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Probabilistic Analysis of Debris Transport in Tsunami-Like Events

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Abstract: With the recent push in the development of probabilistic models addressing loading in extreme flooding event, less consideration has been placed on the development of hazard assessment models for debris loading within these natural disasters. The study presented here examines several parameters identified through a literature review and dimensional analysis that could be consider when assessing debris transport potential. A physical modelling sensitivity analysis was performed to examine how and to the extent at which these parameters influence debris transport. The debris were modelled as scaled-down (1:40 geometric scale) shipping containers transported in a dam-break wave over an idealized, flat, horizontal bed. The motion of the debris was tracked using a camera-based detection algorithm. Based on this analysis, it was shown that the trajectory of the debris can be approximately modelled as a straight line and the deviation from the mean with a symmetric function. The sensitivity analysis showed that both the hydrodynamic conditions and initial configuration of the debris are critical variables in assessing debris transport potential.

Keywords: Debris, Probabilistic Design, Flooding, Natural Disasters, Coastal Engineering, Tsunami

1 Introduction

1.1 Background

Recent events, such as the 2018 Palu Indonesia Tsunami, showed the devastation caused by extreme flooding hazards (Robertson et al. 2019). With uncertainties related to the changing climate and challenges in predicting tsunami events, there has been a major push towards improving hazards assessment techniques. One such effort has been the ASCE 7 Chapter 6 – Tsunami Loads and Effects (2016), which became the first standard in North America to explicitly address tsunami loads and effects from a probabilistic perspective. This standard has predominantly focused on the probabilistic hazard related to hydraulic loading conditions. However, field investigations of major tsunami events has shown the importance in also considering debris loading (Ghobarah et al. 2006, Palermo et al. 2013, Yeh et al. 2013).

Debris loading is caused by the interaction of structures with solid objects entrained within the flow (Nistor et al. 2017). These loads can be broadly classified as debris impact and damming. Debris impact loading is a result of a rapid striking of the debris on the structure; normally treated as contact mechanics problem (Ikeno et al. 2013, Aghl et al. 2014, Stolle et al. 2019a). Debris damming loads occur when debris accumulate at the face of the structure causing a change in the hydrodynamics (Schmocker and Hager 2013, Stolle et al. 2017b) and an increase in drag forces (Parola 2000, Stolle et al. 2018c). While debris loads have been identified as critical in the design process, incorporating them into probabilistic models can be challenging due to the wide-range of variables influencing their transport.

The ASCE 7 Chapter 6 (2016) was the first standard to introduce a methodology for assessing the hazard of debris loading. The methodology was based on a field investigation from the 2011 Tohoku Tsunami (Naito et al. 2014) examining the transport of shipping containers and shipping vessels in the aftermath of the event. The proposed methodology outlines a maximum extent of debris influence defined by a +/- 22.5^{o} spreading angle from the debris source. Any structures within the defined extents must then be designed for debris impact. Due to challenges in determining debris sources in the field and a limited data set, the proposed spreading angle tends to be overly conservative (Naito et al. 2016, Nistor et al. 2016, Stolle et al. 2018b). Additionally, the spreading angle does not consider physically relevant parameters that may influence the transport of debris (Stolle et al. 2019b).

Charvet et al. (2015) proposed a binary model to incorporate within fragility analysis. The model indicates if a debris impact occurs depending on the structures proximity to the debris source. While the model was shown to improve fragility curve accuracy, similar to the ASCE 7 (2016) model, it does not capture physical relevant parameters that may affect debris transport. Lin and Vanmarcke (2010) proposed a model for wind-borne debris impacts in extreme weather events. The model examines physical relevant parameters based on the forces relevant to debris flight times. However, the model considers each debris object individually, while in flooding events, debris are often seen propagating in agglomerations.

1.2 Objectives

Based on a physical modelling test series, the study outlined here examines the influence of several physically relevant parameters on debris transport, focused on parameters that influence the trajectory of the debris within the flow. The study performs sensitivity analysis of several parameters proposed (or hypothesized) to influence the transport of debris and examines how these parameters could be included in future debris hazard assessment methodologies. The primary objectives are:

- Identify parameters that could potentially influence debris transport.
- Perform sensitivity analysis of the identified parameters.
- Examine the relevant parameters and their importance in assessing debris hazard in extreme flooding events.

The study will first present a brief literature review outlining the relevant parameters and dimensional analysis necessary to perform the sensitivity analysis. The experimental methodology will be outlined in Section 2.0 and the results of the sensitivity analysis will be shown in Section 3.0.

1.3 Dimensional Analysis

The dimensional analysis was performed assuming the propagation of uniform, symmetric debris over a flat, horizontal bed with no flow obstructions. The dependent parameter was the lateral displacement of the debris (Δx). Stolle et al. (2018b) showed that lateral spreading was dependent on the hydrodynamic forcing condition, i.e. the water depth (d) and flow velocity (c), and distance from the debris source (Δy). Stolle et al. (2017a) showed that the lateral displacement was dependent on the debris configuration particularly the number of debris within each column of the initial configuration (n) and the initial orientation of the debris (Θ). Stolle et al. (2019b) showed that the number of columns of the initial configuration (r) and the spacing between the debris (S) also dictated the extent of the lateral displacement. As the drag force acting on the debris dictates the influence of the hydrodynamic forcing condition on the debris motion (Shafiei et al. 2016), the area exposed to the flow as defined by the characteristic length (l) and viscosity (μ) will have an influence. The initial entrainment of the debris is also critical in dictating the corresponding motion (Braudrick and Grant 2000, Rueben et al. 2014), therefore, the relative density of the debris (ρ_d) and water (ρ_w) as well as the gravitational constant (g) and coefficient of friction (μ_0) will play a role. Using the Buckingham pi-theorem, the resulting non-dimensional pi-groups were identified as:

$$\Delta x/d = f(\Theta, n, r, \Delta y/d, S/d, l/d, \rho_d/\rho_w, Re, Fr, \mu_0) \quad (1)$$

The dimensional analysis was used to inform the development of the experimental protocol (Tab.). The following sections further examine the factors influencing the trajectory of debris using statistical methods with the objective of developing a model of estimating the lateral displacement of debris under tsunami-like events. The dimensional analysis was limited to an idealized case where no flow obstructions or obstacles were present and the debris is a uniformly built, symmetric object.

2 Experimental Setup

2.1 Experimental Model

The experiments were performed at the University of Ottawa dam-break flume (Ottawa, Canada) (Fig. 1). The flume is 30 m long, 1.5 m wide, and 0.8 m deep, with a false floor 8.45 m long, 0.20 m high placed at one end of the flume. The remainder of the flume was used as a reservoir; impounding a volume of water, which was released by a swinging gate (von Häfen et al. 2018, Stolle et al. 2018a). The coordinate system of the facility is defined from the upstream side of the gate on the bed of the false floor. The positive *y*-axis is in the direction of the flow, the positive *x*-axis is flume right, and the positive *z*-axis in the upwards direction.

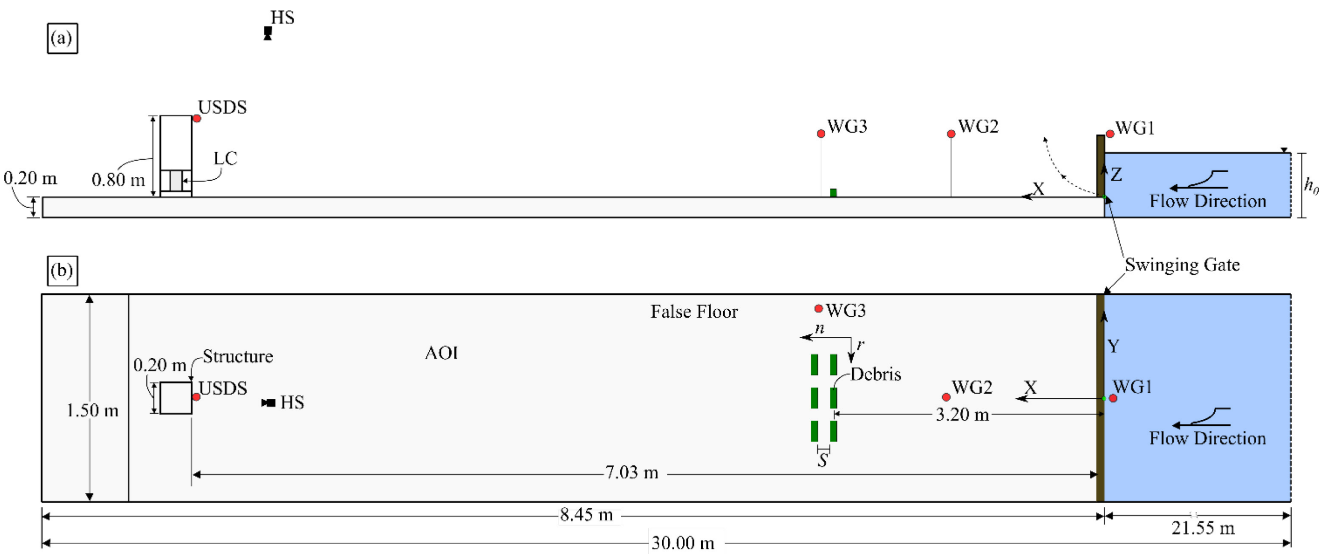

Fig. 1. University of Ottawa dam-break flume. The direction of flow is from left to right with the water reservoir shown in blue. The debris are shown as green rectangles. WG - wave gauge; USDS - ultra-sonic distance sensor; AOI - area of interest; HS – high-speed camera.

The hydrodynamic forcing condition was a dam-break wave generated by the impoundment of water in the reservoir to a specified impoundment depth (h_0). The wave propagated in the positive *y*-direction, entraining the debris placed with the upstream edge of the debris at y = 3.20 m. A full description of the hydrodynamic conditions of the facility can be found in Stolle et al. (2018a).

The debris were modelled as scaled-down 6.1 m shipping containers (0.15 m × 0.06 m × 0.06 m) with a mass (m_d) of 0.286 kg. The debris were placed in different initial configurations defined by the number of columns of debris (r), the number of debris within each column (n), the spacing between the outer edges of the debris (S), and the initial orientation of the long axis of the debris (Θ) (Fig. 1(b)).

The debris were tracked through the area-of-interest (AOI) using a high-definition camera (HS, Basler pi1900-32gc) and following the algorithm described in Stolle et al. (2016). The CAM was externally triggered using a 25 Hz output signal from a data acquisition system (DAQ, National Instruments USB-6009). The signal was simultaneously sampled by a second DAQ system (HBM MX1601B), also sampling the WGs, to synchronize the images with the hydrodynamic data. The estimated synchronization error was approximately +/- 0.04 s.

2.2 *Experimental Protocol*

To perform sensitivity analysis on the transport of debris to the parameters outlined in Section 1.3, several experimental configurations were tested. The hydrodynamic forcing conditions was varied by changing the water depth impounded in the reservoir (h_0). The debris configuration was adjusted by changing the number of columns of debris (r), the number of debris within each column (n), the spacing between the edges of the debris (held constant in the *x*- and *y*-directions) (S), and the orientation of the long axis of the debris (Θ). An Θ -value of 0° refers to the long axis of the debris perpendicular to the flow direction. Tab. outlines the different configurations used throughout the experimental series. Each configuration was repeated a minimum of 10 times.

Tab. 1. Experimental Protocol

Experimental Category	Impoundment Depth (h_0)	Number of Columns (r)	Number of Debris per Column (n)	Debris Spacing (S)	Debris Orientation (Θ)
	[m]	[-]	[-]	[m]	[°]
1	0.20	1	1	0	0
2	0.40	1	1	0	0
3	0.40	1	1	0	90
4	0.20	1	3	0.03	0
5	0.40	1	3	0.03	0
6	0.20	1	6	0.03	0
7	0.20	2	3	0.03	0
8	0.40	1	6	0.03	0
9	0.40	2	3	0.03	0
10	0.50	2	3	0.03	0
11	0.20	2	6	0.03	0
12	0.20	2	6	0.03	90
13	0.40	2	6	0.015	0
14	0.40	2	6	0.03	0
15	0.40	2	6	0.06	0
16	0.40	2	6	0.03	90
17	0.50	2	6	0.03	0

2.3 *Analysis Methods*

The position of the debris was monitored using the HS-camera with an object detection algorithm outlined in Stolle et al. (2016). The detection algorithm was developed for a different experimental series to track the motion of the same shipping containers used in this study, however, the algorithm was limited cases with less than 8 containers. This was due to the passing of individual identifiers between containers in close proximity. To eliminate this issue, the tracking aspect of the algorithm was not used; meaning the algorithm could identify the individual containers but the identifiers could not be passed between subsequent images. Therefore, the trajectory of individual containers could not be established but the position of each container within each image could be established (Fig. 2).

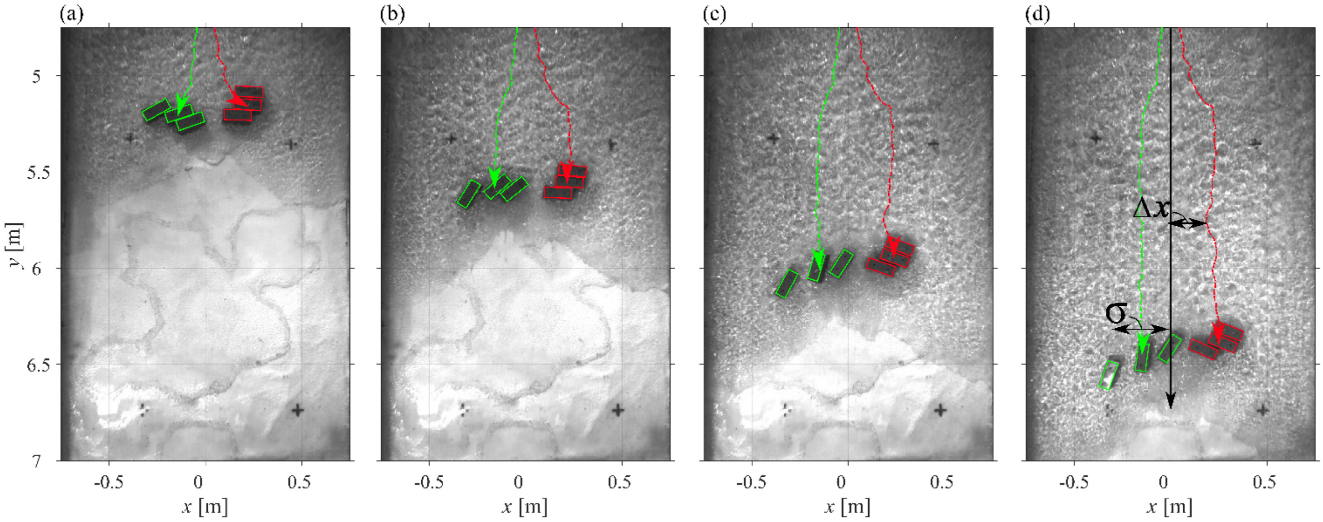

Fig. 2. Evolution of debris trajectory as monitored by the object detection algorithm for Experimental Category 7.

Stolle et al. (2018b) showed that the lateral motion of a single debris object over a flat horizontal surface can be probabilistically modelled as a normal distribution with a mean of zero (Δx = 0 m), however, this does not consider the influence of the initial configuration of the debris. Stolle et al. (2019b) showed that the columns of an initial debris configuration (r) must be considered individually as they tend to diffuse away from each other. To account for these two findings, the debris trajectory was quantified using two variables: the mean trajectory of the column (Δx, i.e. mean x-position of the debris) and the standard deviation (σ) around the mean based on the centroids of the individual debris (Fig. 2(d)).

3 Results

3.1 Sensitivity Analysis

To analyze the influence of the various parameters on debris transport, each parameter was varied independently with all other variables being held constant. Only a single type of uniform debris was used in the experiment, therefore, the influence of the draft was not considered (ρ_d/ρ_w in Eq. (1)). The bed surface was kept constant, therefore, μ_0 was also not considered. For the hydrodynamic variables (c and d), the maximum flow velocity (in this case the wave front velocity) and the maximum water depth at the debris site were used (y = 3.20 m). The mean trajectory and standard deviation are averaged over all the tests within the experimental category.

Fig. 3(a-b) shows the sensitivity analysis of the debris trajectory to the Froude number (hydrodynamic conditions). The mean trajectory in all cases was approximately 0 m, validating the findings from Stolle et al. (2018b) for the single debris case. Uniformly, an increase in the Froude number resulted in a decrease in the standard deviation (Fig. 3(b)). For dam-break waves, the hydrodynamic conditions are driven by the initial impoundment depth, therefore, as the water depth increases as does flow velocity. For the Froude number, since the flow velocity increases Froude by $O(c)$ whereas water depth decreases Froude by $O(d^{1/2})$. Therefore, with greater impoundment depth in dam-break flows, the Froude number will increase. Stolle et al. (2017a) showed the importance of debris interactions with the bed in causing debris spreading. Additionally, the greater the drag force (a function of flow velocity), the less opportunity for lateral diffusion of the debris over the same distance.

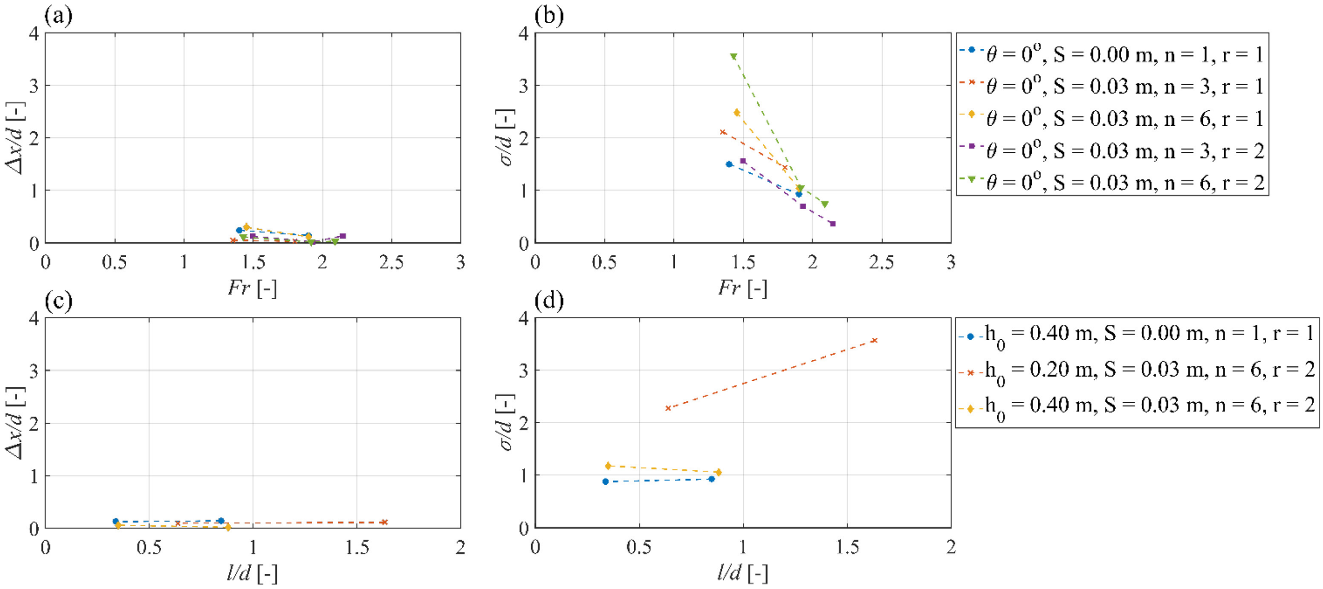

Fig. 3. Sensitivity analysis examining the influence of the Froude number (a-b) and the characteristic length (c-d) on the debris trajectory.

Fig. 3(c-d) examine the influence of the characteristic length on the debris trajectory. The characteristic length shows no clear trend related to the change in the standard deviation. This varies qualitatively from the experiments performed in Stolle et al. (2018b) where the debris tended to rotate towards the long axis parallel to the flow direction, which tended to be more stable. As a result of the rotation, an increase in the standard deviation was observed. However, this could not be established statistically.

Similar to Fig. 3, Fig. 4 shows relatively small mean trajectories, again showing that the lateral diffusion of the debris was approximately symmetrical around zero. The number of debris within a column (n) showed an increase in the standard deviation (Fig. 4(b)). Nistor et al. (2016) showed that an increase in the number of debris within a configuration resulted in more debris-debris interactions which had an associated increase in the spreading. Rueben et al. (2014) also speculated that the presence of other debris could also cause turbulent eddies which could result in increased lateral spreading. Similar to the characteristic length, the number of rows showed no significant increase in the lateral spreading.

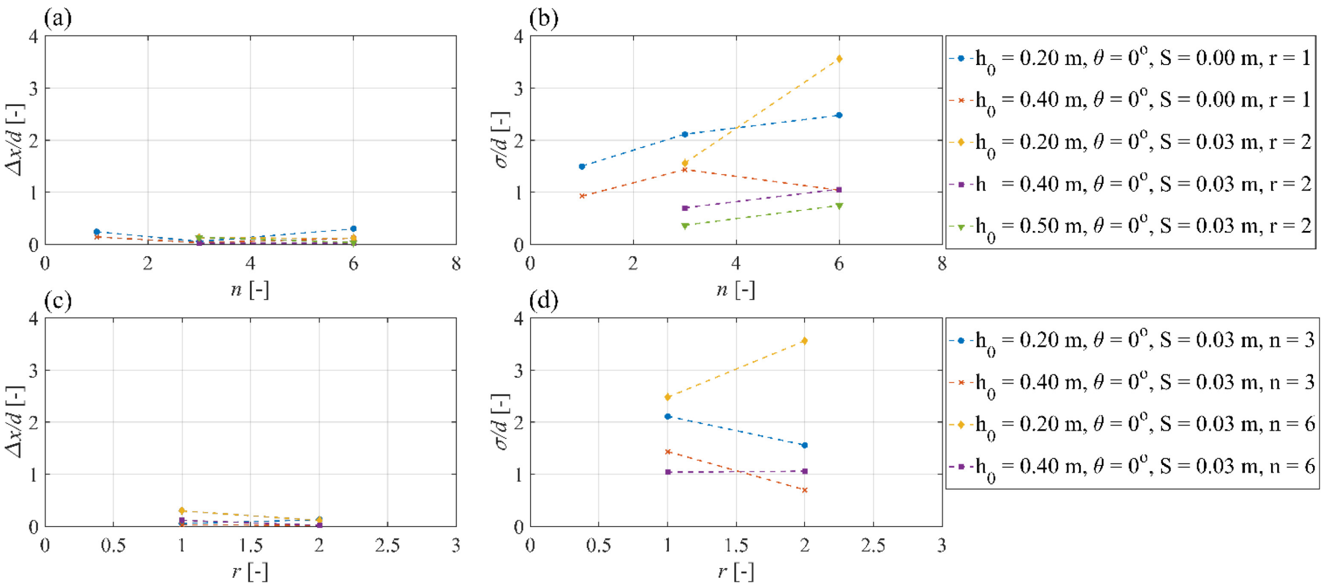

Fig. 4. Sensitivity analysis examining the influence of the number of debris in a column (a-b) and the number of columns (c-d) on the debris trajectory.

Fig. 5 shows the influence of the inter-debris spacing on the debris trajectory. No trend can be observed for the standard deviation. This is potentially due to the limited number of cases that examined the influence of spacing as well as a high potential for a non-linearity that cannot be captured with a limited number of cases. Rueben et al. (2014) noted, in a study of debris dynamics over a slope surface, that the debris appeared to have an “area of influence” related to its obstruction of the flow. Similar to a fixed obstacle, debris influence the surrounding flow as they tend to propagate slower than the surrounding fluid, therefore, it is likely the area of influence is a function of the inertia of the debris, hydrodynamics, and spacing. Further investigation is necessary to address the importance of spacing within this context.

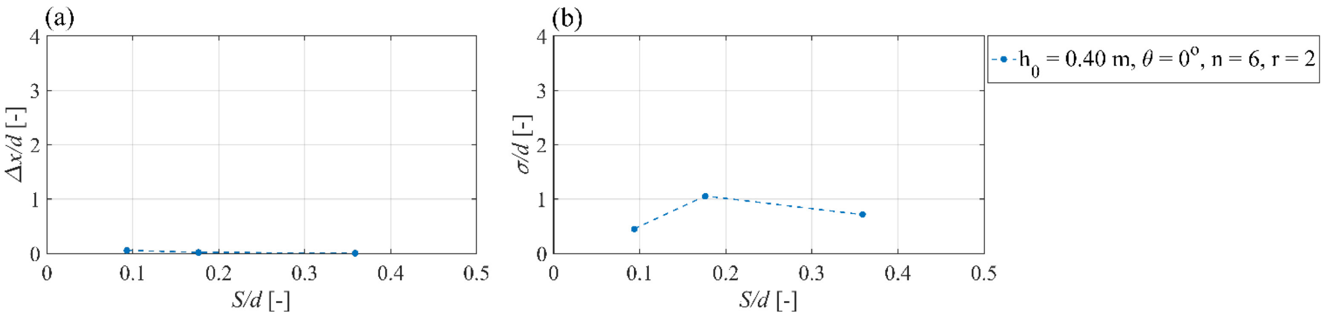

Fig. 5. Sensitivity analysis examining the influence of the spacing on the debris trajectory.

3.2 Regression Analysis

To further address the various parameters outlined in the dimensional analysis and account for spurious variations within experimental categories, multiple linear regression was performed to examine the influence of the outlined parameters on the standard deviation. The variance inflation factor (VIF) (Kenney 1962) was calculated between each of the parameters outlined in Section 1.3 to test for multicollinearity between the parameters (Tab. 1). Multicollinearity can result in large fluctuations in estimated coefficients from the regression. Generally, VIF values greater than 10 indicate collinearity between variables (Farrar and Glauber 1967). In this case, Fr and Re showed, as they both represent the hydrodynamics, high collinearity (VIF > 10). As the model was scaled considering Froude similitude, the Reynolds number would not represent ranges that are typical of tsunami. Therefore, the Reynolds number was not considered in the regression analysis. The ratio l/D and parameter Θ also displayed high VIF values, as the parameter Θ was related to the orientation of the long axis. The parameter Θ was hence removed from the analysis as it does not represent a physical characteristic in the force balance and the length of exposed area to the flow has application in a wide range of geometries.

Tab. 1. Multiple linear regression based on dimensional analysis presented in Section 1.3

		Multiple Linear Regression			
Parameter	Variable	Regression Coefficients (λ_j)	Standardized Coefficients (β_j)	p-value	VIF
Froude number	Fr	-0.390	-0.865	$p << 0.05$	2.337
Characteristic length	l/D	-0.208	-0.591	$p << 0.05$	1.792
Spacing	S/D	0.020	0.039	0.218	2.200
Number of debris per column	n	0.008	0.238	$p << 0.05$	1.260
Number of columns	r	0.051	0.409	$p << 0.05$	1.273

The multiple linear regression showed that the linearized model could explain 62% of the margin of variance (R^2 = 0.617) and was statistically significant ($p << 0.05$). A Kolmogorov-Smirnov test (Smirnov 1948) was performed with the null hypothesis that the residual were normally distributed, ensuring the validation of the assumption of normally distributed residuals ($p = 0.10$).

Each of the coefficients was considered to show a statistically significant trend, except in the case of spacing (Tab. 1). The regression coefficients (λ) are subject to scaling effects due to the difference in magnitude of the parameters. The standardized coefficients (parameters standardized by z-scoring) give a more accurate representation of the effect of each parameter on the standard deviation. The standardized coefficients show that the hydrodynamic conditions have the most significant influence on the standard deviation, which was similarly observed in Stolle et al. (2018b). While the characteristic length and number of columns also show a significant influence.

4 Discussion

The experimental setup was intended to represent an idealized case of a tsunami propagating over coastal plain (Chanson 2006). To ensure the experiment could adequately address the probabilistic nature of debris transport, the scope was limited to represent this specific scenario. As such, the hydrodynamic boundary condition only examined the initial inundation of a tsunami wave and did not consider the results of drawdown or subsequent wave entrainment. The number of debris was limited to a maximum of 12 as further additions resulted in significant model effects due to interactions with the walls of the flume. The inter-debris friction, debris-bed friction, and the buoyancy of the debris were not investigated. As these factors have been shown to have an influence on debris transport, further research is necessary to address these issues. The multiple linear regression could not describe 38% of the variance from the mean, leaving potential to build upon the current data set to address these issues.

For the lateral displacement of the debris, it would be expected that the general importance and influence of the parameters discussed within this study would remain similar at prototype scale. However, the magnitude of regression coefficients (λ_j) could potentially vary significantly. To date, no study has investigated debris motion at sufficiently large scales to address scale effects while this work depicts the first approach towards describing the debris transport process probabilistically where extreme flow conditions are concerned. In particular, parameters, such as turbulence (She and Leveque 1994) and drag (Granville 1976), which scale considering Reynolds similitude are not properly scaled.

The experimental study presented here examined the transport of "extraordinary" debris in a dam-break wave over a flat, horizontal surface. Therefore, limitation need to be addressed in the application of the model in a built environment. Aspects, such as flow channeling or typical surface roughness of debris, are not captured with the current model. Importantly, the direction of flow was also not considered. Features, such as topography or obstructions can have an influence on the direction of flow and would be expected to have a significant influence on the debris propagation. Investigation is necessary to address debris transport through flow obstructions (Goseberg et al. 2016), likely influencing the underlying assumption that the mean displacement of the debris is equal to zero.

Furthermore, the model examines "extraordinary" debris impact where the debris has a distinct source and is immediately entrained within the flow. Other probabilistic models have also included terms that consider debris generation (i.e. from the destruction of houses), the generation of individual debris objects is then modelled as a Poisson distribution (Lin and Vanmarcke 2010, Hatzikyriakou and Lin 2017). However, as the accurate modelling of collapsing structures under hydraulic loading has yet to be addressed, this aspect was not included within this study (Heller 2011).

5 Conclusions

Debris loading on structures is an important consideration in the design of tsunami-resilient infrastructure. To adequately provide hazard assessment methodologies to address debris loading, a more comprehensive understanding of debris transport in extreme hydrodynamic conditions is necessary. The study presented here examines parameters associated with debris transport to develop a basic understanding of how the initial configuration and hydrodynamics influence the trajectory of the debris. Based on this study, the following conclusions can be drawn:

- The motion of debris can be approximately modelled as a symmetric function with a mean lateral displacement of 0 m.
- The hydrodynamic conditions have a significant influence on the deviation of the debris from the mean. The greater the Froude number, the smaller the deviation.

- The initial configuration of the debris also has a significant influence on the deviation from the mean.

While this study provides an initial estimation of how each parameter influences the transport of debris, the study was performed under idealized conditions with a limited flume length. The presence of obstacles and obstructions in a built environment would likely have a significant influence on the spreading of debris. Building upon idealized studies, such as this one, will aid in the development of a comprehensive hazard assessment methodology for debris loading to aid in the design of tsunami-resilient infrastructure.

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