THE EFFECT OF ANCHORED LARGE WOODY DEBRIS ON BEACH MORPHOLOGY: A PHYSICAL MODEL STUDY

Jessica Wilson[1], Pauline Falkenrich[2], Ioan Nistor[3], Andrew Cornett[4], and Abdolmajid Mohammadian[5]

As the demand for nature-based coastal protection methods increases globally, there remains a stringent need to develop evidence-based design guidance for many of these methods and techniques. Anchored Large Woody Debris (LWD) has been used as an economical method of coastal protection for several decades and has, more recently, gained notoriety as a nature-based approach. Existing design guidance, however, is both limited and not significantly rooted in academic research. This paper presents results from the first experimental study related to coastal protection using LWD. Gravel beach response to various LWD configurations were tested at a large scale based on site characteristics and LWD design characteristics made by the authors during the previous field investigation phase of this research project. Tests were also conducted to assess experiment repeatability, sensitivity to test duration, sensitivity to wave height, wave period, and relative water level, and influence of log roughness. The LWD placement elevation relative to the still water level was found to be strongly linked to the beach morphological response and a theoretical relationship was developed between LWD elevation and sediment volume change. LWD design configurations which included LWD below the still water level, such as the Benched configuration, were found to be most effective at stabilizing the beach profile. To realize potential benefits of coastal protection using LWD, significant additional research is needed on the topic, including studies focused on how to best anchor LWD structures and a wider variety of parameters (hydrodynamic conditions and placement techniques).

Keywords: nature-based solutions; coastal protection; large woody debris; gravel beaches; morphology; coastal engineering design guidance; physical modeling

INTRODUCTION

Evidence-based design relies heavily upon field observations and investigations, experimental modeling, numerical modeling, and empirical equations (Hughes, 1993). Traditional coastal engineering techniques, such as seawalls, revetments, and breakwaters, have been studied extensively, allowing for the development of reliable design guidance (e.g. USACE, 2002). However, there has been a growing trend towards the usage of novel nature-based solutions (NbS), due to an increased understanding that NbS could prove more dynamic and adaptive in a changing climate, and may provide more co-benefits than traditional “hard” structures (Bilkovic et al. 2017; Bridges et al., 2021). The uptake has occurred despite the fact that design guidance and best practices are limited for some nature-based techniques (Bilkovic et al. 2017; Pontee et al. 2016), including for coastal protection using Large Woody Debris (LWD) (Wilson et al. 2020; Zelo et al. 2000).

Coastal protection using anchored LWD generally includes logs or driftwood larger than 0.3 m in diameter and 2.0 m in length, anchored and/or partially buried into the shoreline, with or without root masses (Johannessen et al. 2014; Wilson et al. 2019; Zelo et al. 2000). Anchored LWD has been used as an economical method of coastal protection (from wave run-up and erosion) for several decades (e.g., Zelo et al. 2000). It has more recently gained notoriety as a NbS, particularly in regions where natural accumulations of LWD have historically been prevalent (Brennan et al. 2009; Gonor et al. 1988; Heathfield and Walker 2011; Sass 2009). Existing design guidance for LWD, however, is both limited and not well supported by research (Wilson et al. 2020, Falkenrich et al. 2021). Numerous numerical and physical models have been completed on anchored LWD in river environments (e.g., Bocchiola 2011; Braudrick et al. 2001; Hygelund and Manga 2003; Perry et al. 2018; Wallerstein et al. 2001). Recent experimental research by Murphy et al. (2020) has also provided significant insight into the fate and transport of LWD in the coastal environment. However, to date, no known experimental or numerical studies have been conducted on anchored LWD in a coastal environment. The design guidance and documentation that does exist is generally only found in ‘grey’ literature (e.g. Johannessen et al. 2014; Zelo et al. 2000).

[1] University of Ottawa and DHI, Nanaimo, British Columbia, Canada
[2] TU Braunschweig and INROS LACKNER SE, Bremen, Germany
[3] University of Ottawa, Ottawa, Ontario, Canada
[4] National Research Council Canada and the University of Ottawa, Ottawa, Ontario, Canada
[5] University of Ottawa, Ottawa, Ontario, Canada

Due to the lack of research and design guidance, the design of anchored LWD to date has generally been based on (1) anecdotal observations and experience, (2) research that suggests that natural deposits of LWD may promote additional sediment accretion and reduce wave run-up (Eamer and Walker 2010; Gonor et al. 1988; Grilliot et al. 2018; Heathfield and Walker 2011; Huff 2015; Kennedy and Woods 2012), and (3) a continuity of design practices from the river engineering field, where significant literature is available on the function and design of LWD (Bocchiola 2011; Gonor et al. 1988; Hilderbrand, et al. 1998; Kail et al. 2007; Rafferty 2017; Sass 2009).

As the demand for NbS increases globally, there remains a stringent need to develop evidence-based design guidance for many NbS, including anchored LWD. This study was completed as part of the "Efficacy of Large Woody Debris as Coastal Protection" project initiated in 2019 as a novel and collaborative research initiative between the University of Ottawa and the National Research Council's Ocean, Coastal and River Engineering Research Centre (NRC-OCRE) in Canada (Wilson et al. 2020). The study aimed to investigate the efficacy of coastal protection comprised of anchored LWD and develop evidence-based design guidance for its' usage. The initial phase of the project included extensive field surveys at 15 existing anchored LWD project sites in British Columbia (BC), Canada, and Washington State, USA (Wilson et al. 2020). The second phase of the project included a broad experimental wave modeling program to investigate the efficacy of LWD at meeting the design goals of stabilizing the shoreline and reducing wave run-up. The program also served to investigate the most effective configurations of anchored LWD for meeting these goals.

This paper outlines the methodology and results for the morphological component of the experimental modeling program. This paper specifically aims to answer the following three research questions: (1) how does LWD influence the beach profile, (2) what is the optimal configuration for anchored LWD, and (3) how can design guidance be informed?

METHODOLOGY

Experimental Set-Up

The experiments were conducted at a 5:1 (prototype to model) scale, according to Froude scaling, in a 63 m x 1.2 m x 1.2 m wave flume at NRC-OCRE in Canada (Figure 1). The experiment set-up was informed by site observations made by the lead author during the preceding field survey phase of the project (Wilson et al. 2020).

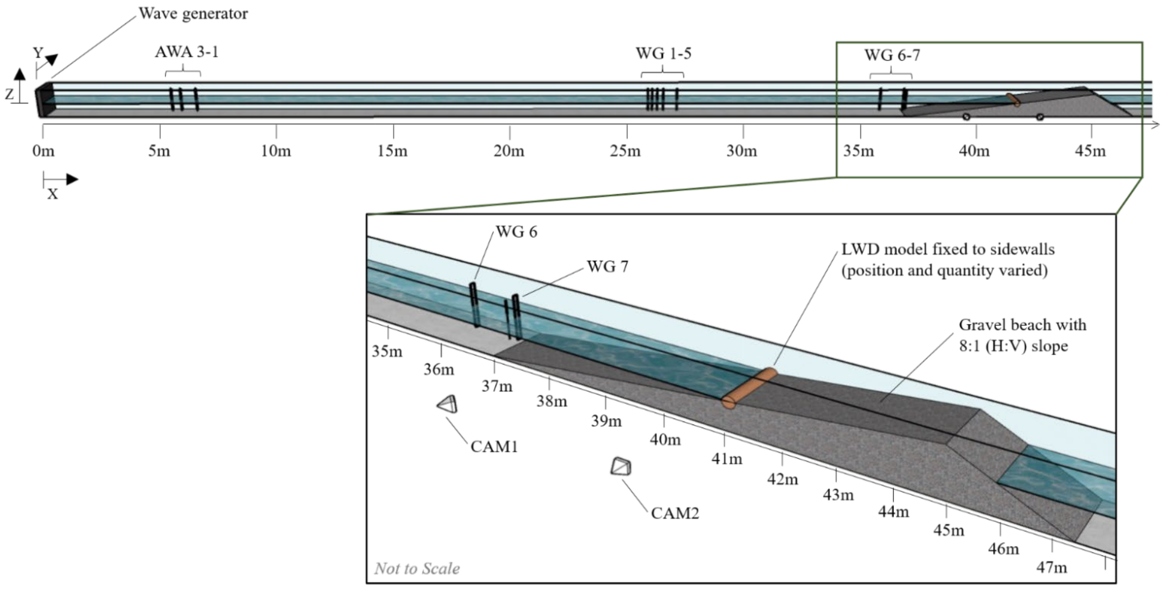

Figure 1. Schematic of experimental set-up (not to scale).

The flume is equipped with a piston-type wave generator at the north end and uses an active wave absorption (AWA) system to suppress wave energy reflected from the beach and LWD structure during the tests. The coordinate system adopted for this experimental program is shown in Figure 1 and is consistent with previous experiments on gravel beach morphology conducted by Atladottir (2008). A constant water depth of 0.6 m was maintained during all experiments and this still water level was set as the datum for all elevation measurements.

A gravel beach with a median grain size, D_{50}, of 7.9 mm (prototype D_{50} of approximately 40 mm, cobble) was installed at an 8:1 (H:V) slope (Falkenrich et al. 2021). The set-up generally coincided previous field observations, which found that anchored LWD structures were generally installed on the upper beach with a slope of approximately 7.6:1 and a sediment size between 18 mm (gravel) to 140 mm (cobble) (Wilson et al. 2020).

Model logs were constructed of hollow PVC pipes with steel and rubber end caps (Figure 2). Each model log was 0.114 m in diameter to simulate a 0.56 m diameter prototype log typical of the LWD observed at sites previously surveyed by the lead author (Wilson et al. 2020). The model logs were fixed in various configurations (i.e., Single, Double, Benched, and Matrix configurations) informed and inspired by previous field observations by the lead author (Figure 3).

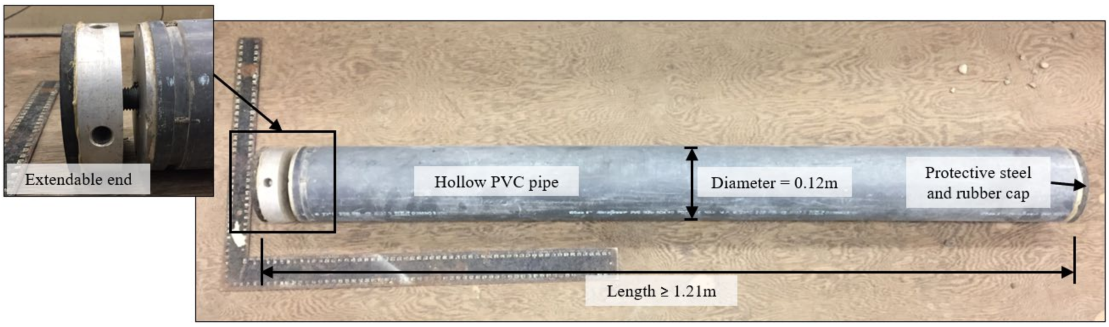

Figure 2. Model log, manufactured with hollow PVC piping, steel caps, and rubber ends. One end extends to provide lateral pressure and fix the log in place.

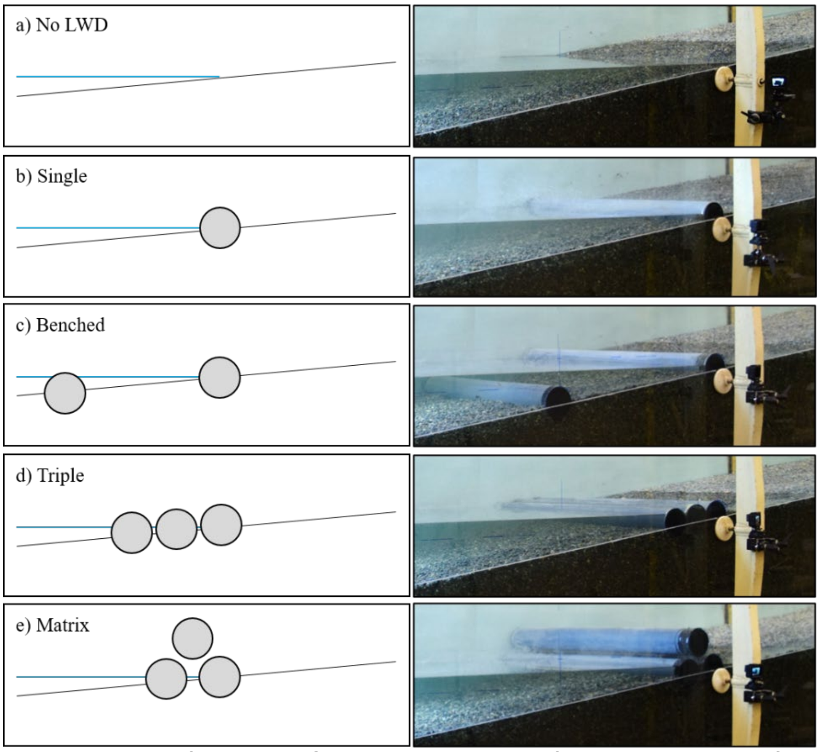

Figure 3. Test configurations. Conceptual sketches (left) and photographs of the experimental set-up (right).

Instrumentation

An array of ten capacitance-wire wave gauges (Figure 1) was used to assist with real-time wave absorption, post-test reflection analysis, and measurement of the incident wave conditions. Wave gauges were calibrated prior to starting the test program and the calibration was checked prior to every test. Wave gauges were re-calibrated periodically during the test program such that the maximum error was less than ±0.5% of the calibration range.

The 3D shape of the beach surface was measured before and after each test using a digital photogrammetry technique, and the pre- and post-test profiles were differenced to determine the beach profile change. Several beach surfaces were also measured using a FARO Focus-3D laser scanner for comparison with, and confirmation of the photogrammetry technique results. A comparison between the beach surfaces created from these two different techniques showed an average vertical difference of approximately 0.003 m and a maximum vertical difference of 0.026 m. Maximum vertical differences were located near the LWD structure, particularly where scouring had developed in front of and underneath the LWD structure. A qualitative review of the data indicated that the photogrammetry technique resulted in a more accurate representation of the beach surface in this area because photograph density was easily increased in the vicinity in order to appropriately resolve these features. Additional information on the photogrammetry technique and post-processing methodology can be found in Falkenrich et al. (2021).

Time lapse photos were also taken to capture dynamic beach profile changes. Photographs were rectified and the beach profile was manually digitized on a 10-minute interval. The digitized beach profile technique resulted in an accurate representation of the profile along the sidewall of the flume (with a mean difference of between 0.005-0.006 m and a maximum difference between 0.018-0.023 in comparison to the photogrammetry surface). However, due to wall effects, the digitized beach profile technique was not an accurate representation of the average beach profile. The digitized beach profile technique was therefore used as an indicator of beach profile evolution to confirm that beach equilibrium was met for each test, but was not relied upon for calculating volumetric beach profile changes.

Experimental Program

Over 60 tests were conducted by the authors. Of those, a subset of 28 experiments is discussed within this paper. All tests were conducted until beach equilibrium was reached (i.e., when little to no changes in the beach profile were observed).

A base set of three target random wave conditions (JONSWAP spectra, γ =3.3) were tested for each LWD configuration: (1) H_s = 0.10 m, T_p = 1.78 s, (2) H_s = 0.15 m, T_p = 2.17 s, (3) H_s = 0.20 m, T_p = 2.51 s. Tests were also conducted to assess experiment repeatability; sensitivity to test duration; sensitivity to wave height, wave period, and relative water level; and influence of log roughness. A complete list of the test variants and wave conditions are included Table 1.

Table 1. Experimental model variants at model scale. The base case (Test 04-v2) is indicated with an Asterix (*).

Test Description	Test No.	LWD Configuration	Log Elevation [m]	Wave Height H_{m0} [m]	Wave Period T_p [s]
Repeatability	01-v1	Single	0.0	0.18	2.38
	02-v1	Single	0.0	0.18	2.38
Simulation duration	04-v1	Single	0.0	0.20	2.51
	04-v2 *	Single	0.0	0.20	2.51
	20-v1	Single	0.0	0.20	2.51
Wave height and period	10-v1	Single	0.0	0.20	3.00
	09-v1	Single	0.0	0.20	2.80
	03-v2	Single	0.0	0.20	2.38
	05-v1	Single	0.0	0.15	2.38
	06-v1	Single	0.0	0.15	2.17
	07-v1	Single	0.0	0.10	2.38
	08-v1	Single	0.0	0.10	1.78
Elevation relative to water level	19-v1	Single	+0.1	0.20	2.51
	22-v1	Single	-0.1	0.20	2.51
	23-v1	Single	-0.2	0.20	2.51
Roughness	59_v1	Single-Rough	0.0	0.20	2.51
No LWD	18-v2	None	0.0	0.20	2.51
	16-v1	None	0.0	0.15	2.17
	21-v1	None	0.0	0.10	1.78
Benched	39-v1	Benched	0.0	0.20	2.51
	40-v1	Benched	0.0	0.15	2.17
	41-v1	Benched	0.0	0.10	1.78
Triple	28-v3	Triple	0.0	0.20	2.51
	29-v1	Triple	0.0	0.15	2.17
	30-v1	Triple	0.0	0.10	1.78
Matrix	46-v1	Matrix	0.0	0.20	2.51
	47-v1	Matrix	0.0	0.15	2.17
	48-v1	Matrix	0.0	0.10	1.78

Analysis of Beach Equilibrium

All tests were conducted until it was visually observed that little to no changes in the beach profile were occurring. Because previous experimental studies on gravel beach morphology did not detail systematic checks and thresholds used to determine beach equilibrium (e.g. Atladottir 2008; de San Román-Blanco et al. 2006; Frandsen et al. 2015; Kobayashi et al. 2011; Lee et al. 2007; Masselink and Turner 2012; Van Der Meer 1988; van Hijum and Pilarczyk 1982), a new method was developed for this study to systematically check that beach equilibrium was achieved after every test.

The beach profile evolution was monitored using digitized time-lapse photos of the beach profile at 10-minutes interval. The maximum absolute 10-minute elevation change, |dh|, was determined and plotted over time for each test. Because the areas directly in front of and behind the structures were subject to rapid scouring or deposition from individual waves, these areas were not included in the analysis. A threshold was set such that once the maximum |dh| remained below the threshold for three consecutive 10-minute intervals, the beach profile was considered to have reached equilibrium. Thresholds were varied in relation to the measured wave height, as follows:

- For $0.08 \text{ m} \leq H < 0.13 \text{ m}$, beach equilibrium threshold = 0.010 m
- For $0.13 \text{ m} \leq H < 0.18 \text{ m}$, beach equilibrium threshold = 0.015 m
- For $0.18 \text{ m} \leq H$, beach equilibrium threshold = 0.020 m.

As a result of this more detailed analysis, rather than relying on visual observations alone, two tests (test 03-v1 and 04-v1) were re-done with longer durations in order to reach beach equilibrium.

Measured Beach Profile Characteristics

Typical gravel beach profile features include an offshore trough, step, and terrace below the still water level, a steeply sloping beach face, and an above water berm (Atladottir 2008; Buscombe and Masselink 2006; Kennedy and Woods 2012; Kobayashi et al. 2011; Powell 1990). Key beach profile characteristics and variables used to compare beach profile characteristics in this study are shown in Figure 4. dh_{max} and dh_{min} are the elevations of maximum accretion and maximum erosion, respectively, measured vertically relative to the original beach profile. X_{crest} and Z_{crest}, and X_{trough} and Z_{trough} are the horizontal and vertical locations of dh_{max} and dh_{min}, respectively. V_{crest} and V_{trough} are the volume changes (measured in m^3 per m width of flume) measured on the upper and lower slopes, respectively, relatively to the original beach profile. The average of these two volumes, V_{avg}, is used as an indicator of the magnitude of sediment transport throughout each test.

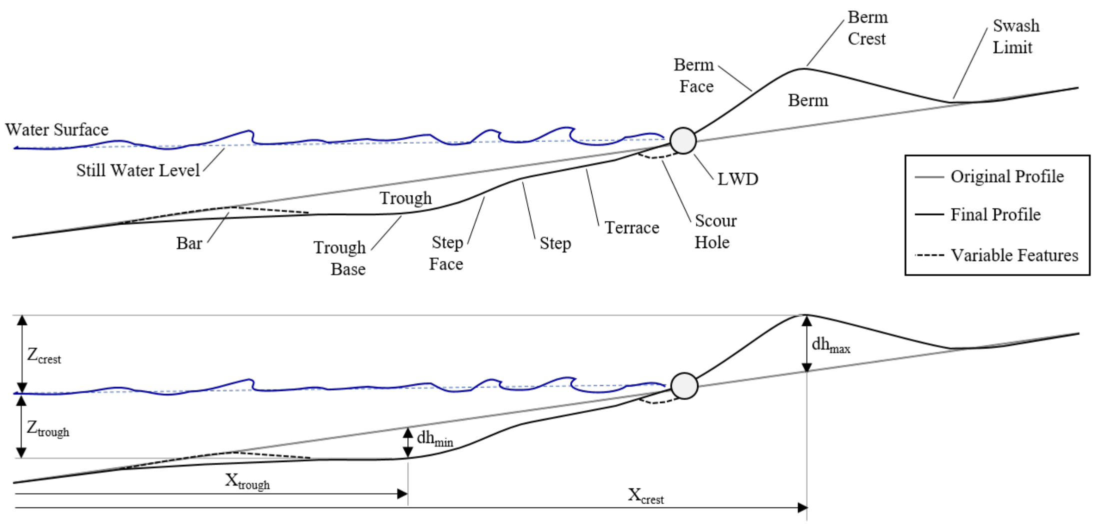

Figure 4. Beach profile characteristics (top) and variables (bottom) (adapted from USACE, 2002).

RESULTS

Repeatability

Two simulations (test 01-v1 and 02-v1) were conducted with the identical wave signal and flume set-up to test repeatability, the results of which are shown in Figure 5. The overall beach shape closely matched for both tests. The mean vertical difference over the entire beach profile was 8.6 mm, with a standard deviation of 6.2 mm. The measured profiles had a maximum difference of 45.1 mm. Maximum differences were located on the beach berm face where there was a steep change in elevation, and directly seaward of the LWD structure, where scouring occurred. The beach crest location was shifted inland approximately 60 mm for test 02-v1. However, the maximum erosion and maximum accretion, dh_{max} and dh_{min}, were within 0.8% and 5.7%, respectively. The volume change on the upper and lower slopes were also closely matched between the two tests, within 1.3% and 0.7%, respectively.

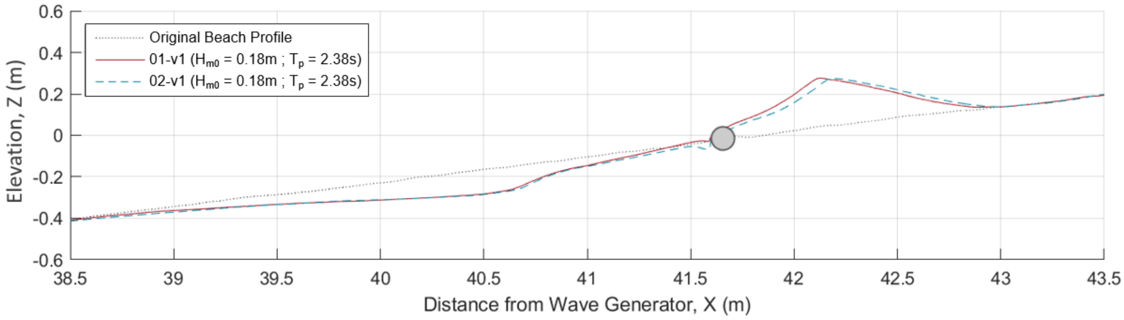

Figure 5. Comparison of the equilibrium beach profile for repeated tests for a Single LWD structure (01-v1 and 02-v1).

Effect of Test Duration

The base case scenario (single LWD with H_s = 0.20 m and T_p = 2.51 s) was tested for three different durations to assess the influence of test duration and the number of waves on beach morphology (Figure 6): (1) 3 hours (test 04-v1), (2) 4 hours (test 04-v2), and (3) 6 hours (test 20-v1). Note that test 04-v1 did not reach beach equilibrium.

The average volume of material that moved from the lower to upper slope, V_{avg}, was 0.169, 0.197, and 0.211 m^3/m for tests 04-v1, 04-v2, and 20-v1, respectively. The rate of volume change was four times higher between hours 3 - 4 (waves 5,370 – 7,230) than hours 4 – 6 (waves 7,230 – 10,820), indicating that the rate of change was highly non-linear. Similarly, the elevation increase at the berm crest, dh_{max}, was 0.262, 0.298, and 0.310 m, while the elevation decrease at the beach trough, dh_{min}, was -0.154, -0.173, and -0.193 m for tests 04-v1, 04-v2, and 20-v1, respectively. The rate of change for these two parameters also decreased in non-linear fashion as test duration increased. The horizontal location of the berm crest stayed at approximately the same location; however, the trough continued to move offshore as the number of waves increased.

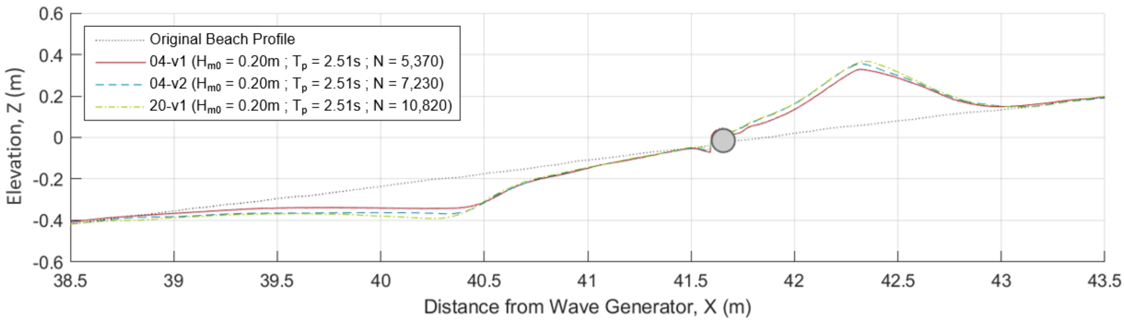

Figure 6. Influence of simulation duration on the equilibrium beach profile. Tests with varying duration (e.g. number of waves) and constant incident wave conditions for a Single LWD structure (04-v1, 04-v2, 20-v1).

Effect of Wave Height and Period

Simulations were conducted to test the influence of wave height and wave period independently on beach morphology for a Single LWD structure, the results of which are shown in Figure 7 and 8, respectively. The beach crest and trough both increased in height/depth and increased in distance away from the LWD structure. The beach terrace maintained elevation, but increased in width with an increase in wave height. Wave period was found to have less of an influence on beach profile behaviour, although an increase resulted in a marginally deeper beach trough and higher beach crest. The beach terrace position and width were maintained, regardless of the incident wave period.

The average volume change, V_{avg}, for each test is also shown in Figure 9. The volume of sediment that moved upslope increased proportionally to the incident wave height. The volume change was only weakly dependent on the wave period.

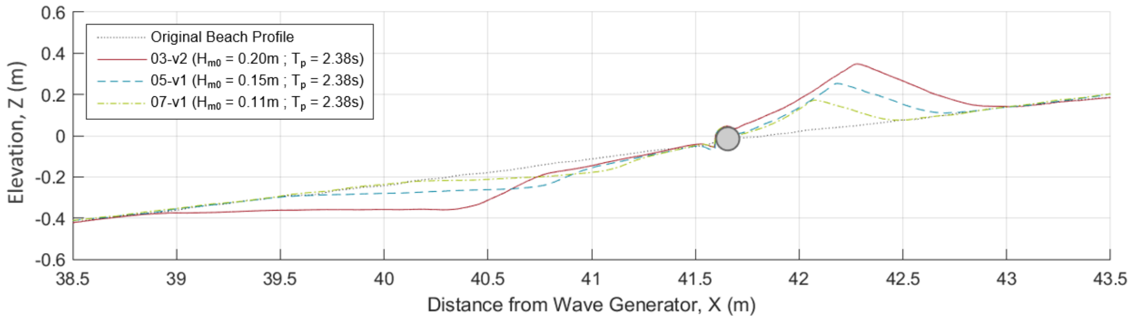

Figure 7. Influence of wave height on the equilibrium beach profile. Tests with varying wave height and constant wave period for a Single LWD structure (03-v2, 05-v1, 20-v1).

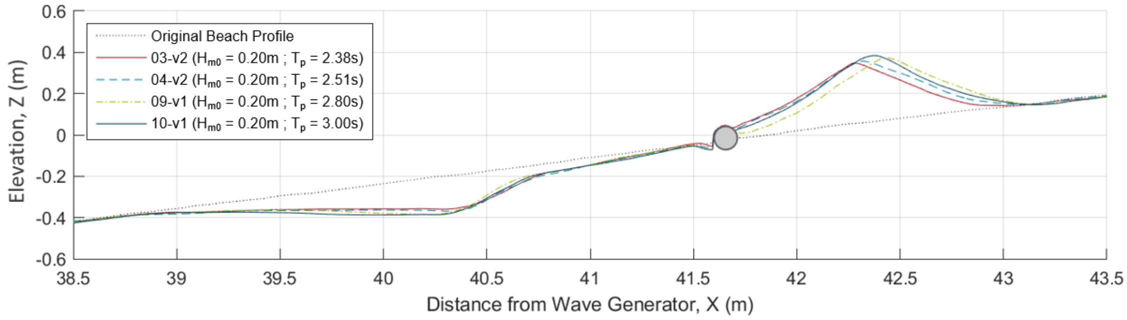

Figure 8. Influence of wave period on the equilibrium beach profile. Tests with varying wave period and constant wave height for a Single LWD structure (03-v2, 04-v2, 09-v1, and 10-v1).

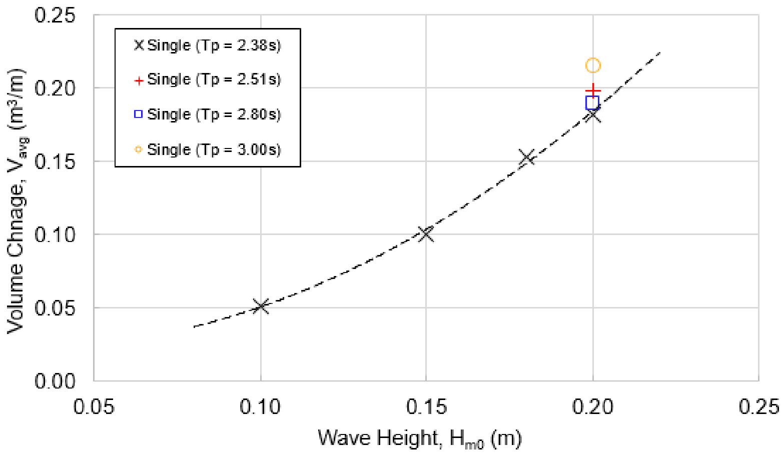

Figure 9. Influence of wave height, H_{m0}, and wave period, T_p, on volume change, V_{avg}, for a Single LWD structure. Dashed line is a fitted second-order polynomial for a constant wave period of T_p = 2.38s.

Effect of Roughness

During the first phase of the research project, Wilson et al. (2020) found that existing anchored LWD projects utilized both logs with and without bark. A sensitivity test was conducted to test the effect of log roughness from bark. This was done by adding a 2 mm thick layer to the surface of the LWD model and incising 4 mm deep roughness elements while maintaining the model's LWD diameter.

The beach crest and trough heights did not change significantly due to the addition of roughness elements (Figure 10). The volume change, V_{avg}, was reduced by 4.7% through the addition of roughness, which is considered to be within the margin of error for these model tests.

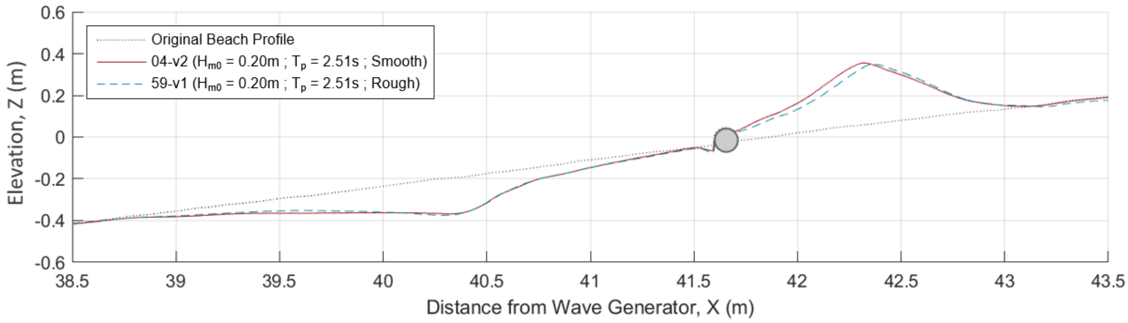

Figure 10. Influence of LWD roughness on the equilibrium beach profile for a Single LWD structure (04-v2 and 59-v1).

Influence of LWD Placement Elevation

Four LWD placement elevations were also tested: +0.1 m, 0.0 m, -0.1 m, and -0.2 m relative to the still water level (Figure 11). The LWD placed at 0.0 m and +0.1 m elevation resulted in nearly identical beach profile shapes and volume changes of approximately 0.200 m^3 per m width.

The LWD placed at -0.1 m resulted in reduced trough erosion and approximately 45% of the volume change, V_{avg}, observed in the two higher placements. The resulting profile was much flatter, with a small offshore trough, a wide beach step, significant scouring directly in front of the LWD, and a depressed beach crest.

The LWD placed at -0.2 m was located approximately where the beach trough would normally form if no structure was present. Placing the LWD at this position resulted in reduced erosion at the beach trough; however, the placement allowed for sufficient energy transmission to erode the beach step, producing significant sediment transport upslope and subsequent berm building. The -0.2 m placement resulted in approximately 70% of the volume change observed in the two highest placements.

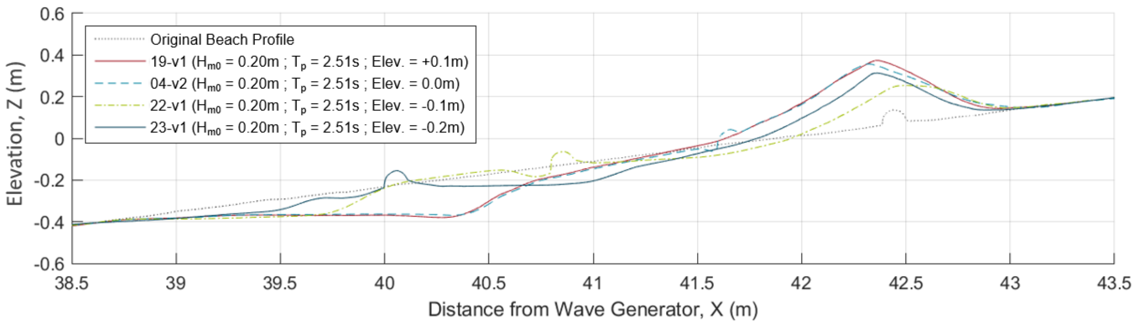

Figure 11. Influence of LWD elevation relative to the still water level on the equilibrium beach profile for a Single LWD structure (19-v1, 04-v2, 22-v1, and 23-v1).

Influence of LWD Design Configurations

Morphological experiments were conducted for four LWD design configurations and a beach with no structures for the three base wave conditions (Figure 12). Comparisons of the volume change, V_{avg}, are provided in Figure 13.

Three of the four LWD configurations were found to cause reductions in cross-shore sediment transport, with the Benched configuration (see Figure 13) being most effective in all three wave conditions. The Benched configuration was found to reduce cross-shore transport and volumetric change, V_{avg}, by up to 45%, compared to an equivalent beach without LWD. The beach trough was also located farther offshore and the beach crest farther onshore for the benched configuration in comparison to all others, resulting in a flatter beach profile overall.

Although less effective than the Benched arrangement, the Triple configuration was also effective at reducing volume change when compared to other options, particularly for the highest tested wave height, where it was responsible for reducing volume change by 26%, relative to the beach with no structures.

The Matrix configuration shifted the beach trough and crest approximately 0.2 – 0.3 m offshore in comparison to the beach with no structures. The configuration was found to nominally reduce volume changes compared to the beach with no structure for at all tested wave conditions.

A single LWD element anchored at the waterline resulted in a similar beach shape to the beach with no structures, with a deeper beach trough and a beach crest with a comparable elevation and position. This configuration was found to be the least effective structure of those tested. In fact, a 10% increase in cross-shore transport was observed for the Single configuration in the most energetic wave condition, compared to the beach with no structures. The other configurations all provided some beach stabilization benefits at all tested wave conditions.

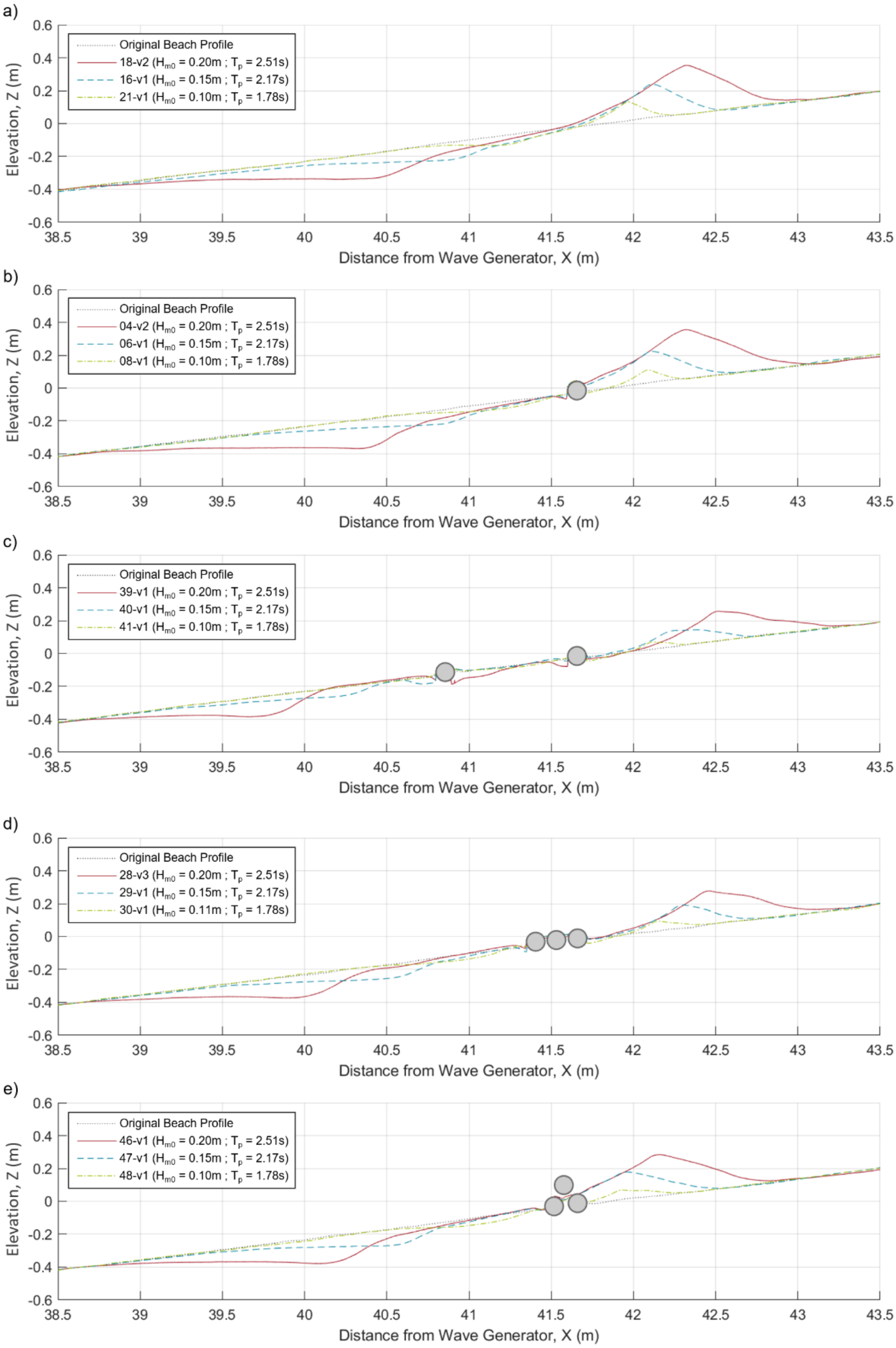

Figure 12. Influence of the LWD design configurations on the equilibrium beach profile under the three base wave conditions, for: (a) None, (b) Single, (c) Benched, (d) Triple, and (e) Matrix-style LWD structures.

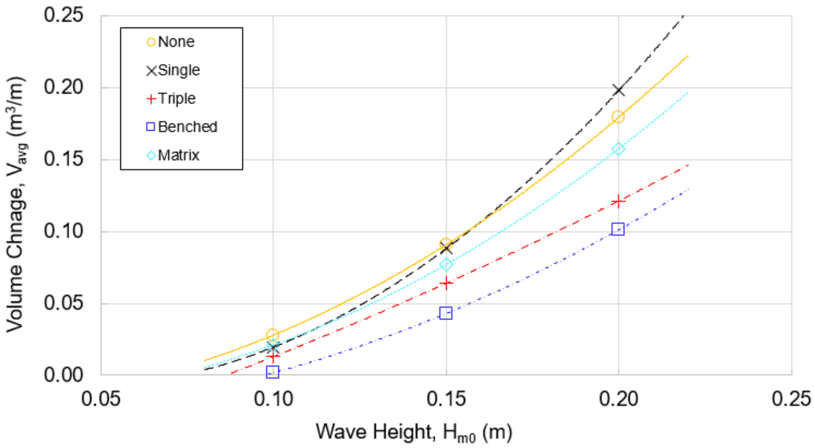

Figure 13. Comparison of volume change, V_{avg}, for each LWD configuration under the base set of three wave conditions. Dashed lines are fitted second-order polynomials.

DISCUSSION

General Observations

Typical gravel beach profile features (offshore trough and step, a steeply sloping beach face, and berm) were all observed during all the simulations, regardless of the presence of LWD structures. The elevation of the LWD structure and the LWD configuration type had a significant impact on the extent and location of the beach trough, the width of the beach step, and the elevation of the beach crest above water.

The wave height was found to significantly influence the beach profile development for the case with a Single LWD at the still water level for an 8:1 (H:V) initial beach slope. For this case, the maximum and minimum elevation changes, dh_{max} and dh_{min}, were found to increase linearly with wave height. Previous research on gravel beach morphology also indicated that wave height was a governing factor in beach profile development (Atladottir 2008; Powell 1990; Van Der Meer 1988). Based on this previous experimental work on gravel beaches with no structures (e.g. Atladottir 2008; Powell 1990; Van Der Meer 1988), wave period was also expected to be an important factor in beach development with LWD. However, a strong correlation was not found between wave period and the maximum or minimum elevation changes, nor the volume change. The lack of correlation may be because (1) the wave height (H_{m0} = 0.2 m) was relatively large and governed profile development, (2) the presence of LWD resulted in a beach response that was more resilient to the wave period, or (3) only a small range of wave periods were tested in comparison to previous studies.

Log Roughness

In a recent study on LWD transport in rivers, Perry et al. (2018) tested the behaviour of rough, natural log models in comparison to smooth models. They found that fabricated dowels exhibited different behaviour than natural wood (branches), suggesting that roughness played an important role in LWD transport and dam formation. As such, roughness elements were modeled to mimic and test the role of tree bark on beach morphology. LWD roughness was not found to be a major variable in beach profile development, although it may moderately reduce sediment transport upslope. Additional research is required to confirm this observation due to the limited number of tests conducted.

Beach Equilibrium

Beach equilibrium can be defined as the beach profile at which the net transport capacity has become zero (Van Der Meer 1988). In this study, beach equilibrium was assessed visually during the simulations and confirmed post-simulation by analyzing time-lapse photos of the beach profile on a 10-minute interval. For irregular waves, beach equilibrium was achieved after between 1500 – 6200 waves. This is consistent with most previous studies of irregular waves acting on mildly sloping gravel beaches, which generally found that beach equilibrium occurred between 3000 - 6000 waves (Atladottir 2008; Kobayashi et al. 2011; van Hijum and Pilarczyk 1982) or 1000 – 3000 waves (de San Román-Blanco et al. 2006; Masselink and Turner 2012; Van Der Meer 1988). Frandsen et al. (2015) found a much longer time for beach equilibrium (approximately 10,000 waves); however, they tested a mixed sand/gravel/cobble beach and only measured the beach profile after 2400 and 9800 waves, finding that beach equilibrium had only been met after the later of the two measurements.

Note that it is challenging to compare the current results on beach equilibrium with previous experiments due to a lack of continuity between test conditions (e.g. wave spectra, wave height, wave period, beach slope, and sediment diameter), measurement/analysis frequency, and a general lack of discussion regarding the metrics used for defining beach equilibrium in the available literature.

Repeatability

The repeated tests resulted in a close match in the overall beach profile shape and the volume of material that moved upslope. The greatest difference in the beach profile were noted on the beach berm face and directly seaward of the LWD structure, where scouring occurred. Scouring was observed to be highly dependent on the interaction of individual incoming waves and the run-down from the preceding wave (Figure 14). The resulting shape and depth of the scour hole therefore varied rapidly throughout the duration of tests. Despite this, there was only a 1% difference in the average volume change, V_{avg}, between the repeated tests. It can be concluded that the morphological response of the beach profile was both comparable and repeatable.

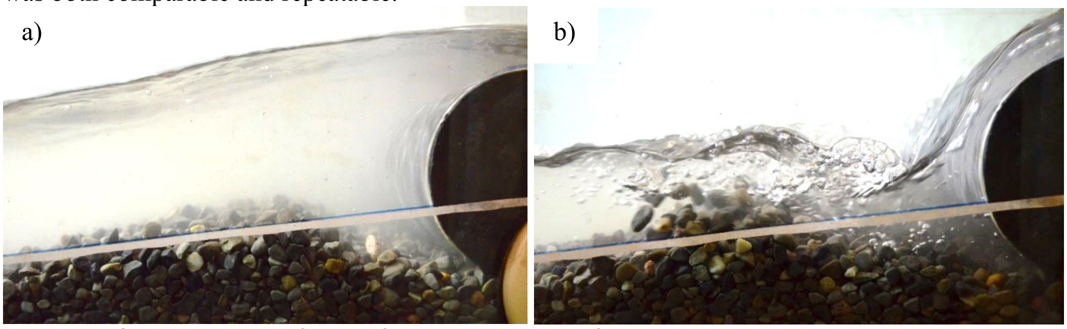

Figure 14. Close-up image of scour formation seaward of a LWD structure, during (a) wave run-up and (b) run-down

Design Guidance

Gravel beaches tend to result in narrow surf zones where waves break closer to the shore than on sand beaches. The offshore step acts as a submerged slope break, located at the base of the swash zone (Buscombe and Masselink 2006). At the step, wave bores develop, shoal, and collapse over the relatively shallow and flat beach section. The step allows waves to shoal in deep water, concentrating wave energy on the inshore edge of the step and creating the conditions to maintain a relatively steep and reflective step face. In part because of the energy concentration, a significant amount of sediment transport and beach profile change occurs near the step (e.g. Atladottir 2008; de San Román-Blanco et al. 2006; Kobayashi et al. 2011; Powell 1990). Th e beach step is therefore understood to force and modulate wave-breaking. The experimental modeling results indicate that the position of LWD is a major variable which controls the volume change and the beach profile shape. The most significant stabilization benefits are observed when LWD is anchored near the seaward edge of this step.

Theoretically there is a lower placement elevation at which the LWD will not influence wave interactions with the beach profile. For this study, the lower limit conceivably lies somewhere between the -0.2 m LWD placement and the maximum trough depth of -0.4 m. Insufficient data is available to develop an empirical equation characterizing the relationship between volume change and LWD placement elevation; however, a theoretical relationship between LWD elevation and volume change was hand-fitted based on the available data and the authors' understanding of the gravel beach profile development (Figure 15).

LWD configurations placed at or above the still water level did not provide significant shore stabilization benefits. For the highest wave heights, there was a potential for LWD to effect larger volume changes than a beach with no structure. Configurations which extended seaward or below the still water level, such as the Triple or Benched configurations, provided the largest benefits in terms of beach profile stabilization. Notably, Single LWD placed at -0.1 m resulted in approximately the same volume changes as the Benched structure for a wave height, H_{m0}, of 0.2 m, suggesting that upper log in the Benched configuration provided little stabilization benefits.

Placement of LWD structures near the beach step to maximize shore stabilization benefits will also locate them in regions of high wave energy, active erosion, and below the still water level. In practice, this creates a design problem of how to anchor a buoyant and mobile material on a dynamically changing slope and, if it becomes mobile, will it cause more damage than benefits.

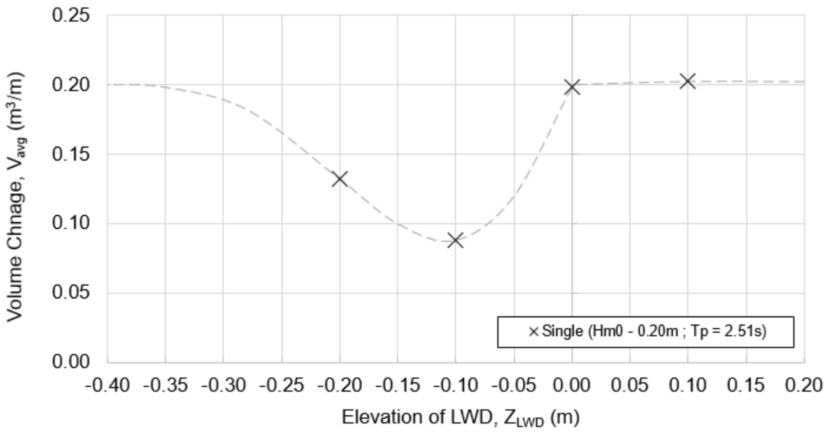

Figure 15. Influence of LWD elevation (relative to the water level at z = 0.0 m) on volume change, V_{avg}, for the base case scenario (single LWD with target wave characteristics: H_s = 0.2 m and T_p = 2.51 s). The gray dashed line is a hand-fitted theoretical relationship between LWD elevation and volume change.

Study Limitations

The experimental program focused on assessing the morphological response of a gravel beach due to various shore parallel LWD structures in comparison to a beach with no structures. Limitations of the study include the following:

- Only one sediment type and gradation were tested, resulting in a beach that was both porous (porosity, n = 40.5%) and homogeneous; however, many of the beaches where these structures are frequently constructed consist of mixed-sediment beaches (Wilson et al. 2020). A low beach groundwater table and porous material is generally understood to enhance sediment accretion on the shoreline, while a high groundwater table or impervious material is understood to inhibit accretion and promote erosion (Masselink and Turner 2012). As such, introducing a semi-impermeable layer and changing the beach porosity or adjusting the groundwater table may significantly modify the beach profile development (Bagnold 1940).
- On porous gravel beaches, larger sediments tend to move onshore and up-slope, while fine material tends to move down-slope (Buscombe and Masselink 2006; Masselink and Turner 2012). This phenomenon occurs because infiltration lowers velocities near the limit of wave run-up (Buscombe and Masselink 2006; Horn et al. 2006). Coarser material, requiring higher flow velocities for transport, becomes stranded on the upper beach, whilst wave run-down has sufficient velocity to wash away finer materials. Although steps were taken to remix sediments during the testing program, these physical processes led to some sediment sorting across the beach profile.
- Model logs were fixed in place on the beach by applying lateral pressure to the side walls of the flume, resulting in a static structure throughout the test duration. Although this behaviour is representative of anchored LWD at the time of initial installation, anchoring systems do generally allow for some dynamic movement of the LWD if sufficient undermining/scouring occurred.
- Due to the 2-Dimensional nature of the wave flume, all waves were normally incident to the beach and all tested configurations were shore parallel. These tests therefore do not consider longshore transport, which is often plays a significant role in erosion potential (Finlayson 2006).
- The models were completed at a 5:1 scale, according to Froude scaling. Generally, Froude scaling is suitable for free-surface flows and large scale and/or turbulent models (Sutherland and Soulsby 2010). Errors from Froude scaling occur when the fluid is not turbulent and viscous effects are non-negligible (e.g., distortion of the Reynolds number) (Heller 2011). No full-scale tests were completed to quantitively assess scale-effects; however, for this test program, the effect of viscous forces was expected to be minimal since turbulent conditions were maintained near the beach and the tests were conducted at a relatively large scale.

CONCLUSION

A comprehensive set of over 60 experimental tests were completed as part of the broader research program, which represented the first experimental study on LWD under wave action. A subset of 28 tests related to the morphological response of a gravel beach with and without various LWD configurations were explored in this paper.

Based on the study results, it was observed that anchored LWD can have significant effects on beach profile development, particularly for structures placed below the still water level, near or on the beach step. Anchored LWD placed near the beach step results in an elongated and flattened beach profile in comparison to a beach with no structure. Modelled configurations resulted typically resulted in reduced volumetric changes (V_{avg} of up to 45%), compared to an equivalent beach without LWD; however, in certain cases (i.e. the Single LWD at low wave heights), increased volumetric changes (V_{avg} up to 10%) were observed.

The study results indicated that, of the four LWD configurations tested, the Benched configuration resulted in the most stable beach profile, followed by the Triple configuration. A Single LWD configuration provided similar beach stabilization benefits as the Benched configuration when placed below the still water level, but may result in additional sediment transport when placed on the upper beach under large wave heights. The Matrix configuration provided only a small reduction in sediment transport. The LWD placement elevation relative to the still water level was found to be strongly correlated to the beach morphological response. Anchored LWD placed on the upper beach appears to provide no beach stabilization benefits.

Existing design guidance on the usage of anchored LWD as coastal protection has, to date, largely been based on anecdotal observations and experience, research on natural deposits of LWD, and a continuity of design practices from the river engineering field. Existing guidance (e.g. Johannessen et al. 2014; Zelo et al. 2000) generally provides the following design recommendations:

1. LWD are most suitable for low to moderate wave energy environments.
2. LWD should be anchored above the high-water mark, but within the maximum wave run-up limit.
3. LWD should be embedded or buried into the beach substrate.
4. LWD can be secured using rocks, root wads, or more traditional anchoring techniques, such as cables and buried blocks.
5. Designs should avoid using completely rigid anchoring systems.

Results of previous field studies by the lead author (Wilson et al. 2020) substantiate recommendation 1. The results of this study suggest that, for anchored LWD to be effective at beach stabilization, they should not be anchored above the high-water mark, contradicting recommendation 2. The study results do not provide insight into the remainder of the existing recommendations. Based on the findings of this study, a <u>revised</u> set of design guidance are proposed, as follows:

1. LWD are most suitable for low to moderate wave energy environments.
2. LWD should be anchored below the design still water level and above the limit of wave run-down to improve beach stability.
3. Benched, matrix, and matt-style configurations are expected to be most effective. Single configurations placed at or above the still water level do not appear to be effective.
4. LWD stability and longevity (i.e. decay rate) should be carefully considered.
5. Installations should be considered as pilot projects due to a lack of research, requiring monitoring and adaptive management.

Despite potential benefits to shore stabilization of coastal protection using LWD, a significant barrier to garnering this potential is how to effectively anchor LWD. To expand this work for engineering application and for the development of design guidance, additional research is required in the following areas:

- Further experimental modeling that includes variations in the initial beach slope, water level, log diameter, and sediment characteristics, including porosity, permeability, and gradation.
- Expand the existing experimental program to include a wide range of wave characteristics and allow for 3-D testing in a wave-basin for longshore sediment transport.
- Study the behaviour of dynamic (as opposed to static) anchored LWD structures.
- Test the influence of LWD structures on wave run-up and overtopping.

REFERENCES

Atladottir, A. 2008. Experimental Investigation of Wave-Induced Morphological Changes of Gravel Beaches. Master's Thesis. University of Ottawa. https://doi.org/https://doi.org/10.1002/ejlt.201200414

Bagnold, R.A. 1940. Beach Formation by Waves: Some Model Experiments in a Wave Tank. *J. Inst. Civ. Eng.,* 15, 27–52. https://doi.org/10.1680/ijoti.1940.14279

Bilkovic, D.M., M.M. Michell, M.K. La Peyre, and J.D. Toft. 2017. Living Shorelines: The Science and Management of Nature-Based Coastal Protection. Taylor & Francis, Boca Raton, FL.

Bocchiola, D. 2011. Hydraulic characteristics and habitat suitability in presence of woody debris: A flume experiment. *Advances in Water Resources,* 34, 1304–1319. https://doi.org/10.1016/j.advwatres.2011.06.011

Braudrick, C.A., G.E. Grant, and J.A. Jones. 2001. Entrainment and deposition of large woody debris in streams: a flume experiment 41, 263–283.

Brennan, J., H. Culverwell, R. Gregg, and P. Granger, 2009. Protection of marine riparian functions in Puget Sound, Washington. Seattle, WA.

Buscombe, D., and G. Masselink. 2006. Concepts in gravel beach dynamics. *Earth Science Review,* 79, 33–52. https://doi.org/10.1016/j.earscirev.2006.06.003

de San Román-Blanco, B.L., T.T. Coates, P. Holmes, A.J. Chadwick, A. Bradbury, T.E. Baldock, A. Pedrozo-Acuña, J. Lawrence, and J. Grüne. 2006. Large scale experiments on gravel and mixed beaches: Experimental procedure, data documentation and initial results. *Coastal Engineering,* 53, 349–362. https://doi.org/10.1016/j.coastaleng.2005.10.021

Eamer, J.B.R., and I.J. Walker. 2010. Geomorphology Quantifying sand storage capacity of large woody debris on beaches using LiDAR. *Geomorphology*, 118, 33–47. https://doi.org/10.1016/j.geomorph.2009.12.006

Falkenrich, P., J.L. Wilson, I. Nistor, N. Goseberg, A. Cornett, and M. Mohammadian. 2021. Nature-Based Coastal Protection by Large Woody Debris as Compared to Seawalls: A Physical Model Study of Beach Morphology and Wave Reflection. *Water,* 13(15). https://doi.org/10.3390/w13152020

Finlayson, D. 2006. The Geomorphology of Puget Sound Beaches, Puget Sound Nearshore Partnership Technical Report 2006-02. https://doi.org/10.1111/jsbm.12106

Frandsen, J.B., F. Bérubé, R. Xharde, and O.G. Tremblay. 2015. Large Scale Experimental Storm Impact on Nourished Beach Using Cobble-Gravel-Sand Mix, in: *Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore, and Arctic Engineering*, 1–10.

Gonor, J.J., J.R. Sedell, and P.A. Benner. 1988. What We Know About Large Trees in Estuaries, in the Sea, and on Coastal Beaches, in: *From the Forest to the Sea, a Story of Fallen Trees,* 83–112.

Grilliot, M.J., I.J. Walker, and B.O. Bauer. 2018. Airflow dynamics over a beach and foredune system with large woody debris. *Geosciences,* 8, 20. https://doi.org/10.3390/geosciences8050147

Heathfield, D.K., and I.J. Walker, 2011. Analysis of coastal dune dynamics, shoreline position, and large woody debris at Wickaninnish Bay, Pacific Rim National Park, British Columbia. *Canadian Journal of Earth Science,* 48, 1185–1198. https://doi.org/10.1139/E11-043

Heller, V. 2011. Scale effects in physical hydraulic engineering models. *Journal of Hydraulic Research,* 49, 293–306. https://doi.org/10.1080/00221686.2011.578914

Hilderbrand, R.H., D.A. Lemly, A.C. Dolloff, and K.L. Harpster. 1998. Design Considerations for Large Woody Debris Placement in Stream Enhancement Projects. *North American Journal of Fisheries Management,* 18, 161–167.

Horn, D., L. Li, D. Hornt, and L. Lit. 2006. Measurement and Modelling of Gravel Beach Groundwater Response to Wave Run-up: Effects on Beach Profile Changes. *Journal of Coastal Research,* 22, 1241–1249. https://doi.org/10.2112/06A-0006.1

Huff, S. 2015. Modeling the Influence of Large Woody Debris on Delta Morphology and Longshore Sediment Transport using the Brazos Delta. Rice University.

Hughes, S. 1993. Physical models and laboratory techniques in coastal engineering. *Coastal Engineering,* 7. World Scientific.

Hygelund, B., and M. Manga. 2003. Field measurements of drag coefficients for model large woody debris. *Geomorphology,* 51, 175–185.

Johannessen, J., A. Maclennan, A. Blue, J. Waggoner, S. Williams, W.J. Gerstel, R. Barnard, R. Carman, and H. Shipman. 2014. *Marine Shoreline Design Guidelines*.

Kail, J., D. Hering, S. Muhar, M. Gerhard, and S. Preis. 2007. The use of large wood in stream restoration: experiences from 50 projects in Germany and Austria. *Journal of Applied Ecology.* 1145–1155. https://doi.org/10.1111/j.1365-2664.2007.01401.x

Kennedy, D.M., and J.L.D. Woods. 2012. The influence of coarse woody debris on gravel beach geomorphology. *Geomorphology*. 159–160, 106–115. https://doi.org/10.1016/j.geomorph.2012.03.009

Kobayashi, N., B.S. Hicks, and J. Figlus. 2011. Evolution of gravel beach profiles. *Journal of Waterways Ports, Coastal, and Ocean Engineering,* 137, 258–262. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000085

Lee, K.H., N. Mizutani, D.S. Hur, and A. Kamiya. 2007. The effect of groundwater on topographic changes in a gravel beach. *Ocean Engineering,* 34, 605–615. https://doi.org/10.1016/j.oceaneng.2005.10.026

Masselink, G. and I.L. Turner. 2012. Large-scale laboratory investigation into the effect of varying back-barrier lagoon water levels on gravel beach morphology and swash zone sediment transport. *Coastal Engienering,* 63, 23–38. https://doi.org/10.1016/j.coastaleng.2011.12.007

Murphy, E., A. Cornett, I. Nistor, and S. Baker. 2020. Modelling Transport and Fate of Woody Debris in Coastal Waters. *Coastal Engineering Proceedings*, 36, 1-1.

Perry, B., C. Rennie, A. Cornett, and P. Knox. 2018. Comparison of Large Woody Debris Prototypes in a Large Scale Non-flume Physical Model, in: *E3S Web of Conferences.* EDP Sciences, Ottawa, 1–8. https://doi.org/10.1051/e3sconf/20184005010

Pontee, N., S. Narayan, M.W. Beck, and A.H. Hosking. 2016. Nature-based solutions: lessons from around the world. *Maritime Engineering,* 169, 29–36.

Powell, K.A. 1990. Predicting Short Term Profile Response for Shingle Beaches, Report SR2 19. Wallingford, Oxfordshire.

Rafferty, M. 2017. Computational Design Tool for Evaluating the Stability of Large Wood Structures. Technical Note TN-103.2 27.

Sass, G. 2009. Coarse Woody Debris in Lakes and Streams. *Encyclopedia of Inland Waters.* https://doi.org/10.1016/B978-012370626-3.00221-0

Sutherland, J., and R. Soulsby. 2010. Guidelines for Physical Modelling of Mobile Sediments. *Proceedings of Coastlab 2010.* 15.

USACE. 2002. Coastal Engineering Manual Part II, *Coastal Engineering Manual.* https://doi.org/10.1093/intimm/dxs026

Van Der Meer, J.W. 1988. Rock Slopes and Gravel Beaches under Wave Attack. PhD Thesis. Delft University.

van Hijum, E. 1975. Equilibrium Profiles of Coarse Material under Wave Attack. *Coastal Engineering*. 939–957. https://doi.org/10.1093/oseo/instance.00076483

van Hijum, E., and K.W. Pilarczyk. 1982. Gravel Beaches: Equilibrium Profile and Longshore Transport of Coarse Material Under Regular and Irregular Wave Attack.

Wallerstein, N.P., C.V. Alonso, S.J. Bennett, and C.R. Thorne. 2001. Distorted froude-scaled flume analysis of large woody debris. *Earth Surface Processes and Landforms,* 26, 1265–1283. https://doi.org/10.1002/esp.271

Wilson, J.L., I. Nistor, and M. Mohammadian. 2019. Nature-based coastal protection using Large Woody Debris: What is it and does it work?. *Climate-Resilient Coastal Natural Infrastructure Workshop*. Halifax, NS. https://doi.org/10.13140/RG.2.2.12171.54564

Wilson, J.L., I. Nistor, M. Mohammadian, A. Cornett, and G.F. Lamont. 2020. Assessing the Legacy of Large Woody Debris as Coastal Protection in BC and Washington. *Salish Sea Ecosystem Conference.* Vancouver, BC. https://doi.org/10.13140/RG.2.2.33556.86406

Zelo, I., H. Shipman, and J. Brennan. 2000. Alternative Bank Protection Methods for Puget Sound Shorelines. Olympia, WA.