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The Process of Scour Surrounding Objects Freely Settling on the Seabed on the Effect of Typhoon Based on DRAMBUIE Model

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ABSTRACT

The process of scour surrounding objects freely settling on the seabed on the effect of typhoon was evaluated based on numerical models, SWAN for waves and DRAMBUIE for scour process.

Generally the orbital velocity is smaller when the water depth gets deeper, and there exists an order of magnitude difference between the orbital velocity caused by winter monsoon and that by typhoon. The depth of scour pit is continuously increasing till the final depth when no infilling occurs. There is a positive relationship between the final depth of scour pit and the near-bottom current velocity, while they are not proportional.

KEY WORDS: The effect of typhoon; near-bottom wave-induced orbital velocity; the accelerated process of scour; objects freely settling on the seabed; the DRAMBUIE scour model; the SWAN wave model.

INTRODUCTION

Bottom mines in shallow water are particularly difficult to find when they are partially or wholly buried. The ability to predict mine burial both for planning and during operations is, therefore, of great importance to the Naval forces. Processes known to contribute to mine burial include burial at impact, usually in low-strength muddy sediments, scour and fill in sandy sediments, focused by this paper, bedform migration or transverse bedform movement, liquefaction or fluidization of the sediment, and so on (Wilkins & Richardson 2007).

By now there have been some models for predicting the scour burial. Comparing with WISSP (Wave-Induced Spread Sheet Prediction) model, NBURY model (developed in 1980 for German Navy), and Mulhearn model (a model about large migrating bedforms developed by the Australian Defense Science Technology Organization), DRAMBUIE (Defense Research Agency Mine BURial Environment) model can combine tidal current, wave, sediment grain size, water depth and the characteristics of bottom-resting objects better when estimating scour and burial progress, and it is more easily implemented than Vortex-Lattice model (developed by Jenkins and Inman at Scripps) (Friedrichs 2001). Moreover it has been verified by in-situ experiments ((Elmore & Richardson 2003), and been widely used by many researchers (Testik et al. 2007; Guyonic et al. 2007; Cataño- Lopera et al. 2007). Therefore, this paper predicts the scour-induced burial of cylinder objects freely resting on the seabed on the effect of typhoon using the DRAMBUIE model.

Most experimental investigations, along with the dimensional analysis, showed that the scour burial depth of the object is primarily a function of the following: the Keulegan-Carpenter (KC) number, the Shields parameter, or both parameters. Other properties that might also play a role are the mean grain size, the density of the sediment and the density of water, the length to diameter ratio of object, and so on (Cataño-Lopera et al. 2007). In this paper, two primary external parameters determining scour burial characteristic are investigated during the scour process, which are the Shields parameter and mean grain size. In shelf seas, the dominant forcing from which the Shields parameter is calculated, are comprised of tidal current and wave motion, expressed as bottom orbital velocity. Over long time scales (such as season) the tidal current remains nearly stable, while the bottom orbital velocity changes intensively, particularly during typhoon events. Hence, this paper will explore the bottom orbital velocity under the action of typhoon events, grain size of seabed and their impacts on the scour depth surrounding the cylinder object in the shelf sea using the DRAMBUIE model. The SWAN (Simulation Wave Nearshore) model is used to numerically simulate the near-bottom wave orbital velocity on the effect of typhoon.

NUMERICAL MODELS AND THEIR IMPLEMENTATIONS

The SWAN Model and Its Implementation

SWAN from <http://swan.ct.tudelft.nl/> is a third-generation wave model for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions. The model is based on the wave action balance equation with sources and sinks.

In this paper, the SWAN model (version: 40.85) is used to simulate the wave-induced bottom orbital velocity U_b and the period of waves.

The main setup of model: the domain is $2^\circ \times 2^\circ$, the spatial resolution is $3' \times 3'$, all boundary condition is open; initial current velocity and wave height is zero.

The Theory of DRAMBUIE and Its Implementation

DRAMBUIE model is developed to predict the burial of isolated free-settling objects (e.g., cylinder mines) resting on a bed of mobile sandy sediment under the action of waves and tidal currents (Friedrichs 2001).

The scientific basis of DRAMBUIE model

An empirical formula (Whitehouse 1998) is used to describe the increase in scour pit depth over time about a target located in a steady, unidirectional flow

$$S(t) = S_{\infty} \{1 - \exp[-(t/T)^P]\} \quad (1)$$

where S_{∞} is final scour depth as time approaches infinity, and also named as equilibrium scour depth, T is the burial time-scale factor which governs the rate of scour pit growth, P is a fitting coefficient, $P = 0.6$ for a horizontal cylinder, $P = 0.5$ for a vertical cylinder.

The value of S_{∞} is given as a relationship between Shields parameter θ_{∞} and critical Shields parameter θ_{cr} in the following manner

$$\begin{aligned} S_{\infty} &= 0 & 0 \leq \sqrt{\theta_{\infty} / \theta_{cr}} < 0.75 \\ S_{\infty} &= S_{\infty \max} (2\sqrt{\theta_{\infty} / \theta_{cr}} - 1.5) & 0.75 \leq \sqrt{\theta_{\infty} / \theta_{cr}} \leq 1.25 \\ S_{\infty} &= S_{\infty \max} & 1.25 < \sqrt{\theta_{\infty} / \theta_{cr}} \end{aligned} \quad (2)$$

where $S_{\infty \max} = 1.15D$ is the maximum depth of scour pit, D is the diameter of cylinder. The presence of cylinder locally speeds up the current velocity via an empirically determined “velocity multiplier”, so the initial grain movement happens when $\sqrt{\theta_{\infty} / \theta_{cr}} \geq 0.75$.

The critical Shields parameter θ_{cr} for initial sediment movement is evaluated empirically to be

$$\theta_{cr} = \frac{0.30}{1 + 1.2D_*} + 0.055[1 - \exp(-0.02D_*)] \quad (3)$$

where $D_* = d_{50}[(s-1)g/\nu^2]^{1/3}$ is the dimensionless grain size, $\nu = 10^{-6}$ m²/sec, is the kinematic viscosity of water, s is the ratio of sediment density to water (2.65 for siliceous sediment), g is gravitational acceleration, d_{50} is the median diameter of sediment particles.

The another variable T is empirically calculated by the following formula

$$T = A\theta_{\infty}^B [(s-1)gd_{50}^3]^{-1/2} D^2 \quad (4)$$

where $A = 0.095$ and $B = -2.02$.

Both S_{∞} and T_{∞} contain Shields parameter θ_{∞} , so the last unknown variable needed to be solved, is defined as

$$\theta_{\infty} = \tau / [(\rho_s - \rho_w)gd_{50}] \quad (5)$$

where τ is the total bed shear stress, ρ_s is the density of sediment, ρ_w is the density of water at the sediment interface.

Calculating the total bed shear stress

In this paper, the widely used and well-proven method presented in

book by Soulsby (1997), and being assessed its performance with experiment data by Elmore and Richardson’s paper (Elmore and Richardson 2003) is chosen to calculate τ . The total shear stress τ is obtained from the stresses induced by wave action, τ_w , and by currents, τ_c . The following formulae show their relationship

$$\tau = [(\tau_m + \tau_w |\cos \phi|)^2 + (\tau_w |\sin \phi|)^2]^{0.5} \quad (6)$$

where ϕ is the angle between the current stress and wave stress vectors, τ_m is the mean shear stress induced by waves and currents, in the same vector direction as τ_c

$$\tau_m = \tau_c \{1 + 1.2[\tau_w / (\tau_c + \tau_w)]^{3.2}\} \quad (7)$$

τ_c is calculated by the depth-averaged current velocity U , and wave-induced stress τ_w is given by the wave-induced bottom orbital velocity U_b .

Implement DRAMBUIE model with MATLAB

The DRAMBUIE model is coded to run on a PC in MATLAB in time-stepped fashion to make it applicable to quasi steady-state conditions. The program is designed to calculate the scour pit depth by inputting current data and wave data at every time step. Here the size of time step is set to be 1 hour for the assumption of quasi-steady state.

Inputs involve the diameter of cylinder $D=0.5$ m, water depth h , median diameter of sediment d_{50} , depth-averaged tidal current velocity U , wave-induced bottom orbital velocity U_b , and wave period T with time resolution of 1 hour. Outputs include total bed shear stress τ , Shields parameter θ_{∞} , final or equilibrium scour pit depth S_{∞} and scour pit depth S .

Numerical tests have been performed to explore the impacts of grain size and bottom orbital velocity on the scour depth surrounding the cylinder objects freely resting on the seabed. The East China Sea is chosen as an ideal locale for the study. In every summer, the East China Sea is strongly affected by the passage of severe typhoon for several times. Storm-waves and currents associated with the passage of severe typhoon generally cause widespread mobilization of bottom sediments, and rapid scour burial of cylinder objects. In this study, the scour processes impacted by typhoon-induced bottom orbital velocities are manifested using numerical tests.

RESULTS

Wave-induced Orbital Velocity Driven by Typhoon

According to the statistic typhoon data, three typical wind fields are used in this study, including winter monsoon of 10 m/s, an outer wind speed of 25 m/s, and a maximum of 35 m/s of typhoon, with the wind direction of 135 degree. Near-bottom orbital velocity numerically simulated by SWAN is shown in Fig. 1 and Fig. 2.

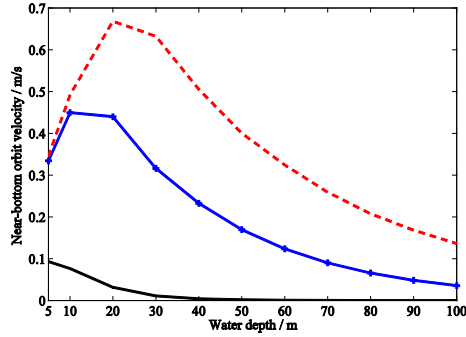


Fig. 1 Orbital velocity at various water depths driven by winter

monsoon of 10 m/s in solid black line, orbital velocity induced by 25 m/s outer wind speed of typhoon in solid blue line with cross marker, orbital velocity generated by 35 m/s maximum wind speed of typhoon in dashed red line

Generally, the orbital velocity is smaller when the water depth got deeper. However, the orbital velocity is not the largest in the smallest depth because of the dissipation of energy induced by wave breaking and bottom friction in shallow waters. As shown in Fig. 1, the largest orbital velocity is 0.45 m/s at 10 m on the effect of 25 m/s wind, which is much larger than 0.35 m/s at 5 m, and can maintain the high level till 20 m water depth. For the 35 m/s typhoon, similar to 25 m/s, the largest orbital velocity is 0.68 m/s at 20 m and remains large till 30 m.

There existed an order of magnitude difference between the orbital velocity caused by winter monsoon of 10m/s and that by typhoon at the same water depth. In Fig. 1, at 20 m, the orbital velocity is 0.04 m/s, 0.43 m/s and 0.68 m/s for winter monsoon, outer wind speed, and maximum speed of typhoon respectively.

domain of $1^\circ \times 1^\circ$ is not uniform distributed at the same water depth. When waves are breaking, the orbital velocity distributes randomly, and the difference between the minimum and maximum is slight, less than 0.01 m/s (shown in Fig. 2c). When the water depth is enough deep, the wave energy will accumulate towards the wind direction due to remainder wind energy. As shown in Fig. 2a, 2b and 2d, the orbital velocity on the northwest gradually enhances towards the southeast as a result of the continuous input of wind energy when the wind direction is northwest. Moreover, the larger wind is, the more obvious energy accumulation is, and the greater velocity difference between the minimum and maximum is.

Process of scour surrounding objects on the effect of typhoon

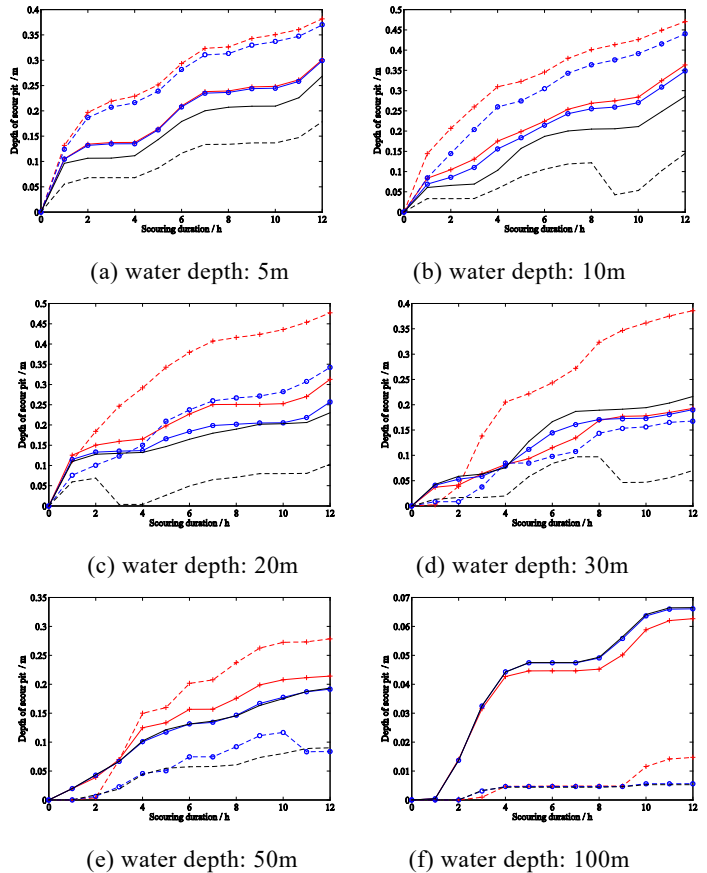


Fig. 3 Process of scour surrounding the object freely settling on the sea bed at various water depths and two different grain sizes of surface sediment on the effect of typhoon and winter monsoon (red cross line: 35 m/s wind speed, blue circle line: 25 m/s, black line: 10 m/s; solid lines: median diameter of grain size $4\mu\text{m}$, dashed lines: $200\mu\text{m}$)

The scour processes surrounding the object with the diameter of 0.5 m freely resting on the seabed are displayed by several numerical tests with various water depths and two different grain sizes of surface sediment on the effect of typhoon and winter monsoon using the DRAMBUIE model. The inputs include the wave-induced orbital velocity calculated by the SWAN model and the semi-diurnal tidal current of averaged 0.4 m/s with the fluctuations on the order of 0.2 m/s.

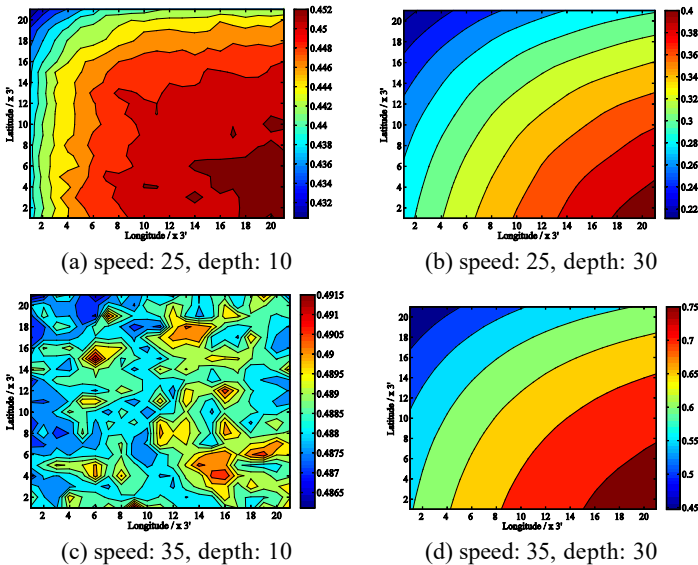


Fig. 2 Near-bottom wave-induced orbital velocity (m/s) driven by typhoon in the domain of $1^\circ \times 1^\circ$ (wind speed in m/s, water depth in m)

The Fig. 2 displays that the wave-induced orbital velocity in the

The scour processes surrounding the object under the 12-hr combined action of tidal currents and wind-generated waves at various water depths are illustrated in Fig. 3.

With the presence of object, the combined velocity mostly exceeds the threshold for mobility for the surface sediment due to “velocity multiplier”, even if the bottom orbital velocity is very small and can be nearly ignored under the action of winter monsoon. Although the shear velocity from the tidal currents alone is regularly above the 3/4 of threshold level to mobilize the sediment, the presence of object will increase the current velocity in front of the object which might exceed the threshold. Once mobilized, the sediment in front of the object will be transported by the mean currents due to both tides and wind, and the local scour firstly in the front of object, then surrounding the object will develop.

As shown in Fig. 3, the scour pit depth generally increases with time under the combined shear stresses exerted on the seabed even though assuming the infill occurrence. Nevertheless, as soon as the currents subside and the shear velocity decreases down to 3/4 of critical velocity, the sediment would fill the pit, and the infill occurs causing the decrease of the scour pit depth. For example, at the ninth hour, when the shear velocity created by both tidal current and 10 m/s wind wave action is less than 3/4 of critical value for sand of 0.2 mm, the scour pit depth diminishes due to infill, as shown in black dashed lines of Fig. 3b at 10 m and Fig. 3d at 30 m.

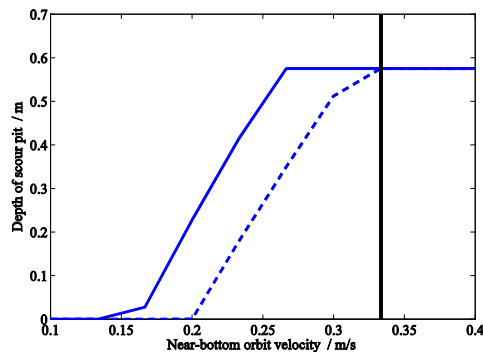


Fig. 4 Final depths of scour pit at various wave-induced orbital velocities (m/s) and two different grain sizes of surface sediment (solid line: median diameter of grain size 4 μ m, dashed line: 200 μ m)

There is a positive relationship between the scour pit depth and the bottom orbital velocity after experiencing 12-hr wave action, while the relation is not linear (Fig.3). For example, at the water depth of 20 m, the depth of scour pit for sand with median diameter of 0.2 mm is 0.10 m, 0.35 m, and 0.48 m respectively, responding to the orbital velocity of 0.04 m/s, 0.43 m/s and 0.68 m/s for winter monsoon, outer wind speed, and maximum speed of typhoon. The orbital velocity of 0.68 m/s at 20 m water depth induced by 35 m/s typhoon is much larger than 0.49 m/s orbital velocity at 10 m, but their scour pit depths are almost equivalent. When the water depth is deeper than the typhoon-impacted maximum, the scour depth surrounding the object will be neglected (Fig. 3f).

The increasing rate of scour depth is not only related to bottom orbital velocity, but also connected with median grain size of sediment on the seabed (Fig. 3 and Fig. 4). That is to say, the depth of scour pit varied

with median grain size of sediment even in same dynamic conditions, whereas the difference between variable grain sizes is not significant. Furthermore, the other protruding phenomenon is that the mobility (or erodibility) of sand alters with the increasing bed shear stress mainly produced by the increasing orbital velocity, causing their scour depths to vary simultaneously. Shown in Fig. 3d and 3e, the curves of scour evolution with different grain size intersect at the second hour at 30 m for 35 m/s wind-generated storm, and at the third hour at 50 m. Fig.4 will partly elucidate the unique phenomenon. In Fig. 4, the final scour depth for clay is all through much deeper than that for medium sand when the orbital velocity is less than 0.33 m/s, whereas the final scour depth for clay is mostly same as that for medium sand when exceeding the value of 0.33 m/s. Therefore, the finer sediment is easier to be scoured when near-bottom current velocity is less than a certain value (such as 0.33m/s in this study). The situation is reversed when the velocity is larger than the value.

CONCLUSIONS

The process of scour surrounding objects freely settling on the seabed on the effect of typhoon was evaluated based on numerical models, SWAN for waves and DRAMBUIE for scour process.

Generally, the orbital velocity is smaller when the water depth gets deeper. However, the orbital velocity is not the largest in the smallest depth because of the dissipation of energy induced by wave breaking and bottom friction in shallow waters.

There exists an order of magnitude difference between the orbital velocity caused by winter monsoon of 10m/s and that by typhoon (assuming an outer wind speed of 25m/s, and a maximum of 35m/s at the center).

The depth of scour pit surrounding cylinder objects is continuously increasing till the final depth (as time approaches infinity) when no infilling occurred. There is a positive relationship between the final depth of scour pit and the near-bottom current velocity, while they are not proportional. At the water depth of 20m, the depth of scour pit is 0.48m, 0.35m, and 0.10m respectively, responding to winter monsoon, outer wind speed, and central speed of typhoon.

The depth of scour pit varies with the median grain size of surficial sediment in same dynamic conditions. Furthermore, the finer sediment is easier to be scoured when near-bottom current velocity is less than a certain value (such as 0.33m/s in this study). The situation is reversed when the velocity is larger than the value.

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