THE ROLE OF COASTAL ENGINEERING AND INNOVATION FOR SUSTAINABLE ADAPTATION OF OUR COASTAL DEFENCE AGAINST SEA LEVEL RISE

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Abstract: Climate change and related sea level rise will affect all of Canada's coastlines, posing significant planning challenges for communities. With conventional coastal defence approaches having well known limitations, alternatives need to be developed, validated, and implemented. As every section of shoreline is unique, this paper demonstrates the role of Coastal Engineering in assessing the metocean conditions, the resulting wave-shoreline interaction and the multidisciplinary coordination necessary to optimize the shoreline adaptation while minimizing the complete life cycle costs and implications. Shorelines provide important ecological services and new coastal protection systems that either minimize disruption to or enhance the ecological services are needed. Coastal Engineers are key leaders of the multidisciplinary teams necessary to respond to the growing challenges.

This paper presents two projects in British Columbia (BC) that demonstrate how Coastal Engineering adds significant value to project outcomes. In the first project, detailed analysis of wind and wave modelling lead to a refined understanding of flood risk during storms faced by a community on Vancouver Island, BC. This work means that the community can plan and optimize its response in a manner that preserves ongoing land use and values while still addressing the critical risk areas. In the second project, the importance and value of innovation in the adaptation of coastal defences to ensure that they are sustainable, effective and economical is demonstrated with an example from the ongoing upgrading of the existing sea dike at Boundary Bay, BC. This ongoing work combines classical dike design principles, detailed numerical modeling of wave overtopping, and intentional use of ecosystems and natural processes to dissipate wave energy to reduce the magnitude of overtopping. This analysis can result in the design of a "Living Dike", with increased benefits to the environment and which can be subsequently upgraded as and when needed as sea level rises.

1   INTRODUCTION

Approximately half the world's population lives within 60 km of the ocean and three-quarters of the world's largest cities are located on the coast (UNEP, n.d.), making coastal areas some of the most densely populated and vulnerable regions in the world. Closer to home, Canada's 243,000 km of coastlines (Taylor *et al.*, 2014) include many small and large communities along them that play critical roles in local, regional and national economies.

Many of these communities and their infrastructure are located in coastal areas that are not naturally in equilibrium, are exposed to both flooding and erosion hazards and contain infrastructure that needs to be either be relocated or protected. In the past, the conventional approach to deal with these issues was to

armour the shoreline to hold its location. These approaches, commonly referred to as "hard" shoreline treatments, include: seawalls and rock armour revetments, various bulkhead systems, gabion, and sea dike systems. An example of a hard shoreline armouring treatment is shown in Figure 1.

Figure 1: Example of hard shoreline armouring: armour rock revetment, Town of Qualicum Beach, BC

These hard treatments often act to reflect and amplify waves directly in front of them. The combined result of a depleted sediment supply from the protected land and increased wave action can lead to a positive feedback loop, where erosion increases the depth of water at the seawall toe allowing for larger wave heights at the shoreline, which in turn increases erosion, and so on. Long-term hard coastal structures can lead to increased flooding, structural failures, and destroyed ecologically valuable intertidal habitat.

In many parts of Canada, increased durations of ice-free conditions will lead to accelerated failure of important coastal infrastructure. Recently, the seawall at the waterfront of the City of Percé, Quebec, was completely destroyed as a result of severe winter storms occurring during periods of ice-free water.

It is clear that climate change and related sea level rise will affect the performance of many existing shorelines whose integrity under changing conditions need to be reassessed. This reassessment will provide opportunities to consider coastal defence alternatives that are "softer" in terms the form of armouring, and which can provide greater ecological services. These alternatives commonly referred to as "soft" shoreline treatments include, often in combination: beach restoration or construction, dune and wetland construction, shore vegetation preservation or restoration and construction of reefs and rock berm features as part of the system. An example of a soft shoreline treatment is shown in Figure 2.
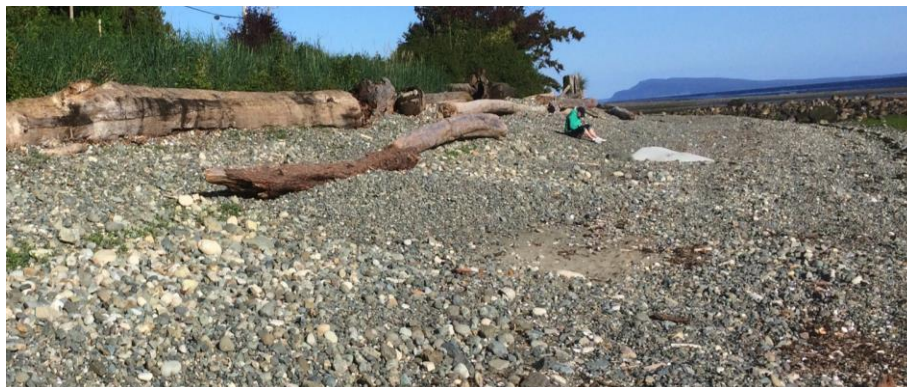

Figure 2: Example of soft shoreline defence alternative: beach enhancement with restoration of vegetation, Town of Qualicum Beach, BC (SNC-Lavalin project)

Soft shoreline treatments may have significant cost advantages when they are properly designed (Lamont *et al.*, 2014). However engineering design guidance for soft alternatives is generally limited. A rigorous assessment of their feasibility requires good understanding of the physical processes of the local coastal area. Successful and economic implementation requires detailed engineering, which generally does not inhibit the underlying cost advantage of these systems.

This paper presents two projects in British Columbia (BC) that demonstrate how Coastal Engineering adds significant value to project outcomes. In the first project, detailed analysis of wind, storm surge, and wave modelling lead to a refined understanding of flood risk during storms faced by the District of North Saanich, a community on Vancouver Island, BC. This work means that the community can plan and optimize its response in a manner that preserves ongoing land use and values while still addressing the critical risk areas. In the second project, the importance and value of innovation in the adaptation of coastal defences to ensure that they are sustainable, effective and economical is demonstrated with an example from the ongoing upgrading of the existing sea dike at Boundary Bay, BC. The locations and open water exposure of the two projects are shown in Figure 3.

2   COASTAL ENGINEERING

Coastal Engineering is a relatively new engineering discipline and unlike many aspects of civil engineering practice includes and requires a wide range of interdisciplinary practise.

The coastal area is an indefinite interface between the land and the sea and in a horizontal sense includes environments occupying some distance both landward and seaward of the shoreline. In a vertical sense it also includes many elements of the atmosphere and the local geology, both onshore and offshore of the area of interest. As the result of ongoing climate change and related sea level rise the coastal area and the associated processes are changing at a pace that has not been experienced in recent times.

Figure 3: SNC-Lavalin project locations in southern Strait of Georgia, BC (examples)

The US Army Corps of Engineers defines Coastal Engineering as a field of practice that includes: meteorology, oceanography, marine science, geology, environmental sciences, hydrology, hydraulics, physics, mathematics, statistics, naval architecture, structural dynamics and planning. Coastal Engineers use their training and experience in all these areas of expertise to develop physical adaptations to solve problems or build resilience in the coastal area and enhance and preserve the human and ecological interaction.

Numerical and physical modeling of coastal processes and metocean interaction with the shoreline or with coastal structures has always be an efficient way to identify governing processes and to solve problems or build resilience. The relatively inexpensive availability of high performance computers has pulled numerical modelling to the forefront of coastal engineering practice and provides hitherto unavailable insight into design scenarios.

Numerical models, however, are reliant on pre-defined inputs, their bundled physics and mathematical bases and the fidelity of variables such as bathymetry, the spatial and temporal discretization of the governing processes, calculation methodology and choice of governing equations to describe the phenomenon under study. Details and the completeness of driving forces including: weather conditions, tides and related currents and the characterization of the seabed can be critically important. Subtle

variations in these parameters can result in significant implications to the model result outcomes and unless explored in some detail may inadvertently sway understanding away from robust and potentially alternative economically efficient solutions.

It is also important to realize that physical processes can vary considerably from location to location, even over relatively short distances. It is very important that Coastal Engineers ensure that a project design basis accurately reflects the conditions in the area of interest.

The remainder of this paper provides some examples of how all these factors and considerations of location can influence the development of appropriate solutions for any project in the coastal area.

2.1   Importance of Meteorology

Every coastal area is exposed to the influence of climate and weather. It is quite possible that one of the most significant meteorological processes is wind, primarily due to its role in the generation of waves; the main forcing function on shorelines. Overwater winds, which tend to be stronger than those experienced on land, generate waves by transferring energy through friction with the water surface. A good definition of the overwater wind, including wind strength, wind direction and their evolution in time, is required to correctly estimate the wave climate at any project site.   Other meteorological processes such as atmospheric pressure, temperature and storm track are also significant factors through their influence on storm surges and the presence or absence of ice.

In the relatively protected waters of southern coastal British Columbia, two local processes that significantly affect the wind field are orographic forcing and sea breeze (temperature) processes. Orographic forcing is the flow of wind around and over barriers and land forms such as mountains, islands and cliffs, which can lead to local important changes in the wind field. The sea breeze effect accounts for the additional forcing from the difference in temperature between water and land. These phenomena can ultimately affect wave generation and therefore the selection of design wave heights.

Local wind behaviour and patterns can often be assessed from long tern data collected by anemometers at fixed locations. However, it is generally not sufficient to rely solely on wind data from a single anemometer close to a project site. Because waves are generated over long overwater fetches, often several 100 km long, it is important to consider the wind field characteristics over the entire water body involved in the overall exposure. As example, Figure 4 shows the wind field over the Strait of Georgia, BC, during a severe storm, interpolated from actual field observations. The spatial variation in the wind field is obvious and demonstrates how wind data from the nearest fixed data site may not be representative of the wind speed and direction over the wave generating fetch.

Reliance on a single source of wind data underestimate exposure and resulting wave heights at times or can be conservative, resulting in larger seastates. Although a conservative approach may be appropriate in many design situations, in the context of adapting our shorelines to sea level rise, it will likely lead to excessive construction costs in an environment where financial resources will be severally tested in the years to come. The Fraser Basin Council, (2016) recently estimated that the cost of adaptation in the lower mainland of BC could be between $19.3 and $24.7 billion for 1 m of sea level rise alone. In 2012, the BC Ministry of Forests, Lands and Natural Resources Operations estimated that raising the existing coastal sea dikes alone in the same area would be $9.5 billion. It will be critically important to ensure that the design process, including definition of the governing processes is as accurate and complete as possible to ensure that adaptation is economically feasible.
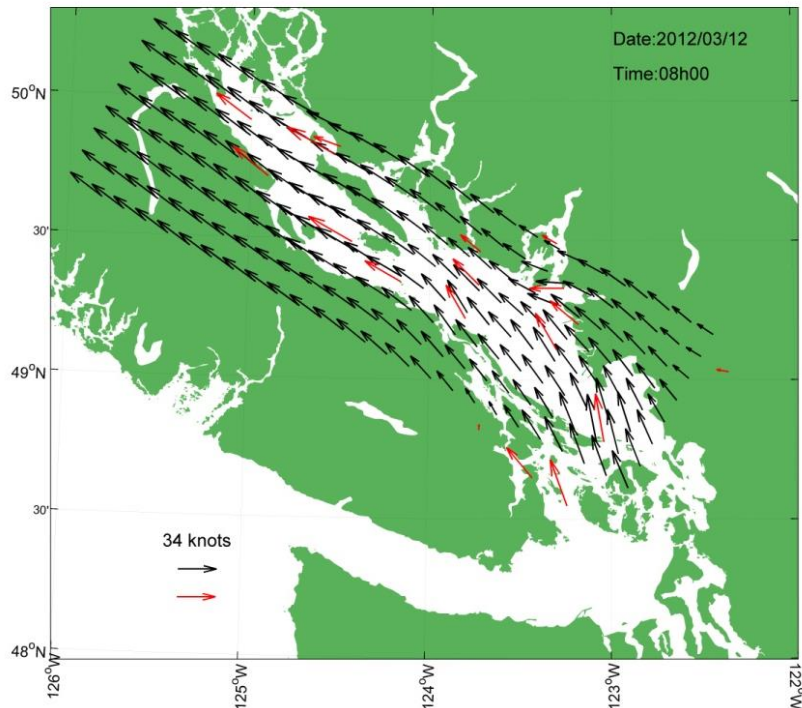
Figure 4: Wind field (black arrows) interpolated from field observations (red arrows) over the Strait of Georgia, BC, during the severe storm of March 12, 2012

2.2   Importance of Location

Coastal storms usually have an associated storm surge component. Storm surge is the rise/fall of the water level due to large scale influences (in BC coastal waters, often over ocean basin or province scale areas) on atmospheric pressure differences and overwater wind forcing on the ocean surface. The magnitude of the storm surge at a particular location will be closely related to the track of the storm system and the exposure at the specific location.

In the design of any coastal infrastructure, it is important to consider different combinations of wind speed, wind direction, and total water level to determine the governing case for a particular location. It can be overly conservative and thus economically inefficient or unnecessary alarming to unrealistically compound a number of low probability processes together.

In addition to different exposure to wind, surge timing and open fetches of water, a particular location may differ from another in terms in terms of bathymetric and topographic features. Such features can have an important influence on the waves reaching the project site as they will influence wave transformation and interactions between wave trains that can either amplify or reduce the wave energy at a specific shoreline.

The following subsections provide two projects in BC that demonstrates how Coastal Engineering, and knowledge of meteorology and location, adds significant value to project outcomes.

3   PROJECT EXAMPLES

3.1   District of North Saanich Flood Construction Levels

The coastal area of the District of North Saanich spans approximately 42 km of the shoreline at the north end of the Saanich peninsula in southern British Columbia (Figure 3). This coastal area includes approximately 713 private, commercial and public land parcels and is exposed to storm winds, waves and

storm surges from 6 primary directions. Following a large regional area preliminary assessment of flooding vulnerability by the regional district for the capital area of Victoria, a refined flood construction level (FCL) study was conducted for the District of North Saanich (DNS) to identify the risk of coastal flooding for sea level rise scenarios of 0.5 m and 1.0 m. FCLs are defined as the underside elevation of a wooden floor system, or the top elevation of a concrete slab, for habitable buildings, and are intended to inform urban development to provide safety and security against flooding or related damage in habitable levels of buildings along within the coastal area.

The shoreline of the DNS is exposed to winds and waves from different directions, including N through SE exposures on one side of the peninsula and SW through NW exposures on the west side of the peninsula. Dominant storm patterns include winter outflow conditions that typically produce NE winds, and more frequent mid-latitude Pacific Ocean storms that generally produce SE, SW, or NW winds. Definition of the FCLs around the entire shoreline of the DNS, requires consideration of different combinations of wind speed, direction and related storm surge to determine the governing case for the each section of the DNS shoreline.

The guidance available in the Province of BC for the definition of coastal flood hazards (BCMoE, 2011) provides design storm surges representative of the Strait of Juan de Fuca and Strait of Georgia for various return periods. However, a detailed analysis of the relationship between wind speed, wind direction, and storm surge shows that strong NE winds are typically associated with negative surges; while strong SE, SW or NW winds are generally associated with positive surges that tend to occur after the peak winds. The characteristics of the surge can change rapidly as the storm passes over the area. It is overly conservative to compound the various factors that contribute to the FCL elevation in a uniform manner over the entire District.

As a result a total of 6 Designated Storm scenarios were identified and the Designated Flood Level for each scenario was defined for both sea level rise of 0.5 m and 1.0 m.

Incident wave climate conditions were based on the Designated Storm conditions and were calculated using an industry standard detailed wave generation and propagation numerical model (SWAN, Holthuijsen *et al.*, 1998). The bathymetry data for the project was a composite of data from NOAA (National Oceanic and Atmospheric Administration) and the CHS (Canadian Hydrographic Services) sources. The numerical wave model utilized three different computational grids, for the NE case, SE cases, and NW & SW cases, respectively. Sensitivity and validation model runs were conducted to determine appropriate model parameters to define the wave climate at the 10m depth contour.

The nearshore wave conditions for one of the SE Designated Storm scenarios, is shown in Figure 5. This image illustrates how the wave climate varies significantly along the shoreline for a specific storm scenario.

Nearshore wave conditions are used to determine the expected wave effects at the shoreline that defines the interaction of incident waves with particular shoreline characteristics. As wave effects are shoreline and coastal structure dependent, the entire DNS shoreline was inventoried and classified into three main types: erodible natural shorelines, non-erodible natural shorelines, seawalls or revetments. Based on this classification and giving consideration to the spatial variability of the nearshore wave climate, it was necessary to identify 39 distinct reaches around the DNS shoreline.

Reach specific wave interaction effect were then assessed to define flood elevations bearing in mind the typical shoreline treatments in each shoreline reach and the level of allowable overtopping of water and subsequent flooding appropriate for the land values and usage in each reach.

The net effect of this very detailed consideration of meteorology, oceanography and location, together with consideration of the physics of the wave shoreline and structure interaction resulted in a lowering of previously recommended FCLs on 25 reaches of the DNS shoreline and the identification of 4 key areas of the district where concentration of future adaptation or resilience planned could be focused (SNC-Lavalin, 2016).
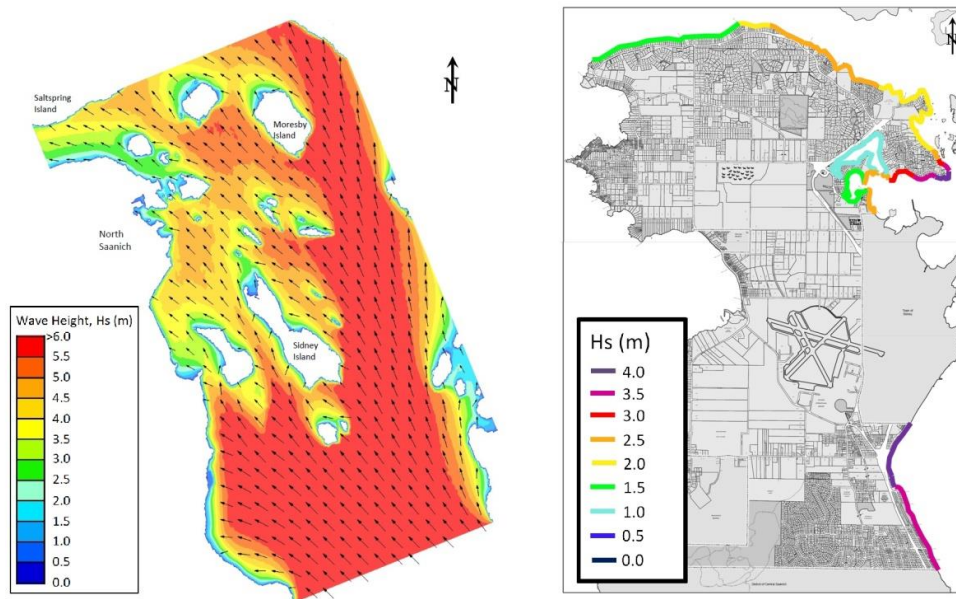
Figure 5: SE Peak Wind Storm Scenario with SWAN result (left), and Compiled Nearshore Wave Heights (right), District of North Saanich, BC

3.2   Corporation of Delta Boundary Bay Dike Upgrades

Recent innovations in Coastal Engineering include advances in numerical analysis tools that, when properly used, allow for comprehensive analysis of complex foreshores. This section describes the application of a numerical model to simulate wave runup and overtopping on complex foreshore and shoreline geometries. This work was applied to a section of Boundary Bay (Figure 3) where overtopping rates on the existing upgraded dike could be significantly reduced, potentially significantly delaying the need to raise the dike.

A traditional approach to estimating wave runup and overtopping of structures has been to use regional scale wave models to estimate the seastate offshore of a structure and then to apply empirical formulae to estimate wave runup and overtopping. However, many shoreline structures depart (in some degree) from the idealised versions tested in hydraulic laboratories upon which much of the empirical formulas are based and which have associated inherent scatter.

Recent guidance (EurOtop, 2016) cautions that empirically derived overtopping rates should be regarded as being within a factor of one to three times actual overtopping rates. Further, extrapolation beyond the simplified structure configurations used for their underlying database may result in inaccurate or even invalid overtopping predictions.

The pre-existing section of dike in Boundary Bay covered by the project has a relatively small and thin layer of riprap on the seaward face (Figure 6). Following large storms pieces of riprap have been dislodged into the foreshore. To lengthen the life of the existing dike structure and to improve resilience for present day storms, the riprap on the seaward face of the dike required upgrading into properly sized armour stones. However, the dike is also adjacent to a Wildlife Management Area (WMA) and the crest is part of a regional parkway used by cyclists and pedestrians. It is important that as further dike upgrades are considered in anticipation of accelerating sea level rises the interaction with the ecologically important WMA is fully considered.

SNC-Lavalin has been an early user of the SWASH wave model for examining wave structure interactions at the shoreline (St-Germain, *et al.* 2014). This model is suitable for simulation of wave

Figure 6: The pre-existing riprap revetment in poor condition (left), and riprap pieces in WMA post storm (right), Boundary Bay, Corporation of Delta, BC

transformation in both the surf and swash zones due to nonlinear wave-wave interactions, wave damping due to vegetation, wave breaking, and wave runup on shorelines or structures (Zijlema *et al.*, 2011). SWASH has been used to assess the performance of the dike upgrade section, along with several variations of the design, to consider both the mean and maximum wave overtopping rates which have both ecological and personnel and property safety issues.

The upgraded design section is shown below in Figure 7. The new rock armour is designed to be placed onto the existing riprap to avoid removing the existing riprap during construction and hence exposure of a completely unprotected dike. The new rock armour is also significantly larger and more uniformly graded for various reasons.
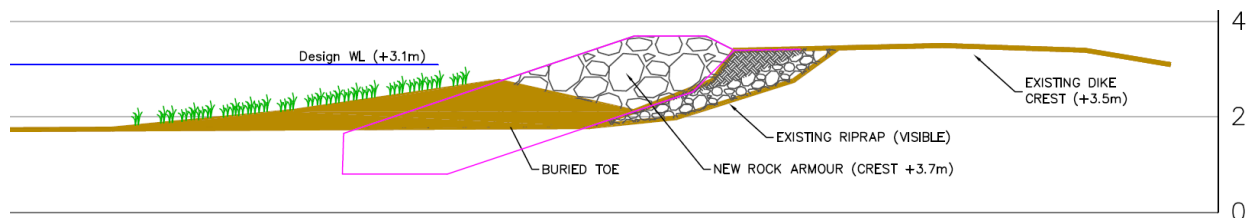

Figure 7: Dike upgrade with buried toe. Y axis shows elevation in metres with respect to mean sea level.

The numerical simulations with SWASH demonstrate clearly the reduction in wave runup compared to the pre-existing dike design. Images of the water surface elevation showing the same time event for the pre-existing and upgraded dike are shown in Figure 8.

A series of numerical simulations were undertaken to evaluate a range of options to enhance the performance of a future dike that can provide the necessary safety against flooding without undertaking major upgrades or dike raising that would require expensive land acquisition. Table 1 summarizes the overtopping rates for various options.

The results of the preliminary SWASH-based analysis show the potential for considerable economic efficiency depending on the configuration of the dike system and the extent to which ecological services are incorporated. Of some interest is the effect of a salt marsh (consisting of a 30m wide swath of 0.3m high vegetation), which results in a notable reduction in overtopping as indicated in case 2.

A non-vegetated raised foreshore is simulated in case 4. In this case, beach nourishment creates a 40m wide swath elevated 0.3m above the existing seabed but it is assumed that vegetation is not present. The absence of vegetation results in an increase in overtopping; however, if vegetation can be assured, for example by the successful restoration of a salt marsh, the expected levels of overtopping are significantly reduced, to the extent that a lower crest elevation, and therefore a more economical solution is more practical.
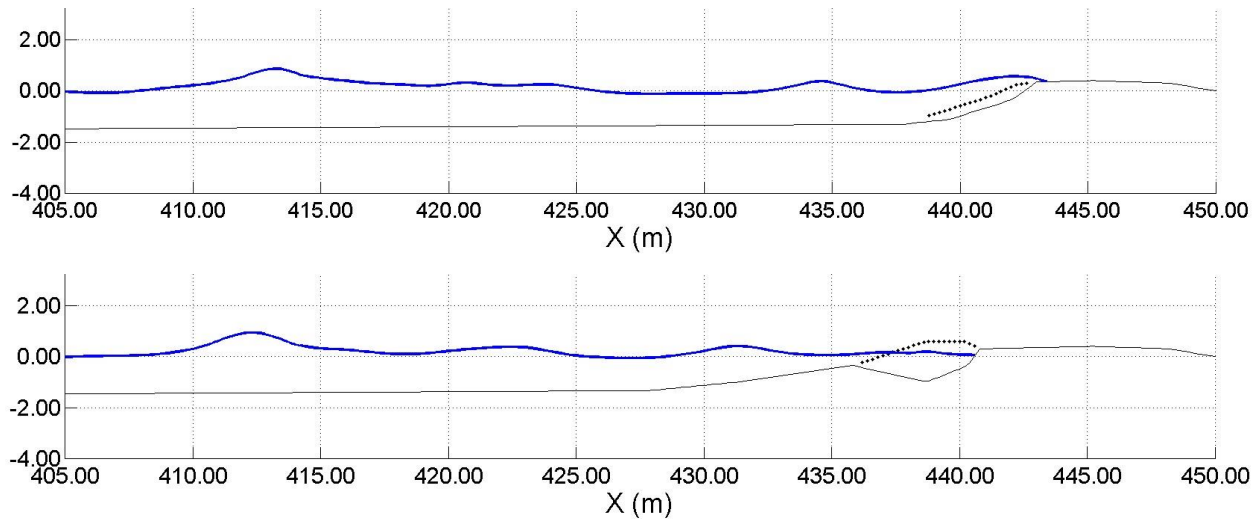
Figure 8: SWASH simulation of overtopping for pre-existing dike (above) and upgraded section (below) at the same time step. Y axes show elevation in metres with respect to still water level.

Table 1: Example table caption

Case	Description	Overtopping Rate (liters/s/m)	
		Mean	Max
1	Pre-existing Dike	42	276
2	Pre-existing Dike with Offshore Salt Marsh Enhancement	17	159
3	Dike Upgrade with Buried Toe	8	170
4	Dike Upgrade with Buried Toe and raised foreshore	9	229
5	Dike Upgrade with raised foreshore & Salt Marsh	3	86

A dike upgrade was successfully constructed in 2015 (Figure 9) using the section tested in case 3. An additional section of the Boundary Bay dike has been upgraded in 2017. As shown in Figure 9, the buried toe of the 2015 upgrade section has re-vegetated naturally. The additional width on the dike crest also allows for a crest strip of vegetation. The crest vegetation was not included in the SWASH model; however vegetation will further reduce wave overtopping and improve safety for any emergency personnel on the dike during a storm event.

Figure 9: Upgraded section of dike at Boundary Bay (2015)

4   CONCLUSION

As sea levels rise the associated wave interaction with existing shorelines presents significant challenges and increasing hazards. This rapidly changing and challenging environment, with the attendant economic implications, emphasizes the importance of interdisciplinary approaches. Qualified specialists in Coastal Engineering will provide a much needed base of knowledge, qualifications and leadership for the development of innovative solutions to the sustainable adaptation of coastal defenses against expected sea level rise.

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