A Numerical Simulation of Wave-Induced Topographic Change in Shallows Composed of Fine Sand

Yong-Hwan Cho¹, Tomoaki Nakamura¹*, Norimi Mizutani¹, Kwang-Ho Lee²

¹ Department of Civil Engineering, Nagoya University, Nagoya, Japan
² Department of Energy Resources and Plant Engineering, Kwandong University, Gangwon-do, Korea

*tnakamura@nagoya-u.jp

Received: May 30, 2014; Accepted: June 17, 2014; Published: October 31, 2014

Abstract. A coupled fluid-structure-sediment interaction model is applied to laboratory experiments on wave-induced topographic changes in shallows composed of fine sand. It was found that considerable erosion was occurred over the shallows in the predicted results for the same still water depth as in the experimental condition, which was a different trend from the measured data. In contrast, the condition of a small increase in the still water depth on the crown improved the computational accuracy of water surface elevations, pore-water pressure and the topographic change in the shallows. These results suggest that a small mean water level rise occurred during the experiments, and induced the different topographic evolutions.

Keywords: Sediment transport, Artificial shallows, Fine sand, Mean water level, Suspended sediment concentration

1. Introduction

In recent decades, dredging work for maintaining harbor channels has been essential because of their importance as traffic hubs. However, the volumes of dredged sand are increasing, and there is a need to use it in a range of innovative ways. The construction of artificial shallows composed of dredged sand is proposed as a way to effectively use dredged sand. Although such artificial shallows are beneficial for coastal environments such as increasing bottom life and enhancing self-purification capacity [1], it is necessary to verify the stability of the shallows because dredged sand contains lots of fine sediments vulnerable to wave action.

The verification of sediment transport problems, particularly for fine sediments in
dredged sand, has many difficulties in laboratory conditions in terms of the degree of similarity. To overcome these limitations, numerical schemes to analyze hydraulic phenomena involving such sediment transport problems are enhanced with advances in the performance of computers. In the past few decades, two-way coupling procedures for fluid dynamic models, considering seabed profile evolution, were developed for uniform flow [2, 3] and waves [4-6]. Nakamura and Yim [7] developed a three-dimensional coupled fluid-structure-sediment interaction model (referred to as FSSM), which was combined with a two-way coupling procedure implemented at every time step to ensure fluid-structure-sediment interaction. In the surf zone where wave breaking occurs, it is important to track air-water interface motion precisely because vortices induced by wave breaking have a significant effect on suspended sediments. Three-dimensional numerical models dealing with complex air-water interface motion and suspended sediment transport were developed [8, 9], in some of which the diffusion of suspended sediment transport was ignored. Nakamura and Mizutani [10] also improved the FSSM to take into account all suspended sediment transport processes of pickup, advection, diffusion, and settling.

Based on the above-mentioned progress in numerical schemes, Nakamura et al. [11, 12] investigated the characteristics of wave-induced topographic change in shallows composed of fine sand in terms of the effects of pore-water pressure using hydraulic experiments and the FSSM. They found that the evaluation of the trend in sediment transport on the shallows was improved by considering the gradient of pore-water pressure on the surface layer. However, it was found that a sediment transport calculation of the FSSM was very sensitive to small variations in various parameters such as the critical Shields parameter, incident wave conditions, and mean water level contributions to wave breaking position and topographic change on the top of shallows, suggesting the necessity for further improvement in the FSSM.

To address this issue, using FSSM, this study first examines the mean water level variation in the hydraulic experiments [11] with two-dimensional numerical simulation and two different initial still water levels, \( h = 0.2250 \) and \( 0.2275 \) m. Specifically, the predicted results of water surface elevation and pore-water pressure are compared with the measured data [11] in the early and latter stages. Moreover, the time evolution of topographic change in the shallows depending on different still water level conditions is investigated, and the final topographic change is compared with the experimental results based on the predicted results of suspended sediment concentration and topographic change. Finally, the effects of a still water level difference on the topographic change, in terms of the mean water variation in the experiments, are discussed.

2. Numerical model description

The three-dimensional two-way coupled fluid-structure-sediment interaction model (FSSM) [6, 7] is composed of a main solver and three modules. The main solver is a large-eddy simu-
A Large Eddy Simulation (LES) model based on continuity and Navier-Stokes equations to compute incompressible viscous air, water, pore-air and pore-water multi-phase flow that considers seepage flow in porous media. The three modules are: a volume-of-fluid (VOF) module based on the multi-interface advection and reconstruction solver (MARS) to track air-water interface motion; a sediment transport module (STM) to compute seabed profile evolution induced by the bed-load and suspended sediment transport and the motion of suspended sediment that considers all transport processes of pickup, advection, diffusion and settling; and an immersed-boundary (IB) module based on the body-force type of IB method dealing with the motion of a movable structure. Detailed explanations of the main solver and the modules can be found in Nakamura and Mizutani [6] and Nakamura and Yim [7].

As stated above, the FSSM employs a two-way coupling procedure to connect the main solver, the VOF module, the STM and the IB module. Figure 1 shows the coupling procedure, which is implemented as follows:

1. The main solver is implemented.
2. The VOF module is implemented using the flow field data obtained from the main solver.
3. The STM is implemented using the flow field data and air-water interface data obtained from the VOF module.
4. The IB module is implemented using the flow field data, the air-water interface data and the seabed profile data obtained from STM.
5. The main solver at the next time step is implemented using the air-water interface data, the seabed profile data and structure motion data to feed back the results obtained from the VOF module, the STM and the IB module into the main solver.
6. This procedure is iterated for a specific number of time steps.

In this study, the main solver, the VOF module and the STM were used to compute wave-induced topographic change in shallows because the motion of a movable structure was
3. Numerical conditions

A schematic of a computational domain is shown in Fig. 2. Based on the experimental setup in Nakamura et al. [11], shallows (crown width: 2.0 m, height: 0.2 m, seaward slope: 1/20), composed of fine sand with a median grain size $d_{50}$ of 0.1 mm, was laid 1.4 m away from a wave generation source/sink, and a 0.20 m high vertical impermeable wall was fixed behind the shallows because it was observed in Nakamura et al. [13] that the surface profile of the shallows exhibited little change on its landward slope. To prevent reflected waves from seaward and landward boundaries, damping zones were set at more than twice the wavelength of incident waves, which will be explained later. Note that the two-dimensional computational domain was adopted to reduce computational cost on the assumption that the shallows had a uniform surface profile in the cross-shore direction.

The computational domain, except for the damping zones, was discretized with uniform numerical cells of 20.0 mm × 5.0 mm. The remainder of the entire domain was discretized with non-uniform numerical cells increasing in size in the x direction to further reduce computational cost. For flow velocity and pressure, the following boundary conditions were used: the slip condition for the surfaces of the bottom boundary and the vertical wall; the Sommerfeld radiation condition for the seaward and landward boundaries; and the constant-pressure condition for the top boundary. For the boundary condition of the VOF function, the gradient-free condition was used for all the boundaries. No bed-load sediment was supplied from the seaward and landward edges of the shallows for the boundary condition of the bed-load sediment transport. For the suspended sediment transport, the following boundary conditions were used: the impermeable condition for the surfaces of the bottom boundary and the vertical wall; and the gradient-free condition for the seaward and landward boundaries.

Table 1 lists the values of the main parameters adopted in the main solver of the FSSM

![Figure 2: Schematic numerical wave flume (W2–W6: wave gages; and P1–P8: pore-pressure gages)](image-url)
The parameters related to porous media were determined based on the experimental results of Mizutani et al. [15]. These were the added mass coefficient $C_A = -0.04$, the turbulent drag coefficient $C_D = 0.45$, and the laminar drag coefficient $C_D = 25.0$. The porosity $m$ of sand was taken as having a typical porosity value of 0.4. The dynamic friction coefficient $d$ was 0.51 [16], the static friction coefficient $s$ was 0.63 [17], and the critical Shields parameter for a horizontal bed was adopted as 0.03.

Regular waves with an incident wave height $H_i$ of 0.065 m, a period $T$ of 1.0 s, and a still water depth $h$ of 0.2250 m, which was selected as a representative wave condition from eight experimental cases [11], were generated toward the shallows. In addition, a numerical experiment in which the still water depth on the crown was increased by 10%, i.e., $h = 0.0075$ m on the crown of the shallows, thereby $h = 0.2275$ m in front of the shallows, was conducted to examine the sensitivity of the still water level to sediment transport because the trends in topographic change in the shallows did not agree between for predicted and measured results in the same still water depth condition. It will be explained later. As the specific waves were generated, water surface elevations were measured at a point near the wave generation source/sink (W2) and four points over the shallows (W3–W6), and pore-water pressure on the surface layer of the shallows was measured at the same points as W3–W6 (P1–P8).

4. Validation of the mean water level

In this section, the predicted results of the water surface elevations and the pore-water pressure are validated with the experimental results for different still water levels, $h = 0.2250$ m, which were identical to the experimental condition, and 0.2275 m, which was proposed in this study to examine mean water level variations in the experiments. The results for the early and latter stages are discussed because of the different tendencies of water surface elevations and pore-water pressures (Figs. 3 and 4).

<table>
<thead>
<tr>
<th>Table 1: Parameters in the FSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>Gravitational acceleration $g$</td>
</tr>
<tr>
<td>Density of water $\rho_w$</td>
</tr>
<tr>
<td>Density of air $\rho_a$</td>
</tr>
<tr>
<td>Density of sand $\rho_s$</td>
</tr>
<tr>
<td>Molecular viscosity of water $\nu_w$</td>
</tr>
<tr>
<td>Molecular viscosity of air $\nu_a$</td>
</tr>
<tr>
<td>Surface tension coefficient $\sigma$</td>
</tr>
</tbody>
</table>
Figure 3 shows a comparison of the water surface elevations in the early stage ($t = 15.0–20.0$ s) and latter stage ($t = 35.0–40.0$ s) in this simulation, in which the red circles are measured results by Nakamura et al. [11] and the blue and pink solid lines are predicted data for $h = 0.2250$ and $0.2275$ m, respectively. Overall, the predicted results show reasonable agreement with measured data in both the early and latter stages except for the results at W5 and W6, where phase shift occurred. In the early stage after the waves were generated (Fig. 3(a)), the predicted results for $h = 0.2250$ m show good agreement with the experimental results in terms of the wave crests and troughs. However, as shown in Fig. 3(b), in the latter stage, the results for $h = 0.2275$ m were consistent with the experimental results at all measurement points.

From the results at W2 and W3 over the area of pre-wave breaking, in the early stage, the predicted capability of the results for $h = 0.2250$ m was better than for $h = 0.2275$ m, which were generally slightly overestimated because of the higher still water level compared with the experiments. However, in the latter stage, the results for $h = 0.2250$ m fluctuated below the measured results, inferring an underestimation of the mean water level. In contrast, it was found that the wave crests were predicted well in the results for $h = 0.2275$ m despite the
slight underestimation of the wave troughs at W2 in the latter stage. Particularly at W3, the results for $h = 0.2275$ m show reasonable agreement with the measured data, which is different from the underestimated results for $h = 0.2250$ m. These tendencies imply that the mean water level variation during the experimental time took place on the sloped shallows after about $t = 20$ s, while the rise in the mean water level around the shallows in the experiments can be assumed to be about 0.0025 m based on the results of the water level elevations. Additionally, a remarkable characteristic is observed at both W2 and W3. In the early stage, the phase of the measured data seems to be a little slower than both the predicted results. This trend is reversed in the latter stage as shown in Figs. 3(a) and (b).

The results at W4 over the post-wave breaking area show a slightly different tendency. In the early stage, the results for $h = 0.2275$ m show better agreement with the measured results than for $h = 0.2250$ m despite the small phase shift. Furthermore, although the results for $h = 0.2275$ m are underestimated near wave troughs with little phase shift, the data for $h = 0.2275$ m are in reasonable agreement with the measured data in the latter stage. It is assumed that the mean water level variation near W4 occurred early than W3, which will be discussed later. At W5 and W6, the magnitude of wave height was well matched to the measured data. However, at W5 and W6 in the area behind the breaking wave, a phase shift was observed and the phase lag became larger away from the breaking point. Consequently, it is essential to overcome this phase shift problem in post-wave breaking area for precisely estimating wave fields in the landward area.

Figure 4: Time series of the pore-water pressure in the shallows at P1, P2, P3 and P4
The pore-water pressure results are depicted in Fig. 4, where the red squares are the measured results [11] and the solid blue and pink lines are the predicted results, the blue lines for $h = 0.2250$ m and the pink lines for $h = 0.2275$ m. In this study, the pore-water pressure results at P1 and P2 over the pre-wave breaking area corresponding to the location at W3, and P3 and P4 over the post-wave breaking area corresponding to the location at W4, are described.

From the results at P1, in the early stage, the crests and troughs of the pore-water pressure for both the predicted results showed good agreement with the measured data, which was different tendency from the results at W3 appearing the better predicted results for $h = 0.2250$ m. This was because the small level difference in the still water in this case had little influence on the pore-water pressure results. However, the predicted results of the pore-water pressures show underestimation in the latter stage (Fig. 4(b)). At P2, which was buried in the shallows 30 mm deeper than P1, the results were underestimated compared with the measured data. It seems that this tendency was dependent on the influence of the porosity. Though a constant value of porosity was used during the numerical simulation, the porosity can vary in the experiments because of natural consolidation and compaction induced by wave action. At P3 and P4 over the post-wave breaking area, the overall predicted results were underestimated. Unlike the results for $h = 0.2275$ m of the water level elevation at W4, the crests were reproduced well for $h = 0.2275$ m, while the troughs were underestimated. In the pore-water pressure results, the phase shift phenomenon also took place at P1 and P2, which was similar to the results at W3 in the experiments.

These results suggest that, in the hydraulic experiments, a slight rise in the mean water level, assumed to be about 0.0025 m, around the shallows, was induced by factors other than the wave setup. In the experiments, a 2.22-m wide wave tank was divided into a 0.40-m wide channel and a remaining channel with a partition board, and shallows was installed in the former wave channel. However, the partition board did not extend sufficiently to a wave absorbing beach at the end of the wave tank. Accordingly, it is inferred that the mean water level rose around the wave absorbing beach at the side of the remaining channel, and its propagation to the 0.40-m wide channel caused the further rise in the mean water level around the shallows. In contrast, in the numerical simulations, it was difficult to simulate such additional rise in the mean water level because the two-dimensional computational domain was used to take into account an appropriate balance with computational cost. Consequently, as shown in Figs. 3 and 4, the increase in the still water depth by 0.0025 m, which was equivalent to 10% of the still water depth on the crown, was efficient for improving the computational accuracy of the two-dimensional numerical simulations. From this result, it is suggested that it is essential to match the mean water level when simulating hydraulic experiments with three-dimensionality using a two-dimensional computational domain with sufficient accuracy.
5. Effects of still water level on the topographic change in the shallows

The final topographic change in the shallows is discussed with respect to the effects of the still water level as shown in Figs. 5(a) and 5(b), which also shows the final profiles of the shallows and the topographic change in the shallows. The red circles are the measured data, the blue solid line is for \( h = 0.2250 \) m, and the pink dashed line is for \( h = 0.2275 \) m.

As shown in Fig. 5(b), in the measured results, erosion and accretion are shown alternately from \( x = 1.5 \) m to \( x = 3.0 \) m, and there is little topographic change in the area behind \( x = 4.0 \) m, where the horizontal region of the shallows begins. However, the predicted results for \( h = 0.2250 \) m shows substantial erosion in the horizontal region of the shallows \((x \geq 3.7)\). In addition, accretion occurred in \( x = 5.0-5.5 \) m and near the vertical wall. In contrast, for \( h = 0.2275 \) m, little topographic change on the top of the shallows was observed, which was consistent with the trend in the measured data. Only a small quantity of erosion took place on the middle of the slope, where incident waves experience shoaling in the form of increasing wave height. Moreover, erosion is also shown near the wall, which differed from the results for \( h = 0.2250 \) m. It is difficult to discuss the validity of the topographic change near the vertical wall because measured data were not available as a result of the limitations in the measurement devices.

From the comparison of the results of still water levels \( h = 0.2250 \) m and \( 0.2275 \) m, the increase in the initial still water level seemed to suppress sediment transport near the top of the shallows by thickening the fluid layer above them. The increase of 0.0025 m in still water level is a very small quantity with 1.1% of total water depth, while it is corresponding to 10%

![Figure 5: Cross-shore distribution of: (a) final shallows profile and (b) topographic change with still water level variation of \( h = 0.2250 \) and \( 0.2275 \) m](image)
of water depth on the crown of the shallows. Moreover, an increase in still water level above the shallows also causes the different hydrodynamic conditions such as a breaking position migration. Wave breaking is one of the important factors of erosion and the unstable and driving flows generated after wave breaking play the important role of eroding and entraining sediments on the bed. Thus, the condition of wave breaking should be considered to estimate sediment transport problems.

As shown in Fig. 6, the tendency for wave breaking in different positions with still water level changes was observed. Wave fields with horizontal velocity $u$ contours were presented over the shallows for $h = 0.2250$ m at $t = 29.0$ s and $0.2275$ m at $t = 29.1$ s. Vectors indicate wave velocity components consisting of $u$ and $w$ in the $x$ direction and $z$ direction, respectively. The snapshots represent the waves on the verge of breaking with the steepest face just before the wave approaching the shallows begins to recede. The positions of the breaking waves varied with the still water levels. Despite the increase of 0.0025 m in the still water level, the position of the breaking wave moved leeward about 0.14 m. Each breaking position was approximately $x = 3.34$ m for $h = 0.2250$ m and $x = 3.40$ m for $h = 0.2275$ m away from the beginning of the shallows in this simulation.

Consequently, as mentioned earlier, the predicted result for the increase of 10% in the still water level on the crown of the shallows represents good correspondence with the measured data in the results of topographic change. These results emphasize again the importance to consider mean water level variation resulting in dissimilar topographic change due to the different tendency of wave fields on the shallows and wave breaking.

6. Suspended sediment concentration

In this section, suspended sediment concentration is discussed to give a better understanding of sediment transport around the shallows and the characteristics of the topographic change in
the shallows with two different still water levels, $h = 0.2250$ and 0.2275 m.

When the initial still water level $h$ was 0.2250 m, the predicted distribution of suspended sediment concentration (Fig. 7(a)) and the topographic change in the shallows (Fig. 7(b)) are depicted. The results were taken at $t = 19.8, 20.5, 24.0, 26.3, 34.5, 38.4$ and 57.6 s, when different suspended sediment movements on the shallows were confirmed between $h = 0.2250$ and 0.2275 m. In Fig. 7(a), the red contour means a high density of suspended sediments concentration. Incident waves experienced shoaling effects when approaching the shallows as shown in Fig. 7(a) at $t = 19.8$ and 24.0 s. As these surface waves were entering a shallower water area on the slope of the shallows with an increase in wave height, wave velocity near the shallows increased, and the shallows were then agitated. This shoaling process on the shallows results in sediments starting to suspend at the location near $x = 1.60$ m away from the beginning of the shallows corresponding to crests of the incident waves. These suspended
sediments with low concentrations seemed to be entrained to $x = 3.60–3.70$ m by the progressing waves. During this process, waves were observed to be breaking at $x = 3.40–3.60$ m accompanied with low but relatively higher suspended sediment concentration (see Fig. 7(a) at $t = 19.8$, 24.0 and 26.3 s). However, most of entrained suspended sediments, which were generated from around $x = 1.60$ m and the wave breaking zone, stayed in the surf zone, about $x = 2.25–3.80$ m, and only a part of the suspended sediments migrated in the direction of the wave progress by the flow generated from the wave breaking. These results were also observed in the result of topographic change (Fig. 7(b)) showing the disturbed temporary topography of the shallows ranging from $x = 2.10–3.50$ m after $t = 19.8$ s.

As time passes, the other trend of the phenomenon of suspensions was observed particularly on the top of the shallows. Prominent suspended sediments occurred near the protruding location (approximately $x = 4.80$ m) on the shallows temporarily at $t = 24.0$ s and the begin-
ning of the horizontal area of the shallows ($x = 4.10$ m) at $t = 26.3$ s. The latter phenomenon of suspensions continues with small quantities of concentration after $t = 26.3$ s, and the erosion near the projecting location, which was transient at $t = 24.0$ s, takes place again at the same position as shown in Fig. 7(a) at $t = 38.4$ s. This result is confirmed in Fig. 7(b) at about $x = 4.80$ m where the protruding location has a little erosion. Eventually, the slight topographic change of the shallows accelerates and continues with erosive events near the same position leading to considerable erosion on the top of the shallows (Fig. 7(a) at $t = 57.6$ s). A remarkable characteristic of this erosion was that copious amounts of suspended sediments, which were generated on the top of the shallows, migrated behind the shallows, contrary to those on the sloped shallows, which mostly stayed in the surf zone. In addition, deposited sediments were observed at $x = 4.90$–5.60 m and near the vertical wall fed from migrated sediments suspended on the top of the shallows. This erosive phenomenon on the top of the shallows lasted until the final time step. These results were clearly observed in the results for the topographic change (Fig. 7(b)).

For $h = 0.2275$ m, the suspended sediment concentration and topographic change in the shallows are presented in Figs. 8(a) and 8(b). Similar to the results for $h = 0.2250$ m, a part of the bottom was agitated near the inclined shallows as shown. A dissimilar characteristic to the results for $h = 0.2250$ m was the suspension near the vertical wall in the early time steps. It is difficult to verify this phenomenon in Fig. 8(b), while a small quantity of suspended sediments is confirmed near the vertical wall indicating thin yellow contour in Fig. 8(a) at $t = 19.8$ s. This initial erosion in front of the vertical wall continued during the simulation time and the amount of suspension gradually decreased with time (see Fig. 8(a) at $t = 57.6$ s). The depth of erosion near the vertical wall was not great compared with the results for $h = 0.2250$ m. Another noticeable characteristic was that there was little erosion on the top of the shallows, which was the identical result to the laboratory experiments (Fig. 5(b)).

Consequently, different still water levels, $h = 0.2250$ and $0.2275$ m, contributed to the separate trend of topographic change and hydrodynamic conditions on the shallows. As mentioned before, the position where the wave breaking occurred and thickened water layer on the crown were the important factor for analyzing erosive phenomenon in the surf zone. The difference of wave breaking position was very small and not enough to explain the different trend in topographic change. The most important factor in initiating sediment movement is the horizontal flow velocity component. In particular, in the surf zone, there are substantially disturbed wave fields generated after wave breakings. At that time, when the waves fall down to the shallower water of the shallows, significantly disturbed and faster flows are generated, which bound up and down. If energetic horizontal flows, enough to trigger incipient sediment movements, approaches closely to the bottom, the surface of the shallows is exposed to erosion such as the results for $h = 0.2250$ m. Furthermore, because of the relatively shallower fluid layer on the top of the shallows for $h = 0.2250$ m, the shallows seemed to be easy to
exposed to the turbulent flows generated after wave breakings. However, an increase of 10% in water level on the top of the shallows seemed to absorb some part of the wave energy, i.e., decrease wave velocity near the bottom, thus reduce the erosion on the top of the shallows. Therefore, in the laboratory experiments, the reason for little erosion on the top of the shallows can be considered to be the aforementioned process as shown in the present simulation based on the phenomenon of the mean water level variation during the experimental time.

7. Conclusions

The improvement in the predictive capability of the FSSM with an increase in still water level has been presented. The predicted results for the water surface elevation and pore-water pressure suggest that an increase in mean water level occurred near the shallows in the latter stage of the experiments because the predicted results for \( h = 0.2275 \text{ m} \) had reasonable agreement with measured data, as opposed to those for \( h = 0.2250 \text{ m} \). The characteristics of sediment transport were also examined based on the suspended sediment concentration. As a result, it is suggested that a small difference in water level over the shallows has significant effects on sediment transport in a shallower region. The difference of the results of the topographic change in the shallows between numerical and experimental data also supports the phenomenon of the increase in the mean water level in the experiments. Although there are some remaining tasks to further increase the accuracy of the model, good predictive capability of the model in terms of sediment transport analysis and wave-induced topographic change was confirmed.

Acknowledgment

The authors are grateful for the financial support of the Japan Society for the Promotion of Science (JSPS) under a Grant-in-Aid for Young Scientists (B) (principal investigator: Tomoaki Nakamura; project number: 26820200).

References


