PHYSICAL MODELLING AND DESIGN FOR SHORELINE REDEVELOPMENT ON THE SOUTH COAST OF BARBADOS

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ABSTRACT

W. F. Baird & Associates Coastal Engineers Ltd. ("Baird") was retained by the Barbados Coastal Zone Management Unit ("CZMU") to undertake a shoreline improvement study for a 1.8 km stretch of coastline on the south coast of Barbados. The shoreline improvement study was the second major component of a broader coastal infrastructure improvement initiative to address public waterfront access, shore protection and beach stabilization on the south coast of Barbados, from St. Lawrence Gap to Rockley Beach. A 3D physical model study was used to support the design of a continuous oceanfront promenade and corresponding coastal protection that would (1) provide lateral pedestrian access along a shoreline that had limited or no access, and (2) improve shoreline stability to resist current and future coastal threats.

The physical model study provided a unique opportunity to test a variety of coastal improvement techniques that would distinguish this section of shoreline, provide coastal protection to private landowners and improve oceanfront access for the public. These techniques were developed and assessed in the context of coastal erosion risk reduction, beach stabilization, habitat restoration, public access and amenity enhancement. The results were incorporated in the overall design process to provide an integrated shoreline solution that balances both access and protection from the natural environment.

KEYWORDS: Coastal Protection, Beach Stabilization, Waterfront Access, Coastal Structures

1 INTRODUCTION

As part of a broader Coastal Risk Assessment and Management Program ("CRMP") for the Caribbean island of Barbados, W. F. Baird & Associates ("Baird") was tasked with developing a solution to waterfront access and shoreline erosion concerns along the south coast of Barbados, from St. Lawrence Gap to Rockley Beach ("SLGRB"). The stretch of shoreline under consideration consists of four distinct beach areas and two rocky headlands. Access to each individual beach area is adequate through public access points; however, pedestrian access around the headlands is dependent on the tide level, as well as wave and beach conditions. The overall project scope included the development of a coastal solution which would provide continual lateral waterfront access along the entire stretch of shoreline, and would provide erosion protection in critically exposed areas and beach stabilization in others. The project is meant to tie into the existing Richard Haynes Boardwalk ("RHB") to the west (completed in 2007) and to the St. Lawrence Gap area to the east. The project location in reference to the island of Barbados is illustrated in Figure 1.1 below.
The south coast of Barbados is a densely populated region with the section of shoreline in question being almost entirely developed. Land use in this region is a mixture of commercial and residential properties, with a small percentage being crown land (parking lots, drainage and access points). Much of the waterfront is occupied by private land owners operating hotels, villas and restaurants. Design features were required to be compatible with these key stakeholders to ensure the overall success of the project.

For the purpose of clarity the section of shoreline which is featured in this project has been divided into the following reaches (refer to Figure 1.2):

- **Reach 0** – Rockley Beach;
- **Reach 1** – Cacrabank Headland;
- **Reach 2** – Worthing Beach;
- **Reach 3** – Sandy Beach;
- **Reach 4** – St. Lawrence Gap.

The primary focus of the physical model study was to investigate, select and refine various design options for the shoreline improvements project. These included a variety of options for walkway alignment, location, elevation and material, and several coastal protection and beach stabilization techniques that considered both shore-tied and offshore structures. The preliminary designs were generally based off of previous project experience, in particular the highly successful adjacent RHB installation (previously design by Baird), located immediately to the west of the project site.

The physical model study was intended to further develop, assess and optimize the overall walkway design with the primary intention of mitigating coastal risk and improving access along the shoreline.
Specifically, the principal objectives of the SLGRB physical model study can be summarized as follows:

- Assess and measure the nearshore wave conditions and wave-induced currents;
- Assess, verify and optimize the stability and performance of the proposed coastal structures under realistic, site-specific, typical (operational) and storm conditions;
- Assess the behaviour and response of the beach (including beach fill) under typical and storm wave conditions; and
- Assess wave overtopping along the walkway and optimize the coastal structures, beach cells, walkway elevations and walkway alignments to minimize the risk of flooding and subsequent downtime due to wave run-up and overtopping of both sea water and sand.

2 PREVIOUS DESIGN EFFORTS

A previous component of the coastal improvement initiative on the south coast of Barbados included a physical model study of the shoreline area immediately to the west of the current project site, undertaken by Baird. This previous study and physical model resulted in the construction of a 1.2 km oceanfront promenade, terminating at the western end of the current project. This promenade was later named the Richard Haynes Boardwalk. The RHB project was extremely successful and the promenade is still a focal point for Barbados tourism to this day. Valuable feedback was obtained from the physical model study and the design and construction of the RHB which was used to support the current design efforts. Portions of the previously designed and constructed RHB are illustrated in Figure 2.1.

Figure 2.1. An Overhead (left) and Perspective (right) View of a Section of the Richard Haynes Boardwalk, which was Completed in 2007.

3 PHYSICAL MODEL JUSTIFICATION

Conducting a physical model can be a significant financial component of an overall project budget and therefore requires sound justification. The alternatives to doing a physical model are to use desktop methods and empirical formulations, or to use a combination of numerical models. The former is the least costly option with respect to engineering as it can be accomplished in a relatively short period of time and with limited facilities and computing power. However, this cost saving is typically more than offset when compared with the conservative nature of desktop methods and the inability to confidently refine and optimize a design. The end product is often over-designed, resulting in higher construction costs and a more invasive or obtrusive coastal solution.

Though hydrodynamic numerical models have seen a great deal of advancement in recent times, the exclusive use of numerical models in complicated coastal structure and shoreline protection projects still involves a reasonably high level of uncertainty. Although wave forecasting, hindcasting and transformation models are efficient and accurate, wave structure interaction and sediment transport models are considerably less reliable. Another important consideration is that the accuracy and confidence level provided by a numerical model are only as good as the model itself and the local data from which the model can be calibrated and validated. As such, in the absence of an exceptional database of local data (bathymetry, waves, currents, tides, wind, sediment properties, etc.), the exclusive use of numerical models in the design of coastal protection solutions can be a potentially risky endeavor.

Given the above points, a detailed physical model study remains the most effective and cost efficient means for designing large scale, complex coastal protection projects. Physical models can provide the designer with an increased level of certainty in the design and typically result in measurable cost savings to the client through design optimization. Physical models can also be effectively coupled with desktop methods and numerical modelling as complimentary means of analysis. This
combined design approach often allows for a successful and optimized design which is achieved in a cost and time-effective manner.

4 SITE DATA COLLECTION

Quality site data is a crucial component of any physical or numerical model study, as models require data from which to be calibrated and verified. A detailed understanding of the local conditions and bathymetry must be achieved such that the model will be a realistic representation of the physical characteristics of the site, and will be driven by the correct inputs at the model boundaries. For the SLGRB Waterfront Improvement project a great deal of data was either available from CZMU’s database, previous Baird studies in the region, or was collected over the course of the study.

An accurate bathymetric dataset was obtained from LiDAR data covering the entire shoreline and seaward to a depth of approximately 35 m. The LiDAR dataset also provided a high level of detail for existing coastal structures, property elevations, drainage paths, reef locations and cliff elevations. Further detailing of these features was done through targeted site investigations involving photographic and topographic documentation. This information was used to accurately replicate site conditions in the physical model.

As part of the broader coastal infrastructure improvement initiative being conducted by Baird, sampling instruments were deployed at six sites to obtain a spatial distribution of currents, waves and water levels at the project location. The locations of the instruments are shown in Figure 4.1. Wave statistics were analysed from all six locations based on data collected from December 2014 through April 2015. This was combined with other metocean data to form an understanding of the hydrodynamics at the project site.

Figure 4.1. Location of Wave and Current Instruments near the Project Site.

The offshore wave climate for Barbados is dominated by trade winds that generate waves which arrive at the island from the east and north east. The operational nearshore wave climate shows that after refracting around the south east corner of the island, waves arrive at the project site from a relatively narrow band of directions (150° to 180°). These waves are typically up to 0.8 m, with wave periods of 8 s or less. Larger storm waves may approach from a broader directional range of 150° to 190°. Extreme waves at the site are however limited by the shallow water depth of the local foreshore.

Throughout most of the year, the waves approaching the shoreline from the SSE give rise to a nearshore current flowing from east to west. This shore-parallel (longshore) current generates a net transport of beach sediment towards the west. This current pattern can be altered or interrupted by passing storms and transient weather systems.

Tide conditions in Barbados have been studied by various organizations and confirmed through the local water level measurements obtained for this study (as well as previous Baird projects in the region). The general tidal conditions in the region are therefore well understood. The water level fluctuations due to tides range from approximately +0.0 m Lamont Datum (LD) (MLLW), to +0.7 m LD (MHHW). Extreme water levels induced by passing storms can reach +1.3 m LD or more.

5 PHYSICAL MODEL DESIGN AND CONSTRUCTION

Physical model testing was carried out at the National Research Council’s Ocean, Coastal and River Engineering (NRC-OCRE) laboratory in Ottawa, Canada. The physical model was constructed in NRC-OCRE’s 50 x 30 m Large Area Basin (LAB) facility at a 1:30 scale. The total stretch of shoreline constructed in the physical model was approximately 1.3 km in length, stretching from Rockley Beach at its western end to St. Lawrence Gap at its eastern limit.
The physical model was designed based on Froude scaling laws. Scale relationships are derived from similitude of the Froude number, which represents the relative magnitude of gravitational and inertial forces, which are the dominant forces when considering gravity waves. Froude scaling laws provide a set of scaling relationships that associate the quantities measured in the model (i.e. wave height and period) with the same quantities in prototype. Together with geometric scaling, the model is able to provide a realistic simulation of the hydrodynamic processes present in the coastal environment. Some of the key parameters considered when planning the scale and layout of the physical model include:

- The physical size of the region being simulated;
- The reliability of the model (including construction materials) when operating at different scales;
- The orientation of the model with respect to wave generation and basin constraints; and,
- The physical characteristics of the laboratory apparatus.

Given the above points, a 1:30 model scale was determined to best satisfy the required balance between accurately representing sediment transport behaviour and maximizing the area of study. This allowed the majority of the project area to be simulated in the model, including the shoreline from Cacrabank Headland (Reach 1) to Sandy Beach (Reach 3). The model layout including the basin limits and location of wave generators is shown in Figure 5.1 below.

![Figure 5.1. SLGRB Physical Model Basin Layout](image)

Physical model bathymetry was constructed using NRC-OCRE’s proven method of backfilling wooden templates and sealing the model surface with a thin layer of concrete. The nearshore bathymetry was replicated using an immovable bed from a depth of -10 m to -1.5 m LD. All areas nearshore of the -1.5 m contour were represented by a mobile (sand) bed.

Particular attention was given to the offshore reef (Worthing Reef) which exists seaward of Sandy Beach (refer to Figure 5.1). The elevation of the reef in the model was carefully surveyed and exposed pea gravel was fixed to the concrete to better represent the roughness of the coral reef. Cliffs, existing property sea walls and other existing coastal features were also included in the physical model to a reasonable degree of accuracy.

The sediment placed at the shoreline was surveyed and shaped prior to certain test series to be representative of the desired beach profile including beach nourishment. It was then allowed to reshape and migrate throughout the course of the tests. Sediment scaling was carefully considered during model design. It is not possible to correctly scale the critical shear stress and settling velocity of sediment according to Froude laws, unless the model scale is very large or the prototype material is very coarse. Therefore, the model sediment was scaled based on fall velocity, as is commonly done in physical models which feature a mobile bed. This technique provides a realistic representation of shoreline response to waves and currents in the physical model, including the identification of accretion and erosion zones and the relative change in shoreline properties, position and profile.

Long-crested irregular waves approaching from 165° and 190° were modelled to represent both operational wave conditions and extreme events, respectively. The wave paddle was split into two segments in order to generate waves from 165° while maximizing the nearshore area that would be modelled (refer to Figure 5.1). The waves generated by each paddle segment were phased in order to create a single long-crested wave field. Wave heights in the model ranged from 0.6 m to 3.0 m (at the wave paddle), with peak wave periods ranging from 6 s to 10 s. Wave conditions were calibrated to both field data and results obtained from numerical modelling of the nearshore environment.

Physical model data was acquired by several means throughout the physical model study, including information acquired
through digital instruments, manual measurements, and visual observation. Digital instruments were used to collect wave and current measurements around the physical model domain. A series of twenty capacitance-based wave gauges and four electromagnetic current meters were deployed within the model domain. Beach morphology (shoreline plan form and profile evolution) was observed and recorded during most test series using innovative manual measurement techniques which included custom-built apparatus that enabled data acquisition in a systematic and repeatable manner.

Finally, photographic documentation (digital video and still frame imagery) of the model was collected throughout construction and testing in order to document the test results. This included video and still images of dye tests performed to track current patterns and flow velocities at various locations throughout the model.

6 EXISTING CONDITIONS

Existing conditions testing was undertaken at three different water levels corresponding to mean sea level (MSL), mean high high water (MHHW), and highest astronomical tide (HAT). Ten different operational wave conditions were simulated during this process, with the following objectives:

- Generate a visual overview and an improved understanding of the coastal processes in the nearshore region at the project site;
- Validate the model by verifying that the coastal processes occurring in the model are similar to those occurring in prototype; and
- Establish baseline conditions so that the relative impact of building offshore and shore-tied coastal structures can be properly assessed.

It was found that nearshore wave heights and energy varied spatially along the project shoreline under existing conditions. Due to the presence and geometry of the offshore reef, the amount of wave energy which reaches the shoreline generally increases from east to west along the project site. During periods of low water levels, the offshore reef has a very strong effect on the nearshore waves and currents. This effect decreases as the water level is increased, resulting in an increasing amount of wave energy being transmitted over the reef.

Under existing conditions tests, the wave-induced longshore current was shown to travel westward along the project site. This current drives the direction and magnitude of sediment transport, similar to prototype observations. The sole exception to the westward current is a large eddy which was shown to exist at the west end of Worthing Beach (Reach 2) (refer to Figure 6.1). The longshore current was found to be strongest immediately offshore from the existing shore-tied groyne between Worthing (Reach 2) and Sandy Beach (Reach 3). This is likely due to the flow constriction which exists between the groyne and the offshore reef at the west end of Sandy Beach (refer to Figure 6.1), causing increased current velocity at this location. The current was shown to be weakest at the eastern end of the model. This is partially due to the presence of the offshore reef but is also likely a model effect cause by the lack of incoming wave energy and flow at the eastern model boundary. A summary of observed current directions and relative current magnitudes across the entire model domain and for operational conditions is illustrated in Figure 6.1.

![Figure 6.1](image_url)  
**Figure 6.1.** Representative (Relative) Current Conditions Under Operational (Typical) Wave Conditions

Sediment transport under existing conditions was generally shown to follow the westward longshore current, as observed in prototype. This resulted in a wider beach along the western half of Worthing (Reach 2) and a narrower beach along the eastern half. Sediment was also observed moving around Cacrabank Headland (Reach 1) and being deposited in the north-west corner of the model basin. Sediment transport along Sandy Beach (Reach 3) was less apparent which is consistent with the lower current velocities observed behind the offshore reef.
7 DESIGN OPTIONS - KEY FINDINGS

Although the physical model was tested under a range of extreme conditions, the primary focus of the study was to assess the performance of the proposed boardwalk and coastal structures under operational conditions. The layout, elevation and structural configuration of the boardwalk were optimized through the assessment of sediment behaviour, overtopping observations and stability of the coastal structures. The placement of various coastal structures was assessed in its relation to the overall effect on coastline morphology and the overall objectives of the project. The following is a summary of specific project objectives to be addressed in the overall design:

- Minimize downtime due to overtopping of sea water onto the walkway;
- Minimize downtime due to overtopping of beach sand onto the walkway;
- Minimize maintenance requirements by reducing the frequency of overtopping events;
- Ensure the stability of coastal structures;
- Provide beach stability to Worthing Beach, Mandarin Bay and Sandy Beach; and
- Provide shore protection to the proposed walkway and existing ocean-fronting properties.

Key observations from the physical modelling study can be grouped into three principal categories; walkway overtopping (of sea-water and sand), beach morphology, and stability of coastal structures.

7.1 WALKWAY OVERTOPPING

A critical component of the walkway design was establishing an effective alignment and elevation along the project length in order to minimize overtopping of both sea water and sediment. Both of these processes would result in downtime and increased maintenance along the walkway, with corresponding economic and operational impacts.

In general, overtopping of sea-water or sediment was not an issue along the eastern half of the project (Reaches 3 and 4) where the offshore reef provides a sheltering effect to the shoreline under operational conditions. As such, the primary focus was on the more vulnerable stretches of shoreline, namely Worthing Beach (Reach 2) and Cacrabank Headland (Reach 1). The walkway along Worthing Beach was shown to be particularly vulnerable to sediment overtopping, while many areas along Cacrabank Headland were consistently subjected to sea-water overtopping (splash).

A fairly simple solution to mitigate overtopping of sediment and sea-water would be to increase the elevation of the walkway and/or the setback from the water line. However, due to the encroachment and elevation of private properties along the shoreline, there were strict limitations on the extent at which this strategy could be exploited. Furthermore, the privacy of local property owners was of key concern, meaning that the elevation of the boardwalk had to be as low as possible below existing property sight lines. Given these limitations, an iterative approach was taken to determine the best compromise for walkway elevation between operational limitations and stakeholder concerns. Figure 7.1 illustrates the final walkway elevations which were recommended as a result of the physical modelling.

![Figure 7.1. Recommended Walkway Alignment and Elevation as a Result of the Physical Model Study](image)

In regions where the walkway could not be elevated or pushed back from the waterline any further and overtopping of sediment or sea-water was still problematic, alternative cross-sections were developed to provide an acceptable solution. Along western Worthing Beach, the proposed solution to sediment overtopping was to construct a 0.5 m high concrete seat wall along the seaward edge of the walkway. This concept proved highly effective in mitigating sediment deposition on the walkway under operational conditions. Figure 7.2 illustrates a picture of post-testing conditions with and without the presence
of a seat wall along western Worthing Beach.

Figure 7.2. Sediment Covered Walkway without Seat Walls (left) and Clear Walkway with Seat Walls (right)

The addition of concrete seat walls to the walkway fronting Cacrabank Headland was also tested and showed favourable results for the reduction of splash on the walkway in this region. However, this solution was not effective enough to entirely eliminate severe splash under operational conditions. As such, a variety of alternative cross-sections were tested with respect to the coastal protection fronting the walkway in this region, including revetments with various slopes, concrete steps, and berm-style revetments. Offshore reefs were also tested as a possible solution. Of the tested concepts, a wide berm revetment was found to be the most cost-effective and efficient in reducing the amount of sea-water splash reaching the walkway surface under operational conditions. Figure 7.3 shows the proposed walkway along Cacrabank Headland armoured with a conventional revetment (alternating stone sizes). Figure 7.4 shows a typical revetment cross section and a berm-revetment cross-section.

Figure 7.3. Cacrabank Headland showing Walkway Fronted by a Conventional Stone Revetment

Figure 7.4. Cross-Sections for Cacrabank Headland Showing a Conventional Revetment (Left) and a Berm Revetment (Right)

7.2 BEACH MORPHOLOGY

A key objective of the project was to provide increased beach width and long-term stability in two regions in particular along the project site: Worthing Beach (Reach 2) and Sandy Beach (Reach 3). The mobile bed of sediment (from the -1.5 m contour shoreward) was used to study the effects that the various configurations of coastal structures would have on beach
A critical conclusion from the physical model study was that beach profiles and planforms were generally stable along Sandy Beach (Reach 3) under operational conditions. This was largely due to the shelter provided by the offshore reef from incident waves, resulting in low currents and wave agitation in this region. It was only under extreme water levels which allowed wave energy to be transmitted over the reef that some sediment migration was observed either offshore or in the westward direction.

Worthing Beach (Reach 2) was more sensitive to wave action under both operational and extreme conditions, with the beach generally displaying erosion at the eastern end and accretion at the western end. This is consistent with the observation of the east-west longshore current noted in both in the physical model and in prototype. Several iterations of offshore reefs were tested to alter the wave action along the eastern end of Worthing and reduce the erosion witnessed in this area. Offshore structures did not result in a reduction in the amount of erosion witnessed, but instead transferred the erosion pattern further down the beach to the west.

A series of 4 rubble groynes spaced at 80 - 100 m proved to be the most efficient means to retain sediment and control erosion at the eastern end of Worthing Beach. With this spacing the structures were shown to operate as a ‘system’ to create independent and stable beach cells. The stable beach crest width within each cell was found to be 3 m or greater measured from the seaward edge of the walkway. This was observed along the entire length of Worthing beach and for all operational wave conditions. With the groynes in place, well developed beach crest elevations along Worthing Beach generally varied from +2.25 m to +2.75 m LD. Figure 7.5 shows two perspectives of the final Worthing Beach alignment after a series of operational condition simulations with groynes in place.

![Image of beach crest with groynes]

Figure 7.5. Examples of Final Worthing Beach Alignment and Beach Crest Location with Groynes in Place after Long Duration Operational Conditions Tests in the Physical Model

### 7.3 STABILITY OF COASTAL STRUCTURES

A wide range in shore-tied and offshore coastal structures was tested for stability over the course of the physical model study. Structure stability was assessed at various locations along the shoreline within the model domain, including a range of structure alignments and geometry (length, crest width and elevation, stone material transition details, etc.). Structures were tested under a variety of wave and water level conditions, from operational to extreme. Results were compared to stone sizes initially determined from a combination of empirical methods and previous design experience at neighboring project sites.

It was determined from stability observations and repeatable photographic analysis that stone gradations of 1.5–3.5 t and 0.5–1.5 t were appropriate for exposed and sheltered shore-tied structures, respectively, under all operational conditions. These stone gradations were also tested under a variety of extreme loading scenarios and showed minimal damage up to and including the design life of the project. In order to achieve an acceptable stone density and fulfill the gradation requirements, the stone would have to be imported to the island.

### 7.4 OVERWATER WALKWAY

A number of private property boundaries presented challenges for the walkway alignment in the Sandy Beach area. This provided an opportunity for the design team to introduce a creative and unique solution to the walkway alignment in this region. The preferred solution was to move this section of walkway offshore and create a piled, overwater section of the
promenade. This was determined to be feasible in this region due to the natural sheltering effect of the existing offshore reef.

The preliminary layout for the overwater walkway is shown in Figure 7.6. This structure was tested in the physical model under a variety of wave and water level conditions to observe wave interaction with the proposed structure. It was shown that an overwater walkway placed at an elevation of +2.0 m LD would be impacted and overtopped rarely during operational conditions and frequently during storm conditions (at elevated water levels). A walkway placed at an elevation of +2.5 m LD would be overtopped only during extreme events. This information was interpreted and coupled with empirical design calculations and similar project experience during the final design process.

Figure 7.6. Layout of the Proposed and Tested Overwater, Piled Section of Walkway

8 CONCLUSIONS

The physical model that was undertaken for the St. Lawrence Gap to Rockley Beach (SLGRB) Shoreline Improvement project served as an essential component of the design process, allowing the designers to refine and optimize the preferred layout in a way that would otherwise not have been possible. This was achieved through detailed investigations of wave and sediment overtopping for a variety of walkway alignments, elevations and coastal structure configurations. Through this process it was found that an arrangement of shore-tied structures provided the most effective way to mitigate erosion, protect the walkway and promote beach stability. The physical model allowed for optimization of these structures and provided a degree of confidence to the designers that would not have been permitted with the use of desktop methods or numerical models alone. In addition, the physical model results were used to calibrate and verify various numerical models used to simulate nearshore coastal processes, allowing for a greater understanding of the project site and surrounding areas.

At the completion of the physical model, careful and thorough consideration was given to both quantitative and qualitative results acquired during the study. This information was used to guide the designers on a range of technical and non-technical issues, such as coastal processes, planning, aesthetics, potential environmental impacts, construction logistics and cost. This information was both supplementary and complimentary to the final design of the shoreline improvement works, and provided tangible added value to the client. The physical model results ultimately played a very large role in the eventual selection and optimization of concepts addressing the overall project objectives while adding a heightened level of confidence to the final design of shoreline improvements for the SLGRB project.

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REFERENCES