Experimental study on tsunami induced debris-laden flow

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**NANYANG
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UNIVERSITY**

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**EXPERIMENTAL STUDY ON TSUNAMI INDUCED
DEBRIS-LADEN FLOW**

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

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**EXPERIMENTAL STUDY ON TSUNAMI INDUCED
DEBRIS-LADEN FLOW**

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List of Nomenclature

English Notation

B	Buoyancy force
C_a	Coefficient of inertia (i.e. added mass coefficient)
C_D	Drag coefficient
D	Width-averaged maximum up-slope distance
F_D	Drag force
F_f	Frictional force
F_I	Inertia force
FDP	Final debris position
FDP_D	Dimensionless final debris position
G	Gravitational force
H	Incident solitary wave height
I	Maximum inundation/ inundation at the different debris mass loading
I_0	Inundation with no debris loading
$I_{Baseline}$	Maximum inundation without debris
I_D	Dimensionless inundation
K	Solitary wave number
L	Distance between the edge of slope and edge of the debris
M_D	Non-dimensional mass loading
M_d	Amount of debris mass
M_w	Mass of water
MDP	Maximum debris position
MDP_D	Dimensionless maximum debris position
$R_{observed}$	Observed runup
$R_{predicted}$	Predicted runup
R	Runup
S	Distance between the white and red rows of debris
SD_D	Standard deviation
SD_N	Normalized standard deviation
SWL	Still water level
V_d	Total volume of the debris
V_{eq}	Vertical equivalent height

V_w	Total volume of the incoming wave
X_{eq}	Horizontal equivalent length
a	Longest dimension of the debris
a_w	Flow acceleration
b	Intermediate dimension of the debris
c	Shortest dimension of the debris
c_s	Celerity of a solitary wave
d_{cr}	Critical flow depth required for a piece of debris to become fully floating
d_m	Flow depth
f	Friction coefficient between debris and slope model
g	Gravitational acceleration
h	Water depth/deep water depth
l_s	Solitary wavelength
m_a	Add mass from the water
m_d	Mass of the debris
n	Sample size
s_{eq}	Equivalent slope gradient
s_f	Fitted slope gradient
t	Time
u_d	Debris velocity
u_w	Flow velocity
x	Distance along the direction of wave propagation

Geek Notation

α	1 st slope gradient
β	2 nd slope gradient
γ	3 rd slope gradient
δ	Fitting constants of dimensionless massloading and inundation
ε	Fitting constants of dimensionless massloading and inundation
η	Solitary wave profile
θ	Slope angle
ρ_s	Density of debris
ρ_w	Density of water

Summary

Tsunami induced debris-laden flow is a destructive process in a tsunami event, since the high speed and energetic tsunami waves could destroy items in its path and carry debris or any items they could move. A key limitation in understanding tsunami debris-laden flows is the lack of both quantitative experimental data and numerical models. In this PhD study, a series of laboratory-based studies had been conducted on debris-laden tsunami waves modelled as solitary waves. The maximum and final debris positions, along the maximum inundation were measured via video recordings for various experimental conditions. The objective was to study the inundation/runup reduction, final and maximum debris location, and the motion of debris due to a solitary wave incident on a composite slope. This included (i) a row of debris located at different positions on the slope, (ii) two rows of debris with different separation distances, and (iii) a single of debris with different sizes and orientations. The composite slope used is a 3-slope setup to be representative of the continental shelf and slope and the nearshore configuration.

In the one and two debris-row experiments, the results showed that the presence of the debris reduced the maximum inundation. The values of maximum inundation, maximum and final debris positions were shown to be more sensitive to the incident wave conditions than the original position of the debris row under the tested wave conditions. The percentage of the debris that was further washed back into the deeper part of the flume (i.e. seaward) was obtained, but the chances of being washed back was small, random and unpredictable. Analysis of the experimental results showed that both the measured inundation limit as well as the position of debris had significant variability, and with the variability increasing with the solitary wave height. Probability distributions and normalized Kernel Density functions were used to characterize the spread and shape in the maximum and final debris positions.

A single equivalent slope was further defined for the composite slope to characterize the wave runup as part of the data analysis. Together with a newly proposed the non-dimensional debris mass loading, the reduction in inundation due to the debris is then characterized via an empirical fit. This fit would allow future predictions of the inundation reduction as dependent on the amount of debris being carried by the solitary wave under such a composite slope arrangement. Such prediction would find use in post tsunami field surveys where the surveyed final debris locations are used to infer the incident wave heights.

For experiment on a single piece of debris, the maximum inundation/runup was unaffected by the piece of debris due to its light weight and small size. However there was a high degree of variability in the maximum and final debris positions as dependent on small changes in debris size or even the same-sized debris but at different initial orientations. The equation of motion for single debris was used to estimate coefficients for the drag, added mass and frictional force based on the observed debris trajectory as captured via video recordings.

This PhD work addresses a research gap in the study of a tsunami event as relating to the effects of the generated floating debris. The work, besides providing detailed experimental data for further analytical work, demonstrated the effect of the debris mass on the inundation/runup reduction and with its quantification over the mass loading range tested. Therefore, the obtained experimental results should be useful to support future calibration or validation of numerical approaches, more extensive experiments over a wider parameter range (e.g. different composite slopes and mass loadings), and to guide field estimations of tsunami wave condition via post-event surveys on the inundation extent.

1.0 Introduction

1.1 Background

A tsunami event is one of the most devastating natural disasters that can occur. Large earth movements, such as submarine landslide, submarine earthquake or volcano eruption, can cause tsunami events. While the resulting tsunami waves have extremely long wavelength but small wave heights in the deep ocean, they transform into a high water displacement with huge volume as the waves approach the shore (i.e. towards shallow water region) while at the same time, traveling at high velocities. The corresponding forces from such an amount of water at high speed generate large debris laden flows shoreward along with severe coastal flooding. Furthermore the extremely high speed of flood water was reported to increase the damage by up to 190% when compared with the damage which are caused by flooding inundation alone (which has nearly zero velocity) (Nadal 2010). It can destroy numerous or even all of the coastal structures in its path and carries any items it could move. The cause of fatalities during a tsunami event is not due to the water wave itself, but also from the debris generated by the tsunami waves. The massive debris generated during the tsunami event may also travel long distances with high speed and power.

The major recorded tsunami events since 1980 are listed in the Table 1-1 below along with the magnitude of the generating earthquake and the estimated death toll. Table 1-1 shows that tsunami activities turned out to be more active since the 2004 Indian Ocean earthquake and tsunami. Loss of lives, damage or destruction of properties and economic loss are various components in the consequence in a tsunami event. Taking the 2004 Indian Ocean earthquake and tsunami as an example, it was a submarine-earthquake initiated tsunami event that affected 18 countries with fatalities of 227,898 and over 10 billion US dollars in material loss and 2 billion US dollars in insured loss (NOAA 2013). Indonesia was the most affected country followed by Sri Lanka, India, Thailand and Somalia. This earthquake and tsunami event had its earthquake source off the west coast of Sumatra with magnitude of 9.2 Mw in 26th December. According to the data from National Geophysical Data Center, the maximum water height reached 50.9 m and the number of runups hit 1,509 times (NOAA 2013). Aceh province of Indonesia located at the north part of the Sumatra was the most impacted province.

Table 1-1 Major tsunami events since 1980 (Pararas-Carayannis 2009, NOAA 2013)

Year	Date	Tsunami Event	Magnitude of Earthquake (Mw)	Death Toll
2013	6 February	Solomon Islands Tsunami	7.9	10
2011	11 March	Great East Japan Tsunami (Tohoku, Japan)	9.0	18,537
2010	27 February	Chile	8.8	558
	12 January	Haiti	7.0	31,6000
2009	29 September	Samoa	8.3	192
2007	12 September	Indonesia	8.2-8.4	>9
	15 August	Peru	8.1	>600
	1 April	Solomon Islands	8.1	50
	13 January	Kuril Islands	8.3	
2006	15 November	Kuril Islands	8.3	0
	17 July	Indonesia	7.7	>600
	3 May	Tonga	7.9	0
2005	28 march	Indonesia	8.7	>2000
2004	26 December	Indian Ocean Tsunami (Aceh, Indonesia)	9.2	227,898
2002	2 January	Vanuatu	7.2	
2001	23 June	Peru	8.1	>138
1999	26 November ¹	Vanuatu	7.3	10
	17 August	Turkey	7.4	17,000
1998	17 July	Papua New Guinea	7.1	>3000
1996	21 February	Peru	7.5	12
1994	4 October	Kuril Islands, Russia	8.1	20
1993	12 July	Japan	7.8	239
1992	2 September	Nicaragua	7.6	170
1985	21 September	Mexico	7.5	40,000 to 50,000
1983	26 May	Japan	7.9	>104

Where, Pararas-Carayannis (2009) is for event which happened before 2009 and NOAA (2013) is for the event which happened after 2009.

Figure 1-1 shows the satellite images of Banda Aceh, Indonesia, before and right after the 2004 Indian Ocean earthquake and tsunami. Figure 1-2 shows another set satellite images of Lhoknga, Indonesia, before and after the earthquake and tsunami. Banda Aceh and Lhoknga are two coastal cities of Aceh Province. Almost all the vegetation and infrastructures were washed away as seen from the images.

Figure 1-1 Satellite images of Banda Aceh, Indonesia, before and after the 2004 Indian Ocean Earthquake and tsunami (Yokoyama 2010)

Figure 1-2 Satellite images of Lhoknga, Indonesia, before and after the 2004 Indian Ocean Earthquake and Tsunami. (Gutro 2005)

After Indonesia, Sri Lanka was the second worst-hit country in the 2004 Indian Ocean earthquake and tsunami event. The tsunami waves arrived at Sri Lanka about 1 hour after the earthquake. The wave heights reached 5 to 10 m. The combined death and missing toll reached 35,322 and the number of people displaced reached 522,600 (NOAA 2013). The upper photo of Figure 1-3 shows a satellite image of Kalutara, Sri Lanka, being attacked by the tsunami waves. The waves strongly attacked the village, flooded the whole area and flowed back to sea side. Strong turbulence was observed at the coastal area near the shore line. The lower photo of the figure shows another satellite image of Kalutara on the 1st January 2004 which was 5 days after the first waves. Vegetation and some manmade buildings, especially near the shoreline, had been destroyed and washed away. Some small waves were still attacking the beach.

Figure 1-3 satellite image of Kalutara, Sri Lanka during and after the 2004 Indian Ocean Earthquake and Tsunami (Gutro 2005)

Another striking example is the 2011 Tohoku earthquake and tsunami. The earthquake happened on 11 March 2011 with a magnitude of Mw 9.0. The maximum water height reached 38.9m at Iwate prefecture where the number of runups hit 6,051 times. This disaster caused 18,537 fatalities and 20,000 million US dollars in economic loss. Unlike the case of 2004 Indian Ocean earthquake and tsunami, there were reliable estimates on the number of houses destroyed or damaged. According to the records from the National Geophysical Data Center, 121,656 houses were destroyed and 197,536 houses damaged in the 2011 Tohoku earthquake and tsunami. Dams and roads were either destroyed or damaged. Based on the records, all the damage and destruction on the houses were due to the earthquake, but most of the fatalities were due to the tsunami. Only 1,409 cases of fatalities arose due to the earthquake, this amongst the 18,537 fatalities in total. (NOAA 2013) Figure 1-4 was taken when the intensive tsunami waves were attacking Tohoku, Japan. The waves were crushing trees and moving the car with extremely high intensity. Figure 1-5 shows the initial tsunami waves with debris attacking the dry land with houses and building being destroyed and a massive debris-laden flow being generated. The destroyed debris was concentrated at the wave front. Figure 1-6 shows the debris deposition during the event.

Figure 1-4 Tsunami waves hitting Tohoku during 2011 Tohoku Earthquake and Tsunami (Naranjo 2013)

Figure 1-5 Massive debris flow in the 2011 Tohoku Earthquake and Tsunami (Lam 2013)

Figure 1-6 Debris deposition during the 2011 Tohoku Earthquake and Tsunami (Edwards 2011)

There were four prefectures affected by the earthquake and tsunami: Iwate Prefecture, Miyagi Prefecture, Fukushima Prefecture and Ibaraki Prefecture. About 54 out of 174 towns/cities of these four prefectures were seriously attacked by the tsunami. Based on the data from Joint Research Centre of the European Commission, there were 88 towns or villages affected by the tsunami (Sunil 2011). The total estimated amount of debris reached up to 25 million tons, and this data further did not include destroyed vehicles and ships and also the areas around the Fukushima Nuclear Plant. As compared to the Great Hanshin earthquake (i.e. the 1995 Kobe Earthquake) generated 14 million tons debris which took the local government 3 years to clear

and dispose (Srinivas 2011). Figure 1-7 shows the huge amount of debris located at Rikuzentakata of Iwate prefecture. The proper disposal, recycling and possible reuse of the debris would be one of the most serious problems for the Japanese government.

Figure 1-7 2011 Tohoku Earthquake and Tsunami: Huge amount of debris at Rikuzentakata, Iwate prefecture (KyodoNews 2012)

It is noted here that tsunami related debris studies was not a priority topic for most scientific research before the 2004 Indian Ocean earthquake and tsunami. To the author's knowledge, most of studies on tsunamis (e.g. Cecionia, Bellottia et al. 2014, Lin, Wu et al. 2015, Wood, Jones et al. 2016, Strusińska-Correia 2017, Takabatakea, Shibayamaa et al. 2017) are focused on warning systems, mitigation measures and evacuations during a tsunami event without considering the effects of buildings being destroyed, and the generation, transportation and deposition of the debris. As such there is a scarcity of experimental data on the resulting debris-laden flow to support theoretical and numerical modelling.

For tsunamis, as the magnitudes are normally extremely high and hard to predict, the efficacy of various suggested wave height minimization and protection methods are difficult to assess. For most tsunami cases, although installed seawalls and vegetation cover would reduce part of the waves, most of the water would still rush into the inner coastal area. The tsunami waves would further destroy almost everything in their path and carry the generated debris until all their energies are dissipated. These make the studies of debris-laden flow become extremely complex, yet extremely important. Furthermore, it is noted the maximum debris positions 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 key challenge to decode the characteristics of tsunami sources (e.g. wave heights) from such debris deposition data which lacks information

on the maximum inundation. Lastly if the pathway of the moving debris could be estimated, local governments could then have a safer evacuation plan in advance. Local governments could also better plan for a more efficient post-event debris clearance and management, if the type, volume and final destination of the debris can be estimated.

1.2 Objectives

As indicated earlier a key limitation in understanding tsunami debris-laden flows is the lack of both quantitative experimental data and numerical models. It is impractical and difficult to obtain real-time measurements during an actual tsunami event. The objectives of this Ph.D are therefore to experimentally study a debris-laden flow under a tsunami wave modelled as a solitary wave to:

- (i) assess the influence of debris on the inundation process,
- (ii) characterize the movement and speed of debris, and
- (iii) quantify the maximum and final location of the debris.

A series of solitary waves with different water depth has been used to represent tsunami waves to experimentally study the debris-laden flow. A solitary wave is chosen, since it can well model the leading wave in a tsunami event and a number of experimental studies have used such solitary waves to model tsunami waves (e.g. Fernando, Samarawickrama et al. 2008, Huang and Yuan 2010, Hana, Hab et al. 2015) . A single of debris with different size and orientation, a row of debris placed at different positions, and two rows of debris with different separation distances, on a continental-shore (i.e. composite) slope model were used to represent different scenarios in a tsunami event. The obtained experimental results would be useful to support future calibration or validation of numerical approaches, and to guide field estimations of tsunami wave condition via post-event surveys on the inundation extent. The experimental results will be also helpful in understanding of the motion of debris and help to predict inundation/runup.

1.3 Scope

This Ph.D. work used a series of idealized debris-laden flow cases to show the importance of the debris laden flow. Solitary waves were used to represent the tsunami waves and a scaled continental shore-slope model was used to present the geometry of a coastal area. Rows of polyethylene blocks were used to present the floating debris. The measured maximum and final debris deposition position and the retardation effects of the debris on inundation and the probability of debris being washed back to the sea were presented. The motion of single isolated debris was also analyzed via several cases.

The scope of the one and two-row debris experiment are to:

- (i) quantify the influence of the debris and initial wave condition on inundation/runup;
- (ii) discuss the behavior and distribution of maximum and final debris position under different wave conditions (i.e. different water depth and incident wave height) and different initial debris conditions (i.e. different initial position of the row of debris and different separation distance between the two debris rows);
- (iii) predict the inundation/runup and their reduction by carrying out an empirical fitting of the experimental data;
- (iv) obtain an equivalent simple slope gradient from the composite slope model; and
- (v) obtain the percentage of debris which are washed back to deeper part of the flume (i.e., seaward).

The scope of single of debris experiments are to:

- (i) study the effects of the piece of debris with different orientation on inundation/runup;
- (ii) quantify the influence of the piece of debris with different initial orientation on its maximum and final debris position; and
- (iii) fit all various force coefficients to the driving equation of motion for individual debris piece.

2.0 Literature Review

2.1 Debris-laden Flow

Tsunami is an extremely hazardous event which generates huge water displacement as it propagates from deep ocean to offshore and then onshore to inundate vast inland areas. The types of debris, which the tsunami flow can transport, could be any obstacle along its path since the waves contain high destructive energy. Therefore, the types of debris can be highly varied, encompassing fine sediments from the

Figure 2-1 2011 Tohoku Earthquake and Tsunami Waves: Debris-laden Flow with fine sediments (PointGenerate 2011)

seabed, rock and boulders along the coast, torn-off pieces from houses, cars, and even ships that are broken off their moorings. Figure 2-1 to Figure 2-5 are photos taken from the 2011 Tohoku tsunami showing the debris-laden flow. Figure 2.1 shows the tsunami flow carrying mixed fine sediments, which can be sands or gravel from the sea bed. Figure 2-2 and Figure 2-3 are the snap shot of debris with the tsunami water showing that large objects such as cars can be transported. Figure 2-4 shows a dislodged house being floated across the Pacific Ocean toward the US west coast. All these show that the types and sizes of debris can be highly varied (Figure 2-5). Different types of debris could result from different dislodge modes and transportation processes during a tsunami. It thus makes the analysis of the behavior and transportation highly case dependent.

Figure 2-2 2011 Tohoku Earthquake and Tsunami: Tsunami: Flow was transporting cars (Patty 2011)

Figure 2-3 2011 Tohoku Earthquake and Tsunami: Cars were swept by tsunami waves (WordPress 2011)

Figure 2-4 2011 Tohoku Earthquake and Tsunami: A house floated across the Pacific toward the US west coast (TMGT 2011)

Figure 2-5 2011 Tohoku Earthquake and Tsunami: Various debris deposition (ACST 2011)

It is noted that this study is focused on floating debris, since large amounts floating debris are generated from an urban coastal region impacted by a tsunami. This is in contrast to studies on boulder motion during a tsunami which has been reported for analysis of tsunamis (e.g. Nott 2003). Furthermore inundation reduction is likely to arise from the debris mass as also studied here.

2.2. Solitary Waves and Tsunami Waves

A tsunami wave is a shallow water wave with extremely long period and wavelength (Anjan 2007). Although its wave height in deep water is small, the shoaling effect will lead a dramatic increase in wave height leading to a huge volume of water that rushes on-shore. The causes of a tsunami event can be due to submarine earthquake or landslide and volcano eruption. Solitary waves and dam-break waves are normally used to model tsunami waves in laboratory studies (see e.g. Fernando, Samarawickrama et al. 2008, Huang and Yuan 2010, Hana, Hab et al. 2015, Kihara, Niida et al. 2015, Chen, Melville et al. 2016). There are a few reasons that the solitary wave is chosen in this PhD study. Firstly, it simulates well the leading wave of a tsunami wave which comprises a series of waves. Secondly it is a travelling, non-dispersive shallow water wave with infinite wavelength. A single solitary wave is bell-shaped with only a crest which is above the still water level. It is stable and non-dissipative, thus able to travel long distances without distortion in its shape. In addition, solitary waves being of permanent form passes through one another without shape distortion. Therefore, reflected waves from the slope model could be easily distinguished in laboratory studies.

The characteristics of a solitary wave can be described via the following equations following (e.g. Daily and Stephan 1952, Synolakis 1987, Madsen and Schaffer 2010). A simple sketch of a solitary wave climbing up a single slope beach is shown in Figure 2-6.

Figure 2-6 Sketch of a solitary wave climbing up a single slope beach. (Note: SWL is still water level)

The solitary wave profile (η) is expressed in Eq. 2-1.

$$\eta(x, t) = H \operatorname{sech}^2(K(x - c_s t)) \quad \text{Eq. 2-1}$$

where, x is the distance along the direction of wave propagation, t is time, H is the solitary wave height, K is defined as solitary wave number (Eq. 2-2) and c_s is celerity of a solitary wave (Eq. 2-3).

$$K = \frac{1}{h} \sqrt{\frac{3H}{4h}} \quad \text{Eq. 2-2}$$

$$c_s = \sqrt{g(H + h)} \quad \text{Eq. 2-3}$$

with g being the gravitational acceleration. Since the deep water incident wave height of a solitary wave is small compared to the water depth, the solitary wave celerity can further be simplified to Eq. 2-4.

$$c_s = \sqrt{gh} \quad \text{Eq. 2-4}$$

The solitary wavelength can be calculated by Eq. 2-5 below.

$$L_s = \frac{2\pi}{K} \quad \text{Eq. 2-5}$$

Madsen and Schaffer (2010) provided an analytical solution of the runup of a single crest solitary wave over a simple slope beach as

$$R = 3.043H\sqrt{Kc_s t_0} \quad \text{Eq. 2-6}$$

where, t_0 is given by

$$t_0 = \frac{h/\tan \theta}{\sqrt{gh}} \quad \text{Eq. 2-7}$$

Synolakis (1987) showed that for non-breaking solitary waves, the runup can be expressed as in terms of the gradient of the beach slope $\tan \theta$, incident solitary wave height H and deep water depth h as

$$\frac{R}{h} = 2.831(\tan \theta)^{-0.5} \left(\frac{H}{h}\right)^{1.25} \quad \text{Eq. 2-8}$$

2.3. Motion of a Single Piece of Debris

It is important to evaluate how debris is transported under wave forcing. Below is a review on the forces that are acted on an individual debris piece incorporating the typical drag and inertia forces as induced by the external flow (Nott 2003, Nandasena, Paris et al. 2011). This review will take a simple cuboid debris as an example (see Figure 2-7), which has the same shape as the debris used in this study. The longest dimension of the debris is represented by a , intermediate axis is b , and shortest axis c .

Figure 2-7 Dimensions of Debris

As shown in Figure 2-8 below, the debris piece when placed on the slope with angle of θ is subjected to gravity, drag, inertia, buoyancy and frictional forces when driven by an external flow such as under a tsunami induced flow. Table 2-1 shows the corresponding forces. The flow is assumed perpendicularly hit on the surface of “ac”. The debris is assumed to be isolated, detached, and not anchored.

Figure 2-8 Forces about a single piece debris

Table 2-1 List of forces experienced by a rectangular shape debris

Drag force	Buoyancy force
$F_D = C_D \frac{1}{2} \rho_w a d_m u_w - u_d (u_w - u_d)$ Eq. 2-9	$B = \rho_w a b d_m g$ Eq. 2-10
Inertia force	Gravitational force
$F_I = (1 + C_a) \rho_w a b d_m a_w$ Eq. 2-11	$G = \rho_d a b c g$ Eq. 2-12
Frictional force	
$F_f = f \left(-\frac{u_d}{ u_d } \right) (\rho_d a b c - \rho_w a b d_m) g \cos \theta$ Eq. 2-13	

where, ρ_w is the density of water, ρ_s is the density of debris, C_D is the drag coefficient, u_w is flow velocity or wave celerity, u_d is debris velocity, d_m is flow depth, f is the friction coefficient between debris and slope model, C_a is coefficient of inertia (i.e. added mass coefficient), a_w is the flow acceleration, θ is the angle of the bed slope, and g is gravity.

For drag force, the incoming flow is towards in the area of “ $a \cdot c$ ”, the characteristic frontal area should be “ $a \cdot d_m$ ”, as only the submerged (i.e. immersed) area should be used to characterize the force. In the frictional force, the term $-\frac{u_d}{|u_d|}$ is used to account for the direction of the frictional force which always acts opposite to the movement of the debris. There are three possible mode of motion that could be experienced by the piece of debris: sliding, rolling and floating (Nandasena, Paris et al. 2011). In the experimental work reported here, the rolling mode was not observed and thus ignored. As for the sliding and floating modes, the key difference between lies in the frictional force.

For floating debris, it means buoyancy force B is greater or equal to debris weight G and the frictional force will not be present. Therefore,

$$B \geq G$$

or,

$$\rho_w a b d_m g \geq \rho_d a b c g$$

After simplification, the floating criterion can be obtained as in Eq. 2-14.

$$d_m \geq \frac{\rho_d}{\rho_w} c \quad \text{Eq. 2-14}$$

Conversely, the frictional force presents during sliding mode and the flow depth condition is given by Eq. 2-15.

$$d_m < \frac{\rho_d}{\rho_w} c \quad \text{Eq. 2-15}$$

With the above, the motion of the debris piece along the flow direction is given by the following equation.

$$(m_d + m_a)a_d = F_D + F_I + F_f + (G - B) \sin \theta \quad \text{Eq. 2-16}$$

where, m_d is the mass of the debris, m_a is the add mass from the water, and a_d is the acceleration of the debris piece. m_d and m_a are expressed via Eq. 2-17 and Eq. 2-18 below

$$m_d = \rho_d abc \quad \text{Eq. 2-17}$$

$$m_a = C_a \rho_w abd_m \quad \text{Eq. 2-18}$$

By substituting Eq. 2-9 to Eq. 2-13, Eq. 2-17 and Eq. 2-18 into Eq. 2-16, the motion of a single piece of debris is governed by:

$$\begin{aligned} & (\rho_d abc + C_a \rho_w abd_m) a_d \\ &= C_D \frac{1}{2} \rho_w a d_m |u_w - u_d| (u_w - u_d) + (1 + C_a) \rho_w abd_m a_w \\ &+ f \left(-\frac{u_d}{|u_d|} \right) (\rho_d abc - \rho_w abd_m) g \cos \theta + (\rho_w abd_m - \rho_d abc) g \sin \theta \end{aligned}$$

Dividing the equation by $\rho_w abc$, the equation is simplified as following:

$$\begin{aligned} & \left(\frac{\rho_d}{\rho_w} + C_a \frac{d_m}{c} \right) a_d \\ &= C_D \frac{1}{2} \frac{d_m}{bc} |u_w - u_d| (u_w - u_d) + (1 + C_a) \frac{d_m}{c} a_w \\ &+ f \left(-\frac{u_d}{|u_d|} \right) \left(\frac{\rho_d}{\rho_w} - \frac{d_m}{c} \right) g \cos \theta + \left(\frac{d_m}{c} - \frac{\rho_d}{\rho_w} \right) g \sin \theta \end{aligned} \quad \text{Eq. 2-19}$$

It is noted that Eq. 2-19 and its various forms have been used in reported small scale laboratory studies for estimations of the coefficient C_D, C_a values (Imamura, Goto et al. 2008, Buckley, Wei et al. 2011, Etienne, Buckley et al. 2011).

2.3 Ice Jam Experiments

To the author's knowledge, this PhD work is the only work on solitary waves with floating debris. Some related researches are in the transportation of boulders, i.e. non-floating debris, by tsunami flows (Goto, Okada et al. 2010, Paris, Fournier et al. 2010, Etienne, Buckley et al. 2011, Nandasena, Paris et al. 2011). However for tsunami events impacting a coastal city, most of the generated debris (e.g. cars, ships, houses and containers) floats (see section 2.1). As such there is little direct relevant past works that can be drawn. However related or similar debris-laden flows can be used as references. River ice flow is one such flow which has similar properties with floating debris and thus is reviewed in detail below.

Both ice and debris float experience similar hydrodynamic forces listed in Table 2-2 below. The individual debris or ice elements have gravity, buoyancy, wind drag and water drag forces acting on them. If the debris or ice is submerged, it may not experience the drag force from wind. When the debris travels with the tsunami flow they will interact with other debris such as the ice-ice interaction in ice flows. Both debris flow and river ice flow also have boundary effects. The boundary effects of the debris flow are from the nearby infrastructures. The boundary effects of the river ice flow are most likely from the river boundaries. The key difference between the two boundary effects is that the river boundary is always continuous while the infrastructure boundary is discontinuous and varies along the path of the inland tsunami flow.

Table 2-2 Similarities and differences between ice and debris

Ice	Debris
Gravity	
Buoyancy	
Drag forces (from wind and water)	
River current	Tsunami wave current
Interaction between ice	Interaction between debris
Interaction between ice and river boundary	Interaction between debris and infrastructures

Overall there are substantial flow similarities between ice- and debris-laden flows. Their similar transporting mechanisms could thus be observed through comparing the video recording of a tsunami event and an ice flow event.

Figure 2-9 (a) to (c) are video frames of debris-laden flow propagating inland during the 2011 Tohoku earthquake and tsunami. The debris-laden tsunami flow pushed all the movable obstacles and carried them together into the dry land with extremely high speed.

Figure 2-9 Video shots from the 2011 Tohoku earthquake and tsunami (Telegraph 2011)

Figure 2-10 (a) to (c) are video frames of the massive debris-laden flows flowing rapidly in coastal cities of Japan. This situation may occur after the first few series of the tsunami wave flows, since the city had ready been flooded by the sea water.

Figure 2-10 Video shots from the 2011 Tohoku earthquake and tsunami (BBC 2011)

Figure 2-11 (a) to (c) are screen shots of a massive ice flow propagating in one branch of the Wild Ammonoosuc River, United States with an initially dry river bank. This river being located at northwest part of United States always faces heavy ice flow and ice jam problems during the winter. The river bank was dry at this part, since the river water was frozen due to the low winter temperatures and the shallow water depth at this part of the river.

Figure 2-11 Ice flow propagating in the Wild Ammonoosuc River (Geller 2011a)

Figure 2-12 (a) to (c) show video screen shoots of the river ice flow propagating at another location of the Wild Ammonoosuc River which had wet water bank conditions. The characteristics of the ice flow as it flowed into the dry river bed, the dynamic motion and ice-ice interactions show similarities with the tsunami debris flow.

Figure 2-12 Ice jam formation at the Wild Ammonoosuc River(Geller 2011b)

However there are also some notable differences between the river ice flow and debris-laden tsunami flow. Firstly, the formation of debris and ice floes is different. Ice chunks are formed from the river water itself due to cold weather freezing condition while the creation of debris is due to the impact of both earthquake and tsunami. Secondly, unlike the tsunami debris-laden flow, the velocity of the river ice flow is milder. Therefore, the ice chunks tend to accumulate over shallow water (Figure 2-13(a)) and motion stopped by obstacles (Figure 2-13(b)). Furthermore the physical scale of the river is not comparable with the scale of the affected area

of a tsunami event in most cases. Nevertheless river ice flow is considered the most similar reference case for debris-laden flow. Thus experimental works and methods developed for river ice flow and ice jam studies could be borrowed as references.

Figure 2-13 (a) Ice chunks were accumulated at shallow water condition, and (b) stopped by the trees (Mary 2010)

Most studies on river ice problems are motivated by the danger arising from ice jams. A massive and heavy ice flow could form a serious ice jam and destroy infrastructures. Figure 2-14 shows the ice flow having destroyed a river structure near the Red River in United States and illustrate the severity of ice jam formation along the Red River.

Figure 2-14 Ice flow damaged a near river structure (Cucheron 2009)

From observations of ice movement, transport mechanisms for the floating ice chips during the initial formation of ice jam are shown in Figure 2-15. These transport mechanisms are: juxtaposition, overturning, entrainment and transport of incoming ice. The dynamic motion of ice is similar to that of floating debris, as the transport mechanisms of floating debris are sliding, rotation and floating (see Section 2.3).

Figure 2-15 Ice chips transport mechanism during the ice formation (Healy and Hicks 2001)

Past reported studies (Healy and Hicks 2001, Healy and Hicks 2006, Healy and Hicks 2007) on ice flow and ice jam have used both laboratory and numerical approaches as it is often too dangerous to have an actual survey during an actual ice jam formation. The laboratory experimental results could be used to calibrate and validate the numerical approaches (Healy and Hicks 2001, healy 2006, Healy and Hicks 2007).

In ice jam or ice flow experiments, an artificial material, polyethylene (Figure 2-16) was used to represent the ice. There were some advantages in using polyethylene chips to represent ice as:

- They have similar densities. The density of ice is 916.7 kg/m^3 at 0°C (Haynes 1978). The density of polyethylene chips, which is used in the ice experiment, is 912 kg/m^3 .
- Polyethylene is one of the artificial materials which can be manufactured in any shapes.
- It is inexpensive and easy obtainable.

However unlike real ice, polyethylene has a non-wetting tendency, i.e. creates surface tension between the polyethylene pieces. To minimize the surface tension effect, the polyethylene chips were soaked into water for days in order to have a coating of micro-organisms. Studies (Zufelt 1992, Wuebben 1995) have shown that the surface tension of the plastic material could be removed by this layer of microorganisms.

Figure 2-16 Polyethylene chips for river ice jam experiment (Shen 2013)

For the experimental studies on ice jam thickening under rapidly increased discharge and ice jam shoving (sudden increased in discharge), some “ice” chips were colored and labelled to work as tracking particles (see Figure 2-17 and Figure 2-18). Extra overhead cameras were placed to capture their movements.

Figure 2-17 Experimental setup to study ice (Healy and Hicks 2007)

Figure 2-18 Tracking particles' position (Healy and Hicks 2001)

Dimensionless position and thickness were used to describe the experimental results on the ice jam formation. Dimensionless position was defined as the ratio of distances from the leading edge of the ice jam to the length of ice jam. Dimensionless thickness was defined as the ratio of the ice jam thickness at the specific location to the average ice jam thickness. (Healy and Hicks 2006).

The ice jam experiments described in detail above guided the design of the experiments on debris flow under solitary waves. In this PhD study, the polyethylene chips were used to represent the floating debris. Similar to in Figure 2-17, top view cameras were also used to capture the movement of floating debris. Also the debris at different initial position was marked in different colors to distinguish between each other in the video recordings (see Figure 2-18).

3.0 Methodology

The experimental methodology is covered in this chapter. It covers the debris material selection (Section 3.1), experimental setup and instrumentation used (Section 3.2), experimental conditions tested (Section 3.3) and the data collection and analysis (Section 3.4). Three sets of experiments were performed for the PhD work. A piece of debris with different sizes and orientations, a row of debris at different location along the beach, and two rows of debris with different separation distances were used. Solitary waves were used in all the experiments to represent long waves such as that from tsunamis.

3.1 Debris Material Selection

The selection of a suitable material to represent the floating debris is one of the key steps in the research setup. The material must have consistent properties, since the experiment must be repeatable and consistent. The material properties considered included size, shape, dry and wet density with further considerations of ease of fabrication. The dry and wet densities have to be less than water density to allow the debris to float. However, the density cannot be too low, since in a real tsunami event, debris generated such as a floating house or container is not that light. The wet density should be between 900 kg/m^3 and 1000 kg/m^3 . In addition, the wet density should be consistent over the experiments, i.e. there should not be a gradual absorption of water. Due to the scale of the laboratory condition, the water depth was set to be 31cm and 34cm and the incident solitary wave heights around 1/10 of the water depth. The floating debris as representative of e.g. a floating house, car or cargo container therefore cannot be too large to be representative. Due to the above considerations, natural material (e.g. wood and bamboo), compressed wooden material (e.g. wooden sticks) and artificial materials (e.g. lecca and polyethylene chips) have been considered for the experiment.

Firstly, wooden craft sticks were considered (Figure 3-1 (a)), since they are inexpensive and easily available. The size and shape was easy to control and their dry density was consistent. The only unknown was the wet density. They were cut into dimension of 2cm length, 1.1cm width and 0.7cm thick (Figure 3-1 (b)) to test for the consistency of wet density. The cut pieces were soaked into water to observe the change of wet density. All wooden sticks sank to the bottom of the tank after few days which implied the wet density was increased to larger than water density making it unsuitable as a debris material.

Figure 3-1 Woodn craft sticks

The reason that the wet density of the compressed wood (i.e. the wooden craft sticks) was not consistent could be due to their properties being changed during its manufacture. Next, natural wooden materials (Figure 3-2) and different types of bamboo sticks (Figure 3-3) were similarly tested by the wet density test. Figure 3-2 (a) to (k) show the natural wooden sticks with circular or square cross sections, with dry densities varying from 32.6kg/m^3 to 615.3kg/m^3 . Figure 3-3 (a) to (g) are different types of bamboo sticks with circular, square or hollow cross sections, with dry densities varying from 553.2kg/m^3 to 845.5 kg/m^3 . The wet density of all the natural materials did not reach a steady value and all the samples tested sank eventually (Figure 3-3 (h)). As such natural wood and bamboo materials were also not suitable.

Figure 3-2 Natural wooden materials

Figure 3-3 Bamboo Materials

One of the artificial materials evaluated was Lecca, an artificial material used in planting. The dry density of the lecca is 40kg/m³. However, Lecca was also not suitable for the experiment because of its irregular shape and undefinable wet density (Figure 3-4).

Figure 3-4 Lecca

Another man-made material polyethylene was considered and which was finally chosen as the debris material. Polyethylene has a non-wetting tendency which meant its dry and wet densities are the same. It is also one of the materials widely and successfully used in experimental studies of ice jam. Polyethylene has a fixed density of 912kg/m³ and could be cut into controllable shapes and labeled as shown in the Figure 3-5 (a) and (b) below. However, due to the limitation of the laboratory saw used, the smallest dimension of the polyethylene debris cut is 1cm length, 0.5cm width and 0.5cm height. Another drawback of polyethylene

debris is its non-wetting tendency which generated surface tension. There were two ways to overcome this: a) soaking the polyethylene debris into water for several days (as following the river ice jam experiment process discussed in the literature review) and b) soaking the polyethylene debris into water with few drops of detergent. The second approach was chosen as studies (e.g. (Adam 1937)) showed that detergent could efficiently reduce or remove the surface tension.

Figure 3-5 Polyethylene chips (a) without colour and (b) with coloured and marked

3.2 Experimental Setup and Instrumentation

The experiments were conducted in a wave flume in the Hydraulics Laboratory of the Nanyang Technological University, Singapore. The flume have dimension of 34m long, 0.55m wide and 0.6m tall. A slope model made of PVC and consisted of three slope angles was used to represent a simplified geometry of coastal area with an offshore continental shelf. The three slopes represented a steeper continental slope and continental shelf, followed by the gentler coastal area (Slatt 2006). The slope mode adopted followed that of Sim, Huang et al. (2013) which was used in a parallel PhD effort to study the inundation changes under the presence of sand dune. His study was aimed at investigating the effects of complex costal topography on the tsunami inundation distance and the effectiveness of sand dunes in dissipating tsunami wave energy. This slope model approximated a typical coastal region. The first slope (see Figure 3-6) had a slope of 1:0.64 (vertical distance to horizontal distance) which represented a continental slope. The second slope (1:14) with longer distance and less steep slope angle represented a continental shelf, and the last slope (1:26) with most flat slope angle represented the much flatter coastal area (Figure 3-7). However it is noted there was no exact scaling down from an actual tsunami wave. Rather here the author used the solitary wavelength to the distance between the tsunami waves in a tsunami event.

The solitary incident wave heights used in the experiment were 2, 3 and 4 cm at 31cm water depth and 1, 2 and 2.5 cm at 34 cm water depth. A wavenumber for the solitary wave can be obtained from Eq. 2-2 and wavelength from Eq. 2-5. The wavelengths in the experimental ranged from 6.26m to 10.17m. If the tsunami wave height and local water depth are assumed to be both 5 m, the wave speed from using Eq. 2-3 is about 10m/s. If the duration between successive incoming tsunami waves is assumed to be 5 minutes, a wave crest separation distance (equivalent wavelength) of 3000 m is obtained. Using this, the horizontal length scale ratio (laboratory to actual) is to 1: 200 to 1: 480.

To avoid of the water leakage near the edge of the slope model, a thin layer of plasticine was applied along the slope edge (Figure 3-6 and Figure 3-7). A scale was marked clearly over the slope, so that inundation and debris position data could be obtained using a consistent scale reference. A piston type of wave maker was used to generate solitary waves which simulated tsunami waves. Four ultrasonic sensors (UltraLab® ULS-40D) accuracy ($\pm 2\text{mm}$) were used to capture the water elevation changes. The sampling rate the the sensors were set at 50Hz. Four Logitech full HD 1080p video cameras were placed to capture the debris movements. The average video frame rate was 20frames/s. Dewesoft (DEWE-43) USB DAQ system was used to synchronize all the hardware for both data recording and digitizing.

Figure 3-6 Top view of the first slope in the slope model with slope angle of 1:0.64 (vertical to horizontal distance)

Figure 3-7 Bird-eye view of the second and third slope of the slope model with slope angle of 1:14 and 1:26 (vertical to horizontal distance) respectively.

There are three sets of experiments were conducted:

- a) Solitary wave flow on one row of debris,
- b) Solitary wave flow on two row of debris, and
- c) Solitary wave flow on one single piece of debris.

The experimental setup of one piece and one row of debris is shown in Figure 3-8. The experimental setup of the study on two rows of debris is shown in Figure 3-9. There was a slight change of angle on the 2nd and 3rd slope as shown in the figures. This was because the slope model was removed from the flume after the experiments on one piece and one row of debris, and reinstalled into the flume for the experiment for the two rows of debris, as necessitated due to a sharing of the wave flume with other research projects

Figure 3-8 Side view of experimental setup for the study on one piece and one row of debris. Cameras 1 and 2 recorded top views while cameras 3 and 4 side views.

Figure 3-9 Side view of experimental setup for the study of two rows of debris. Cameras 1 and 2 recorded top views while cameras 3 side view.

For the study on one row and one piece of debris, four ultrasonic sensors (S1, S2, S3 and S4) were placed on the top of flume to record the water surface elevation changes. A data sampling of 50Hz was used. S1 and S2 were placed 10m and 3m from the slope edge in the upstream direction respectively. S1 was used to capture the water surface elevation far upstream from the shoreline (defined as where the still water level intersects the slope), while S2 was used to record the water surface elevation change near the shoreline. S3 and S4 were placed along the 2nd slope at 0.5 m distance apart so that they did not interfere with each other, and were located

at 0.2 m and 0.7 m from the edge of the 2nd slope, respectively. Four high speed video cameras (Cameras 1-4) were used to capture the debris-laden flow motion from both top and side views. The recording frequency was 30 fps. Cameras 1 and 2 recorded the debris motion for both longitudinal and transverse motions on the 3rd slope. Camera 3 recorded the side view of the 1st slope, and Camera 4 the side views of the 2nd and 3rd slope. Although, the video frames from Camera 3 and 4 were not used for later data digitizing, they helped record the wave changes along the slopes for references.

For the experimental study on two rows of debris, three ultrasonic sensors (S1, S2 and S3) were used to record the water elevation changes. S1 and S2 were placed at 10m and 3cm from the slope edge as before and shown in Figure 3-9, but S3 was the only sensor along the slope model. As before, S1 was used to record the incident wave height from the wave generator, and S2 to record the water surface changes near the shore. S3 was still placed on the 2nd slope to record the wave height on the slope. Only three cameras were used in the setup. Cameras 1 and 2 were placed on the top of the slope to capture the debris movements while only Camera 3 was placed at the side to record from the side view.

3.3 Experimental Conditions

Due to the size limitation of the existing wave flume, two water depths (h) were chosen for this PhD study. The two water depths selected were 31 cm and 34 cm. The higher water depth ($h=34\text{cm}$) represents high tide condition, and the lower water depth ($h=31\text{cm}$) represents the low tide condition. The incident solitary wave height (H) should be no larger than $1/10$ of the water depth to represent realistic tsunami waves, since H/h should be small enough to be a linear long wave in the deep water before the continental slope. 2 cm, 3 cm and 4 cm were chosen as the incident solitary wave heights for the 31cm water depth as readily generated by the wave maker to span a large range of experimental conditions, even though the largest wave height would slightly exceed the H/h ratio for linearity. For 34 cm water depth, 1 cm, 2 cm and 2.5 cm were selected as the incident wave heights. Higher values of wave height (e.g. 3 cm and 4 cm) could not be used at the 34 cm water depth, because the inundation would exceed the upper edge of the slope model. The largest solitary wave height, which can be used without exceeding the upper limit of the slope model, was 2.5 cm. Each of the water depth and wave height combination run was further repeated for 5 to 10 times to ensure the accuracy and to capture the variability in the motion of the debris. For each of the wave height and its corresponding water depth, a baseline value (i.e. the inundation without the presence of debris) was obtained for reference. Sections 3.3.1 to 3.3.3 describe experimental conditions for a row of debris, two rows of debris and one piece of debris.

3.3.1 Experimental conditions of one row of debris

For the study on a row of debris, one row of polyethylene blocks (each block of 1cm long, 0.5cm wide and 0.5cm height) was used to represent the debris source generated in a tsunami event. These debris blocks were placed on the last slope and were located at a distance L away from the edge between the 2nd and last slope as shown in Figure 3-10. L is set to be 5cm, 10cm and 15cm, respectively, to study effects of the location of debris source.

Figure 3-10 Debris position for one row of debris

Figure 3-11 show an example of position of the row of debris at 31cm water depth and 3cm incident wave height. Table 3-1 shows the experimental conditions for test on one row of debris.

Figure 3-11 Top view of the debris position for one row of debris at 31cm water depth and 3cm incident wave height

Table 3-1 Experimental conditions for one row of debris

Water depth, h (cm)	31	34
Target incident wave heights, H (cm)	2,3 and 4	1,2 and 2.5
Distance between the row of debris and slope edge, L (cm)	5,10 and 15	

These initial locations of the one debris-row over 5cm to 15cm then corresponded to prototype locations of 15 m to 45 m when using a typical scaling of 1:300 (see Section 3.2). Furthermore, the dimensions of the individual debris blocks in one debris-row had dimensions 0.5cm to 1cm. Scaling up, the length scales would be 1.5m to 3 m, i.e. corresponding to large debris pieces.

3.3.2 Experimental conditions of two rows of debris

For the study on the effects from the two rows of debris, two rows of polyethylene blocks were used to represent the debris source. The first (white-colored) row of debris was always placed at 5 cm distance away from the edge (see Figure 3-12 and Figure 3-13). The second (red-colored) row of debris was placed at separation distance S from the edge of the first (white) row. S was set as 1 cm, 3 cm and 6 cm to examine the effect of debris row separation. Table 3-2 shows the experimental condition for the two rows of debris. Only one water depth at 31cm with incident wave heights at 2 cm, 3 cm and 4 cm were tested. All the cases were repeated for 5 times, this being smaller than the 10 times for the single debris row cases. This was because the single debris row results indicated a repeat of 5 times sufficiently captured the experimental variability.

Figure 3-12 Debris position for two rows of debris.

Figure 3-13 Top view of the two rows of debris (white and red colored) at $L=5\text{cm}$ and $S=1\text{cm}$.

Table 3-2 Experimental conditions for two rows of debris

Water depth, h (cm)	31
Target incident wave heights, H (cm)	2, 3, and 4
Distance between the white and red rows of debris, S (cm)	1, 3, and 6

3.3.3 Experimental conditions of one piece of debris

For the study on solitary wave flow on one piece of debris experiment, a piece of polyethylene block with various dimensions and orientations was tested. The debris block was placed at on the 3rd slope. It was located at the center of the wave flume and 5 cm (L) away from the edge between the 2nd and 3rd slope (see Figure 3-14).

Figure 3-14 Debris position for one piece of debris (L is the distance between the edge of slope and edge of the debris)

Three debris blocks with different dimensions were tested in this set of experiments (see Table 3-3 and Figure 3-15). The case when a different edge of the debris block was facing the incoming wave was tested via changing the aspect ratio of the debris (length to width ratio) being not one. For example, for debris block with 3cm x 1cm x 0.5cm dimension, both longer edge (the length 3 cm) and shorter edge (the width 1 cm) were tested with different wave conditions. The tested wave conditions were the same as the one row of debris. There were 10 repeats for each case to account for scatter.

Table 3-3 Experimental condition for one piece of debris with tsunami wave

Water depth, h (cm)	31	34
Target incident wave heights, H (cm)	2,3 and 4	1,2 and 2.5
Tested debris blocks (Length x Width x Thickness, cm)	2x2x0.5, 3x1x0.5, and 1x0.5x0.5	
Distance between the row of debris and slope edge, L (cm)	5	

Figure 3-15 Debris blocks with different dimensions.

3.3.4 Data Collection and Analysis

Data comprising the maximum inundation, maximum debris position and final debris position were obtained for each experimental run. As a reference check and to check for data quality, the measured incident wave profile was assessed. Only if the incident wave height matches the target incident wave height as monitored by the Ultralab sensors (difference between actual and target incident wave < 0.5 mm), would the data be used for subsequent analysis. The wave transformation profile is discussed in Section 4.1.

Once the wave profile was determined as a good run case, the captured videos were converted to frames which were screened for the maximum inundation, maximum debris position and

final debris position. Virtual Dub (Version 1.9.11) was used to convert videos into frames. The selected frames were digitized by GetData Graph Digitizer (see Figure 3-16 to Figure 3-19). The pink dots in the Figure 3-16 and Figure 3-17 are the digitized maximum inundation without and with the presence of debris respectively while the black dots in Figure 3-18 are the digitized maximum debris position. Lastly, the picked dots in Figure 3-19 are the digitized final debris position. The digitized points were averaged over the corresponding case to obtain the final averaged maximum inundation, maximum debris position and final debris position. These processed averaged results are discussed in the results and discussion chapters (Chapters 4 and 5).

Figure 3-16 Digitizing the maximum inundation of baseline case

Figure 3-17 Digitizing the maximum inundation with the presence of debris

Figure 3-18 Digitizing the maximum debris position of one row of debris case

Figure 3-19 Digitizing the final debris position of one row of debris case

4.0 Results and Experimental Observation of One and Two Debris-Rows Experiment

This chapter discusses on how the experimental data was processed and experimental observation for the one and two debris row experiments. Section 4.1 describes how the incoming solitary wave behaved and transformed. Section 4.2 describes the flume width-averaged maximum water up-slope distance, inundation and runup for all the experiments runs. Sections 4.3 and 4.4 discuss the various observations made.

4.1 Wave Transformation

The typical water surface displacement profiles as measured by the Ultralab sensors are shown in Figure 4-1 and Figure 4-2. The figures show cases of 2 cm and 4 cm target incident wave height in 31 cm water depth for the one-row-debris experiment. As indicated in the figures, the first peaks of Sensor 1 (S1) and Sensor 2 (S2) are the incident wave height and the values closely met the target incident wave height as expected. The second peaks of S1 and S2 are the first reflected wave from the slope model. Sensors 3 and 4 monitored the wave changes on the 2nd slope as the solitary wave shoaled while climbing and propagating on the slope.

Figure 4-1 Measured water surface displacement at the four-sensor locations for $H=2\text{cm}$ and $h=31\text{cm}$

Figure 4-2 Measured water surface displacement at the four-sensor locations for $H=4\text{cm}$ and $h=31\text{cm}$.

4.2 Width-Averaged Maximum Up-Slope Water Distance, Inundation and Runup

The water up-slope distance (i.e. distance along the 3rd slope as measured from its edge) was digitized from the captured image by GetData Graph digitizer. The digitizing process was done by manually selecting points along the water line in an approximately equal spacing as shown in Figure 4-3. To reduce the wall effect on results, the maximum up-slope distance was taken only over the range of the 45cm portion as shown in Figure 4-3. However, the data points so acquired were not exactly evenly distributed. To avoid bias from this unequal distribution, a weighted average of water climbing up distance was calculated as follows.

Figure 4-3 Calculation of density average water climbing up distance

The width-averaged maximum up-slope distance (D) was calculated by

$$D = \frac{\sum y_n w_n}{\sum w_n} \quad \text{Eq. 4-1}$$

where the weights are based on the distances from the edge of the flume as shown in Figure 4-3 and are given by the following expression:

$$w_1 = \frac{x_2 + x_1}{2} - \frac{x_1 + x_0}{2}$$

$$w_2 = \frac{x_3 + x_2}{2} - \frac{x_2 + x_1}{2}$$

$$\dots$$

$$w_n = \frac{x_{n+1} + x_n}{2} - \frac{x_n + x_{n-1}}{2}$$

The standard deviation (SD_D) as a measure of the spread in the climbing distance was further calculated by

$$SD_D = \sqrt{\frac{\sum w_n (y_n - D)^2 / (N - 1)}{\sum w_n / N}} \quad Eq. 4-2$$

The normalized standard deviation (SD_N) by dividing by the mean is defined as

$$SD_N = \frac{SD_D}{D} \quad Eq. 4-3$$

The width-averaged maximum up-slope distances of the one and two debris-row experiments with different water depth and wave conditions are listed in the Table 4-1 and Table 4-4 below. The corresponding standard deviations of the width-averaged maximum up-slope distance are listed in Table 4-2 and Table 4-5, and their normalized standard deviations in Table 4-3 and Table 4-6. The normalized standard deviations indicate the variation of the water line across the flume as e.g. arising from wall effects is small and are not more than 6% for one debris-row experiment. The normalized standard deviation of two debris-row experiment varied more but still not more than 11%, and this increased value was attributed to the increased amount of debris that provided greater disturbance to the wave front. Hence in the results that follow, all water up-slope distances are presented via their width-averaged values. The standard deviations of the width-averaged values over the repeated runs are also very small. The standard deviations of the repeating runs are listed in Appendix A for all wave conditions.

Table 4-1 Width-averaged maximum up-slope distance (cm) of water for one debris-row experiment

	<i>h=31cm</i>			<i>h=34cm</i>		
<i>H (cm)</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>1</i>	<i>2</i>	<i>2.5</i>
<i>Baseline (No Debris)</i>	60.34	124.90	171.63	62.73	143.65	178.19
<i>L=5cm</i>	49.04	116.67	167.01	54.55	137.36	171.53
<i>L=10cm</i>	48.13	116.98	170.72	54.84	137.42	169.99
<i>L=15cm</i>	48.07	118.40	170.85	54.81	138.08	168.03

Note: L is the distance between the debris row and edge of the slope (see Figure 3-10 in Section 3.3.1)

Table 4-2 Average Standard deviation (cm) of width-averaged maximum up-slope distance of water for one debris-row experiment

	<i>h=31cm</i>			<i>h=34cm</i>		
	2	3	4	1	2	2.5
<i>H (cm)</i>	3.68	6.33	7.01	2.32	5.62	8.54
<i>Baseline (No Debris)</i>	2.65	3.18	4.22	1.66	3.34	4.50
<i>L=5cm</i>	2.56	3.52	4.57	1.42	3.29	4.61
<i>L=10cm</i>	2.61	3.08	5.11	1.55	3.31	4.41

Note: L is the distance between the debris row and edge of the slope (see Figure 3-10 in Section3.3.1)

Table 4-3 Normalized standard deviation of width-averaged maximum up-slope distance of water for one debris-row experiment

	<i>h=31cm</i>			<i>h=34cm</i>		
	2	3	4	1	2	2.5
<i>H (cm)</i>	0.06	0.05	0.04	0.04	0.04	0.05
<i>Baseline (No Debris)</i>	0.05	0.03	0.03	0.03	0.02	0.03
<i>L=5cm</i>	0.05	0.03	0.03	0.03	0.02	0.03
<i>L=10cm</i>	0.05	0.03	0.03	0.03	0.02	0.03

Note: L is the distance between the debris row and edge of the slope (see Figure 3-10 in Section3.3.1)

Table 4-4 Width-averaged maximum up-slope distance (cm) of water for two debris-row experiment

	<i>h=31cm</i>		
<i>H (cm)</i>	2	3	4
<i>Baseline (No Debris)</i>	55.37	124.13	174.67
<i>S=1cm</i>	42.33	111.21	167.65
<i>S=3cm</i>	41.36	112.50	167.47
<i>S=6cm</i>	41.95	113.17	167.55

Note: S is the separation distance between the two debris rows (see Figure 3-12 in Section3.3.2)

Table 4-5 Average standard deviation of width-averaged maximum up-slope distance of water for two-row debris experiment

	$h=31\text{cm}$		
$H\text{ (cm)}$	2	3	4
Baseline (No Debris)	4.84	6.93	6.28
$S=1\text{cm}$	2.64	3.84	5.45
$S=3\text{cm}$	4.40	5.08	4.66
$S=6\text{cm}$	3.34	5.00	4.05

Note: S is the separation distance between the two debris rows (see Figure 3-12 in Section 3.3.2)

Table 4-6 Normalized standard deviation of width-averaged maximum up-slope distance of water for two-row debris experiment

	$h=31\text{cm}$		
$H\text{ (cm)}$	2	3	4
Baseline (No Debris)	0.09	0.06	0.04
$S=1\text{cm}$	0.06	0.03	0.03
$S=3\text{cm}$	0.11	0.05	0.03
$S=6\text{cm}$	0.08	0.04	0.02

Note: S is the separation distance between the two debris rows (see Figure 3-12 in Section 3.3.2)

For subsequent data analysis, the width-averaged maximum up-slope distance was converted to equivalent inundation (as horizontally measured from the shoreline) and runup (vertically measured from the SWL) as shown in Figure 4-4

Figure 4-4 Relationship among width-average maximum up-slope distance D , inundation I and runup R .

Eq. 4-4 and Eq. 4-5 show the formulas used to convert the width-averaged maximum up-slope distance (D) to inundation (I) and runup (R) correspondingly. In these equations (see Figure 4-4), α represents the gradient of first (continental) slope, β represents the gradient of second (continental shelf) slope, and γ represents the last most gentle slope (i.e. the coastal area).

$$I = \frac{\beta}{\sqrt{1 + \beta^2}} \left[1.53 - (h - 0.25)\sqrt{1 + \beta^2} \right] + \frac{\gamma}{\sqrt{1 + \gamma^2}} D \quad \text{Eq. 4-4}$$

$$R = \frac{1}{\sqrt{1 + \beta^2}} \left[1.53 - (h - 0.25)\sqrt{1 + \beta^2} \right] + \frac{1}{\sqrt{1 + \gamma^2}} D \quad \text{Eq. 4-5}$$

The corresponding maximum inundation and runup are given in the Table 4-7 and Table 4-8 (for one debris-row experiment), and Table 4-9 and Table 4-10 (for two debris-row experiment) below.

Table 4-7 Maximum inundation (cm) at 31cm and 34cm water depth for the one debris-row experiment

	$h=31\text{cm}$			$h=34\text{cm}$		
H (cm)	2	3	4	1	2	2.5
<i>Baseline (No Debris)</i>	128.90	193.41	240.11	89.29	170.14	204.66
$L=5\text{cm}$	117.61	185.18	235.48	81.11	163.86	198.01
$L=10\text{cm}$	116.69	185.49	239.19	81.40	163.91	196.47
$L=15\text{cm}$	116.64	186.91	239.32	81.37	164.58	194.51

Note: L is the distance between the debris row and edge of the slope (see Figure 3-10 in Section3.3.1)

Table 4-8 Maximum runup (cm) at 31cm and 34cm water depth for the one debris-row experiment

	$h=31\text{cm}$			$h=34\text{cm}$		
H (cm)	2	3	4	1	2	2.5
<i>Baseline (No Debris)</i>	7.22	9.70	11.50	4.31	7.42	8.75
$L=5\text{cm}$	6.78	9.38	11.32	4.00	7.18	8.49
$L=10\text{cm}$	6.75	9.40	11.46	4.01	7.18	8.43
$L=15\text{cm}$	6.75	9.45	11.47	4.01	7.21	8.36

Note: L is the distance between the debris row and edge of the slope (see Figure 3-10 in Section3.3.1)

Table 4-9 Maximum inundation (cm) at 31cm water depth for two debris-row experiment

	<i>h=31cm</i>		
<i>H (cm)</i>	<i>2</i>	<i>3</i>	<i>4</i>
<i>Baseline (No Debris)</i>	118.03	186.73	237.23
<i>S=1cm</i>	105.00	173.82	230.22
<i>S=3cm</i>	104.02	175.11	230.04
<i>S=6cm</i>	104.62	175.78	230.12

Note: S is the separation distance between the two debris rows (see Figure 3-12 in Section3.3.2)

Table 4-10 Maximum runup (cm) at 31cm water depth for two debris-row experiment

	<i>h=31cm</i>		
<i>H (cm)</i>	<i>2</i>	<i>3</i>	<i>4</i>
<i>Baseline (No Debris)</i>	6.39	9.14	11.16
<i>S=1cm</i>	5.87	8.62	10.88
<i>S=3cm</i>	5.83	8.68	10.87
<i>S=6cm</i>	5.86	8.70	10.88

Note: S is the separation distance between the two debris rows (see Figure 3-12 in Section3.3.2)

4.3 Experimental Observation of One Debris-Row Experiment

4.3.1 Maximum inundation and runup

To observe the effects of inundation and runup due to the presence of one row of debris, the debris row was placed at different positions from the edge of the 3rd slope (see Figure 3-10 in Section 3.3.1) and experiments ran with various wave heights and water depth. Table 4-7 and Table 4-8 (in Section 4.2) show the maximum inundation and runup values without debris, and values with the one debris row of debris as placed at different positions with corresponding wave heights and water depth used. For water depth at 31cm, the incident solitary wave heights were set as 2cm, 3cm and 4cm. For water depth at 34cm, the incident solitary wave heights were set as 1cm, 2cm and 2.5cm. The detailed experimental conditions are listed in Table 3-1 in section 3.3.1.

Figure 4-5 below plots the maximum inundations without debris and maximum inundations when the row of debris was placed at different location with corresponding wave heights and water depth. Figure 4-6 plots the maximum runup without debris and maximum runup when the row of debris was placed at different location with corresponding wave heights and water depth. It is seen that when the incident wave heights increased, so did the maximum inundation and runup. The presence of the debris row reduced the maximum inundation and runup, since the debris would dissipate some of the energy of the wave. The debris row reduced the maximum inundation and runup at each wave height and the corresponding water depth used, but the location of the debris did not have a significant effect on the maximum inundation and runup. Although the maximum up-slope distance of water of each individual run had variations cross flume due to boundary effects and surface tension of water, the final width-averaged values over the 10 repeats of each test run were very close (see Tables in Appendix A for the standard deviation of the repeats of each test run). In addition, while the data points in Figure 4-5 and Figure 4-6 do show a linear relation between maximum inundation and runup with incident wave height, such linear relationships are not general, since there are only a limited number of data points under each condition. More general fits for runup and inundation reduction using all the data from the one and two row debris experiments are developed in Sections 6.1 and 6.2.

Figure 4-5 Maximum inundation I vs incident wave height H at (a) 31 cm and (b) 34 cm water depth for one debris-row experiment

Figure 4-6 Maximum runup R vs incident wave height H at (a) 0.31m and (b) 34 cm water depth for one debris-row experiment

To investigate how much the debris row reduced the maximum inundation, a comparison was made between the baseline maximum inundation and the maximum inundation with the debris row at the different wave heights and corresponding water depth. The comparisons are via a percentage decrease of maximum inundation and runup defined by Eq. 4-6 and Eq. 4-7 below. Table 4-11 and Table 4-12 summarize the reduction of maximum inundation and runup (in %) due to one debris row located at different L .

$$\text{Decrease of maximum inundation} = \frac{I_{\text{Baseline}} - I}{I_{\text{Baseline}}} \times 100\% \quad \text{Eq. 4-6}$$

where, I_{Baseline} is the maximum inundation without debris, and I is the maximum inundation with the row of debris.

$$\text{Decrease of maximum runup} = \frac{R_{\text{Baseline}} - R}{R_{\text{Baseline}}} \times 100\% \quad \text{Eq. 4-7}$$

where, R_{Baseline} is the maximum runup without debris, and R is the maximum runup with the row of debris.

Table 4-11 Decrease (%) in maximum inundation I by comparison with baseline

	$h=31\text{cm}$			$h=34\text{cm}$		
H (cm)	2	3	4	1	2	2.5
$L=5\text{cm}$	8.76	4.25	1.93	9.16	3.69	3.25
$L=10\text{cm}$	9.47	4.09	0.38	8.83	3.66	4.00
$L=15\text{cm}$	9.51	3.36	0.33	8.87	3.27	4.96

Note: L is the distance from the edge to the debris row

Table 4-12 Decrease (%) in maximum runup R by comparison with baseline

	$h=31\text{cm}$			$h=34\text{cm}$		
H (cm)	2	3	4	1	2	2.5
$L=5\text{cm}$	6.02	3.26	1.55	7.30	3.26	2.93
$L=10\text{cm}$	6.50	3.14	0.31	7.04	3.23	3.60
$L=15\text{cm}$	6.53	2.58	0.26	7.07	2.88	4.46

Note: L is the distance from the edge to the debris row

It is seen that the magnitude of decrease in the maximum inundation and runup for both 31 cm and 34 cm water depths dropped with increasing wave height except for the cases of (i) $H = 2.5$ cm at $h = 34$ cm with $L = 15$ cm and (ii) $H = 2$ cm wave height at $h = 31$ cm with $L = 5$ cm. If these two cases were excluded, then a possible qualitative reason for the decreasing amount of maximum inundation/runup with higher incident wave heights could be that the wave energy dissipated by the debris row was about the same. Since the debris row could only dissipate a certain amount of wave energy, higher wave heights would have less of a percentage decrease in inundation than the lower incident wave height cases.

4.3.2 Average maximum and final debris position

The term, maximum debris position, is defined as the farthest location that the debris went upstream. In contrast the final debris position is the position where the debris motion eventually terminated, i.e. particles became stationary, which occurred after some backward (i.e. seaward) displacement from the farthest location. The average maximum debris position for the wave heights at the corresponding water depth are shown in Table 4-13. The corresponding average final debris positions are listed in Table 4-14. Here the averaging was both over the individual debris particle locations and the 10 repeats at each test condition.

Table 4-13 Maximum debris position at 31 cm and 34 cm water depth.

	<i>h=31cm</i>			<i>h=34cm</i>		
<i>H (cm)</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>1</i>	<i>2</i>	<i>2.5</i>
<i>L=5cm</i>	39.63	99.43	146.74	43.37	123.53	156.94
<i>L=10cm</i>	39.44	100.09	150.96	44.01	122.98	154.41
<i>L=15cm</i>	41.21	101.09	151.14	45.03	123.48	152.35

Note: L denotes the distance from the edge to the row of the debris

Table 4-14 Final debris position at 31 cm and 34 cm water depth.

	<i>h=31cm</i>			<i>h=34cm</i>		
<i>H (cm)</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>1</i>	<i>2</i>	<i>2.5</i>
<i>L=5cm</i>	38.99	96.59	141.08	42.65	120.33	153.24
<i>L=10cm</i>	39.05	97.20	145.74	42.48	119.72	149.66
<i>L=15cm</i>	41.00	97.93	144.26	44.24	119.73	147.62

Note: L denotes the distance from the edge to the row of the debris

The results are further plotted in Figure 4-7 and Figure 4-8. Figure 4-7 (a) and (b) plot the average maximum and final debris positions with respect to incident wave heights at 31cm water depth. Similarly Figure 4-8 (a) and (b) plot the average maximum and final debris position at 34 cm water depth. The maximum debris and final debris positions show a similar trend with increasing wave heights for all the original debris positions tested. The incident wave height had significant effects with the maximum and final debris positions increasing monotonically with increasing incident wave height. However, changes in the original position of the debris row did not have much effect. In addition, when the water depth increased from 31 cm to 34 cm, the values of both the maximum and final debris positions increased at the same incident wave height condition. The data in Figure 4-7 and Figure 4-8 suggest a 2nd order

polynomial fit of maximum and final debris position with wave height H and which passes through the initial debris position at location L . However, these fits are not general, because of the limited number of data points under each test condition. In section 6.3, a dimensionless maximum and final debris position are introduced to present a general relation between the debris positions and wave condition covering data from both one and two row debris experiments.

Figure 4-7 (a) Average maximum debris position and (b) average final debris position v.s. incident wave height H at 31cm water depth.

Figure 4-8 (a) Average maximum debris position and (b) average final debris position v.s. incident wave height H at 34cm water depth.

4.3.3 Cross flume variation in maximum water up-slope distance, maximum and final debris position

Figures in Appendix B show the cross-flume variations in the maximum up-slope distance, final positions of the debris, and maximum debris positions for the each experimental conditions of one debris-row experiment. The experimental conditions with their corresponding Figure numbers are listed in Table 4-15 below.

Table 4-15 Figure list of Appendix B showing maximum up-slope distance, maximum and final debris position or every test runs under each condition

h (cm)	H (cm)	L (cm)	Name of Figures in Appendix B
31	2	5	Figure B-1 & Figure B-2
		10	Figure B-3 & Figure B-4
		15	Figure B-5 & Figure B-6
	3	5	Figure B-7 & Figure B-8
		10	Figure B-9 & Figure B-10
		15	Figure B-11 & Figure B-12
	4	5	Figure B-13 & Figure B-14
		10	Figure B-15 & Figure B-16
		15	Figure B-17 & Figure B-18
34	1	5	Figure B-19 & Figure B-20
		10	Figure B-21 & Figure B-22
		15	Figure B-23 & Figure B-24
	2	5	Figure B-25 & Figure B-26
		10	Figure B-27 & Figure B-28 & Figure B-29
		15	Figure B-30 & Figure B-31
	2.5	5	Figure B-32 & Figure B-33
		10	Figure B-34 & Figure B-35
		15	Figure B-36 & Figure B-37

where, h is water depth, H is incident wave height and L is the location of the row of debris away for the slope edge.

The interaction between water and debris on the maximum up-slope distance, maximum and final debris position are shown via the figures in Appendix B as discussed next. In general, for all the test cases, the maximum up-slope distance was a certain distance shoreward from the maximum and final debris positions. The final debris position was also different, reduced from

maximum debris position. The row of debris particles were pushed up by the incoming water, reached the maximum debris position, and then partially brought back by the retreating water. The effects from initial position of the debris row on maximum up-slope distance of water, maximum and final debris position were not significant via examination of the individual test runs.

For all experimental conditions, the final debris position and maximum debris position were different (all runs plotted in the figures of Appendix B). For the cases of smaller incident wave heights ($H=2\text{cm}$ at $h=31\text{cm}$ and $H=1\text{cm}$ at $h=34\text{cm}$), the final positions of the debris particles and their maximum positions were close. For the higher value incident wave heights (i.e., stronger incoming wave energy), some of the debris pieces was carried seaward by the retreating water and this resulted in a significant difference between the final positions and the maximum debris positions.

By examining the repeats of each test run, the maximum up-slope distance, maximum and final distance under the same nominal experimental conditions, are rather varied with a large degree of scatter. Therefore, repeated tests are necessary at each experimental condition in order to obtain ensemble averages. Here, ten repeats were conducted at each experimental condition. Ensemble averaging and normalized Kernel Density functions was then applied to better characterize the observed data on maximum and final debris positions. These ensemble averages and normalized Kernel Density functions are discussed in the later Sections 4.3.3 and 4.3.4 respectively. It is also noted that the maximum debris positions 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 key challenge to decode the characteristics of tsunami sources (e.g. wave heights) from such debris deposition data which lacks information on the maximum inundation. The experimental observations provided here thus could guide later interpretation of such field data.

4.3.4 Ensemble average of maximum and final debris position

Figure C-1 to Figure C-6 of Appendix C summarize the distribution of the maximum and final debris particles via box plots at the different initial positions of the debris row and the different incident wave heights and water depths. The corresponding raw data of the maximum debris position and final debris position are placed at the left side of each box. Thus each plot shows the entire data from all test runs under the same test condition. As each test condition was repeated 10 times and the row of debris consisted of 79 pieces of debris, there were about 790 data points for each box plot. Each box plot further included the mean, median, 25th percentile, 75th percentile, minimum and maximum value of the data points. The mean is indicated by a square box, and median via a horizontal line inside the box. The upper and lower boundaries of the rectangular box indicated the 75th and 25th percentiles respectively. The upper and lower limits of the extension lines indicated the data range of 1.5 times the standard deviation from the mean. Both the mean and median represented the central tendency of maximum and final debris position data over all test runs at each experimental condition. For all the experimental condition and initial debris row positions, the mean and median of the maximum debris position were closer in value than that of the final debris position. This reflected that the final debris positions of the individual debris particles were slightly more skewed compared to the maximum debris position. It also showed that final debris positions were more random than the maximum debris position.

The interquartile range, i.e. the range between the 25th and the 75th percentile held the majority of the data points. It thus represented the typical spread in the final debris position and in the maximum debris position. A more physically more relevant or useful measure of this spread is the interquartile range normalized by the mean. Table 4-16, Table 4-17 and Table 4-18 summarize the data comprising the 25th and 75th percentile values, mean, interquartile range and normalized interquartile range (i.e. interquartile range divided by mean) for the three wave heights at 2cm, 3cm and 4cm, respectively and 31cm water depth. The normalized interquartile range agreed with the observation obtained from average and median. The normalized interquartile range of the final debris position was always larger than that of maximum debris position. It meant the final debris positions varied more. The results clearly showed that the maximum debris position did not vary when the initial position has been changed, since the normalized interquartile range of the maximum debris position only had a maximum 0.5% difference which was very small. However the normalized interquartile range of final debris position had no consistent pattern with a range varying over 7.78% to 13.58%. At 2cm and 4cm incident wave height, the normalized interquartile range decreased with increase of initial debris position. However the data for the case of 3cm incident wave height had the normalized

interquartile range debris increased when the row of debris was 15cm away from the edge of the slope. When incident height increased, the normalized interquartile range decreased. It meant the row of debris tended to be more clustered.

Table 4-16 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) and maximum debris position (MDP) at 2cm wave height and 31cm water depth.

$h=31\text{cm}, H=2\text{cm}$	<i>FDP</i>			<i>MDP</i>		
<i>L, cm</i>	5	10	15	5	10	15
25 th percentile, cm	36.86	36.75	38.63	37.65	37.23	38.74
75 th percentile, cm	42.15	41.99	43.94	42.45	42.20	43.79
Mean, cm	38.99	39.03	41.10	39.63	39.43	41.07
Interquartile range, cm	5.29	5.24	5.31	4.79	4.97	5.05
Normalized interquartile range, %	13.58	13.43	12.91	12.10	12.59	12.29

Table 4-17 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) and maximum debris position (MDP) at 3cm wave height and 31cm water depth.

$h=31\text{cm}, H=3\text{cm}$	<i>FDP</i>			<i>MDP</i>		
<i>L, cm</i>	5	10	15	5	10	15
25 th percentile, cm	93.89	94.52	94.19	97.12	97.46	98.46
75 th percentile, cm	101.85	102.08	104.20	103.47	103.67	105.48
Mean, cm	96.75	97.21	97.94	99.42	100.09	101.09
Interquartile range, cm	7.95	7.56	10.01	6.36	6.20	7.02
Normalized interquartile range, %	8.22	7.78	10.22	6.40	6.20	6.94

Table 4-18 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) and maximum debris position (MDP) at 4cm wave height and 31cm water depth.

$h=31\text{cm}, H=4\text{cm}$	<i>FDP</i>			<i>MDP</i>		
<i>L, cm</i>	5	10	15	5	10	15
25 th percentile, cm	136.34	141.32	140.34	144.59	147.65	147.53
75 th percentile, cm	149.18	152.86	151.74	152.38	156.13	155.84
Mean, cm	141.06	145.73	144.28	146.74	150.96	151.14
Interquartile range, cm	12.84	11.54	11.40	7.79	8.48	8.31
Normalized interquartile range, %	9.10	7.92	7.90	5.31	5.62	5.50

Table 4-19, Table 4-20 and Table 4-21 summarize the data of 25th and 75th percentile, mean, interquartile range and normalized interquartile range (i.e. interquartile range divided by mean) for wave height at 1cm, 2cm and 2.5cm, respectively at 34cm water depth. The observations from this larger water depth experimental condition agreed with that at 31cm water depth. The maximum debris position was more sensitive to the change of incident wave height and not the tested initial debris position. The spread final debris position of a row of debris was larger and more random compared to the maximum debris position. Via observations this was attributed the flow field being more complicated when the wave was retreating back. The normalized interquartile range was varied but with a similar range over 5.88% to 11.41%.

Table 4-19 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) and maximum debris position (MDP) at 1cm wave height and 34cm water depth.

<i>h=34cm, H=1cm</i>	<i>FDP</i>			<i>MDP</i>		
<i>L, cm</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>5</i>	<i>10</i>	<i>15</i>
<i>25th percentile, cm</i>	41.23	40.75	42.57	42.30	42.48	43.51
<i>75th percentile, cm</i>	45.37	45.60	46.81	45.97	46.35	47.21
<i>Mean, cm</i>	42.73	42.49	44.24	43.46	44.01	45.03
<i>Interquartile range, cm</i>	4.14	4.85	4.24	3.68	3.87	3.70
<i>Normalized interquartile range, %</i>	9.70	11.41	9.58	8.46	8.80	8.21

Table 4-20 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) and maximum debris position (MDP) at 2cm wave height and 34cm water depth.

<i>h=34cm, H=2cm</i>	<i>FDP</i>			<i>MDP</i>		
<i>L, cm</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>5</i>	<i>10</i>	<i>15</i>
<i>25th percentile, cm</i>	116.73	116.71	116.98	120.95	120.62	121.29
<i>75th percentile, cm</i>	124.47	124.51	124.79	126.55	126.43	126.73
<i>Mean, cm</i>	120.33	119.73	119.72	123.53	122.98	123.48
<i>Interquartile range, cm</i>	7.75	7.81	7.82	5.60	5.82	5.44
<i>Normalized interquartile range, %</i>	6.44	6.52	6.53	4.54	4.73	4.41

Table 4-21 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) and maximum debris position (MDP) at 2.5cm wave height and 34cm water depth.

$h=34\text{cm}, H=2.5\text{cm}$	FDP			MDP		
L, cm	5	10	15	5	10	15
25 th percentile, cm	150.24	145.84	144.10	154.34	151.75	149.63
75 th percentile, cm	159.25	156.07	154.20	161.35	158.70	156.98
Mean, cm	153.24	149.68	147.57	156.94	154.41	152.24
Interquartile range, cm	9.01	10.23	10.10	7.01	6.95	7.35
Normalized interquartile range, %	5.88	6.83	6.84	4.47	4.50	4.83

4.3.5 Normalized Kernel density function of maximum and final debris position

To further examine the maximum and final debris position of one debris-row experiment, the 790 data points under each experimental condition was processed via the Normalized Kernel density function estimation as available from MathWorks. The Normalized Kernel density function is defined as

$$f(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right)$$

where n is the sample size, $K(\bullet)$ is the kernel smoothing function and h is the bandwidth.

Figure 4-9, Figure 4-10 and Figure 4-11 show the normalized Kernel Density estimation with 2cm, 3cm and 4cm incident wave height at 31cm water depth respectively.

Figure 4-9 Normalized Kernel Density Estimation of (a) maximum debris position and (b) final debris position at 2cm incident wave height and 31cm water depth

Figure 4-10 Normalized Kernel Density Estimation of (a) maximum debris position and (b) final debris position at 3cm incident wave height and 31cm water depth

Figure 4-11 Normalized Kernel Density Estimation of (a) maximum debris position and (b) final debris position at 4cm incident wave height and 31cm water depth

Similarly, Figure 4-12, Figure 4-13 and Figure 4-14 show the data distribution with 1cm, 2cm and 2.5cm incident wave height at 34cm water depth respectively.

Figure 4-12 Normalized Kernel Density Estimation of (a) maximum debris position and (b) final debris position at 1cm incident wave height and 34cm water depth

Figure 4-13 Normalized Kernel Density Estimation of (a) maximum debris position and (b) final debris position at 2cm incident wave height and 34cm water depth

Figure 4-14 Normalized Kernel Density Estimation of (a) maximum debris position and (b) final debris position at 2.5cm incident wave height and 34cm water depth

The obtained shapes of the density function under all tested experimental conditions were unimodal, i.e. close to a normal distribution but with a relatively long tail on the left side (i.e. negative skewness). In general, a larger wave height could cause the debris to move a longer distance shoreward and to spread over a wider region. In terms of the shape of the density function, the difference between the maximum debris position and the final debris position increases with the increasing wave height. This is related to the following two factors: (i) a larger wave height gave a larger wave inundation/runup, and (ii) the magnitude of the friction between the bottom and debris, and the onshore flow were rather random in nature. Those debris pieces that experienced less bottom friction could move longer distances shoreward, while those debris pieces that experienced greater bottom friction would not be able to move very far shoreward. This is especially true when the inundation/runup was high and the flow

depth was shallow at the upper end of the flow. The initial debris positions are indicated via the different colour lines in each figure. There are only small variations in the peak and spread across the three debris initial positions (L). This same conclusion could be drawn from the previous two sections: the initial debris location did not have a significant effect on the motion of the debris and the wave height was the most important factor that determines the final debris locations and the maximum debris positions.

The normalized Kernel Density, which represents a probability density function of debris positions is further examined if the observed skewness can be reproduced. The skewness of the final debris position was calculated and compared with that from the histogram of the observation debris positions (Table 4-22 and Table 4-23) at 31cm and 34 cm water depths. The values of skewness between the two calculation methods are reasonably close except for the case of H=3 cm and L of 10 and 15 cm where the histogram showed much larger skewness. With the exception of these two points the remaining values from the Kernel estimations are within 9% of observed. Furthermore both methods show negative skewness of final debris position all the test conditions.

Table 4-22 Skewness comparison of final debris position between histogram and normalized Kernel Density estimation at 31cm water depth for one debris-row experiment.

	<i>Histogram</i>			<i>Normalized Kernel density</i>		
<i>H, cm</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>2</i>	<i>3</i>	<i>4</i>
<i>L=5cm</i>	-2.20	-4.02	-3.63	-2.07	-3.67	-3.50
<i>L=10cm</i>	-0.98	-3.86	-2.87	-0.90	-1.87	-2.75
<i>L=15cm</i>	-2.72	-3.06	-3.56	-2.64	-2.00	-3.40

Table 4-23 Skewness comparison of final debris position between histogram and normalized Kernel Density estimation at 34cm water depth for one debris-row experiment.

	<i>Histogram</i>			<i>Normalized Kernel density</i>		
<i>H, cm</i>	<i>1</i>	<i>2</i>	<i>2.5</i>	<i>1</i>	<i>2</i>	<i>2.5</i>
<i>L=5cm</i>	-2.87	-4.13	-3.82	-2.71	-3.90	-3.69
<i>L=10cm</i>	-2.55	-5.26	-3.46	-2.41	-5.09	-3.29
<i>L=15cm</i>	-2.92	-5.68	-4.31	-2.74	-5.53	-4.12

4.4 Experimental Observation of Two Debris-Row Experiment

4.4.1 Maximum inundation and runup

This section discusses the effects on inundation and runup due to the presence of two rows of debris at three different separation distances ($S=1\text{cm}$, 3m and 6cm) (see Figure 3-12 in Chapter 3). Only one water depth ($h=31\text{cm}$) with three incident solitary wave height ($H=2\text{cm}$, 3cm and 4cm) was conducted in this set of experiment. Furthermore each of the runs were repeated for 5 times.

Figure 4-15 (a) and (b) below plots the maximum inundation and runup without the presence of debris and the maximum inundation and runup with the two rows of debris, respectively. The observations are similar to that of the one debris-row experiment. When the incident wave heights increased, the maximum inundation and runup also increased. The presence of the two debris rows reduced the maximum inundation and runup, since the presence of debris dissipated some of the wave energy. However the different separation distance only changed the maximum inundation and runup negligibly. The separation distance of 1cm , 3cm and 6cm , which is one, three and six times of the debris length, were chosen to represent debris originally spatially distributed at varying distances from the shoreline. It is concluded that the current values of separation distance did not vary the inundation and runup.

Figure 4-15 (a) Maximum inundation and (b) maximum runup vs incident wave height H at 31cm water depth for two debris-rows experiment

To further examine the reduction of inundation and runup due to the presence of the two debris row, the decrease of maximum inundation and runup are calculated by Eq. 4-6 and Eq. 4-7 in Section 4.3.1. The percentage decrease of inundation and runup are shown in Table 4-24 and Table 4-25 below. The results also showed that at the same incident wave height, the inundation and runup did not change when the separation distance between the two rows of debris changed. This result was quite consistent for all repeats of each the test run. Comparing with the results of the one debris row (see Table 4-11 in section 4.3.1), the additional row of debris did further reduce the inundation. It indicated that the inundation and runup were more closely related to the total mass or volume of the debris with separation distance between the two rows of debris not being a factor.

Table 4-24 Decrease (%) in maximum inundation by comparison with baseline

<i>H, cm</i>	2	2	4
<i>S=1cm</i>	11.04	6.92	2.96
<i>S=3cm</i>	11.87	6.22	3.03
<i>S=6cm</i>	11.36	5.87	3.00

Note: S is the separation distance between two rows of debris

Table 4-25 Decrease (%) in maximum runup by comparison with baseline

<i>H, cm</i>	2	3	4
<i>S=1cm</i>	8.15	5.65	2.52
<i>S=3cm</i>	8.76	5.09	2.58
<i>S=6cm</i>	8.39	4.79	2.55

Note: S is the separation distance between two rows of debris

It is also seen from Table 4-24 and Table 4-25 that the magnitude of decrease in the maximum inundation and runup dropped with increasing wave height as also seen in the one debris-row experiment. The amount of reduction (in percentage) in the inundation and runup also decreased with increasing incident wave height. It is noted that the amount of debris did not change as the separation distance was varied. This fixed amount of debris could only dissipate a certain amount of wave energy, and higher wave heights would have less of a percentage decrease in inundation than the lower incident wave height cases.

4.4.2 Average maximum and final debris position

The averaged maximum debris position for the wave heights and the corresponding water depth are shown in Table 4-26 below. As before, the average was taken over the debris particles and the repeats of each run condition. The corresponding averaged results of the final debris position are listed in Table 4-27. In general, the maximum and final debris positions of both seaward (white) row and shoreward (red) row of debris increased with increasing of incident wave height. The averaged debris position of white and red row of debris were close (1-2cm difference in value) indicating that the white debris row was brought by the incoming wave to well mix with the red row of debris. The average maximum and final debris position of the two debris rows with respect to different incident wave heights at 31cm water depth are plotted in Figure 4-16 (a) to (c) for the 3 debris row separation distances. Under the same wave condition, the maximum and final debris positions of both white and red debris rows increased with increasing separation distance. The incident wave first hit the seaward (white) debris row followed by the shoreward (red) debris row. The red debris row was observed to behave as a “barrier”. When the separation distance was small, it temporarily stopped the front row from moving further. When the separation distance increased, this barrier was a more removed from the seaward (white) debris row which allowed the white debris row to moved further inland. Also in this case, the original position of shoreward (red) debris row was already placed further inland. Hence it was reasonable that the resulting averaged and final debris positions were also further inland. However as the movements of the two debris rows were rather random repeats were needed and conducted. The later sections discuss the debris positions in terms of individual repeats, ensemble averages and via Kernel Density estimation.

Table 4-26 Average maximum debris position (cm) of two debris-row experiment

	<i>White Debris Row</i>			<i>Red Debris Row</i>		
<i>H, cm</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>2</i>	<i>3</i>	<i>4</i>
<i>S=1cm</i>	18.97	92.63	146.78	20.20	91.36	146.25
<i>S=3cm</i>	23.63	92.74	148.61	24.55	92.48	147.08
<i>S=6cm</i>	25.95	96.95	147.75	26.41	96.16	147.12

Note: *S* is the separation distance between two rows of debris

Table 4-27 Average final debris position (cm) of two debris-row experiment

	White Debris Row			Red Debris Row		
H , cm	2	3	4	2	3	4
$S=1\text{cm}$	15.60	88.23	141.04	16.31	88.52	141.14
$S=3\text{cm}$	21.74	88.65	141.49	22.74	87.69	139.90
$S=6\text{cm}$	23.91	91.91	141.44	24.18	91.79	141.08

Note: S is the separation distance between two rows of debris

Figure 4-16 Maximum debris position and final debris position of two debris-row experiment with separation distance (a) $S=1\text{cm}$, (b) $S=3\text{cm}$ and (c) $S=6\text{cm}$ vs incident wave height H .

4.4.3 Maximum up-slope water distance, maximum and final debris position

Figures in Appendix D show the cross-flume variations in the maximum up-slope distance, final positions and maximum debris positions for the each experimental condition of the two debris-row experiment. The experimental conditions with their corresponding figure numbers in Appendix D are listed in Table 4-28 below.

Table 4-28 Figure list for Appendix D showing maximum up-slope distance, maximum and final debris position or every test runs under each condition

h (cm)	H (cm)	S (cm)	Name of Figures in Appendix B
31	2	1	Figure D-1
		3	Figure D-2
		6	Figure D-3
	3	1	Figure D-4
		3	Figure D-5
		6	Figure D-6
	4	1	Figure D-7
		3	Figure D-8
		6	Figure D-9

where, h is water depth, H is incident wave height and S is separation distance between the two debris rows.

In these figures, the solid line represents the maximum water up-slope distance, black circles represent the maximum debris position of white (seaward) debris row, red circles represent the maximum debris position of red (shoreward) debris row, black dots represent the final debris position of white debris row and red dots represent the final debris position of red debris row. The experimental observations are similar to one debris-row experiment. The interaction between water and debris on the maximum up-slope distance, maximum debris position and final debris position are clearly seen in the figures. In general, for all the test cases, the maximum up-slope distance was a certain distance shoreward from the maximum and final debris positions. The final debris position was also seaward from the maximum debris position. The two rows of debris were pushed up by the incoming water and reached the maximum debris position, and then partially brought back by the retreating water. The effects from separation distance of two debris rows on maximum up-slope distance of water, maximum and final debris position were not significant as seen in the individual test runs.

Similar as the one debris-row experiment, the cases of smaller incident wave height 2cm at 31cm water depth (see Figure D-1 to Figure D-3) had the shape of water front of maximum up-slope distance being more distorted, unlike the other experimental runs at 31cm water depth which had a rather smooth profile (see Figure B-4 to Figure B-9). For all the experimental conditions, the final debris position and maximum debris position were different (all cases plotted in Appendix D). For the cases of smaller incident wave heights ($H=2\text{cm}$ at $h=31\text{cm}$), the final positions of the individual debris particles and the corresponding maximum positions were close in their locations (Figure D-1 to Figure D-3). For the higher value incident wave heights (i.e., stronger incoming wave energy), some of the debris pieces was carried seaward by the retreating water and this resulted in a significant difference between the final positions and the maximum debris positions.

By examining the results of maximum up-slope distance, maximum and final distance for each repeated test ran under the same nominal experimental conditions, it is seen that the results were rather random. Therefore, repeating tests are necessary for each experimental condition and five repeats runs were conducted for each experimental condition as constrained by time constraints. Further ensemble averaging and normalized Kernel Density function are thus better choice to further examine the maximum and final debris particle positions as discussed next.

4.4.4 Ensemble average of maximum and final debris position

Figure E-1 to Figure E-9 in Appendix E summarize the maximum debris position and final debris position distribution by box plots of two debris-rows with different separation distance at different incident wave height and 31cm water depth. Similar to the box plots of the one debris-row result, the corresponding raw data of maximum debris position and final debris position were placed at the left side of the box. Each plot used entire data from the all test runs under the same test condition. Since each test condition was repeated 5 times and each debris row (white and red) consisted of 79 pieces of debris, there are about 395 data points in each box plot. The box plots included mean, median, 25th percentile, 75th percentile, minimum and maximum value of the available data points. The mean is indicated by a square box, and median by a horizontal line inside the box. The upper and lower boundaries of the rectangular box indicate the 75th and 25th percentiles respectively. The upper and lower limited of the two extension line indicate the data range of 1.5 times standard deviation from the mean. Comparing with the one debris-row results (box plots), the mean and median were further spaced in the two debris-rows. However similar to the one debris-row, the mean and median of

maximum debris position were more closely located than that in final debris position, this seen for all the experimental conditions and different debris row separation distances. This reflected that the final debris position of debris was more random and skewed compared to the maximum debris position for both debris rows (white and red).

To further quantify the spread, the interquartile range of final and maximum debris positions of both white and red debris rows are summarized in Table 4-29 to Table 4-34 below. Since the white row of debris was mixed with the red row of debris, the combined two debris-row data are further summarized in in Table 4-35 to Table 4-37 with corresponding incident wave height at 31cm water depth.

Similar to the case of one debris-row experiment, the normalized interquartile range agreed with the observation deduced from the average and median values. The normalized interquartile range of final debris position was always larger than that of maximum debris position. It meant the final debris positions varied more. But, the trend of the normalized interquartile range was rather random in the two debris-row experiment for all the data available. There was no ready trend seen with the normalized interquartile range having values over 10.01% - 70.91% for the white row and 9.7% - 69.18% for the red row. The combined two debris-rows had similar interquartile range over 10.46% - 69.5%. Also these values are significantly larger than the one-row case. Thus, more experimental runs should be conducted in the future. However the initial data presented here showed that the debris spread is comparable to the averaged debris distance (maximum or final) and with distribution being complicated and with a high degree of randomness. These need to be considered when performing numerical simulation on debris field movement and also in post-tsunami debris field surveys.

Table 4-29 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) of white and red debris row at 2cm wave height and 31cm water depth with different separation distance.

	<i>White Debris Row</i>			<i>Red Debris Row</i>		
<i>S, cm</i>	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	10.04	15.67	18.03	10.75	17.84	18.87
<i>75th percentile, cm</i>	21.09	27.08	30.34	22.05	27.80	30.11
<i>Mean, cm</i>	15.58	21.71	23.91	16.34	22.73	24.18
<i>Interquartile range, cm</i>	11.05	11.41	12.31	11.31	9.97	11.25
<i>Normalized interquartile range, %</i>	70.91	52.53	51.50	69.18	43.85	46.51

Table 4-30 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of max debris position (MDP) of white and red debris row at 2cm wave height and 31cm water depth with different separation distance.

	White Debris Row			Red Debris Row		
<i>S, cm</i>	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	14.76	19.30	21.15	16.46	20.67	22.21
<i>75th percentile, cm</i>	22.99	28.03	30.70	23.86	28.32	30.43
<i>Mean, cm</i>	18.97	23.63	25.95	20.20	24.55	26.41
<i>Interquartile range, cm</i>	8.23	8.73	9.55	7.39	7.65	8.22
<i>Normalized interquartile range, %</i>	43.39	36.93	36.80	36.62	31.14	31.14

Table 4-31 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) of white and red debris row at 3cm wave height and 31cm water depth with different separation distance.

	White Debris Row			Red Debris Row		
<i>S, cm</i>	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	86.56	85.55	89.35	86.55	85.95	88.68
<i>75th percentile, cm</i>	96.35	94.54	98.55	95.71	95.55	98.52
<i>Mean, cm</i>	88.25	88.66	91.92	88.48	87.71	91.80
<i>Interquartile range, cm</i>	9.79	8.99	9.20	9.15	9.59	9.84
<i>Normalized interquartile range, %</i>	11.09	10.14	10.01	10.35	10.94	10.72

Table 4-32 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of max debris position (MDP) of white and red debris row at 3cm wave height and 31cm water depth with different separation distance.

	White Debris Row			Red Debris Row		
<i>S, cm</i>	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	89.34	89.87	93.82	88.54	89.56	93.27
<i>75th percentile, cm</i>	98.45	98.13	101.31	97.94	98.24	101.23
<i>Mean, cm</i>	92.63	92.74	96.95	91.36	92.48	96.16
<i>Interquartile range, cm</i>	9.11	8.26	7.49	9.40	8.68	7.95
<i>Normalized interquartile range, %</i>	9.83	8.91	7.73	10.29	9.39	8.27

Table 4-33 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of final debris position (FDP) of white and red debris row at 4cm wave height and 31cm water depth with different separation distance.

	White Debris Row			Red Debris Row		
<i>S, cm</i>	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	136.96	137.24	136.10	136.57	136.50	138.02
<i>75th percentile, cm</i>	151.60	152.23	151.97	152.37	151.65	151.71
<i>Mean, cm</i>	141.06	141.50	141.45	141.14	139.89	141.08
<i>Interquartile range, cm</i>	14.64	15.00	15.87	15.80	15.15	13.69
<i>Normalized interquartile range, %</i>	10.38	10.60	11.22	11.20	10.83	9.70

Table 4-34 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of max debris position (MDP) of white and red debris row at 4cm wave height and 31cm water depth with different separation distance.

	White Debris Row			Red Debris Row		
<i>S, cm</i>	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	143.01	144.48	144.35	142.68	143.33	143.22
<i>75th percentile, cm</i>	154.13	154.93	155.22	154.43	154.85	154.37
<i>Mean, cm</i>	146.78	148.61	147.75	146.25	147.08	147.12
<i>Interquartile range, cm</i>	11.12	10.45	10.87	11.75	11.52	11.15
<i>Normalized interquartile range, %</i>	7.58	7.03	7.36	8.03	7.84	7.58

Table 4-35 Summary of 25th and 75th percentile, mean, interquartile range and normalized interquartile range of max debris position (MDP) and final debris position (FDP) of all the debris at 2cm wave height and 31cm water depth with different separation distance.

	MDP			FDP		
<i>S, cm</i>	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	15.48	19.93	21.73	10.33	16.71	18.43
<i>75th percentile, cm</i>	23.46	28.12	30.62	21.43	27.51	30.26
<i>Mean, cm</i>	19.58	24.09	26.18	15.97	22.22	24.05
<i>Interquartile range, cm</i>	7.99	8.20	8.89	11.10	10.80	11.83
<i>Normalized interquartile range, %</i>	40.78	34.03	33.96	69.50	48.57	49.21

Table 4-36 Summary of 25th and 75th percentile, mean, interquartile range and normazlized interquartile range of max debris position (MDP) and final debris position (FDP) of all the debris at 3cm wave height and 31cm water depth with different separation distance.

<i>S, cm</i>	<i>MDP</i>			<i>FDP</i>		
	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	88.80	89.76	93.63	86.55	85.69	88.92
<i>75th percentile, cm</i>	98.27	98.22	101.25	96.15	94.97	98.53
<i>Mean, cm</i>	92.00	92.61	96.56	88.37	88.18	91.86
<i>Interquartile range, cm</i>	9.46	8.46	7.63	9.60	9.27	9.60
<i>Normalized interquartile range, %</i>	10.29	9.13	7.90	10.87	10.52	10.46

Table 4-37 Summary of 25th and 75th percentile, mean, interquartile range and normazlized interquartile range of max debris position (MDP) and final debris position (FDP) of all the debris at 4cm wave height and 31cm water depth with different separation distance.

<i>S, cm</i>	<i>MDP</i>			<i>FDP</i>		
	<i>1</i>	<i>3</i>	<i>6</i>	<i>1</i>	<i>3</i>	<i>6</i>
<i>25th percentile, cm</i>	142.85	143.90	143.79	136.81	137.00	136.83
<i>75th percentile, cm</i>	154.29	154.87	154.85	152.10	151.93	151.92
<i>Mean, cm</i>	146.52	147.84	147.44	141.10	140.70	141.27
<i>Interquartile range, cm</i>	11.45	10.97	11.06	15.29	14.93	15.09
<i>Normalized interquartile range, %</i>	7.81	7.42	7.50	10.84	10.61	10.68

4.4.5 Normalized Kernel density function of maximum and final debris position of two debris-row experiment

Figure 4-17 to Figure 4-25 show the normalized Kernel Density estimations with 2cm, 3cm and 4cm incident wave heights at 31cm water depth and with different separation distances. Similar to the results from the one debris-row experiment, the shapes of the density functions for all tested experimental conditions are unimodal, close to a normal distribution but with a relatively long tail on the left side (i.e. a negative skewness). This tail is also larger than for the one debris-row experimental case. In general, a larger wave height causes the debris to move a longer distance shoreward and to spread over a wider region. Thus at lower incident wave height ($H=2\text{cm}$), the final debris position and maximum debris position became closer when the separation distance increased. When the incident wave height became higher, the final and maximum debris position became indistinguishable. Clearly the two debris rows did not mix well when the incident wave height was not sufficiently large. The author postulated that with further increased separation distances between the two rows of debris, the maximum and final debris position at the same wave height would be further increased.

Figure 4-17 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 2cm wave height and 31cm water depth with 1cm separation distance.

Figure 4-18 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 2cm wave height and 31cm water depth with 3cm separation distance.

Figure 4-19 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 2cm wave height and 31cm water depth with 6cm separation distance.

Figure 4-20 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 3cm wave height and 31cm water depth with 1cm separation distance.

Figure 4-21 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 3cm wave height and 31cm water depth with 3cm separation distance.

Figure 4-22 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 3cm wave height and 31cm water depth with 6cm separation distance.

Figure 4-23 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 4cm wave height and 31cm water depth with 1cm separation distance.

Figure 4-24 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 4cm wave height and 31cm water depth with 3cm separation distance.

Figure 4-25 Normalized Kernel Density Estimation of final debris position and maximum debris position of (a) separation of white and red debris rows, (b) combination of white and red debris rows at 4cm wave height and 31cm water depth with 6cm separation distance.

Similar as the one debris-row experiment, the skewness of final debris position was calculated using the normalized Kernel density (i.e. the estimated probability density function) and compared with the observed histogram. Table 4-38 summarizes the skewness of final debris position (both white and red debris rows) which is calculated by histogram and normalized Kernel density estimation at 31cm water depth. The values of skewness between the two calculation methods are reasonable close, maximum difference of 16%, this occurring at $H=2\text{cm}$. This shows that the normalized Kernel Density estimation is appropriated. All the results show a negative skewness except the case at lowest incident wave height ($H=2\text{cm}$) and smallest separation distance ($S=1\text{cm}$) which had a slight positive skewness. In addition, the skewness is also smaller than for the one debris row case (see Table 4-22 in Section 4.3.5).

Table 4-38 Skewness comparison of final debris position between histogram and normalized Kernel Density estimation at 31cm water depth for two debris-row experiment.

	<i>Histogram</i>			<i>Normalized Kernel density</i>		
<i>H, cm</i>	2	3	4	2	3	4
<i>S=1cm</i>	0.30	-3.07	-3.42	0.27	-3	-3.33
<i>S=3cm</i>	-0.29	-2.66	-3.03	-0.24	-2.59	-2.98
<i>S=6cm</i>	-0.08	-2.40	-2.94	-0.07	-2.33	-2.83

4.5 Intermediate Motions of Waterline and Debris

Detailed time histories of the evolution of the wave front and debris profiles across the flume width are presented in this section. In the previous sections, the results of wave and debris movement i.e. maximum up-slope distance of water, maximum and final debris position are discussed. However, the intermediate motions of the water line and debris are also important, as the intermediate motions could provide insights to the understanding of the water and debris interaction and debris interaction, particularly since the final and maximum debris positions are rather random and the randomness increase when going from one row of debris to two.

When the generated solitary wave runs up on the beach and reaches the model debris placed on the slope, the debris may or may not be moved by the flow as dependent on the frictional force between the debris and the bed as related to the local flow depth via its effect on the submerged weight. The speed of water flow can also be characterized by the flow depth by $V = \gamma\sqrt{gd}$, where d is the flow depth and g is the gravitational acceleration, and γ is an empirical constant (e.g., Foytong et al., 2013). Only when the drag force overcomes than the frictional force, would the debris piece start to move. When a piece of debris becomes fully floating, it could closely follow the flow since the density of debris used here is very close to water, i.e. small added mass. If the debris piece is not fully floating, frictional force would persists and the debris velocity to be slower than that of the overflow. A rough estimate of the critical flow depth required for a piece of debris to become fully floating, d_{cr} , is given by

$$\rho_s h_s = \rho d_{cr}$$

where ρ_s is the density of the polyethylene (912 kg/m³), and h_s is the height of the debris piece. Since $\rho_s/\rho = 0.912$ and $h_s = 0.5cm$ in this study (if the rotation of debris piece is neglected), $d_{cr} = 0.456cm$, which was easily achieved.

Figure 4-26 and Figure 4-27 show how one row of debris move onshore with the water flow for two test conditions, that of a weaker incoming flow (at incident wave height $H=2\text{cm}$) and a stronger flow ($H=4\text{cm}$). The weaker flow had the middle part of the debris row moved with the water line initially when the flow depth was shallow, indicating that those debris pieces were still in contact with the bottom. The case of a stronger incoming wave ($H=4\text{cm}$) had the wave front moving in a bore-like manner (Figure 4-27), and all the debris started to move with the flow almost immediately after the wave front arrival. For the two debris-row experiment, where two sample cases are shown in Figure 4-28 (for $H=2\text{cm}$) and Figure 4-29 (for $H=4\text{cm}$), the seaward (i.e., white) debris row was brought up by the incoming wave and then reached and mixed with the shoreward (red) debris row. When the incident wave height is smaller (i.e. less incoming wave energy), the wave energy was insufficient to mix the two rows of debris (Figure 4-28), but the higher wave height was able to efficiently mix the two debris rows (Figure 4-29). For both one and two debris-rows experiment, a strong wall-like effect as arising from the red debris row could be observed at the lower incident wave height cases (Figure 4-26 and Figure 4-28).

The debris initially followed the flooding water closely once the debris started to move in both the one and two debris-row cases. With increasing time, the debris gradually trailed behind the flow and with increasing dispersal. When the flow approached the inundation limit, the flow depth became very shallow and the flow velocity also decreased. The debris then became in contact with the slope bottom again, and with friction between the debris and the bottom rapidly slowing down the debris. This caused the debris to fall behind the front of the flooding water (waterline). The flow velocity was momentarily zero after the water flow reached the inundation limit, and then the water started to retreat (i.e. reversed direction). In general the debris did not respond significantly to retreating water as the depth of the reversed flow was very thin. However, some pieces of debris, whose positions were not very close to the inundation limit and thus in the deeper depth portion of the receding water flow, could travel a significantly long distance with the retreating water and either landed very close to the shoreline, or even offshore of the shoreline (i.e. washed back upstream).

Figure 4-26 Debris and water propagation at 2cm incident wave height and 31cm water depth with the one row of debris at 5cm initial distance from the edge. The time interval between the transverse profiles is 0.3 s.

Figure 4-27 Debris and water propagation at 4cm incident wave height and 31cm water depth with the one row of debris at 5cm initial distance from the edge. The time interval between the transverse profiles is 0.3 s.

Figure 4-28 Debris and water propagation at 2cm incident wave height and 31cm water depth with the two rows of debris with 1cm separation distance. The time interval between the transverse profiles is 0.3 s.

Figure 4-29 Debris and water propagation at 4cm incident wave height and 31cm water depth with the two rows of debris with 1cm separation distance. The time interval between the transverse profiles is 0.3 s.

4.6 Percentage of debris washed back upstream

Bottom friction and turbulence in the flow are two important contributing factors in the motion of the waterline and the debris, and both contribute the scatter in the measurements and in having some of the debris particles being washed upstream. For example, in the 2011 Tohoku earthquake and tsunami, a primary school boy observed his father's car being swept by the tsunami waves. (Lam 2013)

To demonstrate the degree of uncertainty in the experimental results leading to debris wash-back, Figure 4-30 to Figure 4-35 show data from 10 runs for the cross flume profiles in the measured inundation limit, maximum debris position and the final debris position for the one debris-row experiment. Generally, all the results presented in these figures are clustered around the ensemble average with a small deviation (results further shown in Appendix A). A relatively large scatter could be found in the results of the positions of the debris, but the mean position over all runs and across the flume were very close to the maximum end of the range. However a small portion of the debris either did not closely follow the overflow and was seen to be carried seaward by the retreating water (see e.g. Figure 4.35).

Figure 4-30 Maximum water up-slope distance of baseline (left) and $L=5\text{cm}$ (right) at $H=2\text{cm}$ and $h=31\text{cm}$.

Figure 4-31 Maximum water up-slope distance of baseline (left) and $L=5\text{cm}$ (right) at $H=3\text{cm}$ and $h=31\text{cm}$.

Figure 4-32 Maximum water up-slope distance of baseline (left) and $L=5\text{cm}$ (right) at $H=4\text{cm}$ and $h=31\text{cm}$.

Figure 4-33 Final debris position (left) and maximum debris position (right) for $L=5\text{cm}$ at $H=2\text{cm}$ and $h=31\text{cm}$.

Figure 4-34 Final debris position (left) and maximum debris position (right) for $L=5\text{cm}$ at $H=3\text{cm}$ and $h=31\text{cm}$.

Figure 4-35 Final debris position (left) and maximum debris position (right) for $L=5\text{cm}$ at $H=4\text{cm}$ and $h=31\text{cm}$.

Since the number of the debris being washed into sea was very random, a percentage value was used to quantify the probability of debris being washed to seaside for each wave height and water depth. The probability is computed by:

$$\begin{aligned} &\text{Probability of debris washed upstream} \\ &= \frac{\text{Total number of debris washed upstream}}{\text{Total number of test} \times \text{Total number of debris}} \times 100\% \end{aligned} \quad \text{Eq. 4-8}$$

The results are shown in the Table 4-39 and Table 4-40 below for the 31 and 34 cm water depths respectively. The tables also list the number of tests carried out for each case. As seen the probability of debris washed upstream was low and rather random for floating type of debris used here.

Table 4-39 Number of debris washed upstream at water depth of 31cm

	$H= 2\text{cm}$			$H= 3\text{cm}$			$H= 4\text{cm}$		
<i>Distance to Edge, L</i>	<i>5cm</i>	<i>10cm</i>	<i>15cm</i>	<i>5cm</i>	<i>10cm</i>	<i>15cm</i>	<i>5cm</i>	<i>10cm</i>	<i>15cm</i>
<i>Number of Test</i>	10	11	11	11	10	11	11	10	11
<i>Total Number of debris Washed Upstream</i>	3	1	1	13	9	15	27	7	6
<i>Probability (%)</i>	0.38	0.12	0.12	1.50	1.14	1.73	3.11	0.89	0.69

Table 4-40 Number of debris washed back to sea at water depth of 34cm

	<i>H= 1cm</i>			<i>H= 2cm</i>			<i>H= 2.5cm</i>		
<i>Distance to Edge, L</i>	<i>5cm</i>	<i>10cm</i>	<i>15cm</i>	<i>5cm</i>	<i>10cm</i>	<i>15cm</i>	<i>5cm</i>	<i>10cm</i>	<i>15cm</i>
<i>Number of Test</i>	10	10	10	10	13	10	11	11	11
<i>Total Number of debris Washed Upstream</i>	19	4	12	3	9	3	9	11	13
<i>Probability (%)</i>	2.41	0.51	1.52	0.38	0.88	0.38	1.04	1.27	1.50

5.0 Experimental Observation and Data Analysis on One Piece of Debris

5.1 Maximum Water Up-Slope Distance

To observe the effects of maximum up-slope distance of the incoming wave due to the presence of the piece of debris, a debris block was placed at the edge of the slope. As mentioned in Chapter 3.0, three debris blocks with different dimension and orientation were tested. Figure 5-1 and Figure 5-2 show the maximum up-slope distance of water with different debris blocks for water depth at 31cm with wave height at 3cm and 2cm respectively. Figure 5-1 shows maximum up-slope distance of water of five repeating runs when there is no debris block present. Figure 5-1(b) and (c) shows the maximum up-slope distance of water of ten repeating runs where the debris block with size 1cm x 3cm x 0.5cm was placed at the shore with Figure 5-1(b) for the shorter edge (1cm side) was facing the incoming wave, and Figure 5-1(c) when the longer edge (3cm side) was facing the wave. Figure 5-1(d) and (e) show similar plots: the maximum up-slope distance of water of ten repeating runs where the debris block with size 1cm x 0.5cm x 0.5cm was placed at the shore, with Figure 5-1(d) for the case when the longer edge (1cm side) was facing the incoming wave, and Figure 5-1(e) when the shorter edge (0.5cm side) was facing the wave. Figure 5-1(f) shows the maximum up-slope distance of water with the 2cm x 2cm x 0.5cm debris block. Figure 5-2 is the case with 31cm water depth, but the incoming solitary wave was set to be 4cm. Figure 5-2(a) shows the case where has no debris block is present. Figure 5-2(b) to (f) show the maximum water climbing up distance when different debris blocks with different orientation were placed at the shore. The width-averaged maximum up-slope distance of water is obtained by Eq. 4-1 and their normalized standard deviation is calculated by Eq. 4-2 and Eq. 4-3. The obtained data is listed in Tables F-1 to F-6 in Appendix F. The red solid line is the average of width-averaged maximum up-slope distance of water for each experimental condition. The results show that the presence of the debris block had no effect on the wave as to be expected due to the small size of the block and its low density. As such there was essentially no dissipation in energy of the incoming solitary wave.

Figure 5-1 Maximum Up-slope distance of water at 3cm solitary wave height and 31cm water depth

Figure 5-2 Maximum Up-slope distance of water at 4cm solitary wave height and 31cm water depth

5.2 Maximum and final debris position

The maximum and final debris positions are digitized for each run and for different wave condition. A box-chart plot was chosen to analysis the results to capture the uncertainty. Figure 5-3 to Figure 5-5 are box plots of the maximum debris position (MDP) and final debris position (FDP) under different wave conditions. In the box-chart plots, the actual data points are plotted along with each corresponding box, the whisker range shows the maximum and minimum value of each set of data, and the box range was set as 25th and 75th percentile respectively. The experimental data points are placed at left side of the box plot. From left to right of each figure, different line types represent different debris blocks. Solid-line boxes represent the experimental case with 2cm x 2cm x 0.5cm debris piece. Dash-line and dot-line boxes are for the case of 0.5cm x 1cm x 0.5cm debris block, but with the dash-line having the shorter edge (0.5cm side) facing the incoming wave and dot-line for the longer edge (1cm side) facing the wave. Dash-dot-line boxes and short-dash-line boxes are cases for the 3cm x 1cm x 0.5cm debris block being placed at the shore line with the dash-dot-line for cases where the longer edge (3cm side) were facing the incoming wave and the short-dash-line boxes where the shorter edge (1cm side) were facing the wave. In total 50 runs were performed comprising of 3 different debris sizes, 2 facing configuration and 10 repeats under each wave condition.

Generally speaking, the averaged results show that smaller sized debris (0.5cm x 1cm x 0.5cm debris block) was displaced further inland by the incoming waves due to its light weight. Different initial orientation of the piece of debris did affect its maximum and final debris location. The interquartile range (distance between 25th and 75th percentile data) of maximum debris position was narrower than that of final debris position. This observation was same as one and two debris-rows experiments, since the final debris positions of the single piece of debris was rather random due to the complicated flow field of the retreating water. Due to limited number of data points, there is no solid conclusion could be obtained from the box plots. The same piece of debris with the same initial orientation and wave condition could have the maximum and final debris position varied significantly for each test run. But, this set of data could guide understanding of the motion debris moving with the incoming solitary wave. It could help researchers to calibrate their numerical work. Further data analysis on fitting out a suitable coefficient of drag, added mass and friction is done in Section 6.3.

Figure 5-3 Maximum and final debris position at 31cm water depth with 2cm incoming wave height. All debris blocks have height 0.5 cm.

Figure 5-4 Maximum and final debris position at 31cm water depth with 3cm incoming wave height

Figure 5-5 Maximum and final debris position at 31cm water depth with 4cm incoming wave height

5.3 Single Debris Block- Force Coefficient Fits

To understand the motion of single debris of debris being pushed up by the incoming solitary wave, the driving equation of motion (i.e. *Eq. 2-19*) from Section 2.3 of literature review was applied with the experimentally obtained data. As seen from the equation, the possible forces experienced by a single debris block include the drag force (F_D), inertial force (F_I) along with added mass (C_a) effects, frictional force (F_f) when the debris is non-floating, buoyancy force (B) and gravitational force (G). Therefore, the motion of the debris piece of debris follows *Eq. 2-19* which could then use to infer values of the drag (C_D) and added mass (C_a) coefficients, along with the friction factor f via nonlinear fitting of the observed instantaneous debris positions. This is motivated by that there is of interest to derive values of these coefficients as that could support future analytical works looking in the motion of individual debris pieces.

5.3.1 Fitting Methodology and Results

The application of *Eq. 2-19* required the actual wave condition at each observed particle position, which included the instantaneous water depth, velocity and acceleration of the water. As these were not directly measured in the experiments, the hydrodynamics code Delft3D, ran in a one-layer configuration (i.e. 2D mode) was used to obtain these needed quantities. The acceleration of the wave at the specific debris location was also obtained by differentiation of a polynomial fit of the water flow velocity as calculated from Delft3D. As for the debris, the needed debris block positions were extracted from the trajectory of the moving debris as recorded by a top view high speed camera (30 fps; see Figure 3-8 in Section 3.2), and specifically via manual digitization and extraction from the individual recorded frames. Typically a total of 60-70 points were used to discretize the entire debris trajectory. A polynomial fit to the extracted positions with time was then applied from which the first derivative of the polynomial fit provided the debris velocity and the second derivative the acceleration. These data points along the debris trajectory were then applied to *Eq. 2-19* and the force coefficients estimated via the Matlab non-linear least square fit routine (specifically `lsqnonlin` function of Matlab).

For one-piece debris block experiment, ten repeats had been done for each experimental condition which included a particular size and orientation of the debris (see Table 3-3, Section 3.3.3). However the repeats under the same nominal conditions with the same piece of debris and orientation had wide scatter in the maximum and final debris position as discussed in Section 5.2. This scatter was also reflected in the digitized debris block trajectories. For

example, Figure 5-6 shows the ten repeated run (termed Run 1 to 10) of a 1cm x3cm x0.5cm debris block with shorter 1cm edge facing the incoming 2cm wave in 31cm water depth. This scatter had implications on the success of extracting good fits from the nonlinear fitting as discussed later below.

Figure 5-6 Trajectories of one-piece debris experiment at 2cm incident wave and 31cm water depth with 1cmx3cmx0.5cm debris size (1cm facing incoming wave) of all repeats.

In Figure 5-6, it is seen that the trajectory of Run 3 was particularly separated from the rest, hence it was discarded. Rather the average of the other nine repeated runs was used to obtain an averaged trajectory which is plotted in Figure 5-7 below. As shown the averaged trajectory was distorted after 2.178s, so the data points after 2.178s were not used in the fitting process. Qualitatively, this averaged trajectory reflected that the piece of debris was pushed by the incoming solitary wave, then partially washed back by the retreating water and reached its final debris position. This trajectory was then fitted by a polynomial function (Figure 5-8) and by differentiation to obtain the velocity and acceleration of the debris block. Since the initial position of the debris block was non-zero (i.e. located at 5cm from the edge of the 3rd slope) the fitted debris trajectory was shifted to zero for convenience. This zero-shifted debris trajectory, velocity (u_d) and acceleration (a_d) are shown in Figure 5-9 below.

Figure 5-7 Averaged trajectory of nine repeated runs at 2cm incident wave and 31cm water depth with 1cmx3cmx0.5cm debris size (1cm facing incoming wave)

Figure 5-8 Polynomial fit of averaged trajectory of nine repeated runs at 2cm incident wave and 31cm water depth with 1cmx3cmx0.5cm debris size (1cm facing incoming wave)

Figure 5-9 Trajectory in m (blue), velocity in m/s (red) and acceleration in m/s^2 (green) of averaged trajectory of nine repeated runs at 2cm incident wave and 31cm water depth with 1cmx3cmx0.5cm debris size (1cm facing incoming wave)

As mentioned earlier, the instantaneous water depth (d_m), velocity of the wave (u_w) at each observed particle position are obtained directly from Delft3D calculation results. The time synchronization of the Delft3d calculation with experimental observation was set by visual observation (in the video frames) of the water reaching the debris which had initially dry conditions being placed on the 3rd slope. The acceleration of the wave (a_w) at each observed particle position was further obtained by differentiating the polynomial fit of water velocity. For the case of 2cm incident wave height at 31cm water depth, the instantaneous water depth (d_m), velocity of the wave (u_w) and acceleration of the wave (a_w) at each averaged observed particle positions are shown in Figure 5-10, Figure 5-11 and Figure 5-12 respectively.

Figure 5-10 Instantaneous water depth at each averaged observed particle positions as obtained directly from Delft3D at 2cm wave height and 31cm water depth

Figure 5-11 Velocity of the wave at averaged observed particle positions from Delft3D and its fit at 2cm wave height and 31cm water depth

Figure 5-12 Acceleration of wave at each observed particle position from Delft3D at 2cm wave height and 31cm water depth

The duration of the whole trajectory of the debris spanned 2.178s and the digitized points comprised 67 data points. By using the data and fits above into Eq. 2-19 and applying a nonlinear least-square fit, the obtained drag (C_D), added mass (C_a) and frictional coefficients (f) were 0.512, 0.0 and 0.0753 respectively. These values indicated that added mass effects were negligible and the motion was governed by drag and friction. Using the fitted coefficients, Eq. 2-19 was further numerically integrated twice to obtain a predicted debris trajectory. This is shown in Figure 5-13 below along with the experimentally observed averaged trajectory indicating a good fit was achieved, particularly since their averaged trajectory spanned 9 repeated runs that had significantly scatter.

Figure 5-13 Nonlinear least-square fit of averaged trajectory of nine repeating runs at 2cm incident wave and 31cm water depth with 1cmx3cmx0.5cm debris size (1cm facing incoming wave)

Next a larger debris block with size 2cm x 2cm x 0.5cm at the same 2cm wave height and 31cm water depth was similarly processed by the non-linear fitting method above. Again an averaged debris trajectory was used, this over the ten repeated runs and with the instantaneous water depth, velocity and acceleration at each particle position extracted from the Delft3D run at 2cm wave height and 31cm water depth. The fitting result is shown in Figure 5-14 below. The obtained drag (C_D), added mass (C_a) and frictional coefficients (f) are 1.486, 3.0 and 0.167 respectively. The numerically predicted debris block trajectory also generally matched the observed averaged trajectory. It also lied within the range of the 10 individual debris trajectories (repeats) as shown in Figure 5-15.

Figure 5-14 Nonlinear least-square fit of averaged trajectory of ten repeating runs at 2cm incident wave and 31cm water depth with 2cmx2cmx0.5cm debris size

Figure 5-15 Numerical fitted trajectory v.s. ten individual debris trajectories at 2cm incident wave and 31cm water depth with 2cmx2cmx0.5cm debris size.

The fitted force coefficients obtained the 2cm x2cm x 0.5cm debris block were different from the 1cm x 3cm x 0.5cm debris. This was attributed to the high degree of scatter in the debris block trajectories, even though an averaged trajectory was used. The accuracy in which Delft3d was able to simulate the exact water depth, velocity and acceleration values at the debris locations where the water depths were small and had wetting/drying conditions most likely also contributed to the uncertainties. It is further noted that in some cases examined, the non-linear square fit was unable to converge. This is as shown in Figure 5-16 for the case of a single run (i.e. trajectory) of the 3cm x 1cm x 0.5xm debris (3cm edge facing the wave) under a 1cm incident wave height at 31cm water depth. The experimental trajectory had the expected behavior of the debris block being pushed upslope and with some wash back before stopping. However the iteration in the nonlinear fit stopped with C_D , C_a and f being 0.664, 0.0 and 0.0 respectively. The fitted trajectory was further obviously incorrect.

Figure 5-16 Nonlinear least-square fit of averaged trajectory of ten repeating runs at 2cm incident wave and 31cm water depth with 3cmx1cmx0.5cm debris size (3cm facing incoming wave)

Considering the two cases, 1cm x 3cm x 0.5cm and 2cm x 2cm x 0.5cm debris block where the nonlinear least square fit converged, there are two likely reasons which might cause the difference in the values of the fitted force coefficients. One was that the instantaneous depth, velocity and acceleration of wave as obtained from Delft3d were poor estimates of the actual water conditions experienced by the moving debris. Delft3D as applied is a two-dimensional modeling of the shallow water equation, but the actual incoming flow behaved more like a sheet flow when it reached the 3rd slope. The other possible reason was in the randomness of the debris motion while it was pushed by the incoming wave. Even the same piece of debris moved differently across the repeats. This could be attributed that the experimental wave front variations across the flume while small when compared to the flume width were significant compared to the debris block size. Debris rotation also occurred which meant the instantaneous drag force as dependent on the projected area facing the water also varied under the same scenario. The debris rotation also would have affected the added mass value. Considering the 1cm x 3cm x 0.5cm debris (1cm facing incoming wave at 2cm wave height and 31cm water depth) (see Figure 5-6), the ten trajectories shown approximately exhibited two types of scenarios. There were four runs (runs 2, 7, 9 and 10) in which the piece of debris reached their maximum position and then washed back completely upstream into deeper water. Five runs (runs 1, 3, 5, 6 and 8) had the debris motion stopped, i.e. reached final position on the 3rd slope and did not wash upstream. Run 4 had a completely different behavior in reaching far upslope compared to the rest.

Table 5-1 below summarizes all the cases tried using trajectories from individual runs and averaged trajectories. The RMSE between the fitted and experimental trajectory is also shown.

Table 5-1 Fitting results of individual trajectories and averaged trajectories at 2cm incident wave height and 31cm water depth(shaded rows indicates cases when the nonlinear fits converged well).

<i>Debris</i>	<i>Trajectory</i>	C_D	C_a	f	<i>RMSE (m)</i>	<i>Comments</i>
<i>1cm x 3cm x 0.5cm</i>	Ave of 9	0.512	0.0	0.0753	0.00550	Converged
<i>1cm x 3cm x 0.5cm</i>	Run 1	0.718	0.0	0.214	0.0115	Converged*
	Run 2	0.427	0.0	0.076	0.0115	Converged
	Run 3	0.958	0.0	0.185	0.0097	Converged*
	Run 4	0.0	0.0	0.195	0.044	Converged*
<i>2cm x 2cm x 0.5cm</i>	Ave of 10	1.486	3.0	0.167	0.0295	Converged
	Run 1	0.785	0.0	0.953	0.0222	Converged*
	Run 2	0.0	0.0	0.238	0.0373	Converged*
<i>3cmx1cmx0.5cm</i>	Run 1	0.664	0.0	0.0	0.269	Poor fit

The shaded rows in Table 5-1 indicate the cases where the good fits were obtained over the entire trajectory with RMSE values less than 3 cm, i.e. of the order of the size of the debris block. The “converged*” comment indicated cases where the fitting was good only over the upslope part of the trajectory. The largest RMSE value over these cases was less than 3.8 cm.

Taking Run 2 case of the 2cm x 2cm x 0.5cm debris as an example, the fitted trajectory was in agreement with the experimental for the up-slope part of trajectory but diverged after the piece of debris passed its maximum position (see Figure 5-17). If the fitting is only done for the up-slope portion of the trajectory, the fits is shown in Figure 5-18 below. The fitted C_D , C_a and f were 0.715, 0 and 0 respectively, with the fitted trajectory having a RMSE value of 3.12cm. However, this RMSE value is higher than the RMSE from fitting the whole trajectory which has a slightly smaller RMSE of 3.73cm (shown in even though the latter fit qualitatively did not have the debris stopping and being partially washed back.

Figure 5-17 Nonlinear least-square fit of 2cmx2cmx0.5cm debris of Run 2 case at 2cm incident wave and 31cm water depth

Figure 5-18 Nonlinear least-square fit of up-slope part of trajectory of 2cmx2cmx0.5cm debris of Run 2 case at 2cm incident wave and 31cm water depth

5.3.2 Concluding Remarks on Fits

Taken together, the cases showing the poor fits indicated that the precision of the experimental data and numerical Delft3D calculations were inadequate for obtaining good estimates of the force coefficients. Much more detailed experimental measurements (e.g. improved accuracy in water depth observations beyond that afforded by using video cameras) and higher fidelity numerical simulations (e.g. accounting for the effect of the debris in the thin-sheet water flow conditions) would be needed. The best fits, i.e. shaded rows in Table 5-1, have C_D ranging over 0.517 to 1.486, C_a over 0 to 3, and f over 0.076 to 0.167 and this represented the best estimates that could be made with the current data and approach.

Although C_D , C_a and f are not successfully fitted here, some observations could still be obtained. The drag force was always present and provided the force which moved the debris up slope. The frictional force slowed the debris when it was not floating. Lastly for cases when the debris piece was washed back upstream, it meant the frictional force was insufficient to keep the debris on the slope.

6.0 Analysis

6.1 Equivalent Gradient for Solitary Wave Runup

The experimental study in this thesis used a continental slope/shelf model that had 3 slopes (see Figure 3-8 in Section 3.2) which simulated a propagation path for a tsunami, modelled as a solitary wave arriving from the ocean towards the continental slope and shelf and then onward to near- and on-shore. However, most of the reported studies of tsunami runup modelled as solitary wave runup use a simpler single slope model, as discussed in Section 2.2. Here, the author developed an equivalent gradient for the runup using the experimental results obtained and following a single slope model by Synolakis (1987). The objective is to have an equation that can be applied to solitary wave runup on the 3-slope continental slope/shelf model but with a single equivalent slope that can be related back to the 3 slopes and the incident wave parameters.

For non-breaking solitary wave, Synolakis (1987) related its runup with the incident wave height and water depth. An equivalent slope was reported with expressions as:

$$\frac{R}{h} = 2.831s_f^{-0.5} \left(\frac{H}{h} \right)^{1.25} \quad \text{Eq. 6-1}$$

where R is the runup, h is deep water depth, s_f is the fitted bottom slope and H is incident solitary wave.

For the 3-slope model here, the obtained data of runup (R) with water depth (h) and incident wave height (H) were used to first fit a single slope s_f based on the form of Eq. 6.1. The data used were from the one debris-row experiment with no debris involved (i.e baseline values in Table 4-8 of Section 4.1), since Eq. 6-1 did not take debris into account. The incident wave heights used were actual values recorded by the Ultralab sensor and further were the average of ten repeats under each experimental condition. The data, then consisted of 6 points is listed in Table 6-1. $s_f^{-0.5}$ was then fitted using Eq. 6-1 by a linear function using the values of the last two columns of Table 6-1. Note the linear form of Eq. 6-1 passes through the origin, since when the incident wave height (H) is zero, there should be no runup (R).

Table 6-1 Data for fitting slope gradient by Eq. 6-1

$h, \text{ cm}$	$H, \text{ cm}$	$R, \text{ cm}$	R/h	$2.831*(H/h)^{1.25}$
1.96	31	7.22	0.23	0.09
2.93	31	9.70	0.31	0.15
3.81	31	11.50	0.37	0.21
0.98	34	4.31	0.13	0.03
1.99	34	7.42	0.22	0.08
2.49	34	8.75	0.26	0.11

Figure 6-1 Linear fit of Eq. 6-1 by data obtained from Table 6-1 fitting $R^2 = 0.66$.

As shown above in Figure 6.1, the linear fit gives,

$$s_f^{-1/2} = 2.1055 \text{ or } s_f = 0.226 \quad \text{Eq. 6-2}$$

and therefore, the fitted slope gradient is 1: 4.41 (horizontal to vertical distance).

An equivalent slope gradient (s_{eq}) is next proposed based on this fitted slope (s_f). In the experiments, the nonlinear wave transformation and shoaling of the incident solitary wave occurred over the 1st and 2nd slopes as well as being dependent on the initial wave height and water depth. Therefore, the author hypothesized that an equivalent slope could be defined in terms as:

$$s_{eq} = \frac{V_{eq}}{X_{eq}} \quad Eq. 6-3$$

where the vertical equivalent height (V_{eq}) is given by the sum of the incident wave height and initial water depth (see Figure 6-2). The horizontal equivalent length (X_{eq}) is given by the horizontal distance from the starting position of the slope model to the location of the vertical equivalent height. This definition of the equivalent slope following geometrical arguments follow used by Hughes (2004), where wave momentum flux values were defined to estimate wave runup on smooth, impermeable slope. Casting in terms of the slope angles α and β (i.e. the 1st and 2nd slopes), expressions for V_{eq} and X_{eq} are given by Eq. 6-4 and Eq. 6-5 below.

$$V_{eq} = H + h \quad Eq. 6-4$$

$$X_{eq} = 0.25\alpha + (h - 0.25)\beta + H\beta \quad Eq. 6-5$$

Figure 6-2 Illustration of the V_{eq} and X_{eq} for calculation of equivalent slope (s_{eq})

The calculated equivalent slopes values for each case are listed Table 6-2 below. The averaged equivalent slope (s_{eq}) of the 6 cases is 0.198 which is fairly close to the fitted slope (s_f) i.e. 0.226 with a 12.4% difference..

Table 6-2 List of equivalent slope for the various incident wave heights and water depths

H, cm	h, cm	V_{eq}	X_{eq}	s_{eq}
1.96	31	32.96	150.59	0.219
2.93	31	33.93	164.07	0.207
3.81	31	34.81	176.43	0.197
0.98	34	34.98	178.78	0.196
1.99	34	35.99	193.03	0.186
2.49	34	36.49	200.00	0.182

The obtained fitted slope gradient (s_{eq}) is then can be used to predict the runup ($R_{predicted}$) by rewriting Eq. 6-1.

$$R_{predicted} = 2.831s_{eq}^{-0.5}H^{1.25}h^{0.25} \quad Eq. 6-6$$

This predicted runup ($R_{predicted}$) is compared with the actual experimentally observed runup ($R_{observed}$) (listed in in Table 4-8 of Section 4.1). The comparison is shown in Figure 6-3 below where the difference between $R_{predicted}$ and $R_{observed}$ is around or within $\pm 20\%$ except for the case with the lowest runup. Thus reasonable prediction accuracy was obtained in runup predictions for this 3-slope model now recast via an equivalent slope in the runup predictions.

Figure 6-3 Predicted runup ($R_{predicted}$) v.s. observed runup ($R_{observed}$) from experiment.

6.2 Inundation Reduction with Mass Loading

In actual tsunami events, a key piece of information is the extent of inundation, needed both for pre-event emergency planning purposes and for post-event analysis and estimation of the tsunami wave heights. However the extent of inundation is expected to be highly dependent on the amount of debris in the tsunami flow. The results in Sections 4.3.1 and 4.4.1 showed that the inundation changes were not related to the initial position of the debris (the one debris-row experiment) or the separation distance of the debris (the two debris-rows experiment) for the experimental conditions tested. They were rather more related to the amount of incoming water (i.e. the incident wave height) and the amount of debris present/placed along the 3rd slope (i.e. the coastal area). In particular the inundation reduction of one debris-row experiment was less than the two debris-rows experiment which had twice the debris mass loading. To examine this relationship between inundation reduction with debris mass loading, a non-dimensional mass loading (M_D) defined as the amount of debris mass (M_d) per unit mass of water (M_w) that approached to the beach was developed as shown in Eq. 6-7.

$$M_D = \frac{M_d}{M_w} = \frac{\rho_d V_d}{\rho_w V_w} \quad \text{Eq. 6-7}$$

where, ρ_d is density of debris, ρ_w is density of water, V_d is the total volume of the debris and V_w is the total volume of the incoming wave.

The amount of water (V_w) that approached the beach was based on the maximum inundation point reached over the 3rd slope, i.e. the near-shore/in-land gentle slope, during which the incoming wave flow behaved qualitatively like a sheet flow as observed from the experiments. While an exact calculation of this would be difficult, an engineering approximation was used here whereby the amount of water was approximated geometrically via the triangular region defined by the incident wave height, the maximum inundation point and the beach (Figure 6-4). Thus this approach not only included the debris mass but also the parameters of the incident wave via the maximum inundation. The expression of V_w is then calculated via Eq. 6-8.

$$V_w = \frac{1}{2} \cdot \frac{\gamma}{1 + \gamma^2} D^2 B \quad \text{Eq. 6-8}$$

where B is the width of the wave flume, D is the maximum up-slope water distance and γ the 3rd slope value.

Figure 6-4 Illustration on calculating the amount of water that approached to the beach.

To evaluate this approach of quantifying inundation reduction with debris mass loading using the obtained experimental data, a dimensionless inundation (I_D) is defined as the ratio of the inundation at the different debris mass loading (I) to the inundation with no debris loading (I_0).

$$I_D = \frac{I}{I_0} \quad \text{Eq. 6-9}$$

The obtained experimental points plotted as I_D versus M_D are shown in Figure 6-5. It is noted that the clustering seen was due to each the experimental condition being repeated five to ten times. Figure 6-6 shows the analogous plot if only the averaged value of over the repeats is used.

Figure 6-5 Dimensionless inundation reduction versus dimensionless mass loading with all repeats under each experimental condition shown. The solid line is a non-linear fit from Eq. 6-8.

Figure 6-6 Dimensionless inundation reduction vs dimensionless mass loading by taking only the averaged value of repeats at each experimental condition. The solid line is a non-linear fit from Eq. 6-8.

The plotted I_D vs M_D curves suggested an initially more rapid decrease in I_D with M_D which was then followed by a more gradual decrease. This shape could be empirically fitted by the form of Eq. 6-10 below.

$$I_D = 1 - \tanh(\delta M_D^\epsilon) \quad \text{Eq. 6-10}$$

where δ and ϵ are fitting constants.

The nonlinear least square fitting results of applying Eq. 6-10 are given in Table 6-3 and also plotted above in Figures 6-5 and 6-6.. Fitting condition 1 refers to the case when all the repeats under each experimental condition were used in the fit. Fitting condition 2 refers to the case by taking only the averaged value of each experimental condition.

Table 6-3 Non-linear least square fit of dimensionless inundation and mass loading

Fitting condition	1	2
δ	0.674	0.600
ϵ	0.427	0.409
RMSE	0.0112	0.0114

As seen the fitted coefficients differ little between the two fitting condition as to be expected since Figure 6-5 shows that the repeats for each experimental condition were well clustered.

In view of this, the author proposed using the coefficients derived from fitting condition 1 which then yielded the relationship between the inundation reduction and mass loading as.

$$I_D = 1 - \tanh(0.674M_D^{0.427}) \quad \text{Eq. 6-11}$$

It is interesting to show how Eq. 6-11 for I_D would behave at larger values of M_D beyond the current experiments. This is plotted in Figure 6-7 when it is seen that I_D tapers off at M_D values of 1 and larger. At M_D of 1, I_D gives a value of 0.41 which means implies a 59% of reduction when the mass of debris is equal to the mass of water that inundates the coastal area. This is reasonable as when M_D gets higher (i.e. large amount of debris in the coastal area), the reduction of the inundation should be significant. This interpolation of the results shows that the inundation reduction is highly related to the mass of debris and such effects must be considered in the modeling and post-event analysis of actual tsunami events. However it is noted that the obtained experimental data was restricted in the range of M_D of less than 0.023, so further experiments should be conducted to better establish this relationship.

Figure 6-7 Extended plot of I_D v.s. M_D by Eq. 6-11

As an application of the inundation reduction to a field case, the 2011 Tohoku Earthquake and Tsunami are used. In that event, there were 6 million tons of debris generated in Iwate Prefecture and maximum runup was recorded as 10 m. Assuming a shoreline length given by the square root of Iwate prefecture's area of 15, 278 km², a runup of 10 m and a coastal slope of 1:25 (i.e. same as the experiment here, see sketch in Figure 6-8)), a M_D of 0.037 and inundation reduction of 17% is obtained from Equation (6-11). This strongly indicates that inundation reduction from debris mass loading must be considered in modeling and in post

tsunami event analysis. However it is noted that the obtained experimental data is restricted to $M_D < 0.023$ and further experiments are necessary to better establish this relationship.

Figure 6-8 Amount of water estimated in the Iwate Prefecture.

6.3 Maximum and final debris position with Mass Loading

As shown in last section, the dimensionless inundation reduction (I_D) is dependent on the dimensionless mass loading (M_D) in the form of Eq. 6-7. It is expected that the maximum and final debris positions should also be similarly related to M_D . To evaluate this using the obtained experimental data, two dimensionless parameters of maximum and final debris positions are defined here. They are the final debris position (FDP_D) and maximum debris position (MDP_D) defined as the ratio of final and maximum debris positions over the maximum inundation of the incoming wave at their corresponding experimental conditions respectively (shown in Eq. 6-12 and Eq. 6-13). Here the final debris position, maximum debris position and maximum inundation are the averaged of all the test runs for each experimental condition. The calculated FDP_D and MDP_D from the one and two debris-row experiments are listed in Table 6-5 and Table 6-6 below.

$$FDP_D = \frac{FDP}{I} \quad \text{Eq. 6-12}$$

$$MDP_D = \frac{MDP}{I} \quad \text{Eq. 6-13}$$

Table 6-4 FDP_D and MDP_D of one debris-row experiment

		FDP_D			MDP_D		
h, cm	H, cm	$L=5cm$	$L=10cm$	$L=15cm$	$L=5cm$	$L=10cm$	$L=15cm$
31	2	0.332	0.334	0.352	0.337	0.338	0.352
	3	0.522	0.524	0.524	0.537	0.540	0.541
	4	0.599	0.609	0.603	0.623	0.631	0.632
34	1	0.527	0.522	0.544	0.536	0.541	0.553
	2	0.734	0.730	0.727	0.754	0.750	0.750
	2.5	0.774	0.762	0.759	0.793	0.786	0.783

Table 6-5 FDP_D and MDP_D of two debris-rows experiment

		FDP_D			MDP_D		
h, cm	H, cm	$S=1cm$	$S=3cm$	$S=6cm$	$S= cm$	$S=3cm$	$S=6cm$
31	2	0.187	0.232	0.250	0.152	0.214	0.230
	3	0.529	0.529	0.549	0.508	0.504	0.523
	4	0.636	0.643	0.641	0.613	0.612	0.614

Figure 6-9 and Figure 6-10 plot the dimensionless final debris position (FDP_D) and maximum debris position (MDP_D) versus the dimensionless mass loading (M_D). Both FDP_D and MDP_D

decreased with increasing of M_D , and they were reasonably well approximated via exponential fits as shown with R^2 values larger than 0.85. The data and the fits show that when the mass loading increased (i.e., larger amount of debris or smaller incoming wave height), both the final and maximum debris position were getting smaller relative to the corresponding maximum inundation. In particular when at largest value of M_D shown, the FDP_D and MDP_D , i.e. there was little washback of the final debris (mean) position from its maximum (mean) position.

Figure 6-9 FDP_D v.s. M_D

Figure 6-10 MDP_D v.s. M_D

The spread of in the maximum and final positions of the individual debris blocks are also useful information due to the high uncertainty in the movement of the individual debris,

particularly under the retreating part of the flow. The normalized interquartile range (quantified in Sections 4.3.4 and 4.4.4 for the one and two debris-row experiments respectively) as dimensionless form of the spread is used here. The normalized interquartile range of final and maximum debris position are shown in Table 6-6 and Table 6-7 below expressed as fractions of their mean positions.

Table 6-6 Normalized interquartile range of FDP and MDP of one debris row experiment

$h, \text{ cm}$	$H, \text{ cm}$	Normalized Interquartile Range of FDP			Normalized Interquartile Range of MDP		
		$L=5\text{cm}$	$L=10\text{cm}$	$L=15\text{cm}$	$L=5\text{cm}$	$L=10\text{cm}$	$L=15\text{cm}$
31	2	0.136	0.134	0.129	0.121	0.126	0.123
	3	0.082	0.078	0.102	0.064	0.062	0.069
	4	0.091	0.079	0.079	0.053	0.056	0.055
34	1	0.097	0.114	0.096	0.085	0.088	0.082
	2	0.064	0.065	0.065	0.045	0.047	0.044
	2.5	0.059	0.068	0.068	0.045	0.045	0.048

Table 6-7 Normalized interquartile range of FDP and MDP of two debris-row experiment

$h, \text{ cm}$	$H, \text{ cm}$	Normalized Interquartile Range of FDP			Normalized Interquartile Range of MDP		
		$S=1$	$S=3$	$S=6$	$S=1$	$S=3$	$S=6$
31	2	0.695	0.486	0.492	0.408	0.340	0.340
	3	0.109	0.105	0.105	0.103	0.091	0.079
	4	0.108	0.106	0.107	0.078	0.074	0.075

The normalized interquartile range values versus M_D are shown in Figure 6-11 and Figure 6-12 together with exponential fits (R^2 values are larger than 0.9). It is seen that the normalized interquartile range of MDP was much lower than that of FDP at the same M_D values. Hence the spread of FDP was larger than the spread of MDP, again due to the more complicated nature of the retreating wave. The results also show that when mass loading (M_D) increases, the normalized interquartile range of both MDP and FDP exponentially increased i.e. the spread/uncertainty of the debris position increases with increasing debris mass loading.

Figure 6-11 Normalized interquartile range of final debris position v.s. mass loading (M_D)

Figure 6-12 Normalized interquartile range of maximum debris position v.s. mass loading (M_D)

Taken together, the derived predictions comprise (i) the runup via an equivalent slope analysis (Section 6.1), (ii) the reduction in inundation with debris mass loading (Section 6.2) and (iii) the ratio between the final/maximum debris position to the maximum inundation and mean spread of final and maximum debris position (i.e. normalized interquartile range) (current Section 6.3). These combined results are expected to find utility in guiding future works on the interpretation of tsunami driven debris flows, particularly in assessing the resulting debris positions and their deposition extent. However it is noted that the predictions are based on a limited dataset, specifically the 3 slope model and limited debris mass loading range used, which should be expanded in future works.

7.0 Conclusion and Recommendation

A series of laboratory experiments were conducted to study the motion of debris under tsunami waves modelled as solitary waves. This was via one- and two-row debris blocks located on a 3-slope model which represented a bottom configuration of a continental slope/shelf followed by a gentler inland slope. The experimental data of moving debris were recorded by two top-view cameras, and then digitized out to obtain the maximum up-slope distance, maximum and final debris position. In one debris-row experiment, the row of debris was placed at various distances from the edge of 3rd slope under two water depths with three incident wave height conditions. It was to study the effects of initial location of the debris row on the maximum inundation/runup, maximum and final debris position. In two debris-rows experiment, two-row debris had different separation distances under one water depth with three incident wave height conditions. Experiments were also conducted for the case of a single debris block to study its motion. Different size and weight of debris was chosen, and the orientation of the debris piece was also taken into account. Ten repeating test were done for one debris-row and one debris piece experiment, and five repeating test were done for two debris-row experiment under the same experimental condition.

The experimental results showed that the presence of the debris row, both one and two rows, reduced the maximum water inundation from the baseline case of no debris. The experiments results also showed there was significant randomness in the debris motion which resulted in a significant dispersal in the maximum and final debris positions of the individual debris blocks from the initially spaced debris row(s). Thus the maximum and final debris positions were characterized using (i) mean and median values, (ii) box plots with interquartile ranges via ensemble averaging and (iii) normalized Kernel density functions which provided the spatial shapes of the debris positions.

For one debris-row experiment, the wave height had a more significant effect on the maximum water inundation/runup, and debris maximum and final positions (as characterized by the mean values) than the original location of the debris row. This also held in the two-debris row experiment, i.e. the wave height was still the controlling factor rather than the separation distance between the debris rows. The results also showed that the final debris position was always reduced from the maximum debris position which in turn was less than the maximum water upslope distance. This has practical implications in interpreting real tsunami events if the final debris position from post-event surveys was used to estimate the maximum debris position or water upslope distance. It was also found that some of the debris blocks could be washed upstream into deeper water, but the probability was generally low and random.

Analysis of the experimental data showed that uncertainty in the measured maximum water inundation (both cross-flume and across repeats) was much lower than the uncertainty in the positions of the individual debris blocks. The uncertainty in the measured position of debris increased with wave height of the incoming solitary wave. This had implications in the analysis performed on the motion of a single debris block using data from the one-piece debris experiment. The random trajectory, both during upslope and downslope stages of the single debris block across the repeat runs under the same nominal incident wave conditions implied that only approximate values of the drag and friction coefficient could be extracted from the data.

The inundation and runup data obtained allowed a development of an equivalent slope to represent the 3-slope configuration for runup predictions using the single slope equation from Synolakis (1987). This equivalent slope further used the incident wave height and slope values of the 1st and 2nd slopes of the 3-slope model where nonlinear shoaling of the incident solitary wave occurred. A dimensionless debris mass loading term was further defined as based on the mass of the debris row(s) and the amount of water that travelled up on the 3rd slope (as representing the inundated region) as defined by the incident wave height and maximum inundation point. This dimensionless debris mass loading term is thus dependent on both incident wave parameters and the debris mass present. It is further shown that dimensionless forms of the inundation reduction, final and maximum debris positions and spread in the individual debris blocks can be fitted to the dimensionless mass loading. Taken together, these derived fits have practical applications as they comprise (i) predictions of runup via the equivalent slope, (ii) the reduction in water inundation with debris mass loading and (iii) the mean final debris position and spread about the mean. These results are thus expected to find utility in guiding future works on the interpretation of tsunami driven debris flows post-event, particularly in assessing the resulting debris positions and their deposition extent. However it is noted that the predictions are based on a limited dataset, specifically the 3 slope model, the limited debris mass loading and wave height ranges used, all of which should be expanded in future works.

Lastly the work also provided a detailed experimental dataset that can support further analytical and/or numerical work. An example is in future calibration or validation of numerical approaches, though more extensive experiments over a wider parameter range (e.g. different composite slopes and mass loadings) will be needed.

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Appendix A Average and Standard Deviation Values from One and Two Debris-Row Experiments

Table A-1 The average and standard deviation of maximum inundation (cm) of 2cm incident wave height at 31cm water depth from one debris-row experiment

L	No Debris	5cm	10cm	15cm
Run1	60.70	49.17	48.45	47.29
Run2	60.44	49.81	48.78	47.62
Run3	60.43	48.14	48.43	48.58
Run4	60.16	50.27	48.31	47.63
Run5	60.12	48.71	47.46	48.77
Run6	60.20	49.33	47.087	48.69
Run7		48.66	48.24	48.39
Run8		48.31	48.79	47.59
Run9		48.45	47.84	47.453
Run10		49.58	47.89	48.72
Average	60.34	49.04	48.13	48.07
Standard Deviation	0.22	0.70	0.55	0.60

Table A-2 The average and standard deviation of maximum runup (cm) of 2cm incident wave height at 31cm water depth from one debris-row experiment

L	No Debris	5cm	10cm	15cm
Run1	3.74	2.79	2.01	2.61
Run2	3.62	2.47	2.59	2.78
Run3	3.78	2.55	2.53	2.65
Run4	3.84	1.61	2.27	1.90
Run5	3.67	2.41	2.58	1.95
Run6	3.42	1.75	2.49	2.86
Run7		2.22	2.77	2.48
Run8		3.12	2.61	3.04
Run9		4.29	3.22	1.71
Run10		3.33	2.49	4.11
Average	3.68	2.65	2.56	2.61
Standard Deviation	0.15	0.79	0.31	0.69

Table A-3 The average and standard deviation of maximum inundation (cm) of 3cm incident wave height at 31cm water depth from one debris-row experiment

L	No Debris	5cm	10cm	15cm
Run1	125.61	116.27	115.72	118.52
Run2	124.45	117.54	115.45	118.44
Run3	124.52	117.06	115.36	119.20
Run4	124.64	117.16	115.44	124.19
Run5	125.26	117.15	117.24	118.90
Run6		116.24	116.98	118.16
Run7		116.38	118.22	116.30
Run8		116.46	117.62	116.31
Run9		116.19	118.96	115.99
Run10		116.23	118.82	117.94
Average	124.90	116.67	116.98	118.40
Standard Deviation	0.51	0.50	1.43	2.34

Table A-4 The average and standard deviation of maximum runup (cm) of 3cm incident wave height at 31cm water depth from one debris-row experiment

L	No Debris	5cm	10cm	15cm
Run1	5.83	2.69	4.78	4.23
Run2	6.56	3.21	3.53	2.76
Run3	6.61	2.61	3.79	2.80
Run4	6.50	3.00	2.98	2.67
Run5	6.14	3.92	2.95	2.20
Run6		3.82	3.41	2.80
Run7		2.39	3.61	4.09
Run8		3.25	3.42	3.51
Run9		3.15	3.07	3.12
Run10		3.71	3.63	2.59
Average	6.33	3.18	3.52	3.08
Standard Deviation	0.33	0.52	0.53	0.66

Table A-5 The average and standard deviation of maximum inundation (cm) of 4cm incident wave height at 31cm water depth from one debris-row experiment

L	No Debris	5cm	10cm	15cm
Run1	171.35	166.36	167.99	171
Run2	171.65	166.08	170.98	170.61
Run3	171.51	165.76	171.15	170.11
Run4	171.92	167.65	171.34	170.48
Run5	171.75	167.69	170.88	171.86
Run6		167.02	171.10	169.82
Run7		167.07	171.01	170.79
Run8		167.56	170.23	170.89
Run9		168.13	171.23	171.27
Run10		166.86	171.24	170.92
Run11		166.90		171.59
Average	171.63	167.01	170.72	170.85
Standard Deviation	0.17	0.73	0.33	0.63

Table A-6 The average and standard deviation of maximum runup (cm) of 4cm incident wave height at 31cm water depth from one debris-row experiment

L	No Debris	5cm	10cm	15cm
Run1	7.00	3.60	3.96	5.20
Run2	6.84	4.53	5.67	3.48
Run3	6.89	3.69	4.30	4.59
Run4	7.21	4.97	5.11	5.01
Run5	7.10	5.13	4.46	7.76
Run6		3.94	4.17	6.33
Run7		4.42	4.03	4.79
Run8		2.91	3.73	5.19
Run9		4.68	4.59	4.12
Run10		4.09	5.64	4.31
Run11		4.51		5.45
Average	7.01	4.22	4.57	5.11
Standard Deviation	0.17	0.66	0.69	1.22

Table A-7 The average and standard deviation of maximum inundation (cm) of 2cm incident wave height at 31cm water depth from two debris-row experiment

S	No debris	1cm	3cm	6cm
Run1	53.96	41.17	40.74	40.87
Run2	55.44	42.64	41.35	42.83
Run3	55.51	42.44	40.40	42.00
Run4	56.58	42.59	42.05	42.06
Run5		42.81	42.24	42.00
Average	55.37	42.21	41.13	41.94
Standard Deviation	1.08	0.66	0.80	0.70

Table A-8 The average and standard deviation of maximum inundation (cm) of 3cm incident wave height at 31cm water depth from two debris-row experiment

S	No debris	1cm	3cm	6cm
Run1	124.19	110.66	112.62	112.65
Run2	123.62	111.63	112.72	113.78
Run3	125.08	111.93	112.71	113.71
Run4	123.48	110.63	112.83	112.77
Run5	124.26	111.18	111.59	112.92
Average	124.13	111.21	112.50	113.17
Standard Deviation	0.63	0.58	0.51	0.53

Table A-9 The average and standard deviation of maximum inundation (cm) of 4cm incident wave height at 31cm water depth from two debris-row experiment

S	No debris	1cm	3cm	6cm
Run1	173.88	167.03	166.89	167.03
Run2	174.48	168.09	168.14	167.38
Run3	175.83	167.73	168.23	166.69
Run4	175.10	167.64	167.59	167.67
Run5	174.07	167.77	166.49	168.99
Average	174.67	167.65	167.47	167.55
Standard Deviation	0.80	0.39	0.77	0.89

Appendix B Maximum Up-slope Distance, Maximum Debris Position and Final Debris Position from One Debris-Row Experiment

Figure B-1 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 2cm incident wave height and 31cm water depth (Run1 to 4)

Figure B-2 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 2cm incident wave height and 31cm water depth. (Run5 to 10)

Figure B-3 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 2cm incident wave height and 31cm water depth.(Run1 to 6)

Figure B-4 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 2cm incident wave height and 31cm water depth. (Run7 to 10)

Figure B-5 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 2cm incident wave height and 31cm water depth. (Run1 to 6)

Figure B-6 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 2cm incident wave height and 31cm water depth. (Run7 to 11)

Figure B-7 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 3cm incident wave height and 31cm water depth. (Run1 to 6)

Figure B-8 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 3cm incident wave height and 31cm water depth. (Run7 to 10)

Figure B-9 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 3cm incident wave height and 31cm water depth. (Run1 to 6)

Figure B-10 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 3cm incident wave height and 31cm water depth. (Run7 to 10)

Figure B-11 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 3cm incident wave height and 31cm water depth. (Run1 to 6)

Figure B-12 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 3cm incident wave height and 31cm water depth. (Run7 to 10)

Figure B-13 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 4cm incident wave height and 31cm water depth. (Run1 to 6)

Figure B-14 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 4cm incident wave height and 31cm water depth. (Run7 to 11)

Figure B-15 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 4cm incident wave height and 31cm water depth. (Run1 to 6)

Figure B-16 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 4cm incident wave height and 31cm water depth. (Run7 to 10)

Figure B-17 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 4cm incident wave height and 31cm water depth. (Run1 to 6)

Figure B-18 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 4cm incident wave height and 31cm water depth. (Run7 to 11)

Figure B-19 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 1cm incident wave height and 34cm water depth. (Run1 to 6)

Figure B-20 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 1cm incident wave height and 34cm water depth. (Run7 to 11)

Figure B-21 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 1cm incident wave height and 34cm water depth. (Run1 to 6)

Figure B-22 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 1cm incident wave height and 34cm water depth. (Run7 to 10)

Figure B-23 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 1cm incident wave height and 34cm water depth. (Run1 to 6)

Figure B-24 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 1cm incident wave height and 34cm water depth. (Run7 to 10)

Figure B-25 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 2cm incident wave height and 34cm water depth. (Run1 to 6)

Figure B-26 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 2cm incident wave height and 34cm water depth (Run7 to 10)

Figure B-27 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 2cm incident wave height and 34cm water depth (Run1 to 6)

Figure B-28 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 2cm incident wave height and 34cm water depth (Run7 to 10)

Figure B-29 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 2cm incident wave height and 34cm water depth (Run11 to 13)

Figure B-30 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 2cm incident wave height and 34cm water depth (Run1 to 6)

Figure B-31 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 2cm incident wave height and 34cm water depth (Run7 to 10)

Figure B-32 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 2.5cm incident wave height and 34cm water depth (Run1 to 6)

Figure B-33 Maximum up-slope distance, maximum and final debris positions with 5cm initial debris position of one debris-row experiment at 2.5cm incident wave height and 34cm water depth (Run7 to 11)

Figure B-34 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 2.5cm incident wave height and 34cm water depth (Run1 to 6)

Figure B-35 Maximum up-slope distance, maximum and final debris positions with 10cm initial debris position of one debris-row experiment at 2.5cm incident wave height and 34cm water depth (Run7 to 11)

Figure B-36 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 2.5cm incident wave height and 34cm water depth (Run1 to 6)

Figure B-37 Maximum up-slope distance, maximum and final debris positions with 15cm initial debris position of one debris-row experiment at 2.5cm incident wave height and 34cm water depth (Run7 to 10)

Appendix C Box Plots of Maximum and Final Debris Position from One Debris-Row Experiment

Figure C-1 Ensemble average of maximum and final debris position for 2cm incident wave height at 31cm water depth with one debris row at different initial debris position

Figure C-2 Ensemble average of maximum and final debris position for 3cm incident wave height at 31cm water depth with one debris row at different initial debris position

Figure C-3 Ensemble average of maximum and final debris position for 4cm incident wave height at 31cm water depth with one debris row at different initial debris position

Figure C-4 Ensemble average of maximum and final debris position for 1cm incident wave height at 34cm water depth with one debris row at different initial debris position

Figure C-5 Ensemble average of maximum and final debris position for 2cm incident wave height at 34cm water depth with one debris row at different initial debris position

Figure C-6 Ensemble average of maximum and final debris position for 2.5cm incident wave height at 34cm water depth with one debris row at different initial debris position

Appendix D Maximum Up-slope Distance, Maximum Debris Position and Final Debris Position from Two Debris-Rows Experiment

Figure D-1 Maximum up-slope distance, maximum and final debris positions for 1cm separation distance of two rows of debris at 2cm incident wave height and 31cm water depth. (Run1 to 5)

Figure D-2 Maximum up-slope distance, maximum and final debris positions for 3cm separation distance of two rows of debris at 2cm incident wave height and 31cm water depth.

Figure D-3 Maximum up-slope distance, maximum and final debris positions for 6cm separation distance of two rows of debris at 2cm incident wave height and 31cm water depth.

Figure D-4 Maximum up-slope distance, maximum and final debris positions for 1cm separation distance of two rows of debris at 3cm incident wave height and 31cm water depth. (Run1 to 5)

Figure D-5 Maximum up-slope distance, maximum and final debris positions for 3cm separation distance of two rows of debris at 3cm incident wave height and 31cm water depth. (Run1 to 5)

Figure D-6 Maximum up-slope distance, maximum and final debris positions for 6cm separation distance of two rows of debris at 3cm incident wave height and 31cm water depth. (Run1 to 5)

Figure D-7 Maximum up-slope distance, maximum and final debris positions for 1cm separation distance of two rows of debris at 4cm incident wave height and 31cm water depth (Run1 to 5)

Figure D-8 Maximum up-slope distance, maximum and final debris positions for 3cm separation distance of two rows of debris at 4cm incident wave height and 31cm water depth (Run1 to 5)

Figure D-9 Maximum up-slope distance, maximum and final debris positions for 6cm separation distance of two rows of debris at 4cm incident wave height and 31cm water depth (Run1 to 5)

Appendix E Box Plots of Maximum and Final Debris Position from Two Debris-

Figure E-1 Ensemble average of maximum and final debris position for 2cm incident wave height at 31cm water depth with 1cm spacing between two rows of debris

Figure E-2 Ensemble average of maximum and final debris position for 2cm incident wave height at 31cm water depth with 3cm spacing between two rows of debris

Figure E-3 Ensemble average of maximum and final debris position for 2cm incident wave height at 31cm water depth with 6cm spacing between two rows of debris

Figure E-4 Ensemble average of maximum and final debris position for 3cm incident wave height at 31cm water depth with 1cm spacing between two rows of debris

Figure E- 5 Ensemble average of maximum and final debris position for 3cm incident wave height at 31cm water depth with 3cm spacing between two rows of debris

Figure E- 6 Ensemble average of maximum and final debris position for 3cm incident wave height at 31cm water depth with 6cm spacing between two rows of debris

Figure E- 7 Ensemble average of maximum and final debris position for 4cm incident wave height at 31cm water depth with 1cm spacing between two rows of debris

Figure E- 8 Ensemble average of maximum and final debris position for 4cm incident wave height at 31cm water depth with 3cm spacing between two rows of debris

Figure E-9 Ensemble average of maximum and final debris position for 4cm incident wave height at 31cm water depth with 6cm spacing between two rows of debris

Appendix F Width-Averaged Maximum Water Up-Slope Distance and Cross-Flume Normalized Standard Deviation from One Piece of Debris Experiment

Table F-1 Width-averaged maximum up-slope distance (cm) of water at 2cm incident wave height and 31cm water depth

	1cmx3cm	3cmx1cm	1cmx0.5cm	0.5cmx1cm	2cmx2cm
Run1	55.42	54.61	56.30	52.26	55.64
Run2	55.88	55.32	56.48	53.63	56.43
Run3	56.49	54.97	56.42	52.82	56.40
Run4	56.20	55.53	56.53	52.81	56.23
Run5	56.24	54.95	56.50	52.71	56.93
Run6	56.52	55.47	56.37	53.68	56.41
Run7	56.47	55.24	57.60	56.62	56.57
Run8	55.96	55.40	56.26	53.09	56.75
Run9	55.83	55.37	56.41	53.18	56.08
Run10	56.32	55.79	56.07	53.63	56.33
Average	56.13	55.27	56.49	53.44	56.38
Standard Deviation	0.34	0.32	0.39	1.15	0.34

Table F-2 Cross-flume normalized standard deviation of maximum up-slope distance of water at 2cm incident wave height and 31cm water depth

	1cmx3cm	3cmx1cm	1cmx0.5cm	0.5cmx1cm	2cmx2cm
Run1	0.06	0.07	0.07	0.07	0.08
Run2	0.07	0.06	0.07	0.08	0.08
Run3	0.07	0.07	0.08	0.07	0.08
Run4	0.07	0.06	0.08	0.08	0.09
Run5	0.07	0.07	0.08	0.08	0.08
Run6	0.07	0.07	0.08	0.08	0.08
Run7	0.07	0.07	0.08	0.09	0.08
Run8	0.07	0.07	0.08	0.07	0.08
Run9	0.07	0.07	0.08	0.08	0.08
Run10	0.07	0.08	0.08	1.00	0.08
Average	0.07	0.07	0.08	0.17	0.08

Table F-3 Width-averaged maximum up-slope distance (cm) of water at 3cm incident wave height and 31cm water depth

	No Debris	1cmx3cm	3cmx1cm	1cmx0.5cm	0.5cmx1cm	2cmx2cm
Run1	120.22	118.76	121.13	120.34	122.90	120.34
Run2	120.80	121.94	121.54	121.62	121.97	120.45
Run3	120.77	121.74	121.14	121.29	122.25	117.71
Run4	120.04	121.94	120.36	121.78	121.79	120.95
Run5	120.48	121.67	121.45	121.53	121.99	121.52
Run6		122.21	120.51	121.73	122.12	121.99
Run7		121.52	120.67	121.90	122.24	121.98
Run8		121.48	121.06	118.75	122.19	120.77
Run9		121.71	120.84	122.96	125.84	121.31
Run10		122.05	121.39	124.26	122.43	120.79
average	120.46	121.50	121.01	121.62	122.57	120.78
Standard Deviation	0.30	0.94	0.38	1.37	1.13	1.16

Table F-4 Cross-flume normalized standard deviation of maximum up-slope distance of water at 3cm incident wave height and 31cm water depth

	No Debris	1cmx3cm	3cmx1cm	1cmx0.5cm	0.5cmx1cm	2cmx2cm
Run1	0.06	0.05	0.05	0.05	0.04	0.05
Run2	0.05	0.05	0.05	0.05	0.05	0.05
Run3	0.05	0.05	0.05	0.05	0.05	0.05
Run4	0.05	0.05	0.05	0.05	0.05	0.04
Run5	0.05	0.05	0.05	0.05	0.05	0.04
Run6		0.05	0.05	0.05	0.05	0.05
Run7		0.05	0.05	0.05	0.05	0.05
Run8		0.05	0.05	0.05	0.05	0.05
Run9		0.05	0.05	0.05	0.05	0.05
Run10		0.05	0.05	0.05	0.05	0.05
average	0.05	0.05	0.05	0.05	0.05	0.05

Table F-5 Width-averaged maximum up-slope distance (cm) of water at 4cm incident wave height and 31cm water depth

	No Debris	1cmx3cm	3cmx1cm	1cmx0.5cm	0.5cmx1cm	2cmx2cm
Run1	171.90	173.38	169.49	173.20	172.63	171.30
Run2	173.97	173.60	173.56	172.61	172.88	173.68
Run3	173.38	173.19	173.26	172.25	172.88	174.58
Run4	173.58	173.03	173.19	173.96	172.57	173.35
Run5	173.67	173.46	174.23	172.93	172.82	173.76
Run6		172.49	171.51	173.42	173.61	174.42
Run7		172.92	172.48	173.23	173.53	174.31
Run8		173.35	173.13	173.35	173.51	173.95
Run9		173.50	173.29	173.60	173.24	172.37
Run10		173.75	173.43	172.75	173.54	
average	173.30	173.27	172.76	173.13	173.12	173.52
Standard Deviation	0.73	0.35	1.28	0.48	0.39	1.00

Table F-6 Cross-flume normalized standard deviation of maximum up-slope distance of water at 4cm incident wave height and 31cm water depth

	No Debris	1cmx3cm	3cmx1cm	1cmx0.5cm	0.5cmx1cm	2cmx2cm
Run1	0.03	0.04	0.04	0.03	0.03	0.04
Run2	0.03	0.04	0.04	0.03	0.03	0.03
Run3	0.03	0.04	0.04	0.03	0.03	0.03
Run4	0.04	0.03	0.04	0.03	0.03	0.04
Run5	0.04	0.04	0.04	0.03	0.03	0.04
Run6		0.04	0.03	0.03	0.03	0.04
Run7		0.04	0.03	0.03	0.03	0.04
Run8		0.04	0.04	0.03	0.03	0.04
Run9		0.04	0.03	0.03	0.04	0.04
Run10		0.04	0.03	0.03	0.03	
average	0.03	0.04	0.04	0.03	0.03	0.04