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3D PHYSICAL MODELLING OF WIND AND WAVE OVERTOPPING AT THE BILLY BISHOP AIRPORT REVETMENT

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ABSTRACT

As part of a planned development for Billy Bishop Toronto City Airport, new land reclamation and related marine works are required to extend both ends of the main runway into Lake Ontario. Wave conditions at the eastern end of the runway are relatively mild, as the site is sheltered inside Toronto Harbour. However, an extension at the western end of the runway will be directly exposed to strong winds, energetic wave conditions, high water levels, and winter ice conditions. An engineered revetment is required to prevent erosion, preserve stability, and protect the exposed western reclamation from attack by waves and ice. The design challenge was compounded by the requirement to minimize the frequency and extent of wave run-up and overtopping during storms as much as possible in order to avoid frequent inundation of the runway. At the same time, the crest elevation of the perimeter revetment was limited by the elevation of the existing runway and various other requirements for safe operations at the airport.

A large-scale 3D physical modelling study was undertaken which played a crucial role in developing, testing, and optimizing the design of the perimeter revetment and for costing the marine works. In order to accommodate the stringent design requirements, several innovative revetment design concepts (featuring lower crest elevations, milder slopes, thicker filter layers, and thicker armour layers than normally seen in conventional designs) were tested in a wide range of harsh wave, wind, and water level conditions. With regards to wave overtopping of the perimeter revetment, specifically at the location of the navigational antenna array and jet blast deflector near the end of the runway, this study collected valuable quantitative measurements and qualitative observations.

Keywords: - physical modelling, revetment, wave overtopping, wind

1. INTRODUCTION

1.1 Project Background

Billy Bishop Toronto City Airport (BBTCA) was purpose-built on reclaimed land on the Toronto Islands chain and opened as Toronto's first commercial airport in 1939. It was recently ranked Canada's 9th-busiest airport by passenger numbers. In 2013 Porter Airlines, whose home base of operations is BBTCA, announced their desire to purchase a fleet of new larger aircraft with greater range (the CS100 by Bombardier) and expand operations from a regional airline serving cities in central and eastern Canada and the north-eastern US, to a continental airline serving destinations throughout North America. Introduction of the CS100 would allow Porter Airlines to vastly increase the number of domestic and trans-border destinations served from BBTCA (Porter Airlines, 2013).

Airport Infrastructure upgrades would be required in order to safely and efficiently operate the CS100 at BBTCA. PortsToronto retained WSP Canada Inc. (herein WSP) to identify operating requirements for the CS100 at BBTCA. The major element was the need to extend the main runway by about 400 m (200 m at either end) to accommodate the longer landing and take-off requirements of the larger CS100 aircraft. This extension would include a 150 m Runway End Safety Area. PortsToronto would also need to obtain an exemption to an existing tripartite agreement restricting operations by jet aircraft.

1.2 Marine Works

The proposed extension of Runway 08-26 requires land reclamation work into Lake Ontario on the west end and into the Inner Harbour on the east end (see Figure 1). Wave conditions at the eastern end of the runway are mild, as the site is well protected by the Toronto Islands chain. However, the western runway extension will be directly exposed to harsh wind, wave, and ice conditions from Lake Ontario. The western reclamation must be protected by an engineered revetment to prevent erosion and preserve stability under wave attack. In addition, to ensure that the runway is not frequently inundated by water and ice, the revetment bordering the reclamation must be designed to minimize the volume of water passing over the crest as spray or green-water flows during storm events. Moreover, the crest of the revetment must be maintained at a relatively low elevation to ensure safe landing and take-off operations.

Figure 1. BBTCA Runway 08-26 extension plan (source: Porter Airlines)

1.3 Site Conditions

The city of Toronto and BBTCA are located on the north-western shore of Lake Ontario. WSP conducted a detailed study documenting the existing coastal environment to support the design of the new marine works and the physical model study. This study produced up-to-date information on local bathymetry, lake water levels, wind climate, as well as offshore and nearshore wave climates. A wave hindcast model was used to estimate the offshore wave climate at BBTCA, as no wave measurements over a long period were available close to the project location. The offshore wave climate was computed for a point located 5.2 km south of the airport at an approximate water depth of 70 m, providing a representative offshore wave exposure with maximum fetch in all directions.

As they propagate to shore, various physical phenomena transform the waves as they start to interact with the lakebed. The SWAN numerical wave model was used to transform the offshore wave climate to the tip of the proposed western runway extension at a depth of 8.2 m. An hourly nearshore wave climate was predicted for the period from 1971-2014. In general, maximum wave heights ranging between 2.0 and 2.5 m were predicted, with the exception during the Southern Ontario Blizzard of 1978 where a maximum wave height of 3.4 m was predicted. The incident wave direction is a relatively narrow band between SE and WSW. Waves approaching from southwest are the most frequent and are expected to have the largest wave heights. Prevailing winds are from the southwest, west, and east directions, with maximum speeds on the order of 80 km/h (WSP Canada Inc. 2015).

1.4 Study Objectives

The National Research Council of Canada (NRC) was commissioned to conduct physical modelling studies to support the efficient, cost-effective, and reliable engineering design for the proposed extension to Runway 08-26. The main objectives of the study were to: verify that the proposed revetment designs would remain stable under the extreme design conditions forecasted at the site, and optimize the proposed designs to improve stability, reduce wave overtopping to acceptable safe levels, and reduce construction and maintenance costs where possible.

2. REVETMENT DESIGN CRITERIA

The design requirements for the western runway extension were unique in that the coastal protection works needed to remain relatively low-crested as to not interfere with the Obstacle Limitation Surface (OLS, a government regulation restricting the height of objects located near runways), but also limit wave overtopping and associated spray from reaching the runway or taxiway surfaces such that safe operation of the airport was maintained, especially during winter. Desktop analysis indicated that a conventional revetment design would require armour stone in the order to 10 tonne, with crest heights reaching an elevation of +6.0 to +6.5 m. While this conventional design would likely be stable under extreme wave attack, it did not comply with the OLS regulation. Furthermore, an increased crest width and/or height would be required to control wave overtopping and ensure stability on the leeward side. Information from an aggregates survey indicated that large armour stone would be difficult and/or expensive to source, especially in the quantities required. Hence, an alternative non-conventional design based on mean armour stone weights of lighter than 6 tonne was developed. The design concept was to minimize overtopping and maximize stability by increasing the volume of porous armour and filter materials. It was anticipated that increasing the filter layer thickness would improve the stability of the outer armour layer while also reducing the levels of overtopping. Damage criteria for the rock armour relates to the displacement or loss of stone that would diminish the function of the revetment to withstand extreme wave attack and to control wave overtopping. For this study, little or no displacement of stone along the leeside of the revetment crest was permitted during the principle design conditions (once yearly event); while under overload conditions there should be little or no displacement of armour stone on the front face and crest of the revetment.

The issue of wave overtopping at BBTCA was considered to be an important factor in the rubble-mound revetment design. Criteria for tolerable wave overtopping rates were primarily based on engineering guidelines (TAW, 2002; EurOtop, 2007; Krom, 2012) and were influenced by specific infrastructure to be placed at the end of the western runway extension. It is noted that these guidelines provide only limited information on dealing with wind effects on overtopping. For this study, maximum mean rates of wave overtopping in the area at the end of the runway extension were set as 0.1 L/s/m for servicing of the equipment and 1.0 L/s/m for the infrastructure itself. Although the area immediately behind the revetment crest would not normally have pedestrian or vehicular traffic, a localizer antenna array (LOC) and a jet blast deflector fence will be located near the end of the runway. The LOC is critical to the operation of the airport since it is part of the primary navigation guidance system for aircraft landings and missed approaches. The LOC array can operate with an ice covering of up to 5 cm, but must remain in perfect alignment at all times. It must also be accessible for servicing under almost all conditions. Excessive wave overtopping under freezing conditions could render the LOC inoperable. Overtopping reaching the runway and taxiway surfaces at the western extension was to be minimized as much as possible (ideally <0.1 L/s/m).

Apart from the space requirement on the crest of the revetment for the LOC placement and service access, the LOC cannot be too close to reflecting surfaces due to backscatter considerations. In particular, the rock slopes on the leeside of the revetment crest had to be at least 15 m away from the LOC across a flat area, or be at least 5 m away across a flat area if the top of the revetment crest is at least 1.5 m below the elevation of the antenna heads.

3. PHYSICAL MODEL DESIGN AND CONSTRUCTION

3.1 Model Layout and Construction

The model study was conducted in NRC's 26 m by 36 m Multidirectional Wave Basin (MWB), a state-of-the-art facility for engineering research and performance verification of maritime structures in the ocean environment. The MWB can accommodate water depths from 0 to 2.5 m and features a powerful 30 m long directional wave generator capable of generating a broad range of realistic wave conditions with significant wave heights exceeding 0.5 m.

A three-dimensional physical model of the western runway extension and surrounding lakebed bathymetry was constructed at a length scale of 1:28. This scale represents a reasonable compromise between minimizing scale and boundary effects without exceeding the limits of the MWB facility. All aspects of the model were designed using Froude scaling criterion, which assumes that gravitational and inertial forces are dominant, compared to viscous forces. At this scale, the functional area of the wave basin represented a 0.47 km^2 rectangular footprint of prototype terrain (see Figure 2). The model was oriented within the basin such that the runway extension could be tested in waves approaching from a ~45° range of directions between SE and SW. A side-wall reflection technique was used in this study in order to increase the physical area within the wave basin over which homogeneous wave conditions were generated. The technique involves purposely reflecting waves off the solid guide walls on either side of the wave machine. This side-wall reflection technique was a crucial factor in being able to generate sea-states with mean wave directions of 22.5° relative to the wave machine that were reasonably homogeneous across the test site. Highly efficient expanded-metal wave absorbers featuring reflection coefficients less than 5% were installed around the perimeter of the basin to control unwanted wave reflections.

A faithful representation of the existing lakebed, down to approximately the 9 m depth contour was constructed to ensure that local nearshore wave transformations would be properly simulated in the model. The model bathymetry was formed by placing a thin skin of cement mortar over a moulded bed of compacted gravel. Templates spaced at 1 m (model scale) intervals were used to control the final elevation of the bathymetry surface. Once the cement mortar had cured, several lakebed contours were painted onto the concrete floor to enhance the visual perception of the lakebed.

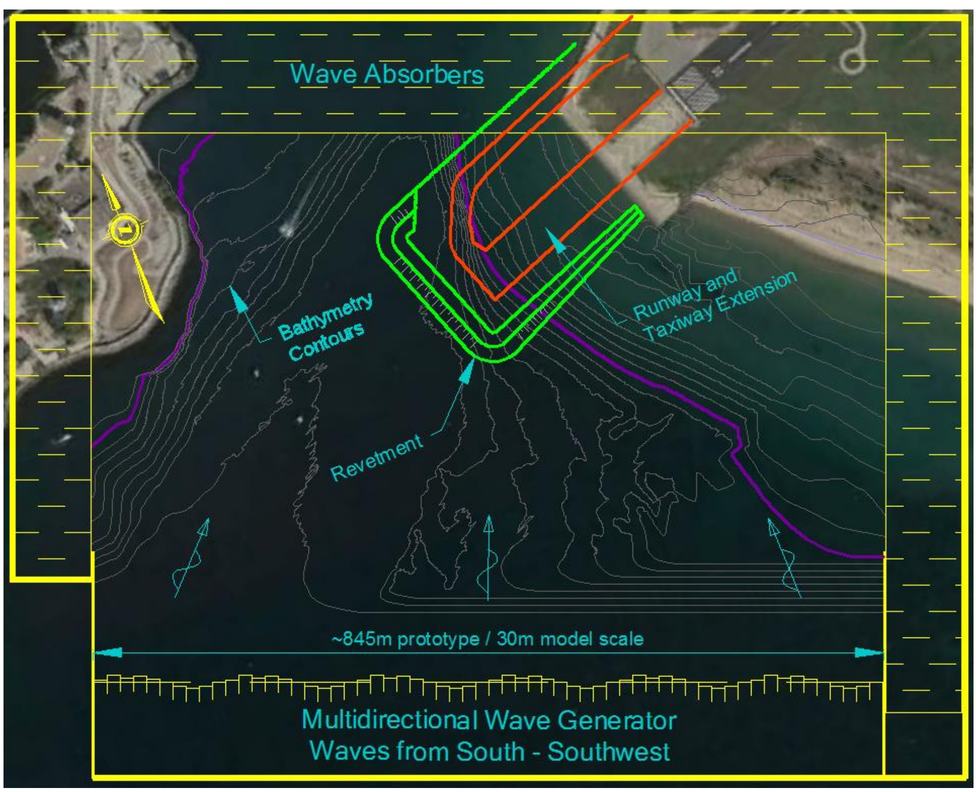

Figure 2. Schematic of the 1:28 scale physical model in the MWB

Careful attention was given to the location, dimensions, composition, and methods of construction of the model structures to ensure that they replicated the proposed designs accurately and faithfully. A total station was used to guide the position and alignment of all structures and ensure conformity with designs. Structure alignment was precisely laid out using a total station, ensuring the overall positioning and curvature of the prototype designs was very well replicated.

A small portion of the adjacent Ontario Place island (see Figures 1 & 2) was included in the model domain. This region, which was not a focus of the study, was backfilled with fine gravel and armoured with a revetment of oversized stone to ensure stability throughout the entire study. It was incorporated to ensure that any effects of waves reflecting from this island would be included in the model. It also provided a visual reminder of its proximity to the runway and the narrowing of the Western Gap harbour channel.

The north side of the proposed runway extension was defined as a vertical retaining wall, and was modelled using marine-grade plywood along the designated alignment. A plywood trench was constructed between the edge of the runway and the edge of land mass along the south and west sides of the runway extension. This trench was built to accommodate overtopping measurement systems at any location behind the revetment and to permit relocation of these systems between tests with minimal effort.

The vertical wall at the existing edge of land mass was modelled using concrete blocks levelled to the runway centre elevation of +2.4 m (all elevations refer to chart datum lake level). Portions of the runway extension and taxiway areas were modelled and simple mock-ups of the CS100 and Q400 aircraft were created to provide additional realism and sense of scale (see Figure 3).

Figure 3. Overview of the 1:28 scale physical model

Rock materials and gradations were carefully prepared to replicate the characteristics of the prototype materials under consideration for use in the prototype construction. Five different gradations of rock material were defined, including two different sizes of filter and armour stone, and one size of core material. Equivalent armour and filter materials at model scale were obtained by sieving locally available crushed limestone aggregate, effectively separating it into different sizes. Measured gradations for the filter and armour rock classes were obtained by weighing a representative sample. In some cases one of the sieved materials matched the design gradation, while in other cases two or more different stone sizes were blended together in order to produce a gradation in better agreement with specifications. In this paper, the various rock gradations are referred to by their M_{50} values. Core materials were scaled by particle diameter and checked via sieve analysis.

A large number of fibreboard templates were prepared and used to guide the placement of the core, filter, and armour materials for each rebuild. Elevations were carefully controlled by surveying the templates using an optical level, and were verified after construction for quality assurance. This technique allows the design profile (shape and elevation) to be constructed to a high degree of accuracy. Once construction was nearly complete, the templates were removed and the locally disturbed areas were patched prior to testing. Core and filter layers were bulk-placed by shovel and then gently hand-packed and shaped to match the desired profile using wooden trowels. The methods used to place the model armour stone attempted to mimic those to be used in the prototype, so that rock behaved similarly and displayed the same kind of interlocking characteristics. Armour stones were placed by hand, unit-by-unit to simulate placement by crane/excavator (see Figure 4a). The outer surface of the filter and armour layers were each painted with different colours to assist in visualizing stone motion and surface damage (see Figures 3 & 4b).

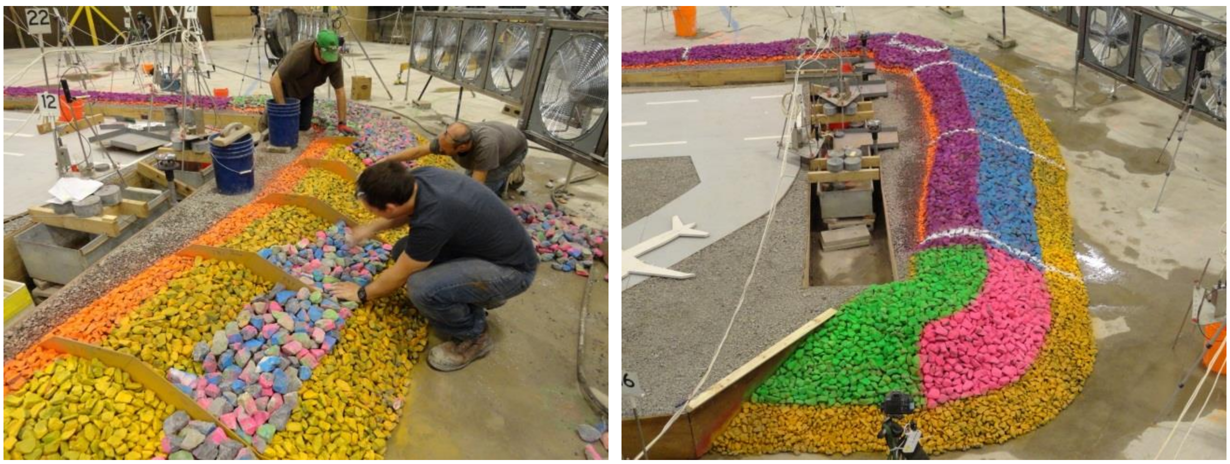

Figure 4. Revetment construction

Several banks of variable-speed fans were set up and operated in the model to generate a local onshore wind and improve the simulation of overtopping by wind-driven spray (see Figure 3). At 1:28 scale, the model is expected to provide reliable predictions of armour stone stability at full scale under equivalent conditions. However, model scale effects relating to fluid surface tension mean that physical processes that are sensitive to surface tension were not simulated correctly in the model. Surface tension is an important parameter affecting aeration and bubble content in breaking waves, the formation and character of spray, and other details of the wave breaking process. For example, the excessively large surface tension will reduce the level of aeration in the model overtopping flows, and cause spray droplets to be over-sized in the model. Nevertheless, wind-driven overtopping was included in the model in an attempt to capture the approximate contribution to the total amount of overtopping.

3.2 Instrumentation

Sixteen capacitance wave gauges were deployed throughout the domain, including one gauge for performing directional measurements. Two ultrasonic anemometers were used to measure wind speeds. The anemometers were mounted on a pipe stand and levelled to +10 m elevation. One anemometer was located directly behind the SW corner while the other anemometer was situated in line with the taxiway/runway intersection.

Three overtopping collection systems were deployed, each consisting of a water storage reservoir, a wave gauge to measure the level of water in the reservoir, and a metal tray to convey the overtopping flow from the crest of the revetment into the reservoir (see Figures 3 & 4b). For this study, the collection trays were positioned along the ‘edge of land mass’ line, several meters (prototype) inland from the crest of the revetment (where overtopping is often measured). Much of the overtopping volumes were absorbed into the filter and armour layers on the crest of the revetment, and only the ‘excess’ overtopping not already absorbed into the rock reached the collection systems. Hence, the overtopping rates at the revetment crest were significantly higher than at the measurement locations. The overtopping collection systems were better suited for measuring moderate to severe overtopping flows, so measuring very small volumes of overtopping (e.g. <0.05 L/s/m) was less precise.

A photographic damage analysis system comprising eight remotely-operated digital cameras was used to monitor the movement of armour stone on the surface of the revetment. Since each camera remained fixed throughout a test series, the movement of individual stones could be detected by comparing photographs taken at different times. Four digital video cameras were also used to record all tests: two cameras provided oblique overhead views while the other two provided close-up views of wave-structure interactions and overtopping at ground level.

4. WAVE AND WIND CALIBRATIONS

Following construction of the bathymetry (but before building any revetment structures), a series of undisturbed wave calibrations were conducted to tune the wave generator command signals and verify the incident wave conditions to be used in the model study. A range of mild, moderate, and extreme conditions were tuned based on available wave climate data. The design wave condition was defined as the annual maximum wave height at three different water levels (corresponding to different months/seasons during the year), with significant wave heights ranging from 2.5 – 3.3 m. An overload condition with significant wave height of ~4.0 m corresponded to an unlikely event with a large return period. Peak wave periods varied from 8 – 11 s, and incident directions ranged from SSW to SW. The scaled wave conditions generated and measured in the model agreed very well with specifications.

Local wind fields featuring a mean wind with gustiness were generated using three banks of five fans each (see Figure 3). Each fan bank was independently controlled by electronic meters, and the resulting wind speed could be varied over a wide range by adjusting the fan RPM. These electronic meters allowed the local winds at the site to be reproduced in the model in a controlled and repeatable manner. Following construction of the runway extension and surrounding revetment, a series of wind calibrations were conducted to tune the fan control settings and verify that the desired wind conditions at the test site were being achieved. Target wind conditions were developed based on available wind climate data. Three wind conditions from the SW with mean speeds ranging from 55 – 75 km/h were modelled. These conditions were considered to be the maximum likely wind speeds at three different water levels (corresponding to different seasons within a typical year).

5. TESTING AND RESULTS

Six distinct test series were conducted during this study. Each test series involved the construction of different revetment cross-sections in various locations, followed by a test program involving exposure to increasingly harsh water level, wave, and wind conditions. The local wave conditions at the toe of the revetment varied due to the variations in local water depth and exposure to the incident waves. During the model study the revetment designs for each area were optimized to accommodate the local wave conditions. For the purposes of this paper, the revetment is divided into four main segments, namely: south face, southwest corner, west face, and northwest corner (see Figure 5). Not all segments were reconstructed for each test series. The southwest corner and southern portion of the west face experienced the most energetic wave attack and the highest amount of wave overtopping and were required to provide protection to the nearby localizer antenna array. A more detailed analysis of the revetment designs is discussed in (Baker et al. 2017).

Accurate measurement of wave overtopping in a 3D model is quite challenging. Overtopping is a complex process, and while it is possible to reliably and precisely reproduce waves in a physical model, the interactions of those waves with the rock-armoured revetment is such that overtopping rates during a repeated test may vary considerably despite being measured in the same way and at the same locations. In some cases, overtopping flows might fall between two collection systems and not be measured on either.

The first overtopping measurement system (OT1) was located directly behind the SW corner and remained unmoved throughout the entire test program. The second and third systems were shifted on several occasions to learn about overtopping rates at different sections behind the west face. Therefore, OT1 remains the best candidate for best comparing the overtopping rates against various cross-section designs. The SW corner crest elevation was lowest during Test Series 2 and 5, which predictably resulted in larger overtopping flowrates. Crest elevations during Test Series 3, 4, and 6 were nearly identical; however, the crest width was notably wider for Test Series 6. Comparing the various designs of the SW corner in terms of stability and control of overtopping, the optimized design featured in Test Series 6 had the best overall performance.

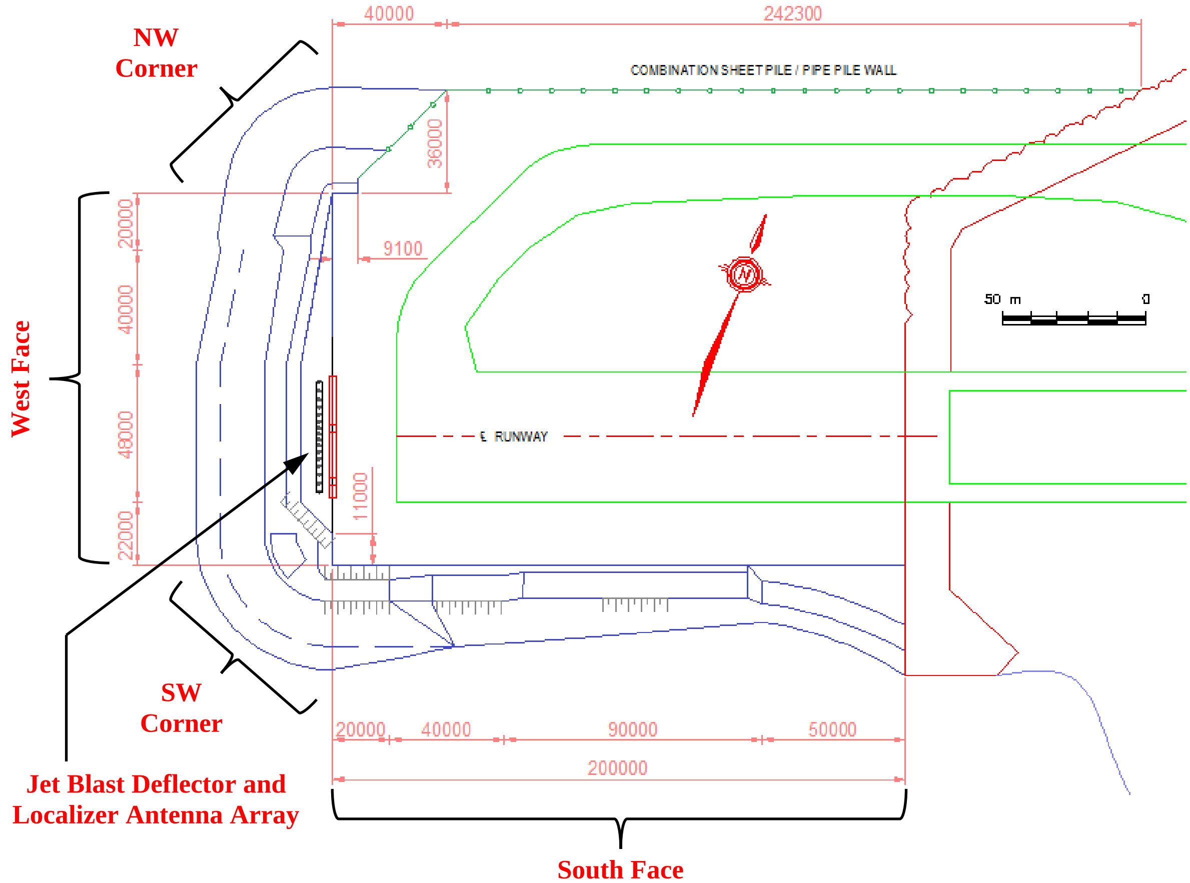

Figure 5. Plan view

On several occasions during each test series, the same seastate was repeated with and without wind, to determine its relative effect on overtopping (see Figure 6). It was absolutely clear, based on qualitative observations and quantitative measurements, that wind caused a noticeable increase in overtopping volume and extent. Visually it was apparent that, once a wave crest ran up to the front crest of the revetment, the wind helped to carry and drive the overtopping flow further inland. Less dissipation occurred on the crest of the structure, resulting in larger volumes of overtopping reaching the leeside of the crest and beyond. Some overtopping spray was observed to reach the end of the runway during severe conditions.

Efforts were made to setup and generate wind in as realistic a manner as possible; however, more rigorous testing (not within the scope of this study) would be required to more conclusively define the effect of wind. For instance, although three different wind speeds were used, they always corresponded with the same water level each time; therefore it is difficult to conclude how the speed of wind affects the overtopping. Regardless, overtopping measurements made throughout the study demonstrated that, compared to a seastate without wind which had relatively low overtopping (e.g. less than 1.0 L/s/m), the same seastate with wind typically saw a three-fold increase in overtopping volumes. The wind had a less noticeable effect when overtopping volumes were significantly larger.

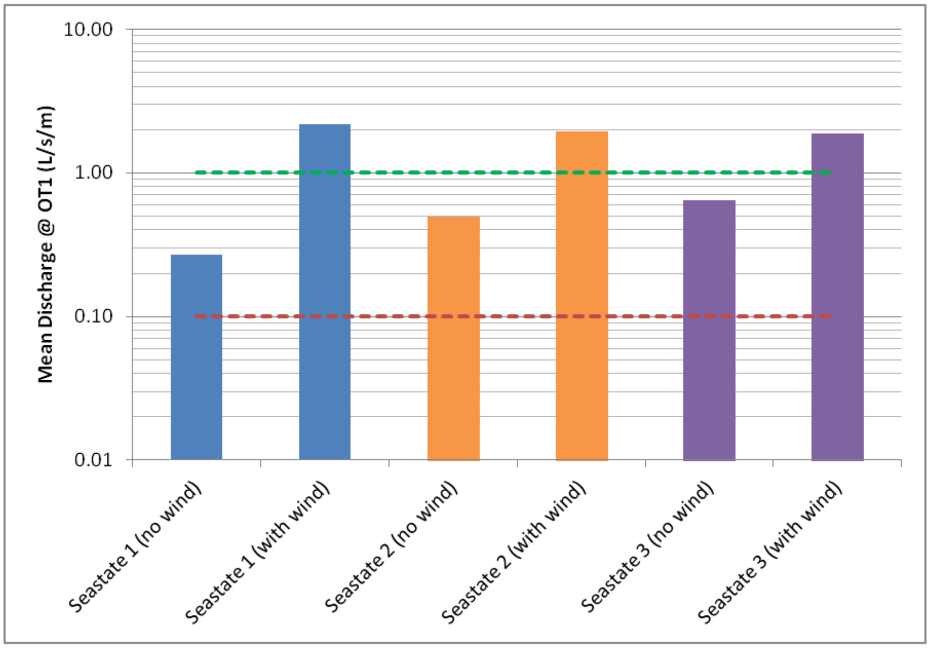

Figure 6. Effect of wind on overtopping measurements

6. CONCLUSION

With regards to a proposed runway extension at Billy Bishop Toronto City Airport, the study objective was to develop an efficient revetment design with low crest elevations that remained stable when exposed to extreme wave and water level conditions, while limiting the frequency and extent of wave overtopping that could impact airport operations. For the principle design wave conditions, the final optimized revetment design saw overtopping volumes less than 1.0 L/s/m. The development and validation of an optimized non-conventional revetment design was guided by a 3D physical model constructed at a geometric scale of 1:28 that included scaled reproductions of: the western end of the existing runway; the proposed 200 m long reclamation; new coastal protection works around the perimeter of the runway extension; the surrounding lakebed bathymetry; and the local water levels, waves, and wind.

Several rubble-mound revetment designs were modelled and assessed in a wide range of wave, wind, and water level conditions. In order to reduce wave runup and overtopping, many of the revetment designs were unconventional, featuring lower crest elevations, milder slopes, thicker filter and armour layers, and lighter armour stone than normally seen in conventional designs. Although there are significant model scale challenges associated with it, wind-driven overtopping was included in the model in an attempt to capture the approximate contribution to the total amount of overtopping. With the optimized designs, no green-water overtopping and only small amounts of spray are expected to reach the runway or taxiway surfaces at any location during once yearly storm events. Moderate amounts of spray may reach the runway or taxiway surfaces during more extreme events, especially with strong winds blowing from SW. At the location of the localizer array and blast fence, overtopping and spray were limited to low rates during extreme conditions; however, published limits for safe serviceability of this equipment are not well defined. Although more rigorous testing (beyond the scope of this study) would be required to better define the effects of wind on wave overtopping, the study demonstrated that strong winds typically caused a minimum three-fold increase in overtopping volumes (when overtopping rates are relatively low).

The physical modelling study played a crucial role in assessing structure performance and optimizing the design of the marine works. The longer runway will allow Porter Airlines to expand operations from BBTCA, reaching destinations across North America. The project will provide options to the citizens of Toronto and help boost the local economy. The longer runway will also improve safety by reducing the risk of a runway excursion.

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