A preliminary laboratory study of motion of floating debris generated by solitary waves running up a beach

Shen, Hung-Tao; Huang, Zhenhua; Yao, Yao; Lo, Edmond Yat Man

2014

Yao, Y., Huang, Z., Lo, E. Y. M., & Shen, H.-T. (2014). A preliminary laboratory study of motion of floating debris generated by solitary waves running up a beach. *Journal of earthquake and tsunami*, 8(3), 1440006-.

<https://hdl.handle.net/10356/101979>

<https://doi.org/10.1142/S1793431114400065>

© 2014 World Scientific Publishing Company. This is the author created version of a work that has been peer reviewed and accepted for publication by *Journal of Earthquake and Tsunami*, World Scientific Publishing Company. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [Article DOI: <http://dx.doi.org/10.1142/S1793431114400065>].

Downloaded on 26 Apr 2023 18:27:52 SGT

Journal of Earthquake and Tsunami
Vol. 8, No. 3 (2014) 1440006 (13 pages)
© World Scientific Publishing Company
DOI: 10.1142/S1793431114400065

A Preliminary Laboratory Study of Motion of Floating Debris Generated by Solitary Waves Running up a Beach

Yao Yao

*School of Civil and Environmental Engineering
Nanyang Technological University
50 Nanyang Avenue, 639798 Singapore
Institute of Catastrophe Risk Management
Nanyang Technological University
50 Nanyang Avenue, 639798 Singapore*

Zhenhua Huang*

*School of Civil and Environmental Engineering
Nanyang Technological University
50 Nanyang Avenue, 639798 Singapore
Earth Observatory of Singapore
Nanyang Technological University
50 Nanyang Avenue, 639798 Singapore
Department of Ocean and Resources Engineering
School of Ocean and Earth Science and Technology
University of Hawaii at Manoa
Honolulu, HI 96822, USA
zhenhua@hawaii.edu
zhhuang@ntu.edu.sg*

Edmond Y. M. Lo

*School of Civil and Environmental Engineering
Nanyang Technological University
50 Nanyang Avenue, 639798 Singapore
Institute of Catastrophe Risk Management
Nanyang Technological University
50 Nanyang Avenue, 639798 Singapore*

Hung-Tao Shen

*Department of Civil and Environmental Engineering
Clarkson University, 8 Clarkson Avenue
Potsdam, NY 13699, USA*

Received 23 April 2014
Revised 16 June 2014
Accepted 9 July 2014
Published

*Corresponding author.

Y. Yao *et al.*

Destructive tsunamis can destroy coastal structures and move huge amounts of tsunami debris. Our current understanding of motion of tsunami debris in tsunami flows is limited. In this paper, we present a preliminary laboratory study of motion of model debris under the action of solitary waves running up a beach. The difference between the waterline of maximum inundation and the final position of debris was examined under various conditions. Effects of solitary wave height, water depth, and the distance of debris source to the shoreline on the maximum inundation, the debris limit, and the final position of debris were examined. In general, the final positions of the debris are different from the waterline at maximum inundation and there is a low possibility that a large amount of debris can be carried by retreating water offshore into the sea.

Keywords: Tsunami; Tsunami debris; floating debris; solitary waves.

1. Introduction

High-speed flows associated with a large tsunami are capable of destroying part or all of an impacted coastal structure and carry anything they could move. The amount of debris generated can be dramatically large and the types of debris can be varied. For the 2011 Tohoku Earthquake and Tsunami, the total estimated amount of debris reached up to 25 million tons, and this did not include the destroyed vehicles and ships and the debris in the areas around the Fukushima Nuclear Plant [Bagulayan *et al.*, 2012]. Some debris also can be washed back into the sea and travel long distances; there were also 5 million tons of debris swept into the Pacific Ocean after the 2011 Tohoku Earthquake and Tsunami. The components of debris during a tsunami event depend on where the tsunami passes by and the energy in the tsunami; they can be the fine sediments from the seabed, cars, ships, broken parts from houses, or even whole wooden houses.

Past tsunami-hazard studies focused on the prediction and modeling of tsunami inundation, coastal protection, and tsunami sediment deposition (including boulder transportation). The floating debris generated during a tsunami event may endanger people battling flooding water to escape, increase the hydrodynamic loads on coastal structures, cause marine pollution, and affect the tsunami recovery process. However, systematic study of tsunami debris is generally lacking. Transport of boulders by tsunami is a closely related topic. Attempts have been made to infer the velocities and causes of overwash flows from tsunamis boulders [e.g. Etienne *et al.*, 2011; Buckley *et al.*, 2012]. Imamura *et al.* [2008], using the shallow water equation, developed a model for the motion of a single boulder on a plain beach; they also verified their model by laboratory experiments. However, boulders are heavier than seawater and their motion is fundamentally different from tsunami debris. Lebreton and Borrero [2013] recently used a numerical model to study the transport and accumulation of floating debris in the ocean for the 2011 Tohoku earthquake and tsunami.

In this preliminary study, a set of experimental results is presented to evaluate the motion of debris caused by solitary waves over a simple composite beach profile. Since wooden houses and mixed-type buildings typically have high damage probabilities [Suppasri *et al.*, 2013], the objective is to show how a row of coastal wooden

houses, after being destroyed by tsunami waves, move with the overland tsunami flows. The experimental data presented in this study include the final debris position and the debris limit (the inland limit of debris motion), and the effects of debris on inundation distance.

2. Experimental Setup

The material used to simulate debris should have consistent properties when wet or dry, including size, shape, density. Polyethylene is found to be a suitable material after testing over a wide range of different materials. Polyethylene has a density of 912 kg/m^3 , and thus the model debris float in water. Polyethylene plates were cut into 10 mm long, 5 mm wide, and 5 mm high cubes. These cube-shaped debris models represent coastal wooden houses. To eliminate the effects of surface tension effects, the model debris were soaked into water with few drops of detergent before placing them in the wave flume [Adam, 1937]. Figure 1 shows samples of the model debris used in this study.

The experiment was conducted in a wave flume, with dimensions of 34 m long, 0.55 m wide, and 0.6 m deep, in the Hydraulics Laboratory of the Nanyang Technological University, Singapore. Referring to Fig. 2, a composite slope, made of PVC and consisted of three slope angles, was used to represent the beach geometry. The beach model was sealed by plasticine to avoid possible water leakage between the model and the two walls of the wave flume. Lines were marked on the surface of the beach model for quantifying the inundation and the motion of debris by an image analysis. A piston type wave maker was used to generate solitary waves, and four ultrasonic sensors (UltraLab ULS-40D), labeled as S1, S2, S3, and S4 in Fig. 2, were used to measure the surface displacements at two offshore locations and two near-shore locations. Four Logitech full HD 1080p video cameras, labeled as Camera 1, Camera 2, Camera 3, and Camera 4 in Fig. 2, were also used to record the inundation process and the motion of the model debris. A sampling rate of 50 Hz was used for the ultrasonic sensors, and a frame rate of 30 fps was used for the

Fig. 1. Polyethylene model debris without color identification (left) and with color identification (right).

Y. Yao *et al.*

Fig. 2. Experimental setup. Not drawn to scale.

video cameras. Dewesoft (DEWE-43) USB DAQ system was used to synchronize the ultrasonic sensors with the video cameras.

For later description of experimental results, the intersection between the slope of 1:14 and the slope of 1:26 is called “berm crest”. The onshore distance, denoted by x , is measured from the berm crest shoreward (i.e. $x = 0$ is the location of the berm crest), and the alongshore distance, denoted by y , is measured from one side of the wave flume, see Fig. 3 for the definitions of x and y coordinates. In this coordinate

Fig. 3. Definitions of x and y coordinates and the arrangement of model debris in the experiment. Not drawn to scale.

system, the still water line was at $x = -53$ cm for $h = 31$ cm and $x = -13$ cm for $h = 34$ cm.

In this initial experiment, we consider one simple scenario where the tsunami debris are generated by a row of destroyed coastal houses. For this purpose, polyethylene cubes are arranged in a row on the 1:26 slope, as shown in Fig. 3, where the onshore distance between the row of model debris and the berm crest is denoted by L . Physically, the onshore distance L represents the location of tsunami debris source. Three values of L were tested: $L = 5.0$ cm, 10.0 cm, and 15.0 cm.

Two water depths were examined in the experiment for each value of L : $h = 31.0$ cm and 34.0 cm, which correspond to two different tide levels. For each water depth, several wave heights were tested: $H = 2.0, 3.0, 4.0$ cm for water depth $h = 31.0$ cm, and $H = 1.0, 2.0, 2.5$ cm for water depth $h = 34.0$ cm. Repeating tests were carried out at least 10 times for each test condition to quantify the uncertainty in the measured results.

3. Results and Discussion

3.1. Wave transformation

Typical surface displacements measured by the four Ultralab sensors are shown in Fig. 4, from which the heights of the incident solitary wave and the shoaling solitary wave were obtained. Depending on the location of each sensor, the measured surface displacement after the incident peak may be affected by either the wave reflected from the beach model or the flow associated with the water retreating from the shore (reverse flow).

Fig. 4. Measured surface displacements at four locations for $H = 2$ cm (left) and $H = 4$ cm (right). Water depth = 31.0 cm. See Fig. 2 for these four locations.

Y. Yao *et al.*

3.2. Motions of waterline and model debris

When a solitary wave generated by the wave generator runs up the beach and reaches the model debris placed on the beach, the model debris may or may not be moved by the flow. If a piece of model debris does not move with the flow, that means the wooden house is not destroyed by the flow; when a piece of model debris moves with the flow, that the house has been destroyed by the flow. The frictional force between a piece of model debris and the bed is related to the flow depth (i.e. the submerged weight), and the speed of overflow is related also to the flow depth by $V = \gamma\sqrt{gd}$, where d is the flow depth and g the gravitational acceleration, and γ an empirical constant [e.g. Foytong *et al.*, 2013]. When the drag force is larger than the frictional force, the debris piece starts to move. If the debris piece is not fully floating, the frictional force will cause the debris velocity to be slower than that of the overflow. When a piece of model debris becomes fully floated, it can closely follow the motion of overflow since the density of model debris is very close to water. A rough estimate of the critical flow depth required for a piece of model debris to become fully floated, d_{cr} , is calculated by

$$\rho_s h_s = \rho d_{cr}, \quad (1)$$

where ρ_s is the density of the polyethylene (912 kg/m^3), and h_s the height of the debris piece. Since $\rho_s/\rho = 0.912$ and $h_s = 0.5 \text{ cm}$ in this study (if the rotation of debris piece is neglected), $d_{cr} = 0.456 \text{ cm}$, which was easily achieved.

Figure 5 shows how the model debris moves onshore with the overflow for two test conditions. For the case of a weaker incoming flow ($H = 2 \text{ cm}$), the middle part

Fig. 5. Motions of the water line and model debris for $H = 2.0 \text{ cm}$ (left) and 4.0 cm (right) with water depth $h = 31.0 \text{ cm}$. The time interval is 0.167 s for $H = 2.0 \text{ cm}$ and 0.333 s for $H = 4.0 \text{ cm}$. IDR = Initial Debris Row.

A Preliminary Laboratory Study of Motion

of the model debris moved with the water line initially when the flow depth was shallow, indicating that those debris pieces were still in contact with the bottom. For the case of a stronger incoming wave ($H = 4$ cm), the wave front is a moving bore, and all the model debris started to move with the flow soon after the wave front reaching the debris. In both cases, after the model debris started to move with the overflow, the debris followed the flooding water closely, and then with time elapsing, the model debris gradually fell behind the overflow. When the overflow approached the maximum inundation (corresponding to maximum runup or runup limit), the flow depth became very shallow and the flow velocity was also reduced. The model debris became in contact with the beach bottom again, and the friction between the model debris and the beach bottom rapidly slowed down the model debris, causing the model debris to fall behind the front of the flooding water (waterline). The flow velocity was zero after the overflow reached the maximum inundation, and then the water started to retreat from the beach (reverse flow). In general, the model debris did not respond too much to retreating water as the depth of the reverse flow was very thin. However, some pieces of debris, whose positions were not very close to the waterline at maximum inundation, could travel a significantly long distance with the retreating water and either landed very close to the shoreline, or even offshore of the shoreline.

During the experiment, it was observed that debris models might rotate in the overflow. When the wave was pushing the debris in the initial stage, only few debris were rotating by the incoming water. Frequent rotation of debris models was observed when the overflow reached the maximum inundation and when the flooding water retreated from the beach.

All three types of breakers were observed in the experiment. Because the flow depth was very shallow in the experiment, sometimes it is difficult to classify a breaker. For $h = 31$ cm, plunging breakers were observed when $H = 3$ cm and 4 cm, but a surging/spilling breaker was observed when $H = 2$ cm. For $h = 34$ cm, surging breaker was observed for $H = 1$ cm, plunging breaker was observed for $H = 2.5$ cm, and surging/spilling breaker was observed for $H = 2$ cm. In the above classification of breakers, we used surging/spilling breaker to indicate that it is difficult to tell whether it is a surging breaker or spilling breaker.

3.3. Difference between the waterline at maximum inundation and the position of model debris

Figure 6 shows a comparison between the waterline at maximum inundation, the final positions of the model debris, and the debris limits for two cases: $H = 2.0$ cm and 4.0 cm with water depth $h = 31.0$ cm. For the majority of the model debris, the final positions of the model debris and the debris limits are almost the same. Since some pieces of model debris could be carried seaward by the retreating water, resulting in a significant difference between the final positions and the debris limits, such large difference is possible only when the incoming waves are strong. The debris

Y. Yao *et al.*

Fig. 6. The waterline at maximum inundation, the final debris positions and the debris limits for $H = 2.0$ cm (left) and 4.0 cm (right) with $h = 31.0$ cm and $L = 5.0$ cm. IDR = Initial Debris Row. Runup limit corresponds to maximum inundation.

limits for a tsunami event are normally not available as measurements from post-tsunami surveys are the final positions of tsunami debris. It is thus a real challenge to decode the characteristics of tsunami sources from such data which lacks information on the maximum inundation.

3.4. Uncertainty in the experimental results

Bottom friction and turbulence in the flow are two important factors affecting the motion of the waterline and the model debris. There is a need to access the uncertainty in the measured waterline at maximum inundation and the positions of the model debris. For this purpose, at least 10 runs were performed for each test condition. To demonstrate the degree of uncertainty in the experimental results, Figs. 7–9 show two sets of data from 10 runs for the measured waterline at maximum inundation, the debris limits and the final positions of model debris (final positions), respectively. Generally, all the results presented in these figures are clustered around their ensemble averages, and only a small portion of the model debris either do not closely follow the overflow or are carried seaward by the retreating water.

We remark that the slightly different slopes on the two sides of the beach model, as shown in Fig. 3, caused a slightly unsymmetrical behavior of both the motion of debris and the inundation flow. In view of the large scatter in the final debris locations and the debris limits, this slightly unsymmetrical behavior does not produce a significant change in the results statistically.

A Preliminary Laboratory Study of Motion

Fig. 7. Measured waterlines at maximum inundation for $H = 2.0$ cm (left) and 4.0 cm (right) with $h = 31.0$ cm and $L = 5.0$ cm.

Fig. 8. Measured debris limits for $H = 2.0$ cm (left) and 4.0 cm (right) with $h = 31.0$ cm and $L = 5.0$ cm. IDR = Initial Debris Row.

3.5. The distribution density functions of the final debris positions and the debris limits

A statistical analysis can be performed using the data from all runs under the same test condition (about 780 data points) to obtain a distribution density function of the debris positions. We use here the so-called kernel density function to analyze the final debris positions and the debris limits. Kernel density functions are closely

Y. Yao *et al.*

Fig. 9. Measured final positions of the model debris for $H = 2.0$ cm (left) and 4.0 cm (right) with $h = 31.0$ cm and $L = 5.0$ cm. IDR = Initial Debris Row.

related to histograms, but possess the properties such as smoothness and continuity by using a suitable kernel function. In this study, a Gaussian kernel is assumed and the optimum bandwidth recommended by Botev *et al.* [2010] is adopted. For the initial potions at $x = 5$ cm, the density functions for $h = 31$ cm and 34 cm are shown in Fig. 10, where the abscissa is the final position or debris limit of a debris piece. All the measured final debris positions and debris limits are also included in Fig. 10 to show the ranges of the data used to compute the density functions.

It can be seen from Fig. 10 that the shapes of density function are unimodal, close to a normal distribution but with a relatively long tail on the left side (i.e. a negative skewness). In general, a larger wave height can cause the debris to move a longer distance shoreward and to spread over a wider region. In terms of the shape

Fig. 10. The measured debris limit (top panels) and final debris position (middle panels), and the distribution density functions (bottom panels) for $h = 31$ cm (left panels) and $h = 34$ cm (right panels) with $L = 5.0$ cm. H is the incident wave height and f is the density function. The dashed line is the density function for the debris limit and the solid line for the final position.

A Preliminary Laboratory Study of Motion

of the density function, the difference between the debris limit and the final debris position increases with the increasing solitary wave height. This is related to the following two factors: (1) a larger wave height gives a larger wave runup, and (2) both the magnitude of the friction between the bottom and debris and the onshore flow are random in nature. Those debris pieces that experience less bottom friction can move long distances shoreward, while those debris pieces that experience more bottom friction may not be able to move very far shoreward. This is especially true when the runup is high and the flow depth is shallow.

For the other two values of L , the density functions of the final debris positions and the debris limits are not too different from those for $L = 5$ cm. For reference, Figs. 11 and 12 show the measured final debris locations, the debris limits, and density functions for $L = 10$ cm and $L = 15$ cm, respectively. It is concluded from comparing Figs. 10–12 that the initial debris location does not have a significant effect on the motion of the debris and the wave height is the most important factor that determines the final debris locations and the debris limits.

Fig. 11. Distribution density functions of debris for $h = 31$ cm (left panel) and $h = 34$ cm (right panel) with $L = 10$ cm. H is the incident wave height and f is the density function. The dashed lines are for the debris limits and the solid lines are for final positions.

Fig. 12. Distribution density functions of debris for $h = 31$ cm (left panel) and $h = 34$ cm (right panel) with $L = 15$ cm. H is the incident wave height and f is the density function. The dashed lines are for the debris limits and the solid lines are for final positions.

Y. Yao et al.

3.6. Remarks on physical modeling tsunami debris in laboratory conditions

In the literature, solitary waves are often used to simulate tsunami waves in laboratory studies [e.g. Kobayashi and Lawrence, 2004; Murata *et al.*, 2010]. This is because that the shape of the wave front of a real tsunami is very similar to that of a solitary wave, and the wave runup is controlled mainly by the shape of the wave front. However, we remark that it is difficult to model tsunami-induced motion of sediment and debris in laboratory due to the following reasons: (1) the length scale of a real tsunami relative to the finite length of a wave flume, (2) the short period of waves in laboratory conditions and the long period of tsunami waves, and (3) the large size of model debris relative to the shallow flow depth in a wave flume test. As a result, the laboratory experiments have to be carried out on a distorted scale model [see, e.g. Chen *et al.*, 2012]. This does not mean that experimental results are not useful in tsunami research. Experimental results can still help us understand physics involved in some very complicated phenomena and in particular, can be used to validate numerical models.

4. Conclusions

A set of experiments was preformed to study the motion of a row of model debris caused by solitary waves running up a beach. Analysis of the experimental results showed that both the measured waterline at maximum inundation as well as the position of debris had high uncertainty, and the uncertainty in the measured position of debris was larger and increased with the strength of incoming waves. The presence of the debris slightly reduced the ensemble-averaged waterline at maximum inundation, and the location of the debris source did not affect the ensemble average of the final locations of debris. The reverse flow associated with retreating water was found to be able to carry some debris a significant distance seaward. The ensemble average of the final positions of debris and the ensemble average of the debris limits were very close to each other, but both did not reach the ensemble average of the waterline at maximum inundation.

Acknowledgments

This work was supported partially by the National Research Foundation Singapore and the Singapore Ministry of Education under the Research Centres of Excellence initiative, and partially by the Institute of Catastrophe Risk Management, Nanyang Technological University, Singapore. This is EOS publication No. 73.

References

- Adam, N. K. [1937] “Detergent action and relation to wetting and emulsification,” *J. Soc. Dyers Colourists* **53**(4), 121–129.

A Preliminary Laboratory Study of Motion

- Bagulayan, A., Bartlett-Roa, J. N., Carter, A. L., Inman, B. G., Keen, E. M., Orenstein, E. C., Patin, N. V., Sato, K. N. S., Sibert, E. C., Simonis, A. E., Van Cise, A. M. and Franks, P. J. S. [2012] "Journey to the center of the gyre: The fate of the Tohoku Tsunami debris field," *Oceanography* **25**(2), 200–207.
- Buckley, M. L., Wei, Y., Jaffe, B. E. and Watt, S. G. [2012] "Inverse modeling of velocities and inferred cause of overwash that emplaced inland fields of boulders at Anegada, British Virgin Islands," *Nat. Hazards* **63**, 133–149.
- Chen, J., Huang, Z. H., Jiang, C. B., Deng, B. and Long, Y. N. [2012] "An experimental study of changes of beach profile and mean grain size caused by Tsunami-like waves," *J. Coastal Res.* **28**(5), 1303–1312.
- Etienne, S., Buckley, M., Paris, R., Nandasena, A. K., Clark, K., Strotz, L., Chagu-Goff, C., Goff, J. and Richmond, B. [2011] "The use of boulders for characterising past tsunamis: Lessons from the 2004 Indian Ocean and 2009 South Pacific tsunamis," *Earth-Science Rev.* **107**, 7690.
- Foytong, P., Ruangrassamee, A., Shoji, G., Hiraki, Y. and Ezura, Y. [2013] "Analysis of Tsunami flow velocities during the March 2011 Tohoku, Japan, Tsunami," *Earthquake Spectra* **29**(S1), S161–S181.
- Imamura, F., Goto, K. and Ohkubo, S. [2008] "A numerical model for the transport of a boulder by tsunami," *J. Geophys. Res.* **113**, C01008.
- Kobayashi, N. and Lawrence, A. [2004] "Cross-shore sediment transport under breaking solitary waves," *J. Geophys. Res.* **109**, C030047.
- Lebreton, L. and Borrero J. C. [2013] "Modeling the transport and accumulation floating debris generated by the 11 March 2011 Tohoku-oki tsunami," *Marine Pollution Bulletin* **66**, 53–58.
- Murata, A., Imamura, F., Katoh, K., Kawata, Y., Takahashi, S. and Takayama, T. [2010] *Tsunami: To Survive from Tsunami* (World Scientific, Singapore).
- Suppasri, A., Imamura, F. and Koshimura, S. [2013] "Tsunami hazard and building damage assessment in Thailand using numerical model and fragility curves," *J. Earthquake Tsunami* **7**(5), 1250028.