Ocean Engineering 100 (2015) 97–106

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Short Communication

Study on threshold motion of sediment and bedload transport by tsunami waves

Changbo Jiang [a,b,*], Jie Chen [a,b], Yu Yao [a,b], Jing Liu [a], Ya Deng [a]

[a] School of Hydraulic Engineering, Changsha University of Science & Technology, Changsha 410114, PR China
[b] Hunan Province Key Laboratory of Water, Sediment Sciences & Flood Hazard Prevention, Changsha 410114, PR China

ARTICLE INFO

Article history:
Received 14 September 2014
Accepted 22 March 2015
Available online 17 April 2015

Keywords:
Tsunami wave
Threshold motion of sediment
Bedload transport
Experimental study
OpenFOAM

ABSTRACT

Tsunami wave produces high bed shear stresses and can mobilize a mount of sediment movements over large areas. In this study, laboratory experiments were performed in a wave flume to investigate sediment transport by tsunami wave attacking sand beaches. The flow field of tsunami wave was calculated by the numerical model OpenFOAM®. The numerical results showed that flow characteristic of simulated tsunami wave uprush and backwash belongs to the rapid unsteady flow. The drag force and its duration are necessary and sufficient to trigger particle entrainment. It is recommended that time-mean near bottom velocity averaging over the force duration rather than the maximum velocity is relevant to better description of the incipient motion phenomenon in rapid unsteady tsunami flow. The experimental results show that some of the commonly used or recent bedload formulas for steady flow or wave are not suitable for the rapid unsteady or non-uniform tsunami flow. According to the experimental data presented in this paper, the bedload transport formulas for the tsunami uprush and backwash processes are proposed. An appropriate criterion of "sediment transport impulse", which is the product of magnitude and duration, is conjectured and could well explain the sandy beach deposition and erosion caused by tsunami wave.

1. Introduction

Devastating tsunami wave can mobilize coastal sediments, resulting in a substantial amount of sediment transport and significant morphological changes in affected coastal areas. The 2004 Indian Ocean tsunami attacked many coasts along the Indian Ocean, a large amount of sediment transport and large-scale coastal erosions occurred at various places along those coasts affected by the tsunami (Paris et al., 2009). To reduce future potential economical losses in coastal areas prone to devastating tsunamis, it is important to understand sediment transport processes under complex tsunami wave conditions. Due to the infrequent nature of tsunamis and the difficulty in conducting timely measurements after tsunami events, tsunami sediment transport is less understood compared to other tsunami characteristics. Investigating the sediment transport induced by tsunamis is not only important for predicting potential tsunami hazards in the future, but also plays an vital role in understanding the tsunami hazards which have occurred in the past.

Tsunami wave with the height of 5–10 m will be inevitably accompanied by very high flow velocities when they penetrate inland (Goto et al., 2007; Matsutomi et al., 2006; Li et al., 2012), which will undoubtedly produce high bed shear stresses and a mount of sediment movements over large areas, resulting in substantial beach erosion and scouring around a large number of structures, and widespread deposition in inland areas (Gelfenbaum and Jaffe, 2003; Pari et al., 2008; Paris et al., 2010). Currently, there exist a few laboratory studies of tsunami erosion and deposition processes (Kobayashi and Lawrence, 2004; Alsina et al., 2009; Tsujimoto et al., 2008; Young et al., 2010; Sumer et al., 2011; Chen et al., 2012). Their experimental results also show that a tsunami is capable of causing sediment motion in both the uprush and backwash phases, and that the backwash process mainly as sheet flow is stronger than the uprush. On the other hand, a limited number of laboratory studies focus on tsunami scour around the structure (Kato et al., 2000; Tonkin et al., 2003; Nakamura et al., 2008; Ca et al., 2010; Chen et al., 2013). Their experiments reveal that the most rapid scour on sand substrate occurred during the tsunami backwash stage.

However, most of their studies focus on beach profile changes, and current knowledge about the mechanisms of erosion and deposition, such as sediment transport, is still limited and yet to be investigated. The threshold motion of sediment and bedload transport are two main aspects of sediment transport reported

* Corresponding author at: School of Hydraulic Engineering, Changsha University of Science & Technology, Changsha 410114, PR China.
E-mail address: jcb36@vip.163.com (C. Jiang).

http://dx.doi.org/10.1016/j.oceaneng.2015.03.011

in the literature. Relative to other tsunami behaviors, they are almost impossible to conduct detailed real-time measurements during tsunami events. However, they were extremely important for tsunami geologists who have made significant effort to estimate the tsunami heights, flow depths and velocities by establishing qualitative relationships between tsunami deposits and tsunami hydrodynamic characteristics.

The threshold motion of sediment on the seabed is an important factor in most types of computations concerned with sediment response to wave or current. Almost all existing formulae of threshold motion are derived based on the assumption that sediment transport can be fully expressed by the streamwise parameters like streamwise velocity (Van Rijn, 1984; Soulsby and Whitehouse, 1997) or boundary shear stress (Shields, 1936; Soulsby and Whitehouse, 1997), whilst the vertical parameters are not included, like vertical velocity or seepage (Yang et al., 2014). Nielsen (1992), Turner and Masselink (1998), Butt et al. (2001) and Yang et al. (2014) all realized that the vertical pressure force is also a very important parameter to express the sediment transport. According to the Yang et al. (2014), accelerating flow produced downward velocity, and decelerating flow generated upward velocity. The Modified Shields Curve could be extended to express the critical shear stress of sediment in non-uniform or unsteady flows with the presence of vertical flow.

Recently, Celik et al. (2010) presented a new criterion for the incipient motion of sediment grains, which indicates that criteria utilizing gross flow characteristics, such as those proposed by Shields, do not account for the force fluctuations and therefore are not sufficient to describe the phenomenon at incipient conditions. It was hypothesized that not only the force magnitude, but also its duration of energetic near bed turbulent events is relevant in predicting grain removal from the bed surface. It was proposed that the product of force and its duration, or impulse, was a more appropriate and universal criterion for identifying conditions of particle dislodgement. Hence, it is worthy to make comparison between the traditional Modified Shields Curve and the New Impulse Criterion in view of judging the incipient motion of sediment grains under tsunami wave action.

The suitability of selected sediment transport formulas for the sediment movement induced by tsunami wave is very vital. A number of sediment transport formulas by currents or wave have been proposed, such as Meyer-Peter and Müller (1948), Wilson (1966), Maden (1991), etc. Generally speaking, sediment transport can be well predicted by many formulae available in the literature for steady, quasi-steady, quasi-uniform rectilinear flow, but may not be satisfied in non-uniform or unsteady flow conditions. Flow associated with tsunami uprush and backwash has strong acceleration or a decelerating process and is far from being steady or uniform. The performances of sediment transport formulas to simulate sediment transport induced by solitary wave or tsunami wave should be discussed. Recently, Li and Huang (2013) evaluated the performances of six widely-used sediment transport formulas for tsunami wave through case studies using open source model packages (XBeach and Delft3D). However, very few laboratory studies on sediment transport formulas for the sediment movement induced by solitary wave or tsunamis waves are found in the literature.

We performed an experimental study to discuss the threshold motion of sediment and bedload transport under the action of tsunami wave. The objectives of this study are: (i) to understand the key features of tsunami sediment movement; (ii) to analyze the performances of sediment transport formulas in a well-controlled laboratory condition. In laboratory studies, it is too difficult in measuring the flow field of the tsunami wave uprush and backwash processes, partly due to fact that the commonly used Acoustic Doppler Velocimeter is single point measurement, and partly due to fact that the Particle Image Velocimetry (PIV) is unable to measure the flow field with sediment movement. OpenFOAM® is a widely used open-source CFD code in modern industry supporting two-phased incompressible flow. With appropriated treatment of wave generation and absorption, it has been proved to be powerful and efficient tools for exploring complicated nearshore wave dynamics (Higuera et al., 2013a,b). Therefore, in order to analyze the sediment transport, we verified the numerical model OpenFOAM® with our experiment data to calculate the flow field during the tsunami wave uprush and backwash processes in this study.

2. Experimental setup and test procedure

2.1. Experimental setup

In general, tsunami wave may take many shapes, but typically takes the form of individual solitary wave, rather than periodic wave. Solitary wave has been used in experimental study as a proxy for tsunami wave forms in most cases (e.g., Goring, 1979; Synolakis and Bernard, 2006), although the accuracy of this approximation is extensively discussed by Madsen et al. (2008). The scaling effects of small-scale sediment transport laboratorial experiments are probably significant, since normally the sand substrate must be modeled at full scale while the tsunami wave is modeled at reduced scale. Very fine sediments cannot be used as a scale model of sand, since finer sediments tend to become cohesive (Tonkin et al., 2003). Published experimental studies very often used solitary wave to simulate tsunami wave. As a result, experiments on beach erosion and sediment movement under solitary wave (Kobayashi and Lawrence, 2004; Young et al., 2010; Chen et al., 2012; Kato et al., 2000; Tonkin et al., 2003; Chen et al., 2013) were based on geometrically distorted models: even though it is possible to generate wave whose waveform is qualitatively similar to that of typical tsunami wave, both the length and time scales of actual tsunami wave cannot be down-scaled in wave flume experiments according to the Froude similarity law. Moreover the fact that natural sand is normally used in model tests also needs to be taken into consideration.

Following Chen et al. (2012), further experiments were conducted in a 2-dimensional (2D) glass-walled wave flume in the hydraulics laboratory in Changsha University of Science and Technology, China. The wave flume was 40.0 m long, 0.5 m wide and 0.8 m high. Referring to Fig. 1, a piston-type wave maker was installed at one end of the flume and a 1/10 sand beach was constructed on the other side of the flume. The sand beach was constructed using the well sorted natural sand. Sieve analysis was performed on the three different random sand samples. The sand had a mean median diameter $d_{50}=0.368$ mm. The mean coefficient of uniformity ($C_u=d_{60}/d_{10}$) for this sand was 2.83 and the mean coefficient of curvature $\left(C_c=d_{30}^2/(d_{10}d_{60})\right)$ was 1.11.

For the convenience of describing the sand beach and the arrangement of the measuring devices, we define a Cartesian coordinate as shown in Fig. 1. A series of solitary waves was selected as incident wave in the flume. The wave conditions examined in the experiments are listed in Table 1.

2.2. Instrumentations

Seven capacitance wave gauges (Canadian RBR Co., Ltd) and four ultrasonic water level gauges (Beijing Sinfotek Science and Technology Co., Ltd) were used to measure the wave surface elevations at selected locations shown in Fig. 1. The wave gauges (WG) were numbered from WG 1 to 7. Their locations (in the coordinate system defined in Fig. 1) were adjusted according to water depth and were given in Table 2. The surface elevations were sampled at 50 Hz. The ultrasonic water level gauges (UWLG) numbered from UWLG 1 to 4 were positioned at certain specified