PHYSICAL ADN NUMERICAL STUDIES ON THE EFFICACY OF MANGROVE FORESTS FOR WAVE ATTENUATION AND STRUCTURAL IMPACT

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INTRODUCTION

Low-lying regions are vulnerable to extreme waves and surges triggered by hurricanes and tsunamis. Anticipated sea-level rise is expected to cause shorelines to encroach further onto coastal land, potentially exacerbating the risk of flood-induced damage to coastal areas. Consequently, the implementation of countermeasure structures is imperative in mitigating wave-induced overland flows. Recently, Natural and Nature-Based Features (green structures), such as mangroves, have garnered significant attention for their potential to mitigate flood hazards. Mangrove forests are acknowledged as ecological buffer zones that effectively attenuate wave energy, protect shorelines, and enhance ecological functions. Dang et al. (2023) conducted a series of 1:16 scaled physical experiments to evaluate the efficacy of mangrove forests in mitigating inundating tsunami-like waves. However, this experiment only quantitatively analyzed flow dynamics at specific positions, and a comprehensive study of tsunami-induced flow patterns in coastal communities, characterized by a series of building arrays shielded by mangrove forests, has yet to be thoroughly investigated. Therefore, this study conducted a numerical investigation to further examine the influences of mangroves on dynamic flooding patterns and force mitigation on a series of building rows.

METHODOLOGY

First, a 1:16 scaled physical experiment was carried out in the wave basin (48.8 m long, 26.5 m wide, 2.1 m deep) at Oregon State University (Figure 1a, b). The physical bathymetry comprised three sections: an 11.7-meter flat bottom, a 1/20 sloping beach, and a 10-meter horizontal platform, representing an idealized coastal city. Transient waves with amplitudes ranging from 0.13 m to 0.21 m and a surge level of 0.98 m were generated using a piston-type wavemaker. Three configurations were tested, including a baseline (non-mitigation) and mangrove forests constructed in four and eight rows (4M and 8M, respectively). Various instruments such as wave gauges (WGs) and ultrasonic wave gauges (USWGs) along with acoustic Doppler velocimeters (ADVs) were used for measurements. Load cells (LCs), a 6-degree-of-freedom load cell (6DOF), and pressure gauges (PGs) were installed in each building element to capture force and pressure measurements (Figure 1a). Figure 1(c - f) depicts snapshots of tsunami-like waves breaking offshore, passing through mangrove forests, interacting with the first building row, and eventually reflecting extensively.

Second, the olaFlow model, implemented on the OpenFOAM platform, was employed to examine the inundating tsunami-like wave flow hydrodynamics in the built environment. The olaFlow solver utilizes the finite volume method (FVM) to discretize the governing equations, including the continuity and Navier-Stokes equations. The Volume of Fluid (VOF) technique is used to track the free surface displacement between the water and air phases. The experimental setup and data illustrated in Dang et al. (2023) were utilized to validate the predictive performance of the olaFlow model, which further examined flow dynamics that the physical experiment could not obtain due to instrumentation limitations.

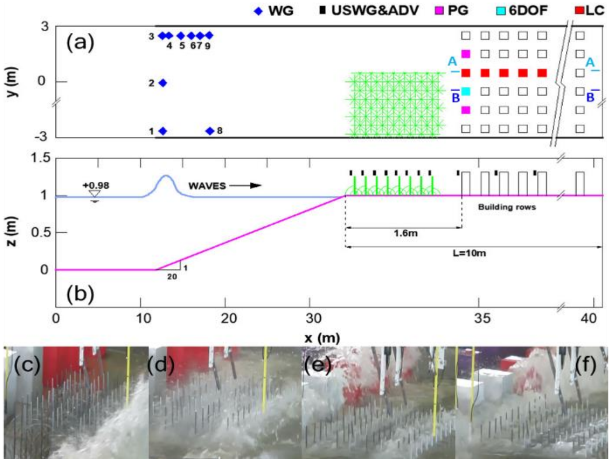

Figure 1 - Plan and cross-shore views of physical setup (a, b - not to scale) and snapshots of overland flow interacting with mangroves and building array (c, d, e, f).

NUMERICAL MODEL VALIDATION

Initial validation involved comparing the time series of horizontal forces from the first to the fifth building rows at a wave amplitude of 0.21 m (Figure 2).

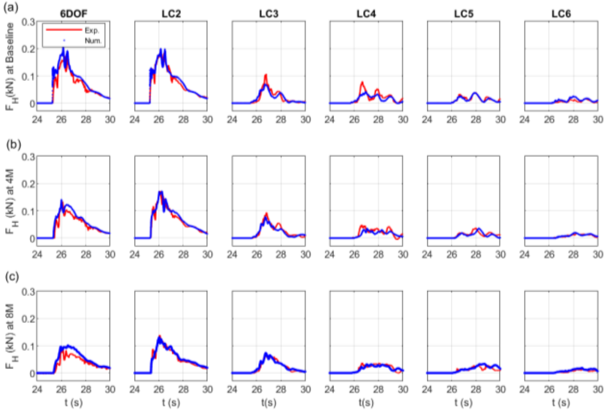

Figure 2 - Time series of measured and simulated horizontal forces in the first five building rows.

The preliminary numerical results demonstrate that the olaFlow model effectively replicates the time series of the experimental horizontal forces in terms of both duration and peak magnitudes. Compared to the maximum measured and simulated forces, the numerical model shows a correlation coefficient (R^2) of 0.98. Additionally, Figure 3 compares the computed and measured instantaneous inundation depths in three configurations, ranging from t = 25.4s to 28.4s. While the envelope diagram of the simulated inundation depth slightly underestimates the measured flow depths at specific instances, the olaFlow model proficiently reproduces the experimental results at different time steps.

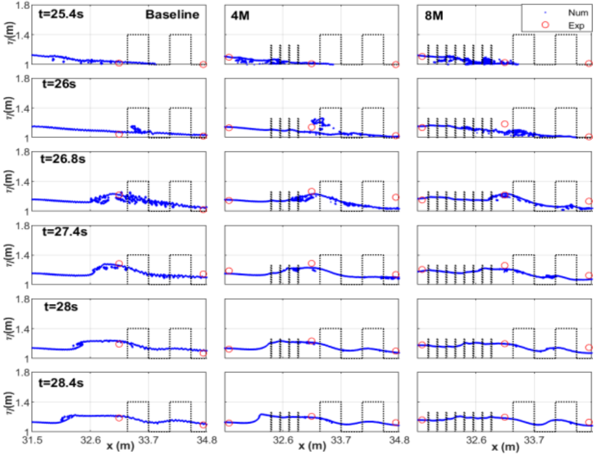

Figure 3 – Envelope of instantaneous inundation depths

RESULTS AND DISCUSSIONS

To investigate the effectiveness of each configuration of mangrove forests in attenuating inundation depth and velocity in the built coastal environment, eight numerical wave gauges collocated with velocity probes were installed in each mangrove row. Figure 4 illustrates the attenuation of tsunami-induced flow depth and velocity in each row, compared to those measured in front of the first mangrove array. The results indicate a slight variation in inundation depths across each configuration, whereas a significant difference is observed in the maximum velocities. Hence, hydrodynamic forces exerted on the mangrove trunks and building elements may depend more on the velocity component than the inundation depth. Furthermore, the 8M configuration reduced the flow depth and velocity by approximately 40% when the overflow passed through the entire mangrove rows.

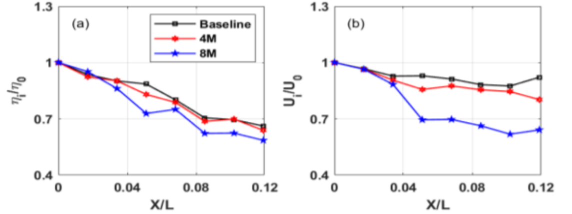

Figure 4 – Variations of inundation depth and velocity attenuation along the mangrove forest.

Figure 5 visualizes the flow patterns of overflows interacting with the front face of the first building row at various time intervals across five configurations, including baseline, partial (Section A-A, Figure 1), and full shelter (Section B-B) by both 4M and 8M configurations. The baseline and partial cover by 4M and 8M induce overland flow overtopping on the first building row; however, full shelter configurations effectively reduce wave run-up and overtopping. In the front face of the first building fully protected by 8M, the maximum run-up height was reduced by 60% compared to the baseline configuration. Moreover, the full shelter provided by the 8M configuration resulted in substantial mitigation of the instantaneous velocities exerted on the first building row.

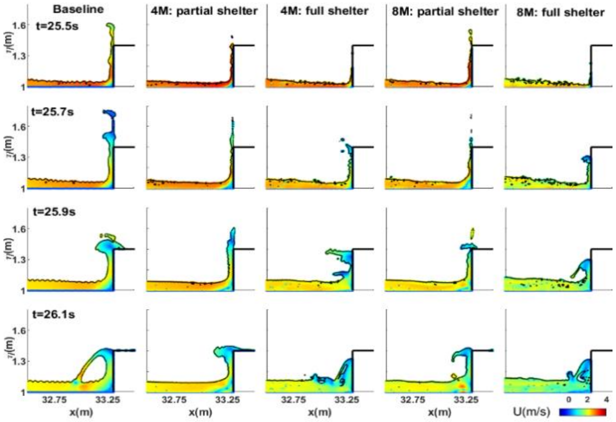

Figure 5 – Cross-shore variations of instantaneous wave run-up and related velocity in different configurations.

The effectiveness of mangrove forests is assessed through a comparative analysis of the hydrodynamic pressures and horizontal forces measured in the building elements. Figure 6 presents the instantaneous hydrodynamic pressure at the time of maximum force and the time series of force. The results indicate that the full 8M case effectively reduces hydrodynamic pressures and horizontal forces compared to other configurations in the first building array.

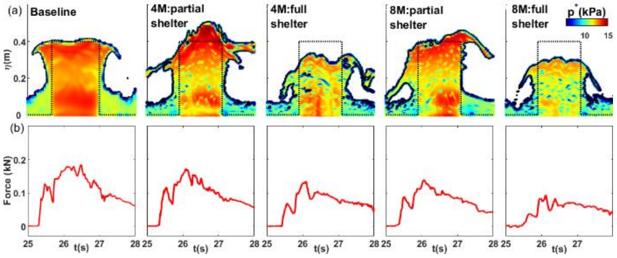

Figure 6 – Instantaneous hydrodynamic pressure at the time of maximum force and time series of force.

ACKNOWLEDGMENT

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