Field Trials on a Living Dike in British Columbia: Wave Attenuation of Edge Treatment Features

by

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Abstract

Flooding poses a significant challenge for coastal cities worldwide, and recent interest has focused on implementing nature-based infrastructure projects for coastal flood risk management. However, a lack of monitoring data and technical guidance hampers their adoption. This study addresses this gap by providing wave transmission coefficients (K_t) for four edge treatment features at the Living Dike pilot project in Boundary Bay, British Columbia. Near-shore wave data from RBR pressure sensors deployed in cross-shore transects at the project site are supplemented by biweekly field observations assessing treatment stability and weathering. The four edge treatment features provided statistically significant reductions in wave height, with the brushwood dam exhibiting the lowest wave transmission coefficients at values of relative freeboard to significant wave height below -2 ($0.25 < K_t < 0.75$). These findings offer valuable insights into the use of nature-based infrastructure projects for coastal flood risk management strategies.

Keywords: coastal flooding; wave attenuation; tidal marsh; nature-based solutions; ecological restoration; Living Dike

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List of Acronyms

BC	British Columbia
CGVD28GVRD2018	Canadian Geodetic Vertical Datum of 1928 Greater Vancouver Regional District 2018
LDPP	Living Dike Pilot Project
NBI	Nature Based Infrastructure
NRC-OCRE	National Research Council of Canada’s Ocean, Coastal, and River Engineering Research Centre

Chapter 1.

Introduction

1.1. General Introduction

Coastal cities around the world are facing increasing exposure to flood hazards due to urbanization of coastal floodplains, sea-level rise, and ecosystem degradation [1,2,3,4,5]. Nature-based infrastructure (NBI) projects, such as restoring coastal wetlands in front of dikes, are hybrid systems of structural and natural elements and are emerging as viable options for coastal flood-risk management [6].

Restored coastal marsh systems or “living shorelines” serve as natural buffers, mitigating coastal flooding and erosion risks by absorbing wave energy, reducing wave heights, and stabilizing shorelines through the establishment of vegetation and the accumulation of sediment [7,8]. The construction process for these projects typically entails depositing fine-grained sediment along a shoreline, followed by the planting of marsh vegetation, and concluding with the installation of a temporary stabilizing edge treatment feature at the leading edge of the project to mitigate wave energy and erosion until the vegetation matures [9].

Despite the success of initial projects, barriers to the wider adoption of NBI persist, including the lack of monitoring data characterizing their performance in diverse environments and the absence of detailed technical guidance for designers [10]. Of particular interest for designers of nature-based coastal infrastructure projects is understanding how different features attenuate waves across various tidal and wave conditions. Understanding this knowledge gap is important, as evidence indicates that reducing wave energy on project sites can increase the efficacy of coastal NBI initiatives [11,12].

This study addresses these knowledge gaps by conducting an analysis of wave transmission coefficients—and providing stability estimates—for four edge treatmentsimplemented within a NBI pilot project in Boundary Bay, British Columbia (BC). The four edge treatments—a brushwood dam, a sand berm, a gravel berm, and an oyster bag berm—previously underwent testing in the National Research Council of

Canada’s Ocean, Coastal and River Engineering Research Centre (NRC-OCRE) wave flume by Provan et al. [9]. Building upon these laboratory findings, this study provides comparisons and additional insights derived from field trials. Notably, this study represents the only known wave dataset examining the effects of multiple nature-based edge treatments on wave attenuation in a field setting. By deploying RBR pressure sensors and conducting measurements over a four-month period, this study performed an analysis of the four edge treatments under various wave and tidal conditions. This research contributes quantitative wave transmission guidelines and qualitative stability estimates to the emerging field of NBI and provides designers with real-world data to guide the development of future coastal NBI flood and erosion risk-mitigation projects.

1.2. Fraser River Delta

The municipalities of Vancouver, Richmond, Delta, Tsawwassen, and Surrey are essential for the economic and demographic future of BC [13]. Their reliance on an extensive network of sea dikes to protect communities, infrastructure, and valuable assets from coastal flooding underscores a pressing need to address the challenges posed by rising sea levels in BC [13]. Positioned along the Salish Sea and the Fraser River, these municipalities confront dynamic flooding threats characteristic of low-lying urban areas worldwide.

These interconnected municipalities are situated on the Fraser River Delta, an estuarine ecosystem crucial to the region's ecological balance and resilience. Stretching approximately 37 km from the Burrard Peninsula to Point Roberts, the active western segment of the delta has evolved significantly since the Pleistocene era. The delta is characterized by substantial fluvial sedimentation that once nurtured expansive brackish tidal marshes along its leading edge [14,15,16]. Along the 13-km inactive southern section of the delta in Boundary Bay, the natural diversion of the Fraser River northward around 5000 BP led to a transition to a halophyte dominated salt marsh [14,16,17].

The Fraser River Delta continues to harbor a rich tapestry of ecosystems, ranging from expansive tidal mud flats to domed peat bogs [17]. Notably, the Fraser River stands as Canada's most prolific salmon river, a testament to the delta's ecological resilience and vitality [18]. Despite this resilience, tidal marshes across the delta are in decline [17,15]. The salt marshes in Boundary Bay have experienced a persistent decline in areal extents since the mid-1900s, and recent research conducted by Eric Balke [15] illuminates the alarming rate of brackish marsh decline along the active delta front [17]. These declines in critical tidal marsh ecosystems pose a threat to the integrity of many of the ecological processes in the Fraser River Delta [15,18]. Of consequential concern is the vulnerability of human flood-protection infrastructure to wave-induced damage caused by the reduction of protective tidal marsh, which further accentuates the need for concerted tidal marsh restoration efforts in the Fraser River Delta [8,7].

1.3. Salt Marshes In Boundary Bay

Tidal salt marshes, situated along the coastal margins of temperate and high-latitude regions, exist in dynamic equilibrium with sediment supplies, tidal inundation, and proximity to sediment sources [19]. In Boundary Bay, the construction of sea dikes likely exacerbated the decline of salt marshes by causing coastal squeeze which was further compounded by anthropogenic sea-level rise and deltaic subsidence [17].

Urbanization-induced alterations in sediment supplies also likely negatively impacted the dynamic equilibrium of these marshes [20]. Local sediment processes play a crucial role in determining the resilience of a marsh against rising sea levels, with low sediment availability leading to reduced marsh resilience [19,20]. Marsh vegetation aids in facilitating increased sedimentation rates by reducing local current velocities and sediment resuspension, which enables marsh expansion [19,21]. For all marsh vegetation, long periods of inundation increase physiological and physical stresses and can significantly constrain growth rates [22]. Additionally, biostabilizers like algal mats (i.e. microphytobenthos) decrease sedimentation by stabilizing sediments, and bioturbators, such as benthic shrimp, increase sedimentation by stirring up sediments and promoting sediment deposition [19,20,21]. If marsh vegetation declines, erosive processes typically revert a marsh platform to a (lower elevation) mud-flat [19]. In addition to these common estuarine pressures, the brackish marshes along the active portion of the Fraser River Delta are exposed to grazing by large populations of Lesser Snow Geese (*Chen caerulescens*) and non-migratory Canada Geese (*Branta canadensis*) [15,23,24]. This biological stressor is one potential factor driving marsh recession along the active portion of the Fraser River Delta [15,23,24]. Research on biological grazing has been confined to brackish marshes at this time and may not apply to the halophytic marsh vegetation in Boundary Bay [23,24,15].

1.4. Living Dike Project

The decline of salt marshes in Boundary Bay has likely heightened the risk of flooding in local communities and depleted crucial estuarine habitat [25]. In response, the City of Delta, the City of Surrey, and the Semiahmoo First Nation have collaborated to launch the Living Dike Pilot Project (LDPP) which aims to evaluate various salt marsh restoration techniques in Boundary Bay, with the overarching goal of mitigating coastal flooding and restoring estuarine habitat. The LDPP was developed in partnership with the Living Dike Roundtable, which is chaired by West Coast Environmental Law and the First Nations Emergency Planning Secretariat and hosts representatives from Indigenous, municipal, provincial, and federal governments, as well as rightsholders, technical experts, environmental regulators, and academic researchers [9]. The LDPP represents one of several pilot studies across Canada dedicated to exploring the potential of NBI projects to serve as alternatives or supplements to conventional infrastructure.

1.5. Project Site

The LDPP site is located in Boundary Bay, which is a shallow bay within the Salish Sea and hosts productive sand-and-mud-flats as well as remnant salt marshes. The Bay is bordered by the American pene-exclave of Point Roberts to the west, the cities of Delta and Surrey to the north, the Semiahmoo First Nation Reserve and the American city of Blaine to the east, and is open to the Strait of Georgia to the south. Shielded by the Point Roberts peninsula, Boundary Bay is protected from most wind-driven waves, with storms typically entering the bay from the south-southwest and southeast directions [26]. The Bay's foreshore has a typical gradient of 1(V):100(H) and is primarily comprised of sand-and-mud-flats [9]. Waves in Boundary Bay are considered to be depth-limited due to the bay's wide intertidal flats and low water depths [9]. Tides in Boundary Bay are mixed semidiurnal with a mean tidal range of 2.7 m, a minimum neap tidal range of 1.5 m, and a maximum spring tidal range of 4.1 m [27]. All of the LDPP sites are located within the Semiahmoo First Nation's traditional territory.

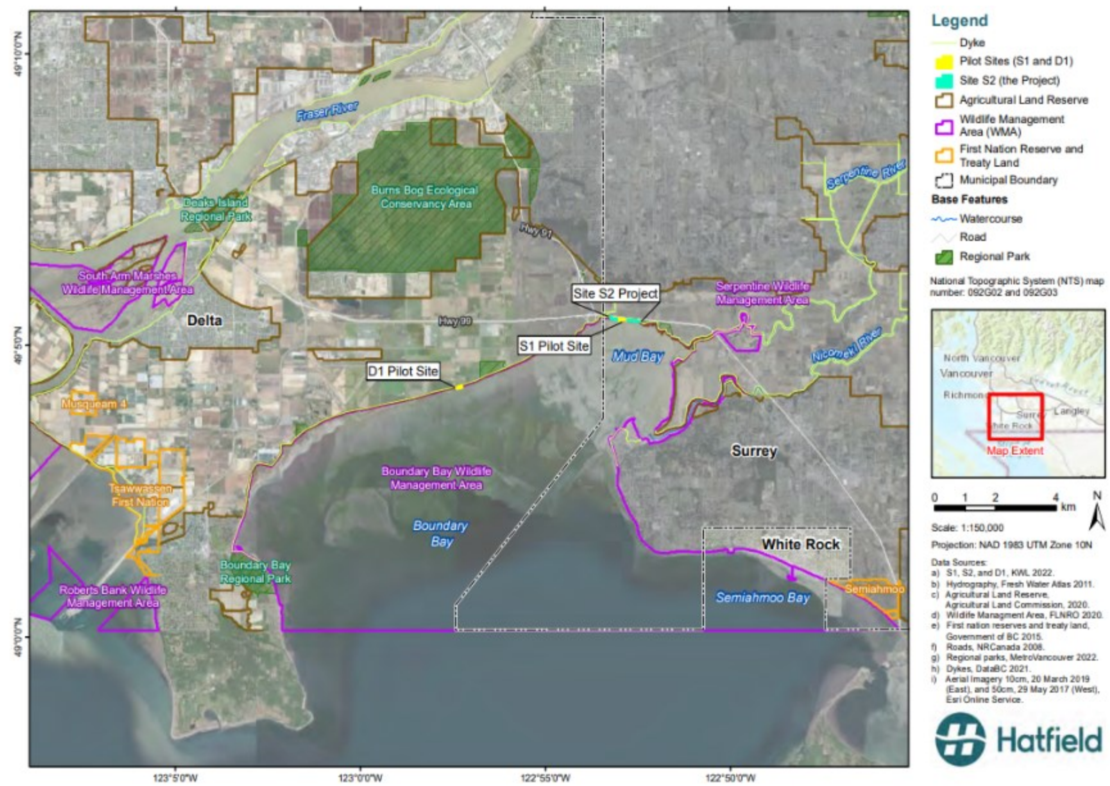

Figure 1: Map overview of the Living Dike pilot project D1 and S1 project locations in Boundary Bay, British Columbia. Created by Hatfield Consultants for the City of Surrey.

Figure 2: Picture overview of the Living Dike pilot project S1 site in Boundary Bay, British Columbia. View south overlooking the test plots. Image courtesy of City of Surrey.

1.6. Project Objectives

The LDPP aimed to evaluate the effectiveness of different restoration techniques (e.g. planting methods, marsh elevation variations, sediment composition, and edge treatments) in restoring the natural salt marsh ecosystem along the Boundary Bay sea dike [28]. This study focused on the four edge treatments: sand berm, gravel berm, brushwood dam, and oyster bag berm, which were intended to stabilize sediment and protect vegetation by reducing wave heights [28].

The D1 (City of Delta) site tested the sand and gravel berms and the S1 (City of Surrey) site tested all four edge treatments [28]. Both sites had subdivided plots to examine the effects of sediment composition, marsh elevation, and planting techniques on vegetation success [28]. This study specifically provided an analysis of the wave transmission coefficients and stability of the edge treatment features on the S1 site.

Figure 3: Approximate locations of the D1 and S1 LDPP sites in Boundary Bay, British Columbia (Google Earth).

1.7. Previous Research

The LDPP exemplifies NBI projects that leverage natural or restored ecosystems to address societal challenges like coastal flooding while also enhancing biodiversity and ecosystem integrity [12]. The Netherlands has been at the forefront of using restored salt marshes for coastal protection and Vuik et al. [8] demonstrated that dikes in the Netherlands featuring foreshore salt marshes exhibited decreased wave loads and run-up compared to dikes lacking marshes. Studies by Möller et al. [29] and Forysinski [7] confirm the wave-reducing capacity of tidal marshes, supporting their role in coastal NBI projects like the LDPP. Literature from salt marsh restoration in Europe and mangrove restoration in Asia has shown that reducing the wave-energy in a tidal restoration project can create the conditions necessary for vegetation to re-establish [8,11]. Upon re-establishment, tidal vegetation naturally attenuates waves [11,7,8].

The NRC-OCRE has been involved in conducting research on nature-based solutions across Canada. In a 2023 study at the NRC-OCRE, Provan et al. [9] tested the capacity of the four edge treatments installed on the LDPP to reduce wave heights in a wave flume. The study found that at water levels of +1.1 m, the gravel and brushwood dams were the most effective at reducing wave heights (reductions in wave heights of 83% and 72%, respectively) and at the +1.5 m water level the study found that only the gravel berm and brushwood dam reduced wave heights (15% and 13%, respectively), with the sand berm and oyster bag berm both providing negligible reductions in wave heights at the higher water level [9].

Provan et al. [9] also noted differences in scour and fill movement associated with each treatment. The brushwood dam in their study experienced scouring through the dam, leading to significant reshaping of the marsh fill leeward of the structure [9]. The sand berm underwent substantial remodeling, with most of the sand moving onto the marsh platform [9]. The gravel berm remained dynamically stable, although scouring occurred behind the berm due to waves breaking over the structure, and the oyster bag berm remained stable throughout testing, with limited movement of the placed fill [9].

1.8. Study Outline

The research objectives of this study are to report the wave transmission coefficients of the four edge treatments at the LDPP S1 site, provide an initial analysis of the weathering of each treatment over an eight-month period, and offer a practical comparison with the findings of the NRC-OCRE wave flume study conducted by Provan et al. [9]. Unlike the laboratory setting of the aforementioned study, our investigation evaluates the performance of the four LDPP edge treatments in a field trial. This distinction allowed for longer test durations and consideration of real-world weathering effects. Taken together, the two studies are complementary and provide an assessment of the effectiveness of the four edge treatments.

This study is structured into two main sections to address our research objectives. The first section focuses on establishing wave transmission coefficient equations for each treatment. By analyzing data collected between October 2023 and January 2024, this section provided valuable insights into the performance of the treatments under varying tidal and wave conditions. In the second section, we qualitatively monitor the weathering of the edge treatments from August 2023 to March 2024. This aspect of the study offered critical design insights for future projects by assessing the durability and long-term effectiveness of the treatments in real-world conditions.

Chapter 2.

Methods

2.1. Wave Monitoring

2.1.1. Experimental Setup

This section of the study outlines quantitative field measurements of nearshore waves and an analysis of wave transmission coefficients for the four edge treatments at the LDPP S1 site in Surrey, BC. Between October 2023 and January 2024, wave data was collected through near-continuous pressure measurements at points along five cross-shore transects (Figure 4). RBR pressure sensors were placed in three instrument transects to observe changes in sea state parameters (wave heights and periods) as waves propagated past each structure for a range of tidal conditions. The measured wave height attenuation across the four edge treatments was assessed and benchmarked against wave heights at an adjacent control transect to isolate the influence of the features from other processes affecting wave transformation (e.g., shoaling, depth-induced breaking, bed friction).

The RBRsolo pressure sensors operated in *wave* mode, sampling 4096 points per sample at 16 Hz with a 20-minute sampling interval. Positioned 0.05 m above the substrate, the RBRsolo sensors were affixed to perforated L-shaped angle bars driven into the substrate (Figure 5).

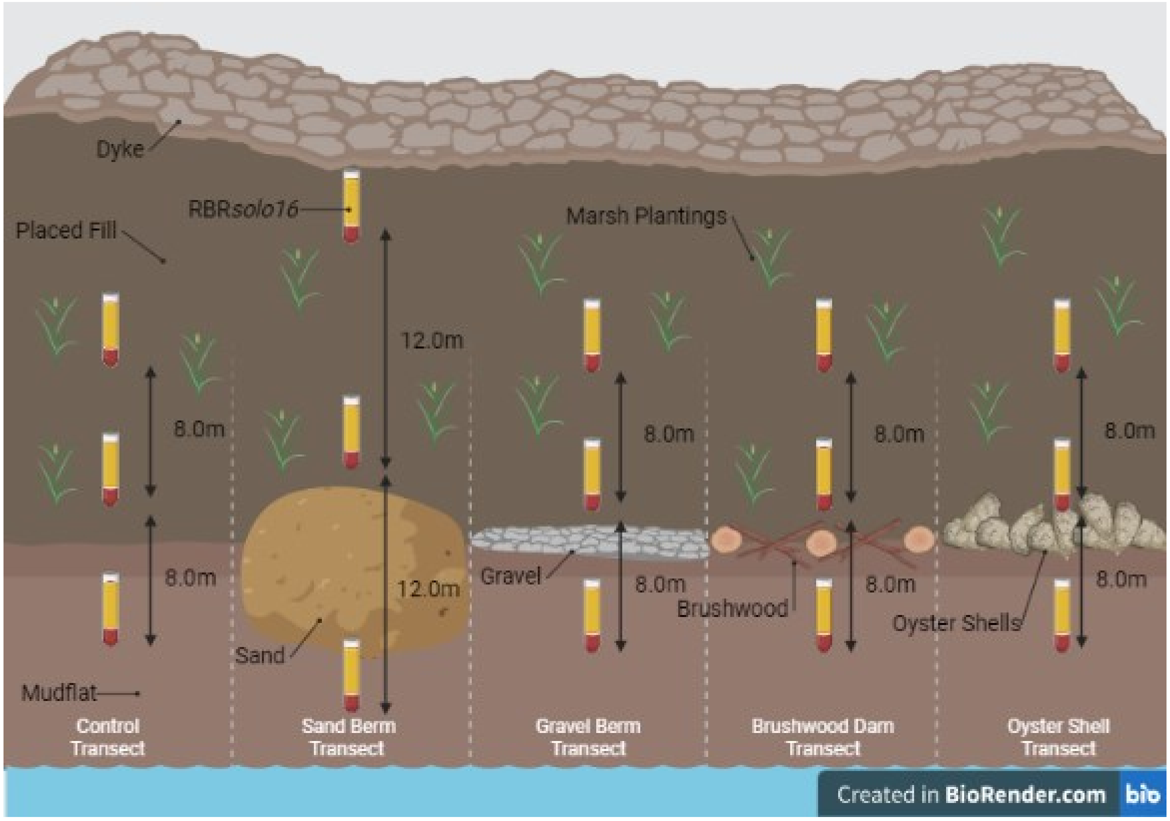

Figure 4: Plan view diagram of the wave monitoring transects at the S1 LDPP site in Boundary Bay, British Columbia. Not to scale.

Figure 5: Image showing an RBRsolo instrument attached to a perforated L-shaped angle bar at the S1 LDPP study site in Boundary Bay, British Columbia, used to obtain wave data from October 2023 to January 2024.

The brushwood dam stands 0.40 m tall and consists of untreated wooden posts, each with a diameter of 0.15 m, serving as anchor points (Figure 6, 7). Bundles of brushwood, measuring 0.30 m wide, and 2.0 m in length, are held together by 6 mm biodegradable twine and are securely fastened to the posts using 16 mm biodegradable rope. The gravel berm has a width of 2.0 m at its peak and has a seaward slope of 1(V):8(H) towards the mudflat (Figure 6, 8). Approximately 0.35 m in height, the berm uses $D_{50} \approx 70$ mm gravel, with an additional granular filter gravel positioned along the landward side of the plot. The sand berm spans 15.0 m in width, stands at approximately 0.40 m in height, features a frontal slope of 1(V):4(H), and is composed of imported sand material ($D_{50} = 0.30$ mm; Figure 6, 9). The oyster berm is approximately 0.40 m tall, 1.0 m wide, and consists of oyster shells enclosed in biodegradable plastic meshing with a mesh size of 1.0 cm (Figure 6, 10). The berm is stacked with three bags on the bottom layer and two on the top, with a granular filter gravel placed on the landward side of the plot. The elevations (in meters above geodetic datum, CGVD28GVRD2018) of the top of each structure are as follows: the brushwood dam ranges from 1.3 m to 1.4 m, the gravel berm stands at 1.1 m, the sand berm at 1.0 m, and the oyster bag berm varies between 1.1 m and 1.2 m. For context, Higher High Water Mean Tide is 1.1 m elevation (CGVD28GVRD2018) and 4.0 m elevation (Chart Datum).

Figure 6: Image showing the four edge treatments at the S1 LDPP study site in Boundary Bay, British Columbia. Clockwise from the top left: brushwood dam, gravel berm, sand berm, oyster bag berm.

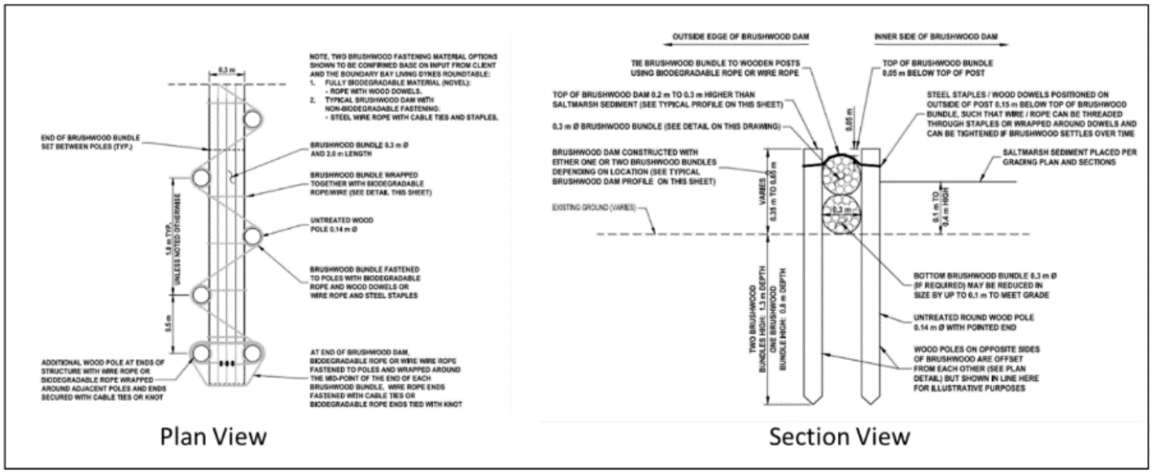

Figure 7: Proposed S1 design detail of the brushwood dam edge treatment [30].

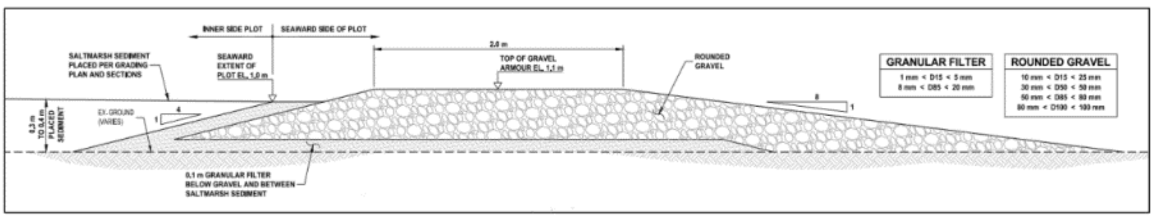

Figure 8: Proposed S1 design of the gravel berm edge treatment [30]

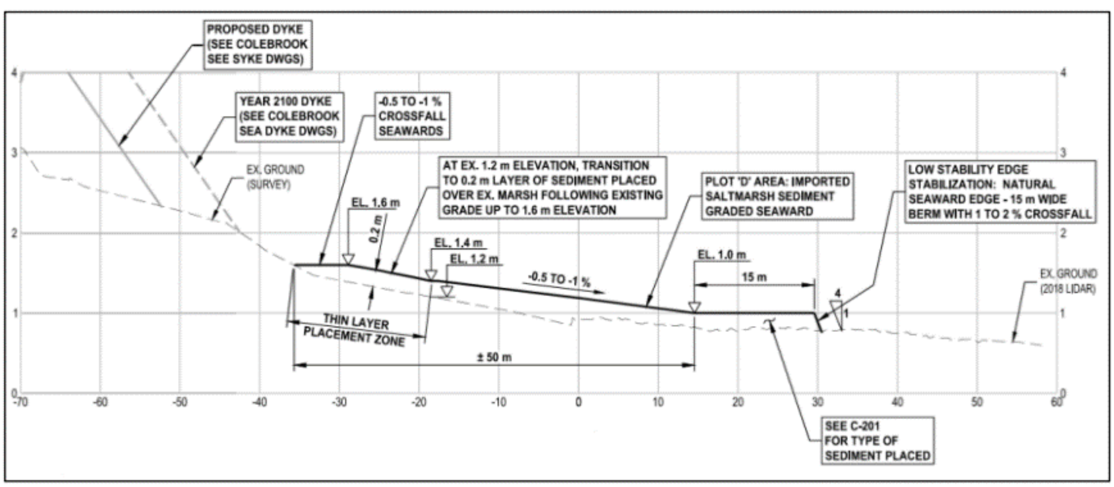

Figure 9: Proposed S1 design of the sand berm edge treatment plot [30].

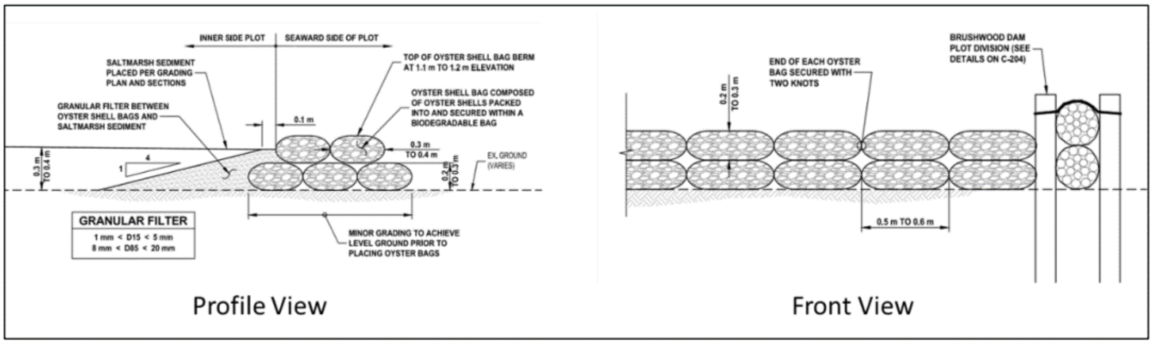

Figure 10: Proposed S1 design of the oyster-shell bag berm edge treatment [30].

2.1.2. Data Analysis

All analyses were performed in R Statistical Software (v4.3.1; R Core Team 2023). Multiple R scripts were used throughout the study and their main assumptions and filters are detailed below. The wave data obtained from the RBR sensors was initially processed through the proprietary Ruskin software that provided the following wave analytics: water depth, significant wave height, significant wave period, maximum wave height, maximum wave period, average wave height, and mean wave period.

Wave Transmission Coefficients

The wave data was analyzed to evaluate wave transmission coefficients for the four edge treatments. The wave transmission coefficient (K_t) is defined as the ratio of the transmitted wave height (measured landward of the edge treatment) to the incident wave height (measured immediately seaward of the edge treatment). A K_t of 0.6 indicates that the transmitted wave height is 60% the size of the initial wave height and that there was a 40% reduction in wave height through the structure. Wave transmission coefficients of the edge treatments were highly dependent on incoming wave parameters and tidal conditions; thus, it was important to use an analysis method that combined these two parameters. The methods outlined by Schmitt et al. [31], in their study of brushwood dams in Southeast Asia, was adapted for this study.

Following the methods of Schmitt et al. [31], the wave transmission coefficients for each treatment were graphed (see Figures 12-14). The x-axis shows the influences of the water depth relative to the crest height of each feature (also referred to as "freeboard", R_c) divided by the incident significant wave heights (H_s). The freeboard, R_c, for each feature was calculated based on elevation data obtained through a handheld survey using a Spectra Geospatial RTK GPS (SP85 GNSS receiver) (vertical precision ±15 mm). The freeboard refers to the location of the water surface in relation to the top of each edge treatment: the R_c is positive when the water level is below the top of the structure and is negative when the structure is submerged, and since the control transect had no structure its freeboard was considered zero at bed elevation. In this case, the use of R_c (instead of water depth) allowed the performance of each edge treatment to be directly compared even though the height of each treatment varied. The ratio of R_c to significant incoming wave height, *Hs,* was then calculated by dividing the R_c for each data point by the H_s from the same data point. The wave transmission coefficient (K_t) is on the y-axis.

Data Filtering

Waves entering shallow water undergo various transformation processes. To isolate the influence of the edge treatments on transmitted wave heights, it was necessary to estimate contributions from other wave transformation processes, such as shoaling. Wave shoaling, which results in an increase in wave height, a decrease in wavelength, and a reduction in wave speed, was accounted for in each edge treatment through the following steps. Estimates of the shoaling coefficient at instrument 1 (*Ks1)* were obtained by taking the ratio of significant wave height at instrument 1 (H_{s1}) and significant wave height at a distance offshore where the wave has no interaction with the seafloor (H_{s0}). The same method was used to estimate the shoaling coefficient at instrument 2 (K_{s2}): which was larger due to it being at a higher elevation on the placed fill. The relative shoaling coefficient ($K_s = K_{s2}/K_{s1}$) was then found by taking the ratio of the shoaling coefficients at instruments 1 (K_{s1}) and instrument 2 (K_{s2}).

The relative transmission coefficients for each data point were then calculated by dividing the ratio of significant wave heights at instrument 2 (H_{s2}) and instrument 1 (H_{s1}) by the relative shoaling coefficient (K_s). The resulting transmission coefficient accounted for the increase in wave heights expected from wave shoaling over the elevated fill sections of the plots.

$$H_{s2} = K_s * K_t * H_{s1} \quad \text{Eq. 1}$$

$$K_{s1} = \frac{H_{s1}}{H_{s0}} \quad \text{Eq. 2}$$

$$K_{s2} = \frac{H_{s2}}{H_{s0}} \quad \text{Eq. 3}$$

$$K_s = \frac{K_{s2}}{K_{s1}} \quad \text{Eq. 4}$$

$$K_t = \left(\frac{H_{s2}}{H_{s1}}\right) * \left(\frac{1}{K_s}\right) \quad \text{Eq. 5}$$

In these equations, K_s is the relative shoaling coefficient which describes the expected change in wave height due to the elevation difference between instrument 1 and instrument 2; K_{s1} is the shoaling coefficient at instrument 1 (calculated from a deep-water wave); K_{s2} is the shoaling coefficient at instrument 2 (calculated from a deep-water wave); K_t is the coefficient describing the reduction in wave height due to transmission through the edge treatments; H_{s0} is the significant wave height in deep-water; H_{s1} is the significant wave height at instrument 1; H_{s2} is the significant wave height at instrument 2.

Other shallow-water wave transformation processes include depth-induced wave breaking, reflection, and frictional dissipation. It was not possible to isolate and remove all these effects from the wave data, and therefore, transmission coefficients likely include some contributions from these processes [32,9,33]. However, since the pressure sensors in each transect were in close proximity to the edge treatments on either side, it is reasonable to expect that any measured decreases in wave heights in the shoreward direction are predominantly caused by the edge treatment.

After accounting for wave shoaling, the *identify_outliers* function, from the *rstatix* package, in R was used to identify outliers in the transmission coefficient dataset, which were then removed. Most of the outliers in the initial dataset were caused by low-water levels at the second set of instruments. Low-water levels would cause the significant wave heights at the second instruments to be unrealistically low, due to the second instrument being at a higher elevation on the placed fill, which would result in unrealistic transmission coefficient values. The analysis portion began after outliers were removed.

Data Analysis

To begin the analysis, the full dataset (four edge treatments and control transect) was run as a multiple linear regression model in R using the *lm* function from the *stats* package. The linear regression model considered three terms: the ratio of freeboard to significant wave height, the different edge treatments, and an interaction term between the two previous terms. All linear regressions were tested for assumptions.

After determining that all three terms had a significant impact on the wave transmission coefficients, a simple linear regression using only one treatment at a time was run to ascertain the linear regression equations for each treatment. To derive the linear regression equations for each individual edge treatment, we applied a simple linear regression model containing only the ratio of freeboard to significant wave height term to datasets containing only the linear portion of data. The range for each individual treatment's linear regression was determined by assessing the endpoints of each linear line displayed in Figure 12. Subsequently, the nonlinear data points were filtered out, and a linear regression analysis was conducted, yielding the corresponding linear regression equations (Table 1).

2.2. Edge Treatment Condition Monitoring

2.2.1. Methods

The condition monitoring study commenced in August 2023, wherein two photo monitoring locations were designated for each edge treatment, and images of the treatments were obtained every two-to-three weeks. During each site visit the treatments were inspected for signs of weathering and detailed notes were taken when these signs were observed. The notes were compiled at the conclusion of the study in March 2024, and the relevant findings are discussed in the results section of this paper.

Chapter 3.

Results

The following chapter presents the results of the four-month monitoring study. Wave statistics from the site are presented followed by the linear equations corresponding to the wave transmission coefficients of each edge treatment and concluded by the results of the degradation monitoring portion of this study.

3.1. Wave Monitoring

3.1.1. Wave Statistics

Wave heights during the wave monitoring period (October 2023 to January 2024) ranged from 0.05 m (the chosen minimum value) to 0.46 m during a large southwestern storm in January 2023; mean wave periods were between 0.5 s and 3.5 s; and the greatest water depth at the first instrument in the control transect was 1.33 m. The wave heights and wave periods increased month-to-month from October to January, with the highest waves and longest wave periods observed in January (Figure 11). This seasonality of larger storm events in the winter was anticipated.

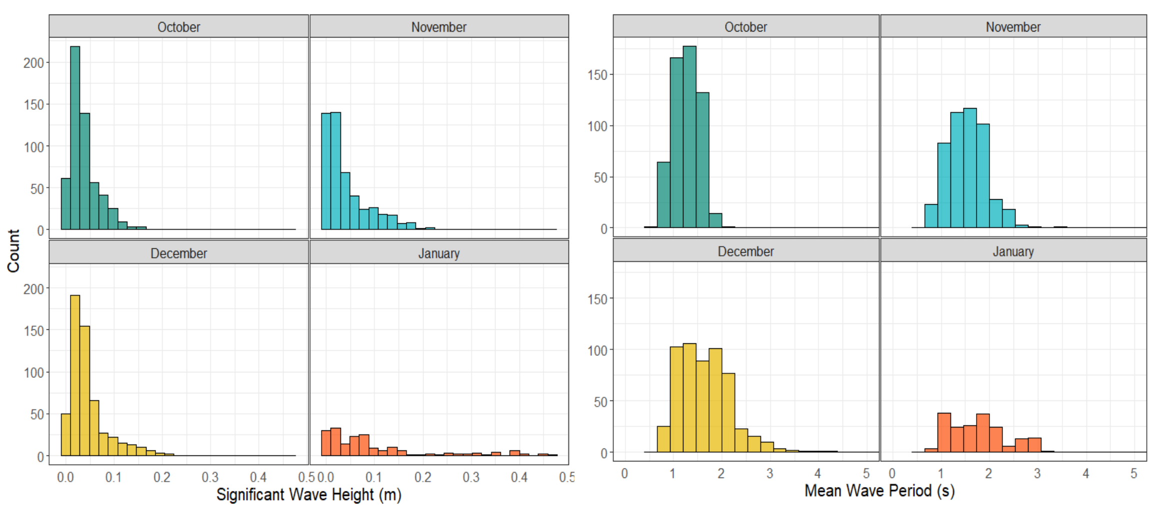

Figure 11: Histograms showing the distribution of Significant Wave Heights (left) and Mean Wave Periods (right) per month throughout the October – January study period at the S1 site in Boundary Bay.

3.1.2. Transmission Coefficients

A graphical comparison of the wave-height evolution for each edge treatment showed that the brushwood dam treatment had a lower wave transmission coefficient than the other treatments at ranges of $R_c/H_s \lesssim -2$ (Figure 12). The oyster bag berm and the sand berm performed similarly, and the gravel berm performed slightly worse at values of $R_c/H_s \gtrsim -2.5$. All four treatments provided statistically significant wave attenuation (p < 2e-16) compared to the control transect. The four edge treatments all had an initial linear slope followed by a trend towards a horizontal asymptote at values of K_t around 1.0. Based on findings from other studies, the main mechanisms of wave attenuation at R_c/H_s values less than 0 (structure fully submerged) are likely structure-induced wave breaking and frictional dissipation [32,33]. Overtopping and reflection reportedly become the predominant mechanisms of wave attenuation at values of R_c/H_s above 0 (structure not fully submerged) [32,33].

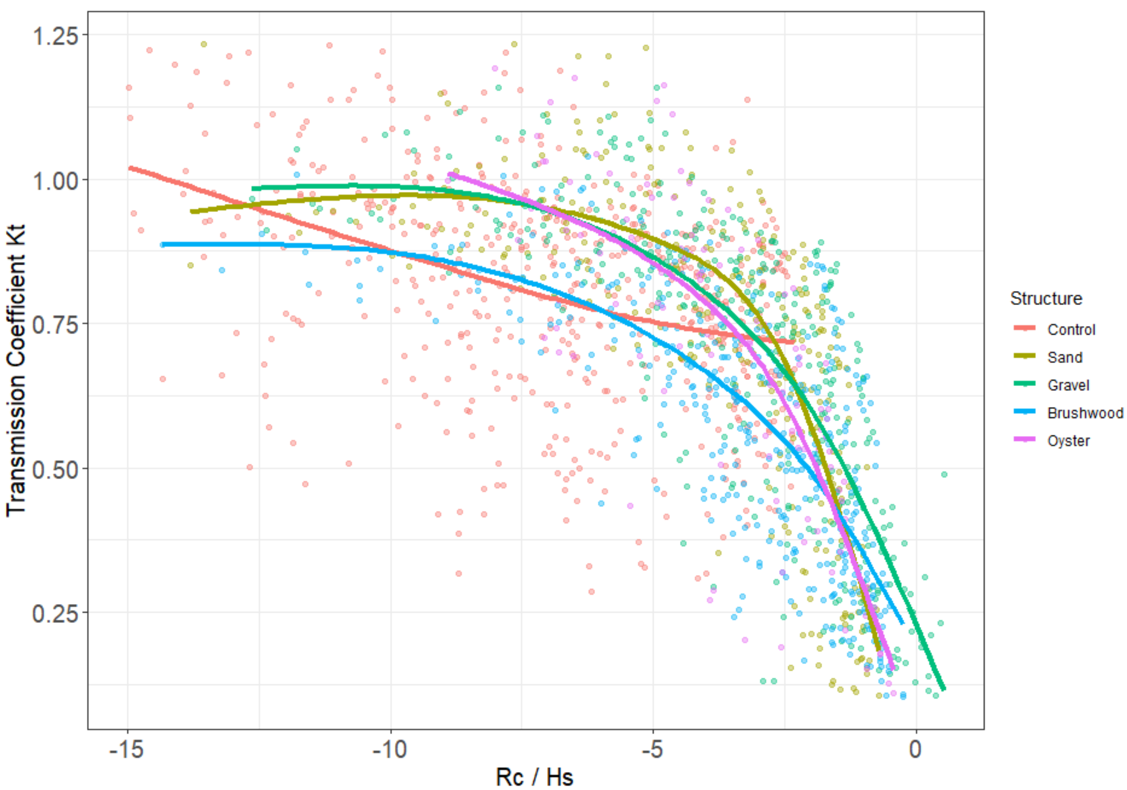

Figure 12: Wave transmission coefficients for the four edge treatments and the control transect. Rc / Hs denotes the ratio of freeboard (for each structure) to significant wave height. Recorded at the S1 LDPP site in Boundary Bay, British Columbia between October 2023 and January 2024.

Transmission coefficients for the sand berm exhibited a sharp initial slope near R_c/H_s = 0, asymptoting to K_t = 1 for decreasing (negative) R_c/H_s (Figure 13). Transmission coefficients associated with the brushwood dam, gravel berm, and oyster-shell bag berm had gentler slopes near R_c/H_s = 0 and more gradual transitions to the asymptote. The transmission coefficient regression curve for the brushwood dam asymptotes to a lower value than the other treatments, at approximately K_t = 0.75, but this is likely an artefact of the lack of data in the lower ranges of R_c/H_s for the brushwood dam dataset. The transmission coefficient for the control transect, which should in theory be close to 1 (since there is no feature or edge treatment), exhibits a roughly linear inverse relationship with R_c/H_s, which is presumably indicative of the increasing contribution of depth-induced wave breaking to wave height attenuation as R_c/H_s increases. The oyster-shell bag berm has fewer data points than the other treatments as monitoring was stopped in November 2023 after a storm event (H_s = 0.30 m) destroyed 60% of the bags.

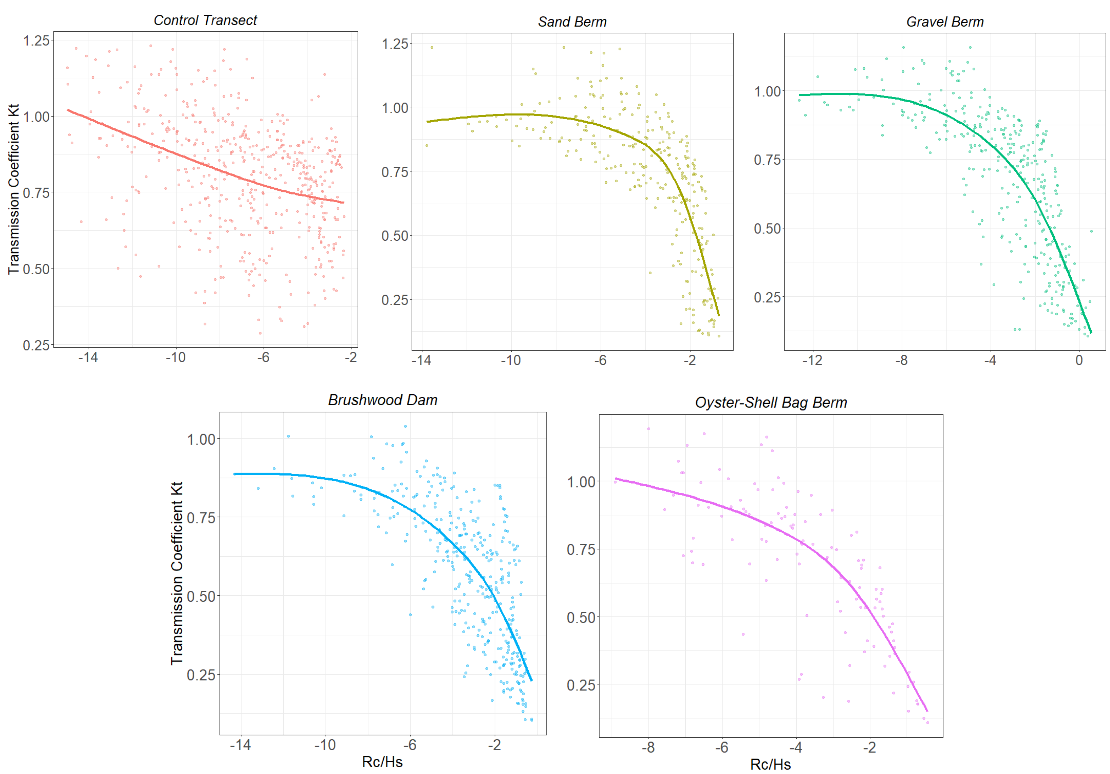

Figure 13: Wave transmission coefficients for the four edge treatments and the control transect. Rc / Hs denotes the ratio of freeboard (for each structure) to significant wave height. Recorded at the S1 LDPP site in Boundary Bay, British Columbia between October 2023 and January 2024. Axis scales vary across plots.

The linear portion of the datasets from the four edge treatments were individually plotted to provide a linear regression equation for each treatment (Figure 13) and a summary table of these equations is provided in Table 1. These linear equations offer estimations for predicting wave transmission coefficients for the four edge treatments across specified water depths and incoming wave heights (for values $-5 \lesssim R_c / H_s \lesssim 0$). These predictions have applicability limited to the observed site conditions: water depths 0.0 - 1.3 m, significant wave heights 0.05 - 0.46 m, and mean wave periods 0.5 – 3.5 s.

The adjusted R^2 values for the four treatments were between 0.41 – 0.47, while all associated p- values were below 2e-16. R^2 values in this range are anticipated in studies that occur in dynamic environments, such as the nearshore environment examined in this study. The highly significant regression coefficients indicate that although the model may not account for a majority of the variance, the relationships between the variables are robust and meaningful. Therefore, despite a lower R^2, the regression models capture the essential dynamics of the system and provide valuable insights for understanding and predicting the wave transmission coefficients of these treatments.

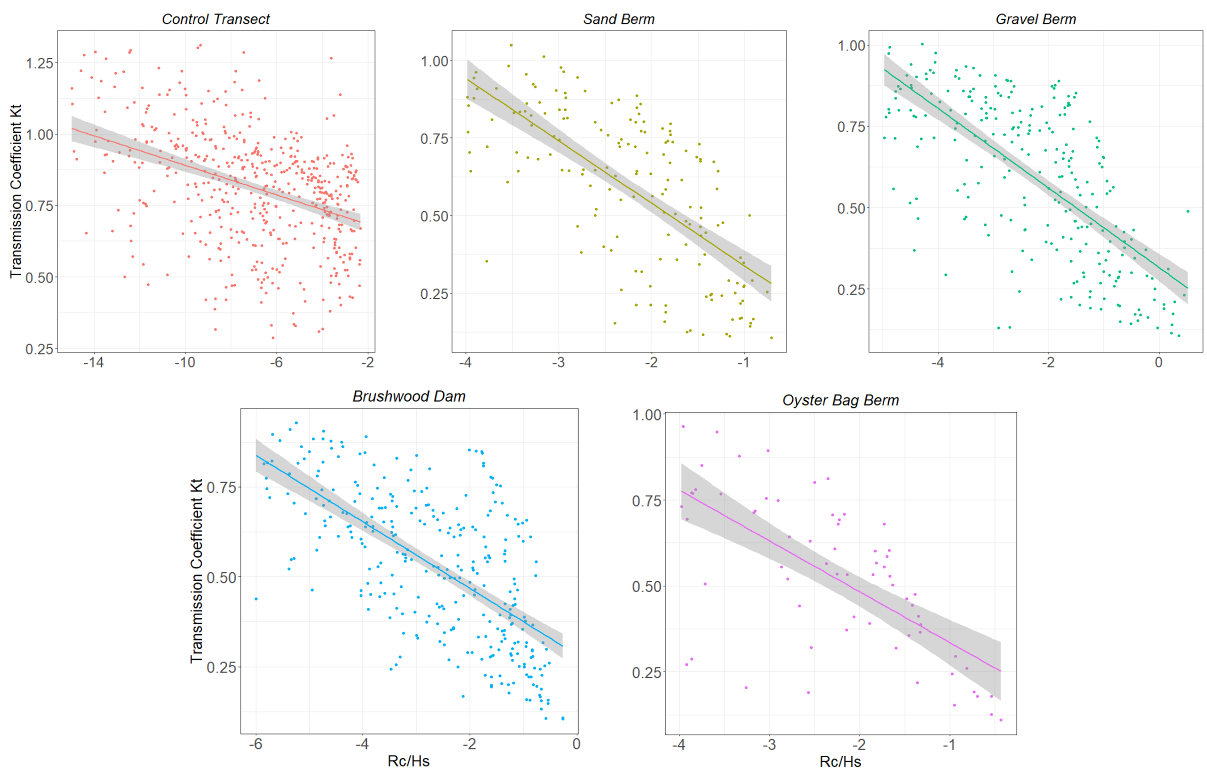

Figure 14: Linear regression lines for the four edge treatments and the control transect. Rc / Hs denotes the ratio of freeboard (for each structure) to significant wave height. Recorded at the S1 LDPP site in Boundary Bay, British Columbia between October 2023 and January 2024. Axis scales vary across plots.

Edge Treatment	*Linear Relationship*	***CI_{95} β_0***	***CI_{95} β_1***	*Adjusted R^2*	*p-value*
Control	$K_t = 0.63 - 0.03\frac{R_c}{H_s}$	[0.59, 0.67]	[-0.03, -0.02]	0.16	<2.2e-16
Sand	$K_t = 0.14 - 0.20\frac{R_c}{H_s}$	[0.06, 0.22]	[-0.23, -0.17]	0.47	<2.2e-16
Gravel	$K_t = 0.32 - 0.12\frac{R_c}{H_s}$	[0.27, 0.36]	[-0.14, -0.11]	0.47	<2.2e-16
Brushwood	$K_t = 0.28 - 0.09\frac{R_c}{H_s}$	[0.25, 0.32]	[-0.11, -0.08]	0.41	<2.2e-16
Oyster	$K_t = 0.19 - 0.15\frac{R_c}{H_s}$	[0.09, 0.29]	[-0.19, -0.11]	0.44	<2.2e-16

Table 1: Linear regression equations for the four edge treatments and the control transect. For values $-5 \lesssim R_c / H_s \lesssim 0$ and observed site conditions: water depths 0.0 – 1.3 m, significant wave heights 0.05 – 0.46 m, mean wave periods 0.5 – 3.5 s, recorded at the S1 LDPP site in Boundary Bay, British Columbia between October 2023 and January 2024.

3.2. Edge Treatment Condition Monitoring

The qualitative monitoring portion of this study was conducted between August 2023 and March 2024. Explained below are the main findings regarding the weathering of each edge treatment.

3.2.1. Sand Berm

The sand berm began to deform three weeks after construction was completed, and movement was noted during small summer storm events (H_s < 0.15 m). Large storm events in November 2023 and January 2024 further flattened the berm slope and moved sand onto the mudflat and fill sections of the plot. It was observed that most of the sediment movement occurred during storm events (H_s > 0.15 m). At the conclusion of this study, the sand berm had decreased in height by approximately 0.10 m and expanded seaward and landward by approximately 3.0 m in both directions. The marsh fill behind the sand berm experienced the most reshaping out of the four treatments and exhibited a 0.14 m decrease in elevation. The initial frontal slope of 1(V):4(H) for the sand berm reshaped to a final slope of approximately 1(V):30(H).

Figure 15: Photo monitoring of the sand berm treatment between August 23rd, 2023 and March 4th, 2024 at the S1 LDPP site in Boundary Bay, British Columbia.

3.2.2. Gravel Berm

The gravel berm was stable with only minor movement occurring during a January storm (H_s = 0.46 m). At the conclusion of this study, the gravel berm was approximately the same height as it was when it was constructed, negligible amounts of gravel had moved from their original positions, and there was no change in slope found. The marsh fill behind the gravel berm also exhibited little movement or scour.

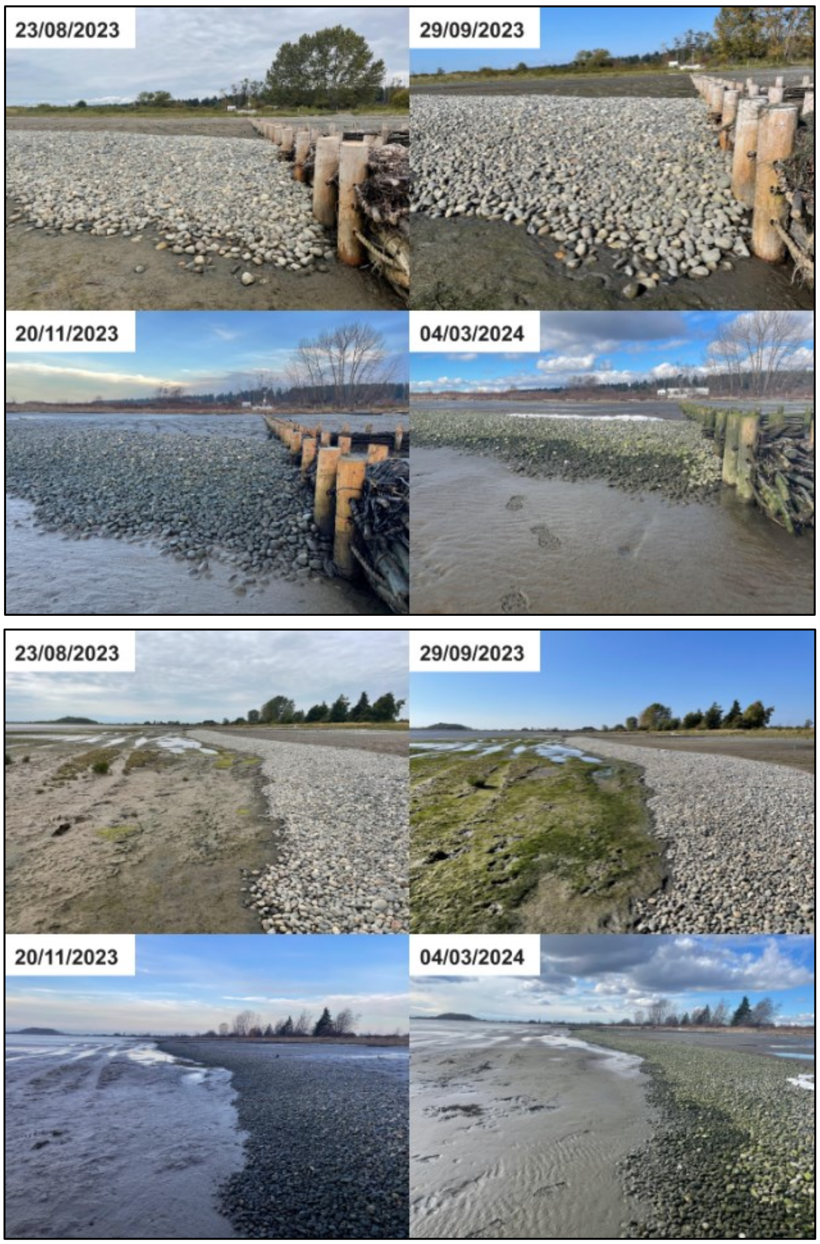

Figure 16: Photo monitoring of the gravel berm treatment between August 23rd, 2023 and March 4th, 2024 at the S1 LDPP site in Boundary Bay, British Columbia.

3.2.3. Brushwood Dam

The brushwood dam began to exhibit fraying on the 6 mm biodegradable twine, used to secure the bundled brushwood, in November 2023, three months after installation. The thicker 16 mm biodegradable rope used to secure the bundles to the posts did not show signs of fraying. After the November 2023 storm event (H_s = 0.30 m), one bundle of brushwood had split open, and that portion of the dam likely became ineffective. Further signs of fraying on the rest of the bundle twine was noted in December and two more sections of the dam came apart after a storm event in January 2024 (H_s = 0.46 m). The placed marsh fill elevation, at the interface with the brushwood dam, decreased by approximately 0.10 m and the slope landward of the structure steepened from the constructed 1(V):100(H) fill slope to a slope of 1(V):25(H). The new slope extended approximately 8.0 m landward of the dam before returning to the original fill elevation.

Figure 17: Photo monitoring of the brushwood dam treatment between August 23rd, 2023 and March 4th, 2024 at the S1 LDPP site in Boundary Bay, British Columbia. The March 4th, 2024 image shows a repaired brushwood bundle.

3.2.4. Oyster Bag Berm

The oyster bag berm showed signs of weathering one month after construction was completed. Tears in the biodegradable bags used to hold the shells in place were evident after the first summer storms. During the November storm event (H_s = 0.30 m) 60% of the bags were torn open, most of the shells in the first layer of the berm were spread across the site, and the biodegradable mesh bags were observed strewn around the site. The damage from the storm resulted in the lowering of the oyster bag berm below its constructed height and rendered it less effective as subsequent wave data showed higher wave transmission coefficients. A subsequent storm event in January 2024 damaged the rest of the bags and at the end of the monitoring study approximately 80% of the oyster bag berm had been destroyed. During the period before the November 2023 storm, little marsh fill movement took place, and no scour was noted behind the oyster bag berm.

Figure 18: Photo monitoring of the oyster-shell bag berm treatment between August 23^{rd}, 2023 and March 4^{th}, 2024 at the S1 LDPP site in Boundary Bay, British Columbia.

Chapter 4.

Discussion

This study presents the only known wave dataset illustrating the effects of multiple constructed nature-based salt marsh edge treatments on wave height attenuation in field trials. Other studies typically focused on a singular edge treatment, while this study allowed the direct comparison of treatment types for the same tidal and wave conditions. The use of accurate RBR pressure sensors, and the relatively long measurement period of four months spanning a winter season, allowed an array of wave and tidal conditions to be captured and analyzed in this study. Further, the mirroring of the NRC-OCRE wave flume study by Provan et al. [9] allowed comparisons to be drawn between laboratory and field trials and highlights the additional insight that can be gathered through field trials.

4.1. Wave Monitoring

The primary findings of this investigation indicated that all four nature-based edge treatments attenuated incoming waves, with their efficacy contingent upon wave and tidal conditions, as seen in other studies [9,31,32,33,34]. The brushwood dam provided the greatest wave attenuation at values of $R_c/H_s \lesssim -2$ and continued to attenuate waves at more negative ratios of R_c/H_s compared to the other treatments. The other three structures did not practically contribute to wave attenuation for values of $R_c/H_s \lesssim -4$. This finding is in concordance with other studies of the wave attenuation characteristics of submerged breakwaters (both nature-based and conventional variants) whose configurations resemble the sand, oyster bag, and gravel berms [32,33,34]. The greater wave height reduction observed with the brushwood dam is likely attributed to its porous structure, which functions akin to a horizontally slotted breakwater, coupled with its inherent flexibility [35,31]. Horizontally slotted breakwaters excel in dissipating short-period waves, such as those encountered at the project site (mean wave periods ranging from 0.5 s to 3.5 s) but exhibit reduced effectiveness against longer-period waves [35]. Hence, a future examination of the brushwood dam's efficacy in attenuating longer-period waves would be pertinent. The flexural properties highlighted above were previously identified by Schmitt et al. [31] as a fundamental mechanism for wave dissipation in brushwood dams in their study of bamboo brushwood dams in Southeast Asia [11,31].

The sand berm outperformed the gravel berm in ranges of $R_c/H_s \gtrsim -2.5$, possibly due to its greater width. Conversely, the sand berm exhibited the least wave attenuation at ranges of $R_c/H_s \lesssim -2.5$, potentially attributable to the smooth sand surface, which is less conducive to frictional dissipation compared to the other treatments [32,34]. The oyster bag berm was more effective than the brushwood dam and gravel berms under conditions with lower freeboard and higher wave heights (R_c / $H_s \gtrsim -2.5$) which might be due to the irregular oyster shell arrangements having a higher roughness value (i.e. increased friction) compared to the smooth gravels and brushwood bundles [32,34]. The scatter in the data should be borne in mind when considering the patterns described above.

Provan et al. [9] similarly found that all four treatments can attenuate wave heights and may be effective depending on desired transmitted wave heights, incident wave heights, and freeboards. However, our findings differ in that we found that the brushwood dam was the most effective treatment at reducing wave heights at values of R_c / $H_s \lesssim -2$. Further contrary to our results, Provan et al. [9] identified the gravel berm as the most effective treatment at reducing wave heights across their tested wave heights and water levels, whilst in our study the gravel berm performed worse than the brushwood dam and oyster bag berm. These discrepancies may stem from the additional factors associated with field trials compared to laboratory models. Our findings indicated that, in real-world applications, the brushwood dam would likely offer the most substantial reduction in wave heights on a project site with similar wave heights and periods. However, adjustments to the other three treatments, such as increasing their height, width, roughness, porosity, or modifying material size and slope, could potentially enhance their effectiveness.

4.2. Edge Treatment Condition Monitoring

The brushwood dam was shown to hold up well to wave conditions, which was expected given their use on similar projects in Europe and Asia [25,11]. However, the study observed recurrent failures in the twine binding the brushwood bundles, a phenomenon not reported in prior research. It is hypothesized that the abrasion of the bundle twine by driftwood during high tides might be a contributing factor. This hypothesis is supported by the lack of fraying on the perpendicular brushwood dividers (used to separate plots) that were not exposed to driftwood impacts and associated damage. Boundary Bay's abundance of driftwood may explain why such weathering/damage mechanisms were not previously documented in European or Asian studies. Increasing the thickness of the bundle twine could mitigate the risk of failure, irrespective of the underlying cause, thereby prolonging the longevity of the brushwood dams. Failure of the brushwood dam was not reported in Provan et al.’s [9] laboratory study which highlights the importance of conducting field trials. Studies such as Schmitt et al.'s [31] investigation into bamboo and rope brushwood dams indicated that minor adjustments in design could potentially extend their lifespan to five-to-seven years [11].

The brushwood dam in this study showed a similar pattern of sediment loss as reported by Provan et al. [9], which involved erosion of marsh fill through the brushwood dam and the subsequent steepening of the marsh fill slope. The loss of marsh fill at the interface of the brushwood dam contrasted with the gravel berm which exhibited negligible fill loss. One contributing factor to this difference may be the presence of smaller pea-gravels (i.e. filter gravel) directly landward of the gravel berm, which likely served as a sediment filter. An area warranting further investigation could involve incorporating filter gravels into future brushwood test plots or modifying the brushwood dam, as successfully tested by Provan et al. [9], to have a tighter weave and less sediment loss. The absence of sediment movement observed on the gravel berm was intriguing, as Provan et al. [9] reported the development of scour holes on the leeside of their gravel berm during testing. A possible explanation for this lack of scouring may be that the changing tides on-site did not allow for sustained wave breaking on the leeward side of the berm and that the model used by Provan et al. [9], which used a fixed water level for its three-hour tests, was overly conservative. This is an area that warrants further investigation.

It was observed that the control plots experienced an approximate 0.1 m decrease in bed elevation between October and December 2023. It remains to be seen whether this observed change amounts to a permanent loss of sediment from the plot or is indicative of a seasonal pattern of sediment movement wherein nearshore sediment loss occurs during winter storms and reaccumulates during summer months—which is a typical phenomenon observed in beach systems [36]. Long-term (multi-year), continuous monitoring of bed elevations is needed to better understand the seasonal and interannual sediment dynamics in Boundary Bay, which exert control on the effectiveness and sustainability of the nature-based infrastructure at the site.

The gravel berm demonstrated effective wave reduction capabilities and remained very stable throughout the eight-month observation period. This finding was contrary to expectations based on the findings of Provan et al. [9], whose laboratory experiments indicated that the gravel berm would be dynamically stable. The variance in results likely stems from the larger sized gravels ($D_{50} \approx 70$ mm) used at the S1 site compared to the gravel ($D_{50} = 29$ mm) used by Provan et al. [9]. The stability of the gravel berm at the S1 site may not be ideal for two key reasons. Firstly, the gravel exceeds the typical sediment size found in the bay [17], which is a departure from the reference ecosystem where larger gravels are not prevalent. Secondly, observations indicated limited movement of the berm gravels during large storm events ($H_s = 0.46$ m). Such persistence during storms implies that the berm may retain its integrity longer than necessary to meet the initial requirements for the saltmarsh restoration goals and instead add more long-term hardened shoreline to the bay, which ultimately restricts sediment supplies to adjacent shorelines and results in coastal squeeze.

As previously mentioned, the primary objective of the edge treatment structures is to mitigate wave heights on-site until saltmarsh plants have sufficiently reestablished, and findings from the condition monitoring study reveal that the gravel berm is likely to endure well beyond this timeframe [7,8,9]. This prolonged persistence of the gravel berm may not align with the overarching project goals. As per an NBI guidance report issued by the State of California, berms with over-sized gravel provide limited habitat values to the local ecosystem and more closely resemble traditional hardened coastal defense structures [37]. In addition, recent studies in Washington State [38] have found that shoreline armouring has an increasingly negative ecological and geomorphological effect the further down it is placed on a shoreline. The most significant impacts were observed for armoring structures installed below the 0.30 – 0.60 m Higher High Water Mean Tide (HHWMT) level, a zone comparable to the placement of the gravel berm and other edge treatments [38]. Because the gravel berm is located further down the shoreline compared to traditional armoring methods, there is potential for it to cause increased adverse impacts on both local ecologic and geomorphic processes [38]. To potentially avoid these effects, it would be pertinent for future studies to test a berm with gravel sizes between 2-20 mm, which are ideal for forage fishes in the Salish Sea, are closer to the sizes used by Provan et al. [9] and are similar to the sizes of gravels typically found in Boundary Bay [37,39,17].

The sand berm exhibited significant movement of sediment throughout the study period. During summer storms (H_s = 0.20 m), sediment movement downslope was gradual, whereas during winter storms (H_s > 0.30 m), significant changes occurred with a flattening of the frontal slope to a 1(V):30(H) ratio from the constructed ratio of 1(V):4(H). These findings align with observations made by Provan et al. [9], though the sand berm slope in their study had a final slope of 1(V):16(H). The differences in slope between the two studies may be explained by the wave flume study's short duration (3 hours) compared to the eight-month long field trial [9]. The observed reshaping diminished the sand berm's effectiveness towards the end of the study period, as seen by higher wave transmission coefficients. The marsh fill behind the sand berm also exhibited a 0.14 m loss in profile elevation, based on a walked transect elevation survey using a Spectra Geospatial RTK GPS (SP85 GNSS receiver)(vertical precision ±15 mm), which was the greatest elevation decrease of any of the treatments. It is possible that the sand that was moved offshore by winter storms will be redeposited on the site throughout the summer, and continued monitoring of the site is recommended [36].

The oyster bag berm initially demonstrated effectiveness in reducing wave heights at values of $R_c/H_s \gtrsim -4$ which corresponds closely to the wave transmission findings of Sigel's [32] study on wave attenuation in artificial oyster reefs. However, the oyster bag berm experienced near-total destruction following a storm event in November 2023 (H_s = 0.30 m) only four months after construction. Prior to the storm event it was noted that the biodegradable bags enclosing the oyster shells were susceptible to being cut by the movements of seaborne objects (i.e. driftwood). Following the November 2023 storm event, it was observed that 60% of the oyster bags in the berm were cut open, with the shells scattered nearby. The movement of driftwood during tidal cycles likely cut the bags, leaving the berm vulnerable to shell dispersion during storm events. Following the November 2023 storm event, the biodegradable bags were strewn across the site, posing an entrapment hazard to wildlife. Further research is required into alternative methods of securing the oyster shells. Previous studies have examined the use of gabion cages as a means of securing oyster shells, as demonstrated in projects like the

Eastern Scheldt Oyster Reef pilot project [40], though the use of gabion cages may present other limitations in saline environments.

The treatments investigated in this project are relevant to various mudflat or sandflat estuaries within the Salish Sea, as well as other similar locations across Canada. The edge treatments were subjected to limited exposure to ice conditions, which did not involve impacts with thick pieces of ice. Exploring the effects of such conditions is a potential area for future research, particularly for projects situated in Atlantic or Northern Canada.

4.3. Confounding Factors

The condition monitoring phase of this study occurred from August 2023 to March 2024, during which two storm events with significant wave heights (H_s) exceeding 0.30 m occurred, which aligns with the expected return periods for this area [9]. Coastal erosion typically intensifies during storm events, and it would have been advantageous to capture more extreme storm events in our data collection, as the weathering impacts on the edge treatments would likely have been magnified under these conditions. In addition, the range of observed wave periods in this study is small, due to limited swell exposure at this site; thus, long-term monitoring spanning multiple storm seasons is recommended, and caution should be taken when extrapolating these findings to sites exposed to longer period swells or boat wake.

Due to logistical constraints, this study did not account for the angle of incoming waves. Prior research indicated that wave dissipation diminishes by a factor of sin(Θ) for oblique waves (where Θ is the angle of incidence) [11]. In this study, all waves were presumed to approach the shoreline perpendicularly, a reasonable assumption given that large waves could only enter the bay from a south-southwest direction, which would result in waves arriving near-perpendicular to shore at the study site. However, it is likely that some of the scatter observed in the wave transmission coefficient data (Figures 12-14) is due to waves entering the site at oblique angles.

The sand berm edge treatment required the instruments in its monitoring transect to be set twelve meters apart, due to its larger width, as opposed to eight meters apart for the other edge treatments. This altered instrument configuration should be borne in mind when drawing comparisons between data at the sand berm and the other edge treatments.

4.4. Implications

The efficacy of the sand berm diminished due to the high mobility of the sand, which underwent substantial reshaping during the study period. Consequently, the sand berm may not be the optimal edge treatment for this location unless a long-term maintenance strategy involving regular sediment replenishment is implemented.

The oyster bag berm effectively attenuated waves but experienced the most significant weathering among all structures due to the weakness of the biodegradable bags. To address this issue, adopting steel gabion cages, designed to rust out within a few years, could offer a viable solution. This approach was proven effective in the Eastern Scheldt Oyster Reef pilot project [40], but additional testing would be required in Boundary Bay.

The gravel berm demonstrated effectiveness and is expected to remain stable for an extended period. However, this may not align with the project's long-term objective of allowing salt marsh plants to re-establish on the site, as the gravel berm could impede local ecologic and geomorphic processes [37,38]. One potential solution could involve using smaller diameter gravels in future projects, as used in Provan et al.'s study [9], to create a dynamically stable berm and provide suitable sized gravels to support forage fish spawning [38,39].

Primary recommendations for the brushwood dam focus on bolstering its durability. The bundle twine securing the brushwood bundles was susceptible to fraying, compromising the structure's efficacy. Increasing the bundle twine diameter is recommended to mitigate this design concern and enhance the brushwood dam's longevity. The brushwood dam was the only edge treatment to attenuate waves at all tested values of R_c/H_s and provided the most wave attenuation at values of $R_c/H_s \lesssim -2$. These results indicate that with minor design changes the brushwood dam may be a desirable edge treatment option for future projects in locations with similar tidal and wave conditions to this study.

Chapter 5. Conclusions

This study delves into the wave attenuating capacity and weathering rates of four nature-based edge treatment features on the LDPP in Boundary Bay, BC. The findings indicated that all four edge treatments exhibit potential for attenuating waves effectively. With some modifications, the brushwood dam, oyster bag berm, and gravel berm could serve as promising edge treatments for a scaled-up version of this project, while the sand berm may be too susceptible to sediment movement—pending verification through longer-term monitoring. Notably, this study corroborates the findings reported by Provan et al. [9] that all four edge treatments can be effective at reducing wave heights depending on desired project outcomes and highlights the importance of conducting field trials to observe weathering elements not accounted for in wave flumes. Monitoring the response of planted marsh vegetation to the different edge treatments at the LDPP will further develop our understanding of each treatment's efficacy.

This research demonstrates that nature-based edge treatments can provide effective wave attenuation to salt marsh restoration projects in semi-sheltered, macrotidal mud-and-sand-flat estuaries in BC. We hope this study will enable designers to more confidently implement nature-based coastal flood and erosion risk management projects across Canada.

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