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Numerical and Physical Modeling to Inform Design of the Living Breakwaters Project, Staten Island, New York

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Abstract: The Living Breakwaters project is an innovative implementation of coastal resilient infrastructure that aims to increase physical, ecological, and social resilience by attenuating damaging storm waves, reducing or reversing long-term coastal erosion, enhancing ecosystems by creating structured marine habitat, and fostering social resilience. In order to meet these diverse goals, the Living Breakwaters have a number of unique features including reef streets and ridges, crenulations, specialized stone gradations and ecologically enhanced concrete armor units and tide pools. In order to reduce the likelihood for down-drift erosion, a balance between slowing longshore sediment transport to reduce long-term beach erosion and providing storm wave reduction needed to be reached. To inform the design and the benefits of the Living Breakwaters, an understanding of the wave conditions, sediment transport, and the shoreline response to the project were required and the design and performance the breakwaters, including the ecological enhancements, needed to be assessed. A suite of modeling tools and techniques were required to fully understand all elements of design and performance. This paper presents a summary of the methods used, results and lessons learned from the Living Breakwaters modeling program.

Keywords: breakwaters; ecological enhanced concrete; physical modeling; numerical modeling; coastal processes

1 Introduction

The Living Breakwaters project is an innovative implementation of coastal resilient infrastructure that aims to increase physical, ecological, and social resilience by attenuating damaging storm waves, reducing or reversing long-term coastal erosion, enhancing ecosystems by creating structured marine habitat, and fostering social resilience by encouraging the use and stewardship of the shoreline and near-shore waters. The project is located in the waters of Raritan Bay (Lower New York Harbor) along the shoreline of Tottenville and Conference House Park in southern Staten Island. This area of Staten Island experienced significant wave damage during Superstorm Sandy.

In order to meet these diverse goals, the Living Breakwaters have a number of unique features including reef streets and ridges, crenulations, specialized stone gradations and ecologically enhanced concrete armor units and tide pools. In addition, in order to reduce the likelihood for down-drift erosion, a balance between slowing longshore sediment transport to reduce long-term beach erosion and providing storm wave reduction needed to be reached.

To inform the design and the benefits of the Living Breakwaters, an understanding of the wave conditions, sediment transport, and the shoreline response to the project were required. In addition, the design and performance the breakwaters, including the ecological enhancements, needed to be assessed. A suite of modeling tools and techniques were required to fully understand all elements of design and performance.

2 Numerical Modeling Program

2.1 Wave Transformation Modeling

To support the design layout and geometry of the Living Breakwaters, the long-term wave climate in the nearshore area adjacent to the Living Breakwaters project site was developed. The SWAN wave transformation model was used to transform U.S. Army Corps of Engineer (USACE) wave hindcast data from the entrance of New York Harbor to the project area. From the long-term wave climate data, extreme wave statistics are estimated. Additionally, the long-term wave climate forms the boundary conditions to the shoreline change modeling presented in the Shoreline Change Modeling section.

The Simulating WAves Nearshore (SWAN) wave transformation model has been applied for the determination of wave condition estimates in coastal areas by a global community of researchers and engineering consultants. For wave transformation modelling in Lower New York Bay and Raritan Bay, the SWAN model is capable of simulating the important wave processes that govern the generation and transformation of waves from offshore to nearshore adjacent to the project site including wind-wave generation, shoaling, refraction, wave breaking, wave to wave interactions, and energy changes due to bottom friction. SWAN is a spectral model that allows concurrent modeling of higher-frequency, locally generated wind waves and lower-frequency waves that are generated farther offshore.

2.1.1 Model Simulations

The intent of the wave simulation is to transform 30 years of hourly wave data offshore to usable wave climates at the project site. Hourly hindcast wave data were available from 1982 to 2012 at the USACE's Wave Information Study (WIS) station #63126 (Jensen, 2010). The station location is shown in Fig. 1. Station #63126 is the closest hindcast data available for Staten Island. The hourly wave condition data from WIS station #63126 were applied at the offshore boundary of the SWAN model for transformation. Water level variation due to astronomical tide and storm surge was included in the wave model from the National Oceanic and Atmospheric Administration's (NOAA's) Sandy Hook station #8531680. Inclusion of water level variation improves wave transformation modeling, especially in the nearshore areas close to the Living Breakwaters. Long-term wind measurements were available at several locations near to the project site: John Fitzgerald Kennedy (JFK) Airport; Newark Airport; Sandy Hook; and Bergen Point.

Because of the general correlation of wind speed and direction between the four measurement locations, the wind field from the Newark Airport gage was selected for use in the SWAN model. The computational grid for the SWAN model was a 300-meter rectangular grid, refined in the nearshore areas to 50 to 100 meters. The bathymetric and topographic information assigned to the computational grid was the same developed as part of the Federal Emergency Management Agency's (FEMA's) Region II coastal analysis performed for New York City and New Jersey (FEMA, 2014). Nearshore data in the vicinity of the Living Breakwaters obtained by multi-beam bathymetric and beach transect survey superseded FEMA's information within the survey limits (Hill International, 2015; MFS, 2015).

The SWAN model results were validated against wave measurements made by an Acoustic Doppler Current Profiler (ADCP) deployed by Rutgers University from January 2012 to April 2012 (Roarty, 2016). In general, the simulated wave conditions match the measured wave conditions well.

2.1.2 Model Results

Wave transformation results were extracted in the vicinity of the potential breakwaters. These extraction locations are summarized in Fig. 2. Location p6, shown on Fig. 2, was selected as a primary location, central to the breakwater layout, for analysis and comparison of wave statistics. Extreme wave conditions help to inform design conditions at the breakwaters site. To estimate representative return wave periods, the transformed 30-year hourly wave data were used. Annual maximum wave heights from each year of the simulation period (1982 to 2012) were used to estimate extreme wave conditions. The Weibull, Gumbel, and Generalized Extreme Value (GEV) distributions were fit to the transformed annual maximum wave data. Comparing the best-fit from each of the three distributions, it was determined that the Gumbel distribution provided the best extreme wave statistics for the transformed 30-year hourly wave data. During the design process, the extreme wave heights were further refined based on a directional analysis (Tab. 1).

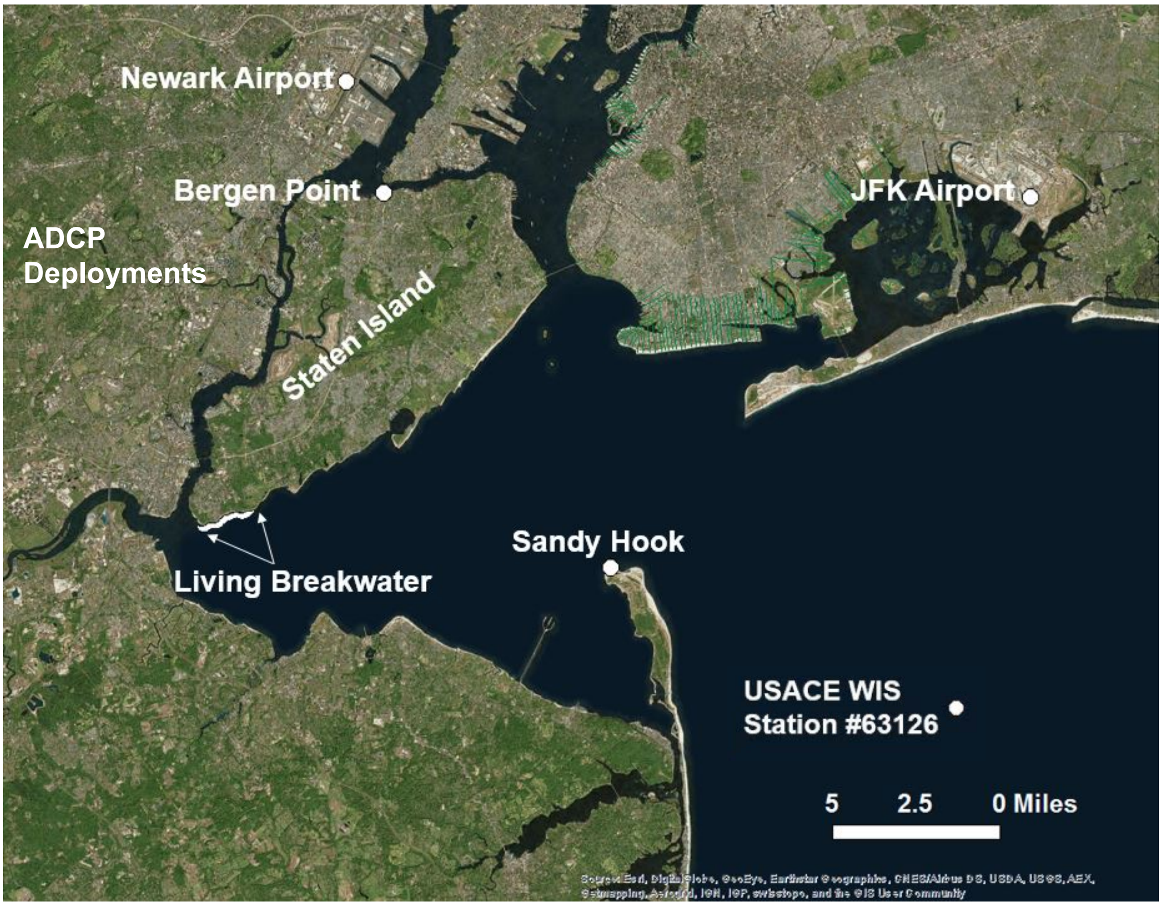

Fig. 1. Living Breakwaters Location and Data Sources.

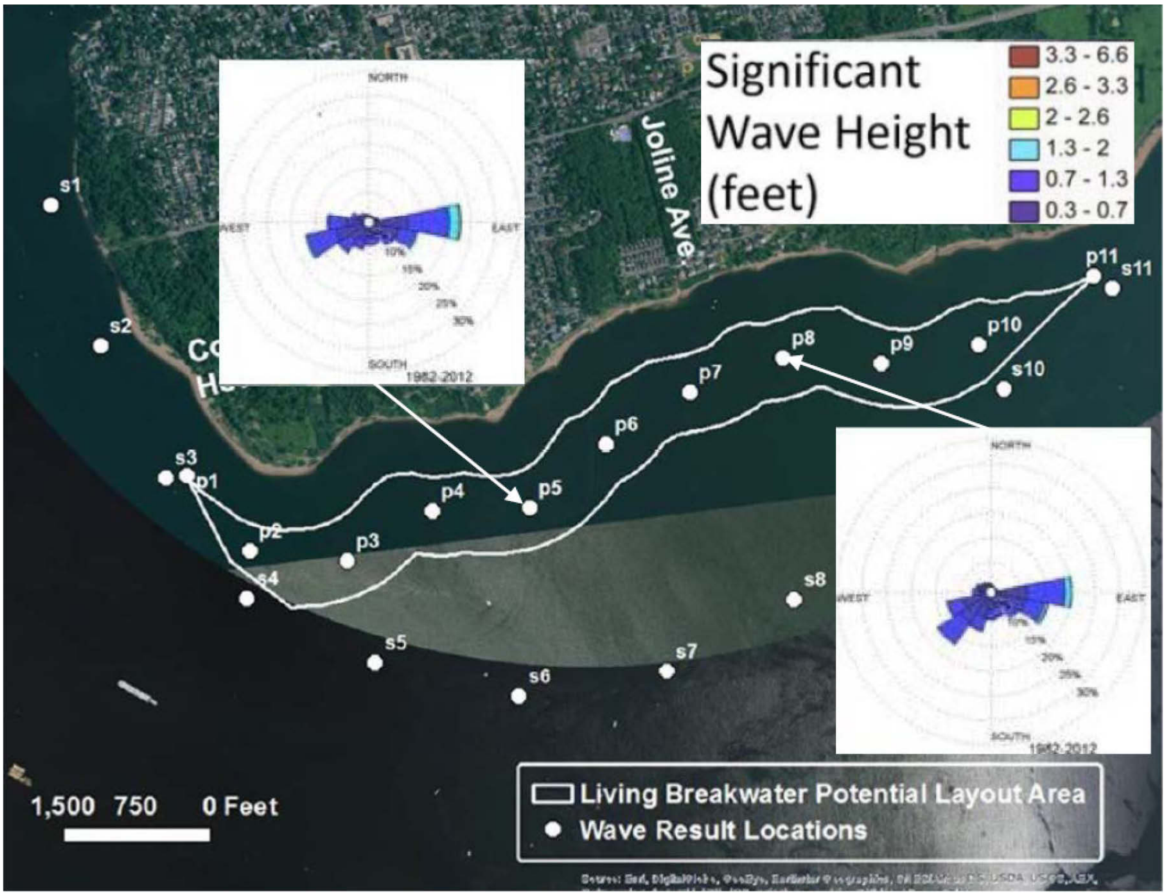

Fig. 2. Representative wave roses of the 30-year hourly wave transformation results at selected wave monitoring locations within the preliminary evaluation area for the Living Breakwaters.

Tab. 1. Design Conditions Summary

100-year Return Period Wave Conditions		
Direction	East (90°)	East-South-East (120°)
Significant Wave Height (m)	1.6	1.3
Peak Wave Period (sec)	5.0	4.8
Design Water Levels (m - NAVD88 Datum)		
100-year Return Period		3.9
100-year Return Period Plus Sea Level Rise		4.7

2.2 Shoreline Change Analysis

A historical shoreline change analysis was performed based on orthoimagery available between 1978 and 2012, covering the range of the wave hindcast (1982 to 2012). The high water position for each orthoimage was delineated, allowing the long-term rate of change to be inferred. From the analysis, the locations where the largest shoreline change have occurred were delineated as were areas influenced by existing shoreline structures. Uncertainty estimates were also determined. The rates of shoreline change exceed 0.3 m per year (1 foot per year) in the western portion of the study area, with the greatest shoreline erosion rate at 1.1 m per year (3.5 feet per year).

2.3 Shoreline Change Modeling

Shoreline change modeling was an important component of the Living Breakwaters modeling approach throughout the design process. Using the long-term nearshore wave climate conditions developed in the Wave Transformation Modeling and the orthoimagery-based historical shoreline change described in the Shoreline Change Analysis section, a shoreline change model, using

GENESIS, was developed. GENESIS is a commonly used and widely accepted shoreline change model, known as one-line model. The underlining assumption is that the cross-shore beach profile does not change with time, so that the active profile only moves parallel to itself, assuming the cross-shore profile is in long-term equilibrium. It simulates long term planform evolution of the shoreline in response changes in longshore sediment transport from incoming waves and coastal structures.

The model was calibrated to the observed historical shoreline changes between 1978 and 1996. The calibrated model was validated to reproduce the shoreline changes between 1996 and 2012. The long term (20 years) shoreline changes for the without-project, or baseline conditions were then modeled for various breakwater layout scenarios. The GENESIS modeling was performed over a 20 year period, which allows comparison of the various scenarios in development of the Living Breakwaters design.

The results of the 20-year baseline simulation indicated that historic shoreline erosion rates trends would continue into the future. With the Final Design scenario of the Living Breakwaters, the model results showed that shoreline erosion and retreat are mitigated with extensive areas of shoreline accretion near the areas of the neighborhood with the greatest potential exposure to storm damage. Erosion rates were reduced or reversed throughout the project area. The model confirmed the Final Design layout of the breakwater system achieves a shoreline response in balance with the projects goals, including cost and footprint optimization.

2.4 Storm Wave Modeling Near Breakwaters

The transformation of the wave climate and the wave penetration in the nearshore region close to the proposed Living Breakwaters alignments is important for understanding the performance of the breakwaters relative to wave attenuation and optimization of layout and geometry. During earlier design phases model simulations were performed using the REFDIF model to allow a more rapid assessment of alternatives. During the Final Design phase the advanced wave model FUNWAVE was applied for a more detailed study of the breakwater's performance. This included the setup of the Fully Nonlinear Boussinesq Wave Model (FUNWAVE) and the simulation of the wave transformations for baseline conditions (without the breakwaters in place), and with the proposed designs in place. The FUNWAVE model includes processes of wave refraction, diffraction, shoaling, full/partial reflection, transmission, bottom friction, wave breaking and runup, wave-induced currents and wave-current interaction. FUNWAVE simulates wave propagation over nearshore bathymetry and around the structures allowing for the evaluation of the influence of variables such as water levels and wave directions on the resulting wave heights and wave periods along the shore.

2.4.1 Model Simulations

Based on the directional frequency analysis and wave roses of the 30-year wave data hindcasted by the wave transformation model, the east (E) and east-southeast (ESE) directions are the maximum wave and dominant wave directions, respectively. The computational grid was developed to extend well beyond the limits of the proposed Living Breakwaters layout zone. The computational grids were assigned a 1-meter spacing with a rectangular grid with dimensions of 2601 nodes by 1501 nodes for E grid and with dimensions of 2101 nodes by 2451 nodes. As storm wave mitigation was the primary design requirement, modeled scenarios focused on 100-year return period surge and wave conditions. Sea level rise scenarios were also considered.

During the Final Design phase, approximately 36 FUNWAVE simulations were completed as part of the performance and cost optimization process. This included looking at both East and East-South-East waves, 100-year and 100-year plus sea level rise water levels, and modifications to breakwater location (distance offshore and horizontal position), length and gap width. For the Final Design, the focus was mostly on small changes to improve performance or to reduce cost without impacting performance. Fig. 3 shows the FUNWAVE results with and without the project.

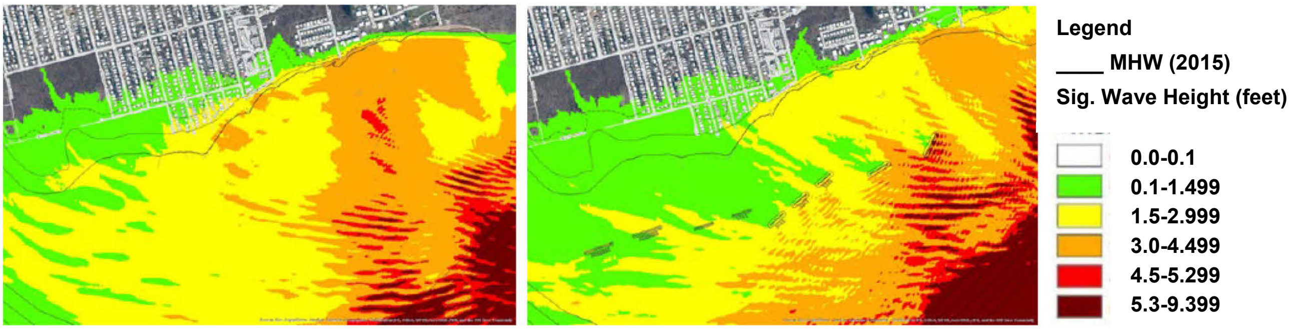

Fig. 3. Comparison of FUNWAVE model results without (left) and with project (right)

2.5 Sediment Transport Modeling

As part of the design process an evaluation of sediment transport and the impacts of the breakwater system on sediment movement, deposition, and erosion in the project area was performed. In addition, an evaluation of tidal flushing with the project is place was analyzed. The Delft3D suite of models was selected for its ability to efficiently simulate the interaction of tides, winds, currents, waves, and sediments. Three modules within the suite are used in the simulations conducted as part of this study: FLOW, WAVE, and MOR. The FLOW module of Delft3D simulates the interaction of winds and astronomic tides to predict water levels, currents, and shear stresses on the sea floor. The WAVE module uses the SWAN spectral wave model to simulate wind driven waves in a nonstationary mode to simulate their propagation throughout the model domain and informs the flow module of wave radiation stresses that drive additional water level set-up. Finally, the MOR (MORphology) module is used to compute how the interaction of currents and waves drive sediment resuspension, deposition, transport, and topographic changes to the seabed due to suspension and deposition.

The models were validated with Acoustic Doppler Current Profiler (ADCP) data collected at the project site. The validated model was used to understand how the construction of breakwaters would affect patterns of sedimentation and erosion. Model simulations were conducted for daily conditions as well as for storm conditions. The one month-long daily conditions simulations were used to observe how the breakwaters might impact transport over long periods of time while the 4-day Hurricane Sandy condition was used to observe how the breakwaters affected sediment transport during short, energetic events. The combined nonlinear effect of waves and currents is calculated by the Deflt3D model into a maximum bed shear stress. The bed shear stress determines if sediment will be suspended (based on grain size). If sediment is suspended, the model hydraulics then move the sediment until current velocities drop below the value required to keep the sediment suspended and it is deposited on the bottom. Fig. 4 shows example results of bed shear stress results. Bed level changes over a one month period are shown in Fig. 5.

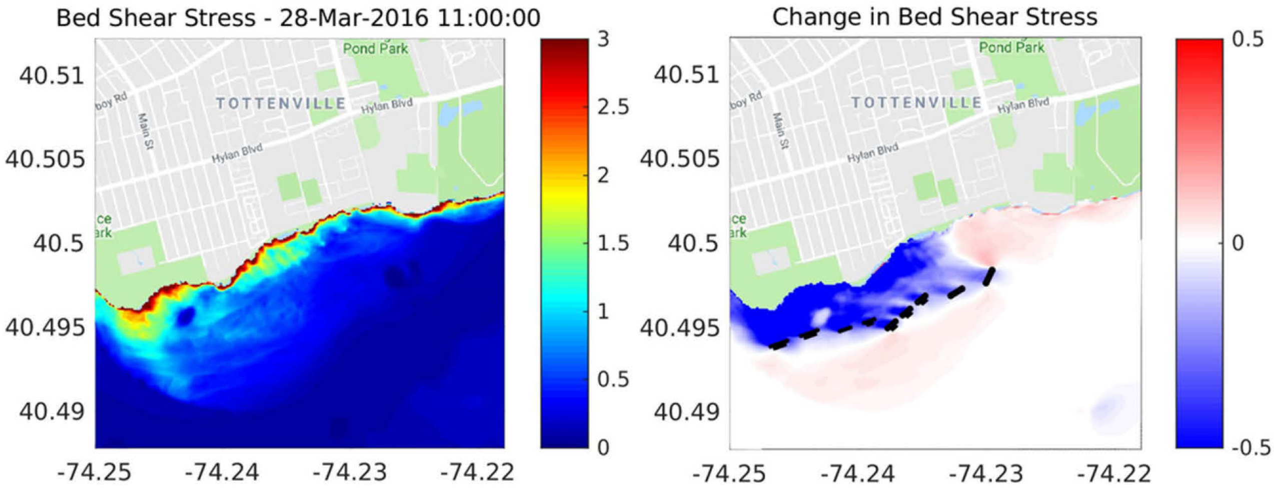

Fig. 4. Bed shear stress without breakwaters (left) and with breakwaters installed (right). Shear stresses are shown in N/m2. Breakwaters are shown in black for reference.

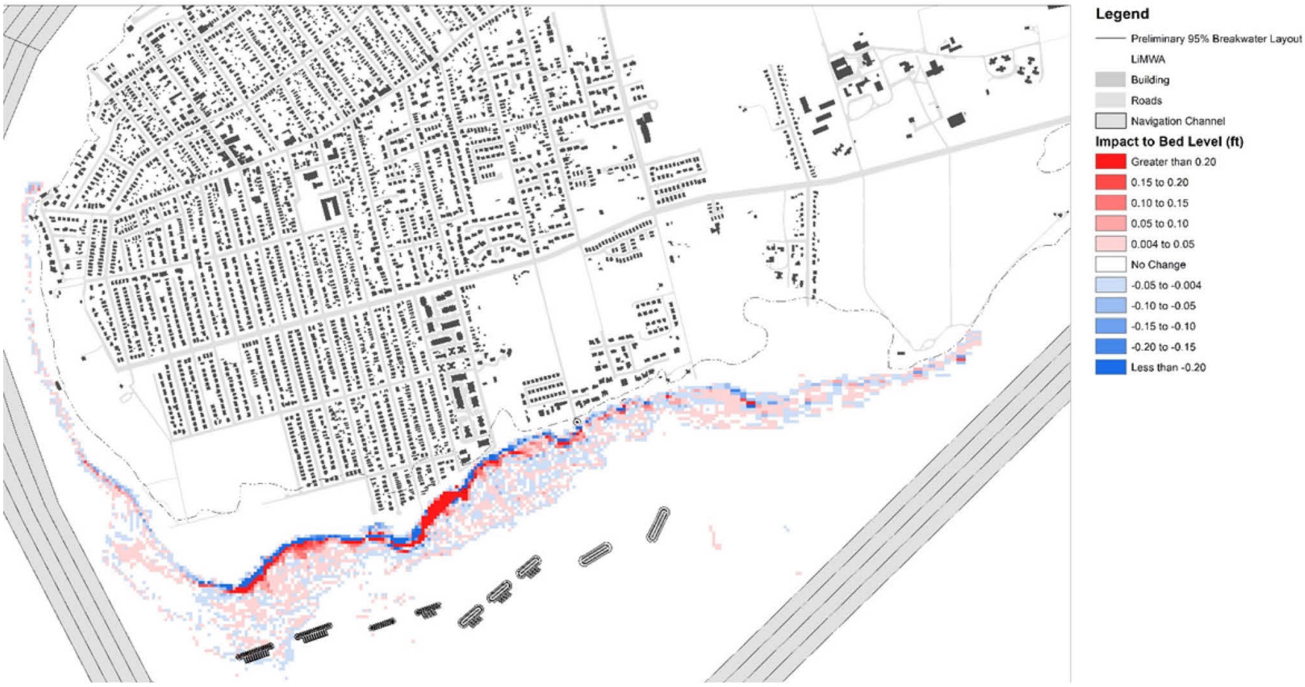

Fig. 5. Impact to bed level due to installation of breakwaters after 1 month of simulation for the 250μm grainsize.

2.6 Modeling of Flows and Sediment at the Breakwaters

Hydrodynamic modeling of the nearfield around the breakwaters was performed using a computation fluid dynamics (CFD) model. This allowed for an evaluation of flows and sediment motion in detail around the breakwaters and in and through the reef streets. This modeling allowed for adjustments to be made to breakwater and reef ridge orientation and configuration during the preliminary design. The computational fluid dynamics (CFD) model, FLOW-3D, was utilized to evaluate different layout designs of the reef streets and reef ridges, to predict the sediment transport potential within the near-field of a breakwater, and to assess circulation and flushing within the reef streets. FLOW-3D is a highly-accurate CFD software program that specializes in solving transient, free-surface problems.

Model grids were developed for two different breakwater configurations, varying reef ridge angles, lengths, and reef street widths. Grid cells in the reef streets were approximately 1 ft by 1 ft with grid cells around breakwater head approximately 2.5 ft by 2.5 ft. All cells were 0.25 ft in the vertical direction. This resulted in approximately 1.5 and 2.6 million elements or cells. Each breakwater configuration was tested for mean flood or mean ebb tide. These tidal currents and directions were determined through an analysis of locally collected Acoustic Doppler Current Profiler (ADCP) data. Two instruments were located in the Living Breakwaters project. Based on early sediment surveys of the area a median grain size of 0.35 mm that was utilized in the analysis.

2.6.1 Model Simulations

Each breakwater configuration was tested for mean flood or mean ebb tide. These tidal currents and directions were determined through an analysis of locally collected Acoustic Doppler Current Profiler (ADCP) data. Based on early sediment surveys of the area, a median grain size of 0.35 mm was utilized in the analysis.

2.6.2 Analysis and Conclusions

The proposed breakwater designs simulated all showed acceleration and separation of the approaching flow as it moves around the breakwater (Fig. 6). This separation leaves an area of low velocity upstream of the breakwater. The length of the reef ridges was sized to remain inside this low velocity region to reduce the potential deposition from incoming sediments into the reef streets and to protect the edges of the reef streets from local scour. During ebb tide, the flow reverses and the reef ridges and streets are now downstream of the breakwater. A counter-rotating circulation pattern develops in the lee of the breakwater, that promotes exchange between the outer flow and the reef streets. Finer grained sediments that may be transported from the far-field are unlikely to be deposited in the vicinity of the structure. The large flow accelerations and turbulence of the flow will overcome the low settling potential of the fine-grained sediments.

Next, then angle and separation of the reef ridges was tested. While the majority of the flow accelerates around the breakwater, some flow does penetrate into the reef streets during flood tide. During ebb tide, the circulation pattern in the wake drives flow over the reef streets. The ridge angle design had three goals: (1) to protect against local scour; (2) to protect against deposition within the reef streets; and (3) to provide adequate exchange for nutrients out of the reef streets in order to provide habitat conditions suitable for the target species. Based on these three goals, the angled reef street design shown in the below figures was selected. This design reduced the potential for scour, showed low deposition potential within the reef streets, reduced the potential for deposition upstream of the reef ridges, protected against sediment transport occurring from waves reflecting from the breakwater trunk, and allowed adequate exchange of nutrients within the streets. The sediment mobility was assessed with the Shield's parameter, which balances the strength of the flow pushing on the sediment against the sediment size and weight. Areas shown in Fig. 7 in red are areas where the sediment is expected to be in motion along the sea floor. Areas not in red are where no sediment motion is predicted.

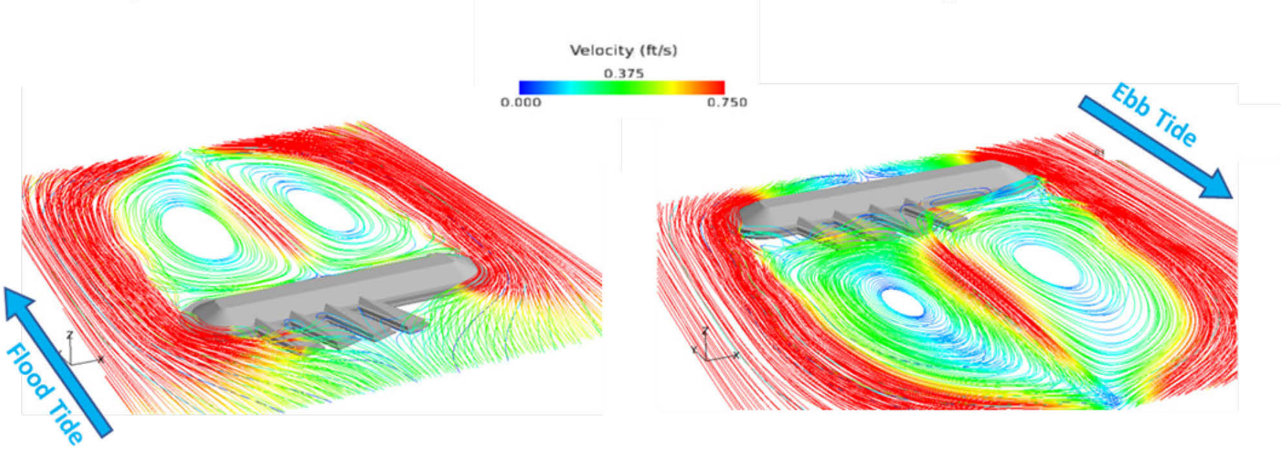

Fig. 6. Flow Pattern Around Breakwater and Reef Ridges.

The effect of the crenulated crest was also explored with the CFD model. At mean water level, the flow patterns were similar to those produced with breakwaters without crenulations. At mean high water, a portion of the flow moves through the crenels, changing the flow pattern (Fig. 10). The impact of the flow through the crenels and the impact on the sediment transport potential in the reef streets was examined. Flow through the crenels results in lower velocities around the structure ends, but high velocities within the crenel themselves. The fluxes into/out of the reef streets and tracer removal are smaller for the MSL simulations than observed with no crenulations. Fluxes into/out of the reef streets and tracer removal are much larger for the MHW simulations. Jets created by the flow through the crenel create large flows in the nearby reef streets and the MHW simulations show a loss of symmetry in the wake.

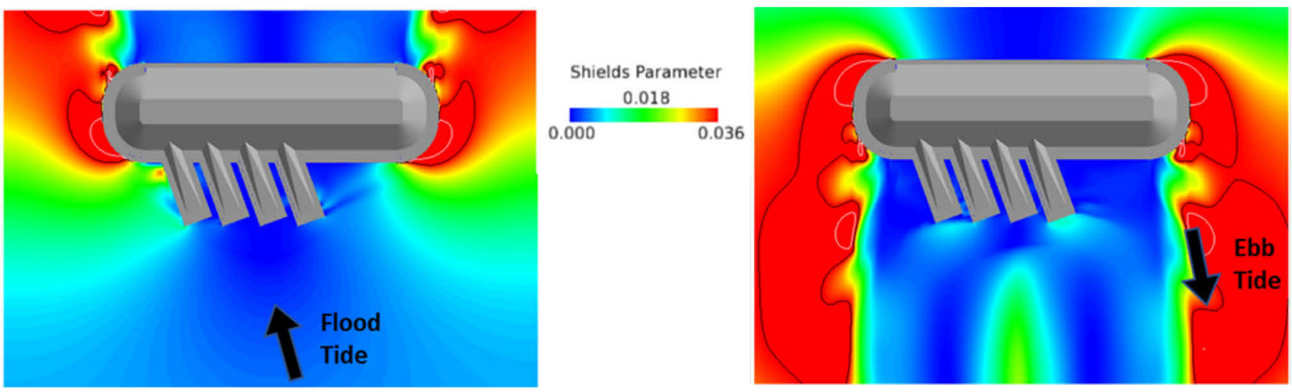

Fig. 7. Sediment Transport Assessment

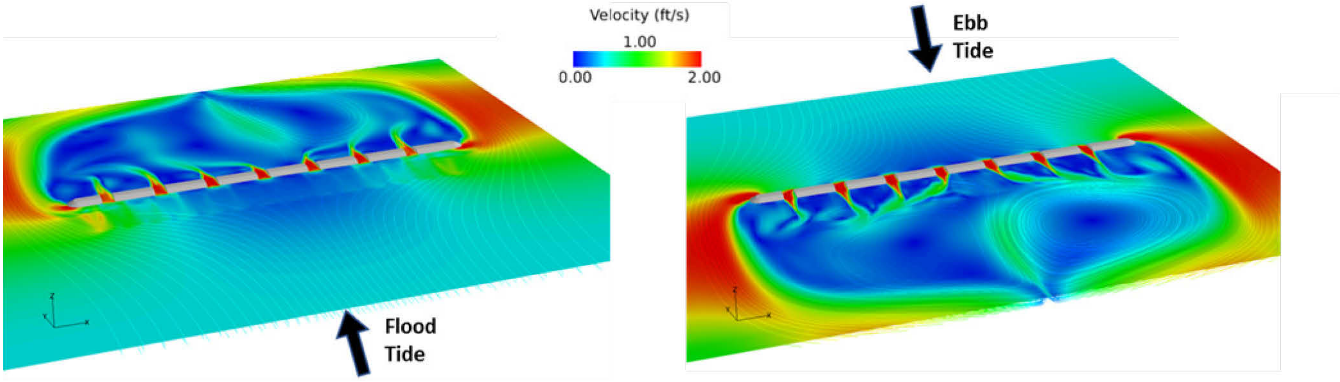

Fig. 8. Flow Pattern Around Crenulations

3 Physical Modeling

In addition to numerical modeling, a series of physical model tests were performed to assess stability of the breakwater design and confirm the overall wave attenuation performance of the Living Breakwater system. Physical model studies can offer highly realistic scaled simulations of the interaction of waves with coastal structures and are a reliable method to optimize structure designs. Physical model testing was carried out at the National Research Center Canada (NRC).

The main objectives of the physical modeling are to assess the structural stability and design of the breakwaters under wave action and varying water levels and confirm the wave attenuation performance of the system, including: evaluating the stone sizing and gradation for the breakwater trunk and reef ridges (stability of stone); evaluating non-traditional features including the reef ridges and reef ridge connection to the breakwater, the crenulated crest, tide pools and ECOncrete® armor units; confirming breakwater dimensions; assessing wave transmission and attenuation; gaining improved understanding of flow characteristics and potential sediment transport patterns around the breakwaters

To assess these parameters the physical modeling was divided into two parts: a 2D and 3D features and sections model; and a 3D breakwater system model. These two sets of physical model studies supported the optimization and verification of engineering designs of the Living Breakwaters. The first set (Features and Sections Model) focuses on optimizing and verifying the design of the living breakwater design elements to ensure they are well adapted to local conditions, including extreme conditions, while the second set (Breakwater System Basin Model) focuses on verifying the overall performance of the entire project comprised of the system of multiple living breakwaters.

For the features and sections model, a 1:20 scale model was constructed of breakwater cross-sectional segments (2D) and a single breakwater (3D) to properly represent the forces that determine the stability of the breakwaters. The large area required to model the entire Living Breakwater system required scaling of 1:80 to fit within the largest available basin dimensions at NRC and while this scale is too small to assess stability of the breakwater elements, it can simulate the wave attenuation and associated water circulation patterns effectively.

3.1 Breakwater Features and Sections Model

The breakwater features and sections model focused on assessing the stability of the breakwater armor stone and non-typical design features, such as crenelated crests, ECOncrete® armor units, and the reef ridges/streets under storm wave conditions and varying water levels. For the 2D model layout eight different breakwater sections were developed to evaluate stability and wave attenuation performance of different breakwater designs under various wave and water conditions. Design parameters varied across the breakwater sections included: crest height and width; presence and number of reef ridges; presence of a leeside berm.

Fig. 9 (left) shows the layout of the 2D model sections evaluated. Based on the outcome of the 2D testing, a final quasi-3D model structure, Fig. 9 (right), was constructed and tested. The 3D model layout utilized two similar breakwater sections at different angles relative to wave approach and placed at different elevations.

Fig. 9. 2D Model Sections (Left) and 3D Model Layout (Right)

Overall, the breakwater sections tested met design performance and survived waves larger than the 100-year design values. The armor was stable under the range of conditions tested. Some movement of the reef ridge toe stones was observed when rock and ECOncrete® armor units were mixed along the outward toe edge. Testing showed some movement of the smaller armor on the reef ridges particularly under the larger waves, but this is likely acceptable as the ecological benefit of the varied gradation and mix of smaller stones is desired. In all cases there was no complete failure of the layer and the ridge remained intact. Testing indicates that the tide pool units experience some displacement when placed along the crest of the structures. Based on these results, placement of the tide pool units was adjusted. The results of the wave transmission were incorporated into the numerical modeling of storm waves described in the Storm Wave Modeling Near Breakwaters section.

3.2 Breakwater System Model

The breakwater system model included a scaled reproduction of the foreshore bathymetry, the Staten Island shoreline, and the new breakwater structures. Nine breakwater structures were included in the large scale 3D model of the breakwater system in three different configurations. All three configurations included nine breakwater segments varying the length and location to shorten some of the gaps between structures and reduce the level of wave agitation on their leeside. The 3D physical model was constructed at 1:80 length scale in NRC's 30 m by 50 m Large Area Basin.

4 Overall Summary and Conclusions

In support of the design of the Living Breakwaters substantial modeling efforts have been undertaken throughout the design process. While the modeling generally focused on four main modeling areas: wave attenuation; shoreline change; sediment transport; and physical modeling, other specific questions have also been addressed through the use of state of the art numerical and physical modeling tools.

Using the GENESIS model, shoreline change modeling was applied to optimize breakwater layouts and to assess the shoreline response of the selected the Final Design layout. The Final Design layout effectively reduces historical erosion rates and maintains the beach. The shoreline restoration provides a means add beach width immediately to a critical narrow portion of the shoreline with the modeling demonstrating the breakwaters will help maintain it over time.

Risk reduction through wave attenuation is another key goal of the project. Throughout the design process REFDIF and FUNWAVE have been used to test the performance of and optimize breakwater layouts. Including testing varying crest elevations, breakwater lengths, gap widths and distance to shore. A fully nonlinear water wave model, FUNWAVE, was applied to evaluate the wave protection performance and impacts on the waves near breakwaters and waves acting on the shorelines. The model results demonstrate that the Final Design is effective at reducing wave energy. The target goal of wave heights less than 1m (3 feet) in the project area in the lee of the breakwater under 100-year conditions and 0.8 m of sea level rise was achieved for the final design scenario.

Hydrodynamic modeling showed the potential for some increase in flood current velocities around the eastern breakwater and for ebb currents between the breakwaters and shoreline. However, both increases appear to be within the envelop of velocities in the project area (without the breakwaters).

Hydrodynamic and sediment transport modeling conducted using the Delft model suite indicated a reduction in bed shear stress and hence less suspension of sediments near the shoreline for both daily and storm conditions, as well as velocities consistent with the 'no-project' condition. The western breakwaters showed some potential for deposition but overall the sediment accretion is along the shoreline as simulated in the shoreline change modeling. The modeling showed negligible impact on sediment movement and deposition in and around the navigation channel which appears to be outside the influence of the breakwaters.

The CFD model FLOW-3D was used to aid the ecological design of the reef streets by examining various lengths, spacings and positions of the reef streets.

Physical modeling confirmed the stability of the majority of the armor stone and the ECOncrete® armor and tide pool units. Slight modifications to toe stone, reef ridge material and tide pool placement was implemented based on the modeling. The physical modeling also provided additional detail on wave transmission, especially with regard to the crenulated crest breakwaters. The Breakwater System model confirmed the overall wave attenuation performance of the breakwaters, but also suggested some attenuation optimizations that were incorporated into the Final Design.

In summary, the numerical and physical model simulations have demonstrated that the Living Breakwaters are effective at achieving the overall project goals to reduce shoreline erosion trends, maintain the shoreline, and reduce wave energy in front of residential areas, without impact on the navigation channel.

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