest of the defence and damage the armour layers. The latter is the erosion of the foreshore at the base of the defence that may undermine the structure (e.g. CIRIA 1986). This study will focus on the beach morphological changes and toe scour processes that lead to failure of defences and flooding.

Beach slope and profile in front of the defence are an important design consideration of sea defences. Bed level at the defence may be reduced by several meters in a large storm. This beach lowing would increase the still water depth at the structure; therefore, allow larger waves to arrive at the structure without breaking. In turn larger waves lead to more beach lowering and wave overtopping and larger wave loading and the process continues and form a positive feedback that eventually undermines the structure (Zou and Reeve, 2009).

Steady streaming and wave breaking are significant controlling factors in sediment transport and beach profile changes around a coastal structure. The experimental study by Fredsøe and Sumer (1997) demonstrates that the steady streaming and plunging breaker generates a scour hole in front of and at the lee-side of the breakwater respectively. Tsai et al. (2009) conducted laboratory experiments of toe scour in front of a Seawall on a beach slope of 1:5 under regular waves. They found that the scour depth produced by a plunging breaker is larger than that by a spilling breaker or a non-breaking wave. Young and Testik (2009) carried out a laboratory study of two-dimensional onshore scour along the base of submerged vertical and semi-circular breakwaters on both sloping and horizontal sandy bottoms and found that the characteristics of scour are independent of breakwater shape or type.

In case of non-breaking waves, Sumer and Fredsøe (2000) and Sumer (2007) found that the reflection from the breakwater forms a standing wave which generates the steady streaming in front of the breakwater, consisting of top and bottom recirculating cells. The formation of bottom cell is related to the boundary layer over the bed and the near bed

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[*] Corresponding author. The Lyell Centre for Earth and Marine Science and Technology, Institute for Infrastructure and Environment, Heriot-Watt University, Edinburgh, UK.
E-mail addresses: z.peng@fugro.com (Z. Peng), qingping.zou@gmail.com (Q.-P. Zou), cvelinpz@126.com (P. Lin).

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sediment motion responds to these recirculating cells. Consequently a scour and deposition pattern in front of the breakwater emerges in the form of alternating scour and deposition areas lying parallel to the structure. However, in case of breaking waves, the complex process of wave breaking generates a strong downward jet to erode the bed and mobilize the sediment at the toe of a vertical wall, which presumably leads to scour at the toe of a seawall (Sumer, 2007).

Earlier numerical models for predicting scour at sea walls include those by Rakha and Kamphuis (1997) which is built upon a phase resolving Boussinesq wave model. Although this type of studies represent progress, they do not adequately address the complex physics arising from the wave breaking, streaming and turbulence near the bed and coastal structure as discussed above. As with the majority of beach morphological models, these models are depth averaged and unable to resolve the eddies in the immediate proximity of the sea wall; and therefore fail to predict toe scour (Rakha and Kamphuis, 1997). Lin and Liu (2003) concluded that the RANS (Reynolds Averaged Navier-Stokes Solver) models by Lin and Liu (1998) can run for a long time until the wave reaches a quasi-steady state, providing an accurate flow field for the simulation of sediment transport in the surf zone. Recently this model has been further developed and used widely to investigate wave-structure interactions and subsequent coastal flood risks (Garcia et al., 2004; Lara et al., 2006; Losada et al. (2008); Peng and Zou 2011; Zou and Peng 2011; Zou et al., 2012).

Gislason et al. (2009a) applied a Navier-Stokes solver to examine the energy and momentum flux and the streaming velocity for standing waves in front of a fully reflecting wall. Hajivalie and Yeganeh-Bakhtiary (2009) used a numerical model based on Reynolds Averaged Navier-Stokes (RANS) equations and a k-ε turbulence model to study the effect of breakwater steepness on the hydrodynamic characteristics of standing waves. Later on, Yeganeh-Bakhtiary et al. (2010) found that the recirculating cells of steady streaming were generated in front of vertical breakwaters in the presence of fully standing waves but not partially standing waves.

Following Pedrozo-Acuña et al., 2006; Yeganeh-Bakhtiary et al., 2010, Gislason et al. (2009b), the bed profile is updated by solving the sediment conservation equation based on the time-averaged sediment transport rates predicted by the bed-load sediment transport equation by Fredsøe and Deigaard (1992) using the hydrodynamics predictions by the phase-resolved RANS-VOF model. Due to the complexity of sediment transport process, the instantaneous sediment transport rate is normally calculated by empirical formulae derived from experiments, e.g. Meyer-Peter and Mueller (1948) and Madsen (1991). We adopt this approach since it is able to capture the bed profile change and is more robust than the fluid and soil two-phase model by Hajivalie et al. (2012).

Many state-of-art morphological models use the classical lower order Lax–Wendroff or modified Lax–Wendroff schemes and becomes unstable after a long simulation time. Therefore, Long et al. (2008) investigated the stability and performance of several finite difference schemes and recommended a fifth order Euler-WENO scheme for wave phase-resolving sediment transport models. In order to resolve the slumping of sandy materials, Liang and Cheng (2005) proposed a sand-slide model to account for the avalanche without consideration of the mass conservation of bed materials. More recently, Jacobsen (2015) proposed a geometric sand sliding routine on unstructured grids to assure the mass conservation in computational morphodynamics. In this study, we will extend Liang and Cheng (2005) sand sliding model by improving its mass conservation since the present hydrodynamics model and their model are both based on a structured grid.

Liang and Cheng (2005) used a RANS model to successfully simulate the observed wave induced scour behaviour beneath a submarine pipeline. Marieu et al. (2008) developed a morphology module in combination with an existing RANS model to study vortex ripple morphodynamics. Liu and García (2008) applied a RANS-VOF model to simulate the local scour at the bridge piers. Khosronejad et al. (2012) coupled a RANS model with a morphological model and immersed boundary method to study the scour around bridge piers of three different shapes. Baykal et al. (2015) used a 3D RANS model coupled with a morphological model to examine the flow and scour patterns around a vertical cylinder in a steady current. Only recently has the RANS-VOF (Volume-Of-Fluid) numerical modelling been used to study the scour process at coastal structures. Gislason et al. (2009b) investigated the two-dimensional scour and deposition in front of vertical and sloping Seawalls by coupling a 3-D Navier-Stokes solver with a k-ω turbulence model and a morphological model. They were able to reproduce the well-known alternating scour and deposition pattern in front of the breakwater (e.g., Sumer and Fredsøe, 2000). The free surface was tracked by integrating in time the kinematic boundary conditions based on the free surface volume flux, therefore, wave breaking is not resolved in their study. Tofany et al. (2014, 2016) applied the RANS-VOF model to simulate scour and overtopping in front of a vertical breakwater for different wave conditions. Their work was limited to standing or partial standing waves over a flat bottom in front of the structure. Wave breaking was not considered either. On the other hand, Hajivalie et al. (2012) applied an Euler–Lagrange flow and soil two-phase model to examine the scour in front of a vertical breakwater. The sediment phase was treated as an assembly of discrete sand grains and the scour was predicted as the motion of a granular media using a Lagrangian approach.

More recently, Jacobsen et al. (2014a, 2014b) successfully simulated the formation and development of a breaker bar under regular waves using the OpenFOAM (Open Field Operation and Manipulation) which is an open source code of two phase RANS-VOF flow model (Jasak, 1996; Weller et al., 1998; Jacobsen et al., 2012), by considering both bedload and suspended sediment transport. Besides the hydrodynamic model grid, they adopted a separate set of mesh for bedload transport and morphology model and another set of mesh for suspended sediment transport model, which is similar to the hydrodynamic mesh but without the near bottom cells. Their model results at these three sets of grids are synchronized frequently and validated against the laboratory study by Scott et al. (2005) for breaking waves over a fixed bar and the experiment by Baldock et al. (2011).

In this study, a novel partial cell technique on structured grids is developed to track the location of the evolving water-soil interface. This method is in analogy with the VOF method. It has a number of advantages over the traditional method used in morphological modelling. For example, it enables us to use the same orthogonal structured grids for morphological, sediment transport and hydrodynamic models and avoid adapting grids to the evolving beach morphology, therefore, consume less CPU and minimize the potential discontinuity issues at the water–soil interface and the resulting model instability. An improved sand-slide model with better mass conservation of bed materials is introduced to resolve the avalanche behaviour of the sediment motion. The RANS-VOF hydrodynamic model is combined with a bedload sediment transport model and a morphological model to predict the beach profile changes and toe scour on both flat bottom and a sloping sandy beach in front of a vertical Seawall. In order to get a better handle on the initial beach profiles in the simulations, the RANS-VOF model has been further extended to cope with complex bathymetry, such as a ripple bed.

2. Model description

A hydrodynamic model and a bed-load sediment transport model have been combined with a morphological model to investigate the hydrodynamics of wave interactions with a seawall behind a sandy beach slope and the control factors of beach profile change and toe scour in front of vertical seawalls (Zou et al., 2012).

2.1. Hydrodynamic model

The Reynolds Averaged Navier-Stokes solver with a Volume-of-Fluid free surface capturing scheme (RANS-VOF) by Lin and Liu (1998) has been further developed in the past years and will be further extended