Large-Eddy Simulation of Cross-Shore Hydrodynamics under Random Waves in the Surf and Swash Zones

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Introduction

- Sand dunes play an important role in minimizing the impact of beach erosion and breaching during storms.
- The understanding of the interactions between the hydrodynamics and complex geometry is limited.

Objectives

- Provide a better understanding of the cross-shore interactions between hydrodynamics and complex geometry in coastal region.
- Validate the capability of 3D wall-modeled large-eddy simulations (LES) for coastal applications.
- Compare LES and XBeach results and further provide insights for potential XBeach improvements.

Numerical Model

Model Formulation

- 3D large-eddy simulations (LES)

$$\frac{\partial \tilde{u}_i}{\partial t}+\tilde{u}_j\frac{\partial \tilde{u}_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i}+\nu\frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j}-\frac{\partial \tau_{ij}^{sgs}}{\partial x_j}$$

- Standard Smagorinsky closure

$$\tau_{ij}^{sgs}-\frac{1}{3}\tau_{kk}^{sgs}\delta_{ij}=-\nu_t\tilde{S}_{ij} \qquad \nu_t=\left(C_s\Delta\right)^2\left|\tilde{S}_{ij}\right|$$

- Volume of fluid (VOF) method

$$\frac{\partial \alpha}{\partial t}+\frac{\partial \alpha u_i}{\partial x_j}+\frac{\partial u_{r,j}\alpha(1-\alpha)}{\partial x_j}=0 \qquad \rho=\alpha\rho_w+(1-\alpha)\rho_a$$

Boundary Conditions

- Near-wall modeling: rough wall function

$$E'=\begin{cases}E & , \ K_s^+\le 2.25\\ \dfrac{E}{f_n} & , \ K_s^+>2.25\end{cases} \qquad K_s^+=C_\mu^{1/4}K_s\frac{\sqrt{k}}{\nu_w}$$

$$\nu_{t_w}=\nu_w\left(\frac{y^+\kappa}{\ln\left(E'y^+\right)-1}\right) \qquad y^+=C_\mu^{1/4}y\frac{\sqrt{k}}{\nu_w} \qquad f_n=\begin{cases}1+C_sK_s^+ & , \ K_s^+\ge 90\\ \left(\dfrac{K_s^+-2.25}{87.75}+C_sK_s^+\right)^{\sin\left(0.4258\ln K_s^+-0.811\right)} & , \ K_s^+<90\end{cases}$$

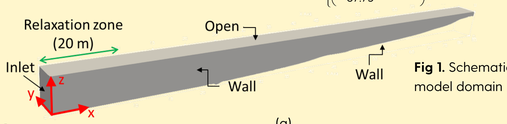

Fig 1. Schematic of the model domain

Mesh

- Background mesh: 12 x 12 x 4 cm
- Surface refinement: 6 x 6 x 2 cm
- Near-bed mesh: 3 x 3 x 0.333 cm
- Total number of grid points: 8-9 M

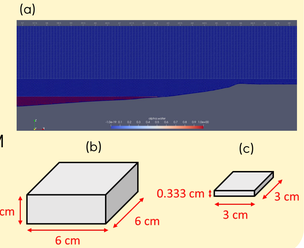

Fig 2. Schematics of the numerical mesh (a) near the berm, (b) surface refinement mesh, and (c) near-bed mesh

Physical Experiment

- Conducted in the Large Wave Flume at the O.H. Hinsdale Laboratory, OSU.
- A real dune profile from Mantoloking, N.J. was scaled down and reconstructed.
- Wave conditions scaled from Hurricane Sandy (10/22–11/02, 2012).
- Irregular waves generated from the TMA spectrum

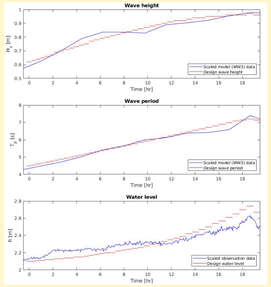

Fig 3. Scaled wave conditions

Fig 4. Snapshots of the scaled dune before trial no. 1

Results

Model Validation

- Index of agreement
- IA > 0.8 in most locations

$$IA=1-\frac{\sum_{i=1}^{N}\left(M_i-O_i\right)^2}{\sum_{i=1}^{N}\left(\left|M_i-\bar{O}\right|+\left|O_i-\bar{O}\right|\right)^2} \qquad 0\le IA\le 1$$

M: modeled results *O*: observed results

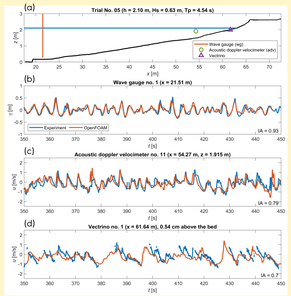

Fig 5. Trial 05: (a) sensors locations, (b) surface elevations at the offshore side, (c) flow velocities in the inner surf zone, (d) flow velocity near bed in the swash zone.

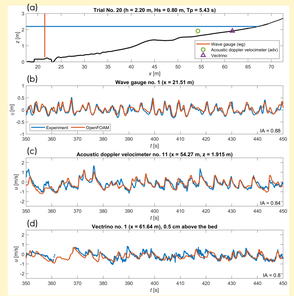

Fig 6. Trial 20: (a) sensors locations, (b) surface elevations at the offshore side, (c) flow velocities in the inner surf zone, (d) flow velocity near bed in the swash zone.

Higher order quantities

- **H_{RMS}:**
  - Experimental and OpenFOAM results agree with each other.
  - XBeach does not capture shoaling well.
- **Skewness:**
  - The overall comparison between experimental and OpenFOAM results is satisfactory.
  - XBeach under-predicts skewness before wave breaking and over-predicts in the inner-surf zone.
- **Asymmetry:**
  - OpenFOAM is able to predict the asymmetry very well.
  - The asymmetry predictions of XBeach are good before waves break, but later over-predict with a factor of two in the inner-surf and swash zones.

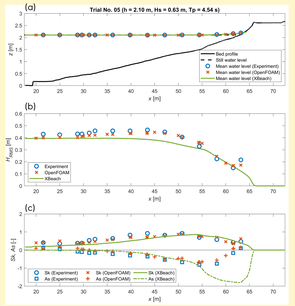

Fig 7. Trial 05: (a) bed profile and mean water level, (b) root-mean-square wave height, (c) skewness and asymmetry.

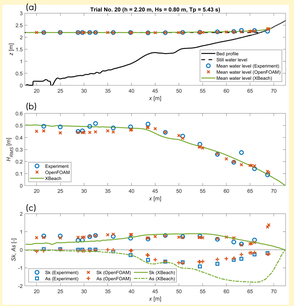

Fig 8. Trial 20: (a) bed profile and mean water level, (b) root-mean-square wave height, (c) skewness and asymmetry.

Undertow

- OpenFOAM is able to provide the mean velocities for the entire model domain.
- The undertow results by OpenFOAM well agree with experimental data and can further be used to validate XBeach.
- XBeach over-predicts the undertow in the inner-surf zone in the case without sandbar (i.e., trial no. 5).
- In the case with sandbar (i.e., trial 20), Xbeach's undertow prediction shows good agreement with OpenFOAM and experiments.

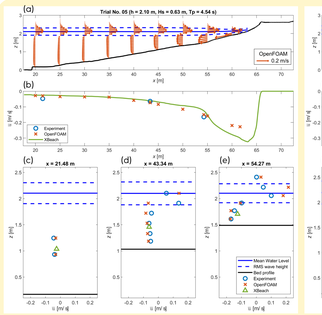

Fig 9. Trial 05: (a) mean velocity, mean water level and root-mean-square wave height (OpenFOAM results), (b) cross-shore undertow, (c), (d) and (e) horizontal velocity profile at x = 21.48, 43.35 and 54.27 m.

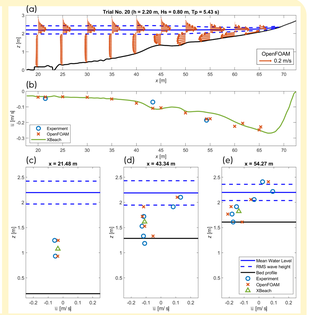

Fig 10. Trial 20: (a) mean velocity, mean water level and root-mean-square wave height (OpenFOAM results), (b) cross-shore undertow, (c), (d) and (e) horizontal velocity profile at x = 21.48, 43.35 and 54.27 m.

Summary

- This study shows the capability of 3D wall-modeled large-eddy simulations (LES) for coastal applications.
- OpenFOAM model results of surface elevation and flow velocity time series show high agreement with experimental data.
- The mean water level, root-mean-square wave height, skewness and asymmetry predictions by OpenFOAM agree well with experimental data. XBeach slightly misses the some and greatly over-predicts the asymmetry in the inner-surf and swash zones.
- The undertow results by OpenFOAM show good agreement with experimental data and can further be used to validate XBeach. In the case with sandbar, XBeach shows good agreement with OpenFOAM and experimental results. But it over-predicts the undertow after wave-breaking in the case without sandbar.

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