LOADING AND STRUCTURAL RESPONSE OF DEVELOPED SHORELINES UNDER WAVES, SURGE, AND TSUNAMI OVERLAND FLOW HAZARDS

Pedro Lomonaco, Oregon State University, pedro.lomonaco@oregonstate.edu
Andre Barbosa, Oregon State University, andre.barbosa@oregonstate.edu
Dan Cox, Oregon State University, dan.cox@oregonstate.edu
Tori Johnson, US Naval Academy, vjohnson@usna.edu
Adam Keen, University of Southern California, adam.s.keen@gmail.com
Andrew Kennedy, University of Notre Dame, Andrew.B.Kennedy.117@nd.edu
Patrick Lynett, University of Southern California, plynett@usc.edu
Joaquin Moris Barra, University of Notre Dame, JoaquinPablo.MorisBarra.1@nd.edu
Hyoungsu Park, University of Hawaii at Mãnoa, hpark9@hawaii.edu
Sungwon Shin, Hanyang University, sungwshin@ehanyang.ac.kr

BACKGROUND

Inundation from storms like Hurricanes Katrina and Sandy, and the 2011 East Japan tsunami, have caused catastrophic damage to coastal communities. Prediction of surge, wave, and tsunami flow transformation over the built and natural environment is essential in determining survival and failure of near-coast structures. However, unlike earthquake and wind hazards, overland flow event loading and damage often vary strongly at a parcel scale in built-up coastal regions due to the influence of nearby structures and vegetation on hydrodynamic transformation. Additionally, overland flow hydrodynamics and loading are presently treated using a variety of simplified methods (e.g. bare earth method) which introduce significant uncertainty and/or bias.

This study describes an extensive series of large-scale experiments to create a comprehensive dataset of detailed hydrodynamics and forces on an array of coastal structures (representing buildings of a community on a barrier island) subject to the variability of storm waves, surge, and tsunami, incorporating the effect of overland flow, 3D flow alteration due to near-structure shielding, vegetation, waterborne debris, and building damage.

LABORATORY EXPERIMENTS

A large-scale bathymetry was constructed in the Directional Wave Basin (DWB) and configured so it enabled the simulation of surge, waves, tsunamis and overland flow. The main model is a flat platform (10 m x 10 m) elevated 1 m over the original basin bottom (Figure 1). A 1:20 slope was also installed as a foreshore bathymetry. The model was located at the center across the basin and two split walls were installed to compartmentalize the leeside of the barrier island, forming a so-called lagoon. Two high-discharge pumps were installed on each side of the model, pumping from the lagoon to the seaside of the split walls, creating a recirculation pattern simulating a steady overland flow. Two dummy breakwaters were also installed on each side to dissipate wave energy and prevent wave reflection.

The experimental plan considered measurement of the undisturbed wave, tsunami and current conditions, experiments with dye release, debris transport, and installation of 100 buildings to create a coastal community where 8 of them were fitted with pressure gauges and load cells to assess the impact loads of the incoming waves (Figure 2 and 3). The test plan also included the installation of a seawall with varying lengths, a detached submerged breakwater, a low-profile alongshore continuous seawall, and a parcel-size patch of mangroves, yielding the comparative effect on the hydrodynamics and structure loads for each case.

The final paper will include a detailed description of the experimental procedures, model layout, instrumentation and dataset characteristics, emphasizing the comparative results of horizontal forces under the different tested configurations.

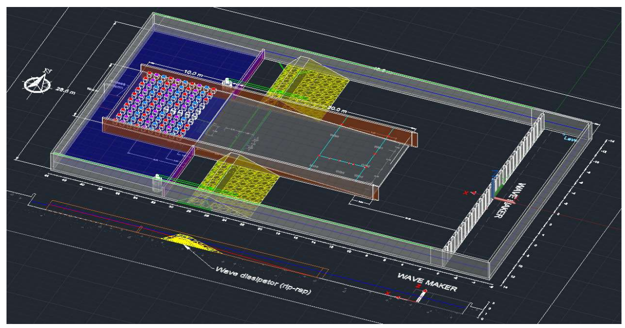

Figure 1 – CAD rendering of the DWB at Oregon State University depicting the foreshore bathymetry and developed barrier island, as well as the recirculation sections to generate steady overland flow.

Figure 2 – Overview of the developed barrier island in the DWB during a test execution. In the foreground, the coastal community represented by 100 buildings. On both sides, the return flow sections, pumps and wave absorbers.

Figure 3 – Detail of the instrumented buildings (identified by the silver boxes) during an irregular wave test. Two buildings were fitted with a vertical array of pressure gauges (shown at the center of the image), five with in-line load cells (shown on the background of the image), and one with a submersible multi-axial load cell (not shown).

TESTING FACILITY

The Directional Wave Basin (DWB) is 48.8 m long and 26.5 m wide, with 2.1 m high walls and a maximum still water depth of 1.5 m. It is constructed as a reinforced concrete reservoir, with a 15 cm wall and floor thickness. A vehicle access ramp, 3 m wide, allow equipment and materials to be transported conveniently into and out of the basin. A bridge crane with a capacity of 7.5 tons spans the length and width of the DWB to position the models and to facilitate instrumentation. Unistrut inserts are placed in rows at 2.1 m spacing to affix specimens, and instrumentation throughout the basin. The DWB wavemaker is a multidirectional piston-type system with 30 independently-programmable servomotor-driven points. Each drive point has a maximum stroke of 2 m and a maximum velocity of 2 m/s. The wavemaker is capable of generating repeatable regular, irregular, tsunami, and user-defined waves, and active reflected wave cancellation system.

INSTRUMENTATION

Resistive and acoustic wave gauges were deployed at different locations to capture the free-surface evolution in space and time. Nine resistive wave gauges were located between the wave machine and the model specimens at the beginning of the 1:20 foreshore slope. The gauges were deployed in a configuration enabling the separation of incident and reflected waves, as well as to assess the formation of cross-waves. Seven acoustic gauges were installed on the instrumentation bridge to capture the evolution of the wave as it propagates over the barrier island. The layout of the acoustic gauges considered the geometric distribution of the 100 buildings. The instrumentation bridge was located at different locations and the wave conditions repeated to increase the resolution of the measurements of the overland flow. An additional acoustic probe was also used to measure at the leeside of the barrier island, identifying the final variation of the free surface elevation before the lagoon.

Up to seven acoustic Doppler velocimeters (ADV) we also installed on the instrumentation bridge co-located with the acoustic wave gauges, capturing the three-dimensional detail of the overland flow at different locations in front of and surrounded by the coastal buildings.

Wave gauges and ADVs measured with a sampling rate of 100 Hz.

Twelve pressure gauges were installed on two of the coastal buildings, at the front row, configuring two arrays with six probes each, to measure the vertical profile of the wave and current-induced dynamic pressure acting upon the structures. The design of the instrumented coastal buildings is shown in Figure 4.

In-line load cells were fitted inside of five coastal buildings, from the first to the fifth row (see Figure 3) to measure the evolution of the dynamic total axial load on each of the five structures as the waves (and current) interact and propagate towards the lagoon. The load cells were installed inside each of the buildings by means of a specifically designed mini-reaction frame (shown in Figure 4).

One submersible multi-axial load cell was also installed inside of a coastal structure to capture the three-dimensional nature of the forces and moments. This was particularly interesting during the experiments with the semi-infinite seawall and mangrove patch, given the asymmetry of the overland flow.

Structural parameters (i.e. dynamic pressures and loads) were measured with a sampling rate of 1 kHz.

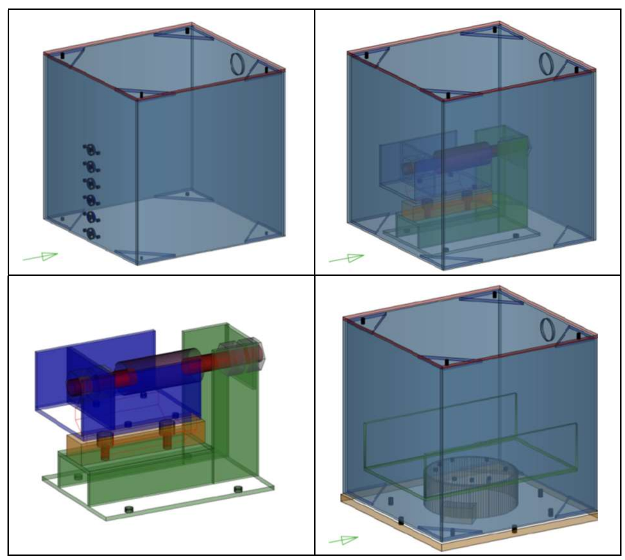

Figure 4 – Design of (a) coastal structure fitted with pressure gauges; (b) coastal structure fitted with in-line axial load cells; (c) the mini-reaction frame to measure axial loads on each of the coastal structures; and (d) coastal structure fitted with a multi-axial load cell.

Finally, four PTZ overhead cameras were deployed overlooking the barrier island to track the motion of waterborne debris as well as the release of dye for the calibration and validation of the diffusive terms and turbulent advection in numerical models. Additionally, hand-held video cameras and GoPros were installed at different locations and instances to capture e.g. breaking conditions at the shoreline, wave propagation along the different streets of the coastal community, or tracking the release of debris from a pier installed offshore.

EXPERIMENTAL PLAN

The experimental plan considered a series of different configurations of the model, as well as varied hydrodynamic conditions.

Model configurations included:

- Bare earth. Undisturbed conditions in the absence of coastal structures, debris or mangroves (92 trials with solitary, transient and irregular waves, with and without current).
- Waterborne debris. Release or drag of mid-scale debris in the absence of coastal structures (117 trials with solitary, transient and irregular waves, with and without current).
- Array. Experiments with 100 coastal structures in a 10 x 10 array (126 trials with solitary, transient and irregular waves, with and without current).
- Mangrove trees. Experiments with two different patch sizes of small-scale mangrove trees protecting the instrumented coastal structures (23 trials with transient and irregular waves, with and without current).
- Partial wall. Experiments with a semi-infinite non-overtopping alongshore wall with lengths varying from 2.3 to 7.1 m starting from one side of the testing section (52 trials with transient, solitary and irregular waves, with and without current).
- Seawall. Experiments with a low-crested vertical seawall embracing the full width of the testing section protecting the coastal structures (12 trials with transient, regular and irregular waves, and 13 trials including an offshore breakwater, with and without currents).
- Offshore breakwater. Experiments with a submerged offshore breakwater parallel to the shoreline protecting the coastal structures (12 trials with transient, regular and irregular waves, and 13 trials including the seawall, with and without currents).
- System ID. Experiments to characterize the structural characteristics of the instrumented coastal structures (10 hammer tests to identify natural frequencies, stiffness and damping coefficients).

Hydrodynamic conditions included:

- Variations in the still water depth (0.55 m to 1.16 m at the wave machine, -0.45 m to 0.16 m relative to the barrier island elevation).
- Solitary waves (wave height from 0.075 m to 0.2 m).
- Transient waves (generated with an Error Function with durations from 10 s to 80 s).
- Random waves (using TMA and Pierson-Moskowitz spectra, significant wave heights of 0.1 m to 0.2 m and peak period of 2.25 s).
- Regular waves (wave heights of 0.1 m to 0.2 m and period of 2.25 s).
- All wave conditions have been tested with and without the effect of an overland flow rate of 252.4 liters per second across the barrier island.

Overall, 471 trials have been executed as part of the testing program, creating an extensive database for model validation and interpretation of the simulated physical processes.

The wave conditions tested are presented, in dimensionless form, in Figure 5, where the wavelength has been computed at the water depth measured in front of the wave machine, i.e. at generation. Figure 5 also includes the regions of validity for different wave theories, as well as the breaking limit due to wave steepness. Note that the wavelength for the Solitary and Transient waves have been estimated assuming the length occupied by 95% of the free surface envelope.

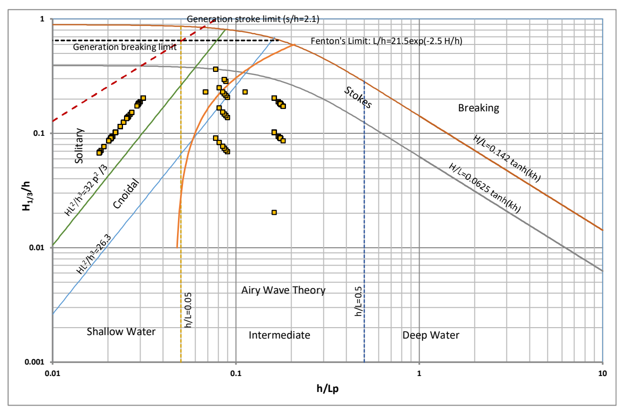

Figure 5 - Wave conditions tested, defined in front of the wave machine. The plot includes the regions of validity for different wave theories.

Post-processing of the data is currently ongoing, and publication of the outcomes will provide a closer insight on the major parameters affecting storm surge or tsunami overland flow and the interaction with a coastal community formed by an array of buildings which may be protected with vegetation or man-made structures.

ACKNOWLEDGEMENTS

This work has been partially supported by the National Science Foundation through Grants CMMI-1661015, 1661052, 1661315 and CMMI-1519679 (NHERI).