Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 126 (2015) 285 – 289

Procedia Engineering

www.elsevier.com/locate/procedia

7th International Conference on Fluid Mechanics, ICFM7

Unsteady characteristics of sediment transport under non-harmonic waves

Yinjun Li, Jifu Zhou*

Key Laboratory of Environmental Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

---

Abstract

Sediment transport under waves is one of the key dynamic processes of coastal sediment motion. Previous studies for this issue are mainly based on linear wave theory and quasi-steady simplification. However, waves in real circumstance are always irregular, generally with a certain degree of asymmetry and/or velocity-leaning especially in shallow water. It is envisaged that sediment movement under non-harmonic waves is different from sinusoidal waves. Based on large eddy simulation of turbulent flows in wave boundary layer, a modified method is proposed to calculate sediment transport rate under non-harmonic waves. It is further used to explore the influences of flow acceleration and the phase lead between the free stream velocity and bed shear stress on sediment transport rate in different phases of one wave cycle for forth-leaning. The net transport rate is found to increase with the degree of asymmetry and velocity-leaning index. Both the acceleration and the phase lead have a great influence on average transport rate in each phase.

Keywords: forth-leaning wave, large eddy simulation, unsteady sediment transport

---

1. Introduction

Sediment transport under waves is of crucial significance for coastal engineering. Due to the effects of nonlinearity, shoaling, refraction, reflection, diffraction, etc., waves in real circumstance are always non-harmonic, generally with a certain degree of asymmetry and/or velocity-leaning. In addition, wave induced sediment transport is indeed an unsteady process, though engineers deal with it by means of quasi-steady concept. Therefore, it is necessary to delineate unsteady sediment transport mechanism under non-harmonic waves, especially in shallow water area.

---

* Corresponding author. Tel.: +86-010-82544203
E-mail address: zhoujf@imech.ac.cn

doi:10.1016/j.proeng.2015.11.243

There have been a few researchers who studied sediment transport in asymmetric oscillatory boundary layers. Some of them expressed sediment transport rate as a function of the free stream velocity [1-3]. These models are able to predict sediment transport rate reasonably in steady flows. Nonetheless, it is of more physics to relate sediment transport rate to bed shear stress or Shields number in the case of unsteady flows, where phase lead exists between the bed shear stress and the free stream velocity [4-6]. In order to account for the unsteady mechanism of wave induced sediment transport, Nielsen et al. proposed a modified formula that relate sediment transport rate to flow acceleration and the phase lead between the bed shear stress and the free stream velocity. Their formula is of more physical implication, but they determined the phase lead by fitting to experiment data [7, 8]. This approach makes the phase lead be an empirical factor. In fact, the phase lead is a physical quantity. It is 45° for waves in laminar flow regime. In turbulent flow regime, it can be determined by numerical model.

In the present study, a new modified method is proposed and applied to study unsteady sediment transport under non-harmonic waves. Taking the forth-leaning asymmetric wave as an example, we have investigated the effects of degree of asymmetry and velocity-leaning index on sediment transport. Particular attention is drawn to the differences of sand transport rate in the acceleration and deceleration phases.

2. Calculation Methods of sediment transport rate

Owing to the physical implication, Nielsen's model [8] is adopted here, which reads

$$\Phi(t)=\frac{q(t)}{\sqrt{(s-1)gd_{50}^{3}}}=\begin{cases}A_0 sign\left\{\tau^*(t)\right\}\left|\tau^*(t)\right|^{0.5}\left\{\left|\tau^*(t)\right|-0.05\right\}, & \left|\tau^*(t)\right|>0.05\\ 0 \qquad , & \left|\tau^*(t)\right|<0.05\end{cases} \tag{1}$$

where $\Phi(t)$ and $q(t)$ are the instantaneous dimensionless and dimensional sediment transport rate respectively; A_0 is an empirical coefficient; s=2.65 is the density ratio of sediment to water; g is gravitational acceleration; d_{50} is median diameter of sediment; $\tau^*(t)=\tau_0(t)/(s-1)gd_{50}$ is Shields number, also called dimensionless shear stress; $\tau_0(t)$ is the instantaneous shear stress , which is expressed as

$$\tau_0(t)=\rho U^*(t)\left|U^*(t)\right|; \qquad U^*(t)=\sqrt{\frac{1}{2}f_{2.5}}\left(\cos\varphi_\tau U(t)+\frac{\sin\varphi_\tau}{\omega}\frac{dU(t)}{dt}\right) \tag{2}$$

Here, ρ is water density; U^* is the frictional velocity; U is the free stream velocity; $f_{2.5}$ is a bed roughness of $2.5d_{50}$; φ_τ is the phase lead between the bed shear stress and the free stream velocity; ω is the wave frequency.

Based on Nielsen's model, we propose three methods to calculate sediment transport rate depending on how to get $\tau_0(t)$. Method 1 is to use Nielsen's model exactly, in which $\varphi_\tau=51^o$ was determined by fitting experiment data. Method 2 is to use Eqs. (1) and (2), but φ_τ is obtained by LES instead of 51°. Method 3 is just to use Eqs. (1), but $\tau^*(t)$ is obtained by LES [9].

Two sets of experiment data for oscillatory sheet flow sediment transport under non-harmonic waves are used to verify the three methods in the present study: Experiment A from Watanabe & Sato [2], Experiment B from Ribberink et al. [1]. Figure 1a shows the comparison of the net sediment transport rates obtained by the three methods and experimental results from Experiment A. It is seen that the results of Method 2 and 3 are almost the same and both show a better agreement with experiment data than Method 1. And the corresponding coefficient A_0 is calibrated to be 12, 24 and 24 respectively. Using the calibrated coefficients, we verify the three methods by the data of Experiment B as shown in figure 1b, which once again demonstrates that Method 2 and 3 are better. Hereafter, we take Method 2 as a new modified method to calculate sediment transport rate.

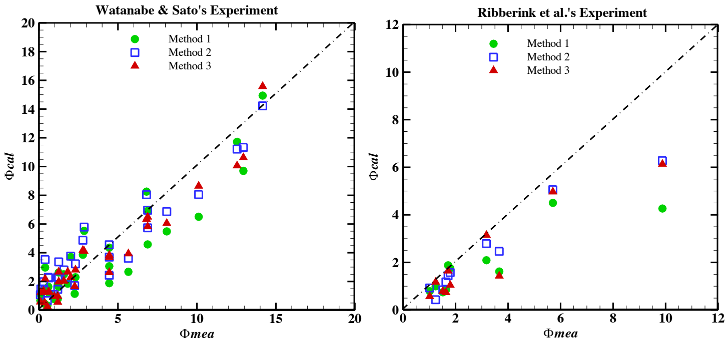

Fig. 1. Comparison of experiment and three calculated dimensionless sediment transport rate. Experiment data is from (a) Watanabe & Sato [2] and (b) Ribberink et al. [1].

3. Characteristics of sediment transport under non-harmonic wave

3.1. Characteristics of net sediment transport under forth-leaning asymmetric waves

Forth-leaning asymmetric wave is generally with a certain degree of asymmetry and/or velocity-leaning as shown in figure 2. The velocity can be expressed as blow [10]:

$$U(t)=U_w\sqrt{1-r^2}\,\frac{\sin(\omega t)+\dfrac{r\sin\varphi}{1+\sqrt{1-r^2}}}{1-r\cos(\omega t+\varphi)} \tag{3}$$

Where U_w is the amplitude of the velocity; r, φ are waveform parameters ($0\le r<1$, $-\pi/2\le\varphi\le\pi/2$). The velocity expression results in a forth-leaning wave when φ is equal to 0, or a first-order cnoidal wave when φ is equal to $-\pi/2$. Both the parameters have a great influence on the degree of asymmetry As and velocity-leaning index β of waveform, which are respectively defined as

$$As=\frac{U_c}{U_c-U_t}\,,\qquad \beta=1-\frac{2T_{cu}}{T} \tag{4}$$

According to the new modified method, the variation of dimensionless net sediment transport rate Φ versus As and β is presented in figure 3. It can be seen that Φ increases with As and β. And it can be inferred from the figure that As contributes more to the increase of net sediment transport rate Φ than β.

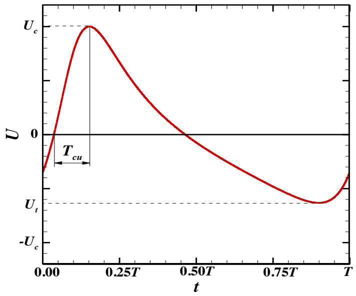

Fig. 2. Variation of forth-leaning asymmetric wave velocity.

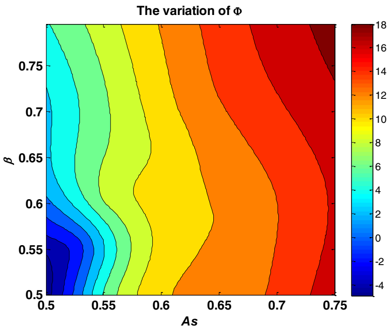

Fig. 3. Contours of dimensionless net sediment transport rate on As-β plane.

3.2. Unsteady characteristics of sand transport under forth-leaning waves

In order to study the unsteady characteristics of sediment transport, we take the forth-leaning wave as an example to explore the effect of acceleration and phase lead or phase difference between bed shear stress and free stream velocity on sediment transport in the acceleration and deceleration phases.

For acceleration and deceleration phases of the forth-leaning waves (Fig. 4), the acceleration approximately remains unchanged, but there exists the difference between the peak phase lead ϕ_c and the valley phase lead ϕ_t which depend on the velocity-leaning index β as shown in figure 5. Thus the phase lead is the main factor to influence sediment transport for a certain forth-leaning wave.

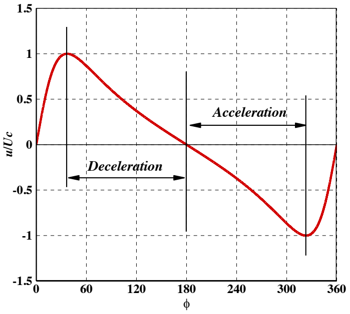

Fig. 4. The acceleration and deceleration phases of forth-leaning waves.

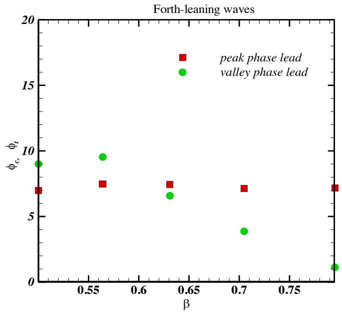

Fig. 5. The peak and valley phase lead (ϕ_c and ϕ_t) versus velocity-leaning index β.

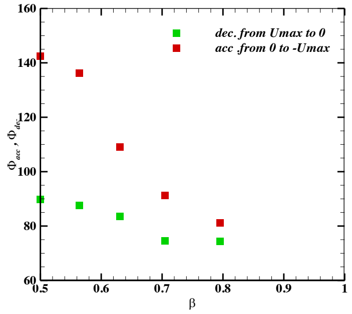

Fig. 6. The dimensionless averaged sediment transport rate of acceleration and deceleration phases (Φ_{acc} and Φ_{dec}) versus β.

Figure 6 shows the dependence of the dimensionless averaged sediment transport rate of acceleration and deceleration phases (Φ_{acc} and Φ_{dec}) on β. It is observed that for the same forth-leaning wave, the averaged sediment transport rate in acceleration phase is greater than that in deceleration phase. In the meantime, the averaged sediment transport rate in each phase decreases with β increasing and Φ_{acc} decreases faster.

For the same forth-leaning wave, the difference of Φ_{acc} and Φ_{dec} could be attributed to the difference of ϕ_c and ϕ_t. Due to the influence of phase lead, the bed shear stress is asymmetric and some percentage of sediment moves inversely. With β increasing, both Φ_{acc} and Φ_{dec} decrease with acceleration amplitude. The decrease of ϕ_t suggests that the range of large bed shear stress becomes smaller, so Φ_{acc} decreases faster than Φ_{dec}.

4. Conclusion

A modified method has been proposed to calculate sediment transport rate by non-harmonic waves, which exhibits a better agreement with experiment data. Based on this method, we have discussed the effects of degree of asymmetry and velocity-leaning index on net sediment transport rate for forth-leaning asymmetric waves. It is observed that sediment transport rate increases with the degree of asymmetry and velocity-leaning index. In addition we take the forth-leaning wave as an example to further explore the influences of flow acceleration and the phase lead between bed shear stress and free stream velocity on the variation of average sediment transport rate in different phases. Results show that the average sediment transport rate in each phase decreases with flow acceleration and the phase lead as well.

Acknowledgements

We very much appreciate the financial support to this work from the National Natural Science Foundation of China (11172307 and11232012) and 973 Program (2014CB046200).

References

[1] J.S. Ribberink, A.A. Al-Salem, Sediment transport in oscillatory boundary layers in case of rippled beds and sheet flow, J. Geophys. Res. 99 (1994) 707-727.

[2] A. Watanabe, S. Sato, A sheet flow transport rate formula asymmetric forward leaning waves and currents, Proc. 29th ICCE, Lisbon, World Scicentific, pp. 1703-1714.

[3] M. Dibajnia, T. Moriya, A. Watanabe, A representative wave model for estimation of nearshore local transport rate, Coast. Eng. J. 43 (2001) 1-38.

[4] Suntoyo, H. Tanaka, A. Sana, Characteristics of turbulent boundary layers over a rough bed under saw-tooth waves and its application to sediment transport, Coast. Eng. 55 (2008) 1102-1112.

[5] Suntoyo, H.Tanaka, Effects of bed roughness on turbulent boundary layer and net sediment transport under asymmetric waves, Coast. Eng. 56 (2009) 960-969.

[6] D.A. Van der A, T. O'Donoghue, J.S. Ribberink, Measurements of sheet flow transport in acceleration-skewed oscillatory flow and comparison with practical formulations, Coast. Eng. 57 (2010) 331-342.

[7] P. Nielsen, D.P. Callaghan, Shear stress and sediment transport calculations for sheet slow under waves, Coast. Eng. 43 (2003) 347-354.

[8] P. Nielsen, Sheet flow sediment transport under waves with acceleration skewness and boundary layer streaming, Coast. Eng. 53 (2006) 749-758.

[9] J.B. Chen, J.F. Zhou, Q. Zhang, LES of asymmetric wave-induced flow, Proc. 6th. Int. Conf. Fluid Mech. 1367 (2011) 261-264.

[10] T. Abreu, P.A. Sliva, F. Sancho, A. Temperville, Analytical approximate wave form for asymmetric waves, Coast. Eng. 57 (2010) 656-667.