Laboratory and Numerical Simulation of Tsunami Wave Inundation within a Partially Sheltered Structural Array

Zhongduo Zhang[1], Andrew Kennedy[1], Joaquin P. Moris[2], Damrongsak Wirasaet[1]

[1]University of Notre Dame, [2]Universidad Católica del Norte

Background

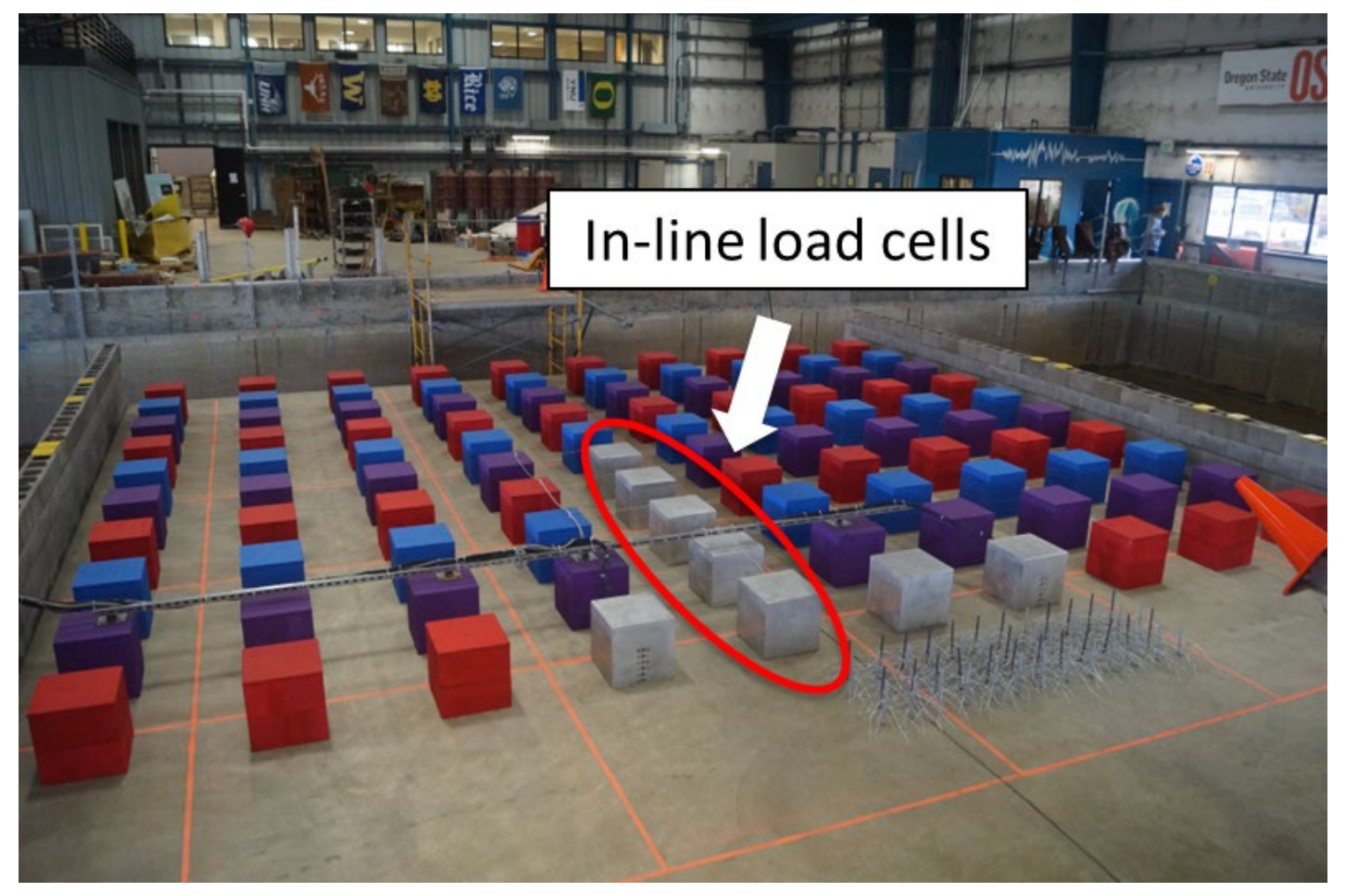
In recent years, tsunamis have been recognized as one of the most catastrophic natural disasters in the world, highlighted by the 2004 Indian Ocean tsunami and the 2011 Tohoku earthquake and tsunami. These countries affected by tsunamis like Indonesia, Thailand and Japan usually arm their coast with sea walls to provide protection for coastal urban regions.

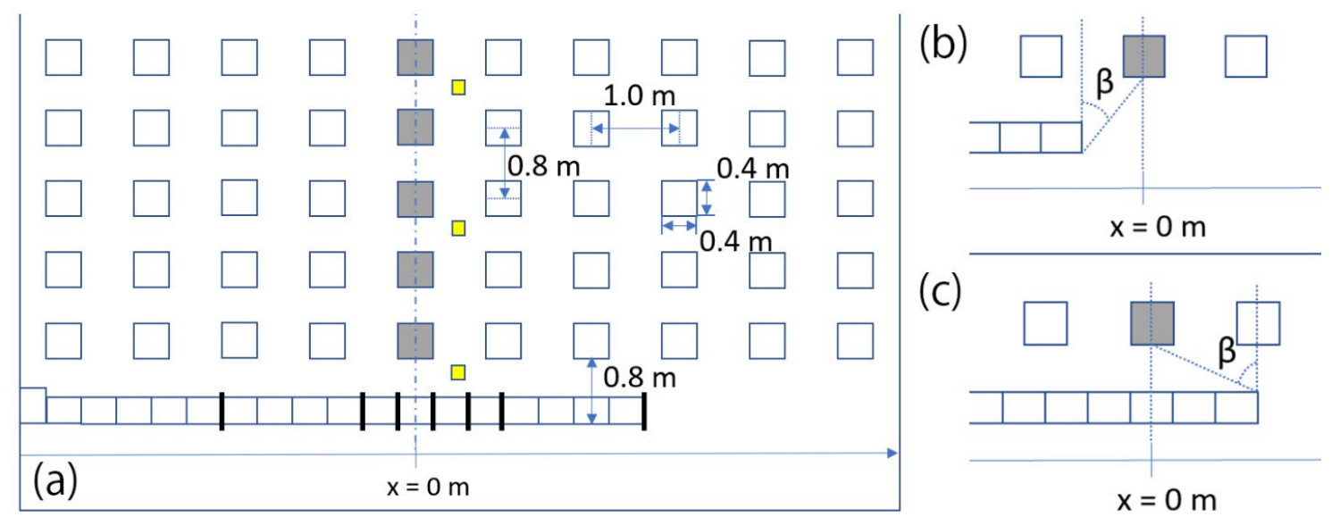
However, surveys have found during both tsunami events, several sections of breached sea walls had led to extensive damage in those coastal regions (Dalrymple and Kriebel, 2005; Sato, 2015). Previous studies have examined the sheltering effect by macroroughness to individual structures, but limited knowledge is available on the sheltering and flow concentration effect by a partially standing wall to a field of structural array.

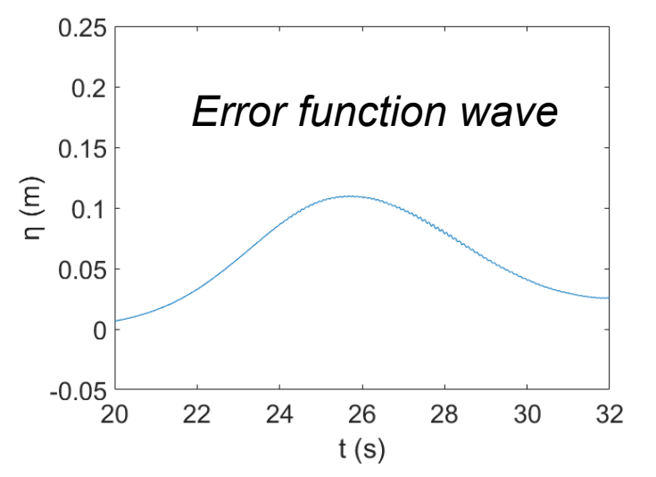
Laboratory Experiment

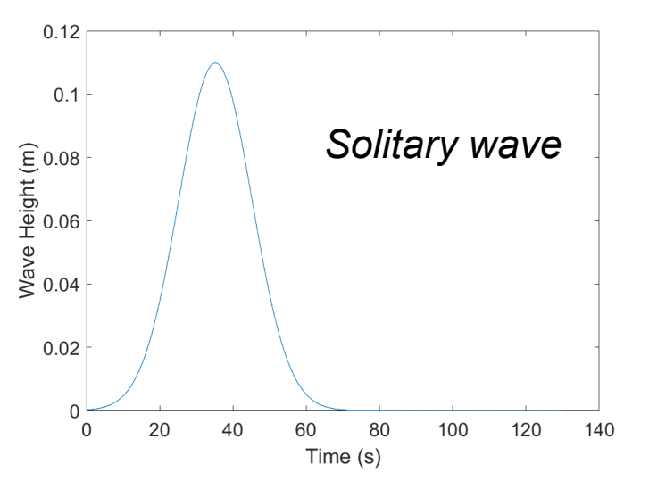
The experiment was conducted at the Oregon State University Directional Wave Basin (DWB). A 10 × 10 array of cubic macro-roughness structures was placed at the beach section to represent a developed coastal region. Among the structures, five of them had built-in load cells to record inline (in the direction of wave propagation) wave loading (Moris et al., 2021).

A partial wall with seven varying wall lengths was placed in front of the first row of structures. A no-wall condition was also conducted for comparison. Two different wave types were generated by the wavemaker: tsunami-like waves generated using an error function and solitary waves. The error function waves were non-breaking while solitary waves had intense wave breaking. A pump was used to create a current in the test section for several cases, and both high water level with current conditions (inundation cases) and low water level without current conditions (run-up cases) were studied.







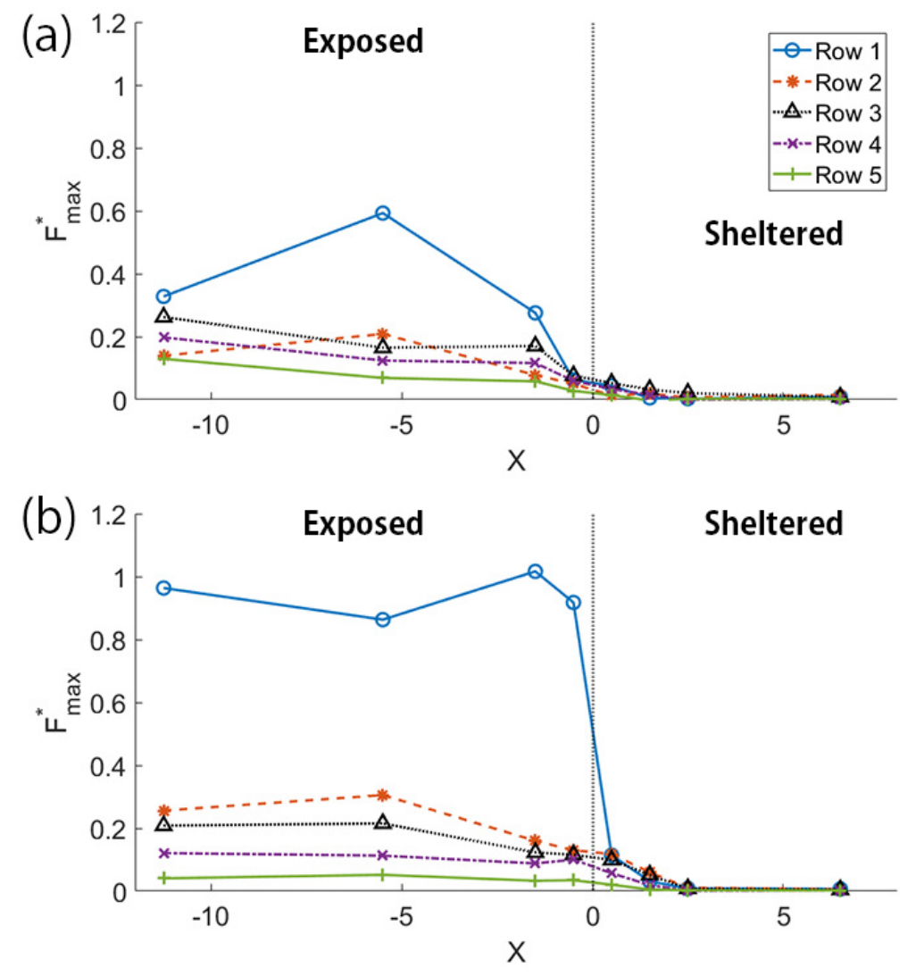


Experiment Results (Loading)

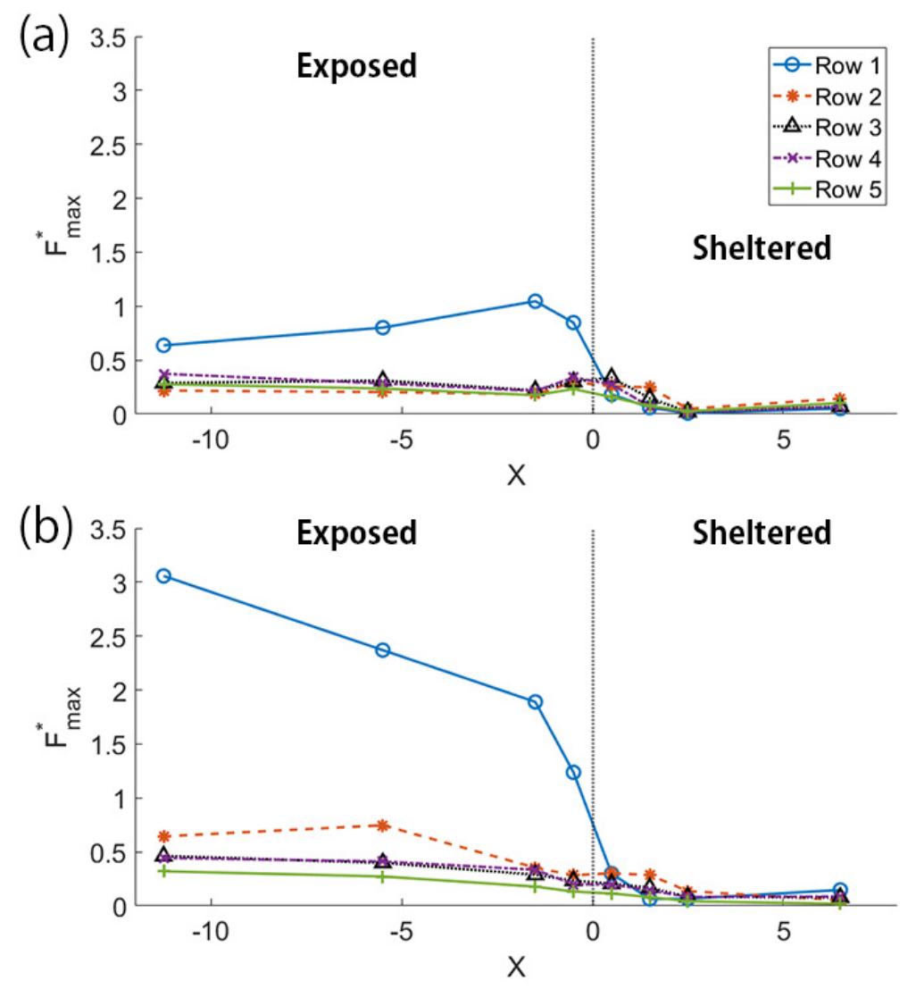
Experiment results show that for most cases the highest loading occurs in the first row of structures when the partial wall ends just before the structure, leaving it barely exposed. This appears to be due to flow concentration around the end of the wall which focuses waves and currents towards the structure. On the other hand, wave loading on structures that are completely shielded by the seawall is significantly smaller. These results suggest that in most situations the location of coastal structures relative to the partial seawall determines their sustained load.

However, for solitary wave inundation cases, where a breaking wave arrives at an already inundated region, the magnitude of wave loading is found mainly decided by the location of the wave breaking. In this experimental setting, when the partial wall is longer, the wave breaking point shifts closer to the structural array. In the meantime, the wave loading decreases as the wave breaking point gets closer to the structural array. Also, regardless of cases, those structures located at the second row and behind sustain significantly lower loading due to shielding from the rows in front.

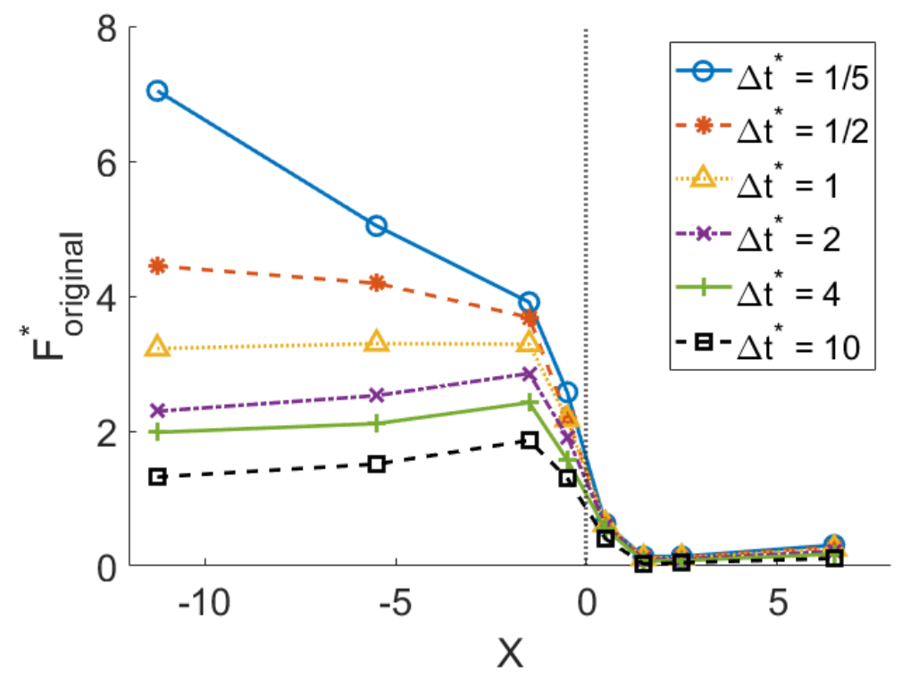
Time-averaged loading analysis indicates that although the largest short-duration loads occur when breaking occurs at or near the structures, these decrease rapidly with increasing averaging time. In contrast, flow concentration near the end of the wall unrelated to breaking may generate larger loads for longer averaging periods.



Runup Case



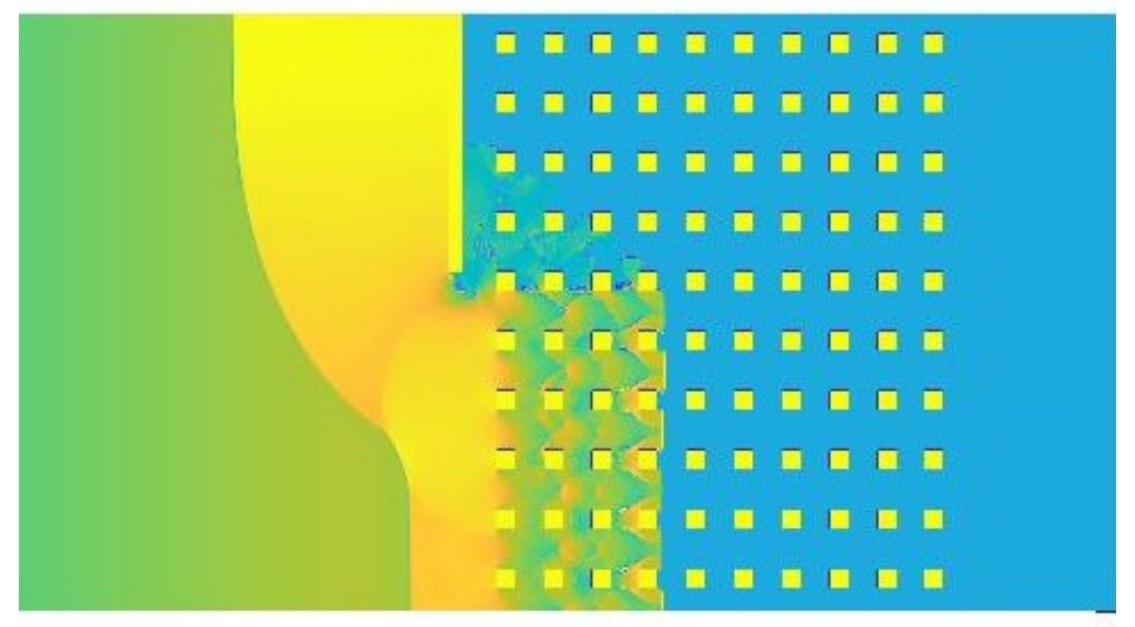
Inundation Case
(a) error function waves
(b) solitary waves



Time-Averaged Analysis
(Solitary Wave Inundation)

Numerical Modeling

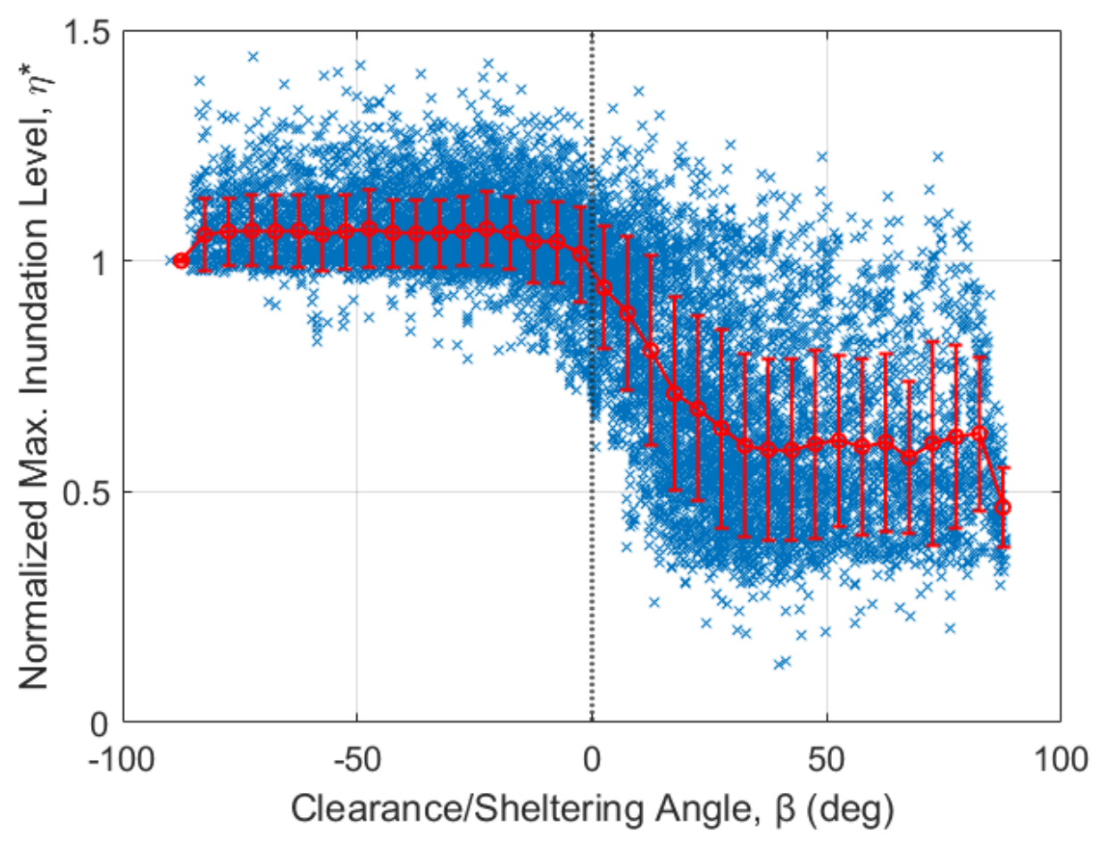
A numerical simulation using a 2D shallow water equation model described by Kennedy et al. (2019) was conducted to further study the inundation level and flow velocity within the structural array.



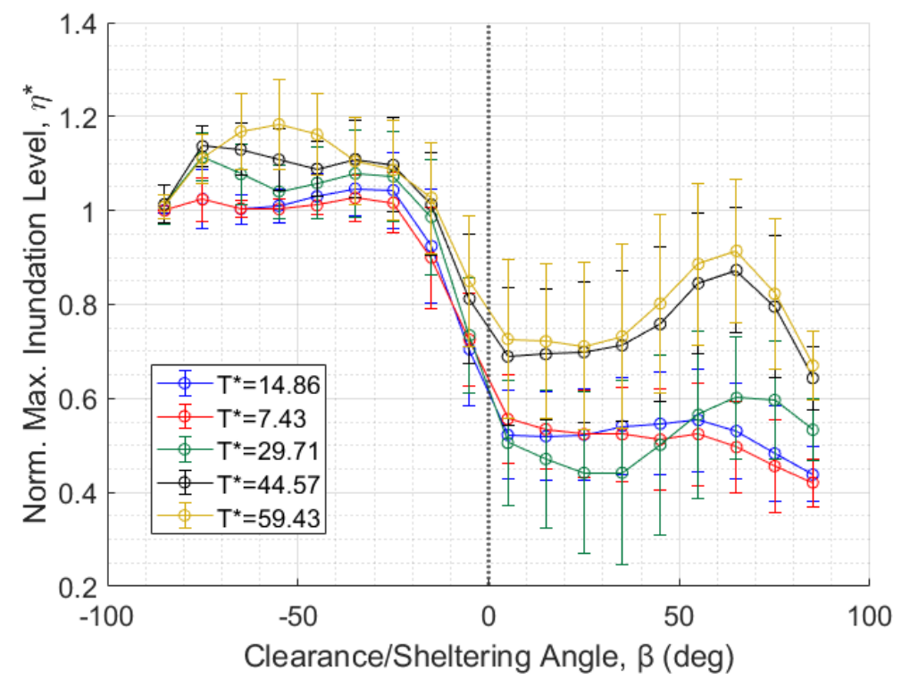
The simulation was run for the error function waves runup cases, with a Gaussian free surface resembling the error function wave used in the original experiment selected as the input wave. The generated input waves allow for modifications of wave properties. The variables for the simulation include initial wave height (0.0824m, 0.1098m and 0.1373m), wave time scale (7.5s, 15s, 30s, 45s and 60s), and structure size (0.3m, 0.4m and 0.5m). The model scale is 1/25.

Modeling Results (Inundation)

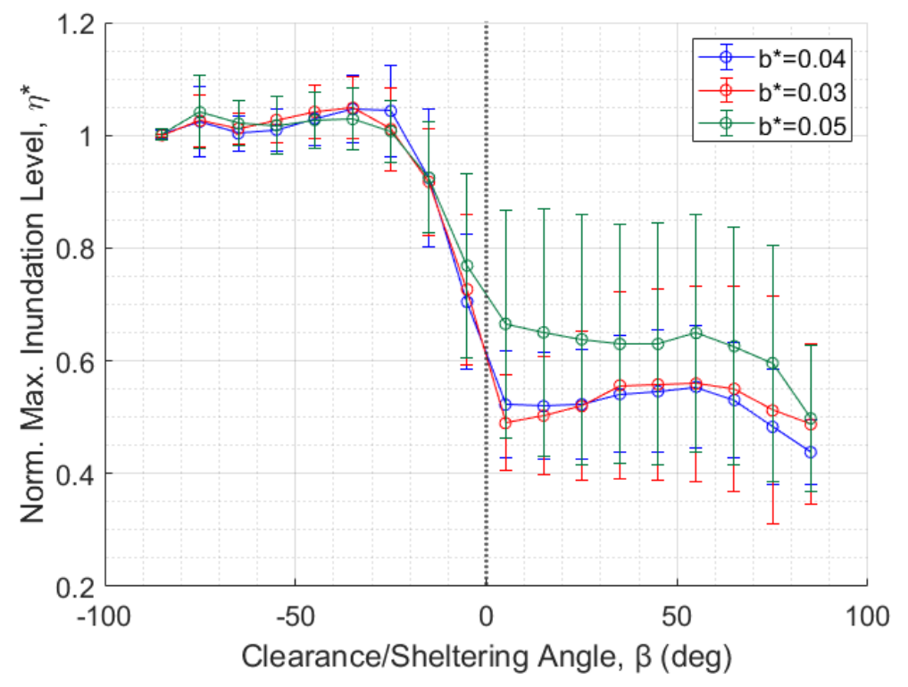
Some of the preliminary results from the numerical modeling are shown here. The overall comparison for maximum inundation level shows limited scatter and a clear trend in the relationship between maximum inundation level and partial wall location. Overall results portrait the sheltering effect as well as the increased inundation when the data collection point is exposed comparing to the no wall case.



Overall Inundation Results



Wave Time Scale Comparison



Structure Size Comparison

For comparisons between different model variables, results show that maximum inundation increases with longer wave time scale, especially for region behind the wall, meaning reduced sheltering effect. Also, maximum inundation increases with larger structure size, or narrower streets.

Conclusions

Loading

- Largest loads are observed on the first row.
- Loads decrease to the order of less than 50% of the no wall loads when sheltered by other structures in the array and less than 10% when sheltered by the wall.
- When the wall ends just before a structure, flow concentration effects generate larger sustained loads on the structure, even greater than the no-wall case.
- For inundation cases with breaking waves, loads increase at the front row with longer distance between the wave breaking location and the front row structure.

Inundation

- A location left exposed by the partial wall has larger maximum inundation level than the no wall case.
- Longer wave time scale leads to larger max. inundation, especially behind the wall.
- Larger structure size leads to larger maximum inundation throughout the array.

References

Dalrymple, R. A., and Kriebel, D. L., 2005. Lessons in Engineering from the Tsunamis in Thailand. Bridge, Natl. Acad. Eng., 35(2), 4–16.

Kennedy, A. B., Wirasaet, D., Begmohammadi, A., Sherman, T., Bolster, D., and Dietrich, J. C., 2019. Subgrid theory for storm surge modeling. Ocean Modelling 144, 101491.

Moris, J. P., Kennedy, A. B., and Westerink, J. J., 2021. Tsunami wave run-up load reduction inside a building array. Coastal Engineering 169, 103910.

Sato, S., 2015. Seawall Performance Along Southern Coast of East Japan Impacted by the 2011 Tohoku Tsunami; A Note for the Reconstruction Process. In: Santiago-Fandiño, V., Kontar, Y., and Kaneda Y. (eds), Post-Tsunami Hazard. Advances in Natural and Technological Hazards Research, vol. 44. Springer, Cham. doi:10.1007/978-3-319-10202-3_13.