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The Effect of Tsunami Barrier Texture-Pattern on Tsunami Wave Amplitude

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Key Words: tsunami, wave barrier, amplitude, texture pattern, surface roughness, channeling, dissipation

Author's Summary: The large tsunami that struck Japan's northeast coast in March 2011 resulted in more than 19,000 deaths and more than $300 billion in material damage, largely because of the failure of high, concrete, off-shore tsunami barriers to stop the tsunami from inundating coastal cities. New, innovative tsunami barrier designs are needed to prevent this type of disaster from occurring in the future. This paper examines how texture patterns constructed from artificial turf and placed on the surface of an artificial tsunami barrier affected tsunami amplitude in a test tank, concluding that a perpendicular pattern is most effective and contributes to a significant reduction in tsunami amplitude.

Abstract

Recent tsunami-related disasters demonstrate the need for the development and implementation of new, more effective tsunami barrier designs. Rectangular, concrete barriers are often ineffective at stopping tsunami from inundating populated coastal regions; their failure can result in death and destruction. This paper presents the results of laboratory experiments that examined the effect of tsunami wave barrier texture-patterns on tsunami amplitude. Three tsunami barrier texture-patterns (perpendicular, parallel, and diagonal) were tested. Artificial turf strips were used on a rectangular prism-shaped barrier to assess which pattern was most effective in amplitude reduction. The procedure used was to generate a wave, then measure wave amplitude beyond the textured barrier at the end (designated shoreline) of a wave simulation tank. The perpendicular pattern barrier produced the lowest average wave amplitude, whereas the parallel and diagonal pattern barriers produced average amplitudes that were higher than the control amplitude. The wave barrier design concepts presented here could benefit vulnerable coastal areas by improving tsunami barrier performance and reducing tsunami destruction.

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Introduction

On March 11, 2011, a major tsunami with waves as high as 9 m struck the northeast coast of Japan after an 8.9 magnitude earthquake radiated from its epicenter offshore from Sendai, Japan. In some cities in Japan, high tsunami barriers—huge walls of concrete—had been built along the shore to prevent a tsunami from reaching the land. In many cities, the barriers did not stop the tsunami waves and the cities were inundated, resulting in more than 19,000 deaths and more than $300 billion in material damage. The Japan tsunami and similar tsunami-related disasters demonstrate the need for the development and implementation of new, more effective tsunami barrier designs.

Major tsunamis have caused significant losses of life and property over the past decade. Thomas and Cox [1] reported on tsunamis including the December 2004 Sumatra tsunami that killed 228,000 people and resulted in billions of dollars in damage. The aftermath of this tsunami was examined by Dalrymple and Kriebel [2], who reported that low-lying seawalls interacted with the tsunami bore to reduce damage behind the seawall. In 2011 in Kamaishi, Japan, however, the world's longest (1.9 km) sea wall, which was built in the city's harbor at a cost of $1.5 billion a few years earlier, was overwhelmed by tsunami waves that submerged the city center [3].

Two preliminary studies were conducted previously. The first study examined how to improve the design and performance of tsunami wave barriers by investigating the effect of tsunami barrier *shape* on tsunami wave amplitude at the shoreline. Rectangular prism, sea-side concave, and hill-shaped barriers were tested (with no barrier as the control) and the results showed that the rectangular prism-shaped barrier produced the lowest mean wave amplitude. The second study examined the effect of tsunami barrier *texture* on tsunami wave amplitude at the shoreline. Artificial turf, rock, and bubble wrap textures (with smooth texture as the control) were tested on a rectangular prism-shaped barrier, and the results showed the artificial turf-textured barrier produced the lowest mean wave amplitude.

Research by Fernando and McCulley [4], Gippel et al. [5], and Osti et al. [6] demonstrated the effect of flow patterns and barrier patterns on tsunami wave energy, afflux (the rise in water level on the upstream side of a structure or constriction), and tsunami flow pressure. The effects of fringing reefs on tsunami inundation in American Samoa were studied and modeled by Gelfenbaum et al. [7], who demonstrated that coastal embayments and incised channels on reefs can produce tsunami wave amplification. Channels incised into fringing reefs were shown to increase tsunami inundation, yet embayments that both narrowed landward and had incised channels resulted in the greatest increase in inundation.

In their study of coral poaching and tsunami destruction in Sri Lanka, Fernando and McCulley [4] reported that tsunami wave intensity increased due to focused water-jetting though low-resistance paths created by illegal coral poaching on coral reefs. The model simulations of Kunkel et al. [8] demonstrated that both reflection and frictional dissipation contributed to the reduction of wave energy transmitted over a reef, yet evidence of wave energy being focused through reef gaps was not found.

Gippel et al. [5] investigated the hydraulics of large river debris, showing linear debris oriented diagonally to flow generated the lowest drag coefficients, and debris oriented perpendicular to flow produced the highest afflux. Multiple surface-roughness elements positioned perpendicular to flow and spaced less than two diameters apart resulted in a skimming flow effect [9]. In skimming flow, the objects act hydraulically as one continuous object, exerting a lower drag than the expected total drag resulting from the sum of the individual elements.

According to Osti et al. [6], in regions where mangrove forests serve as natural tsunami barriers, the density of healthier forests, compared to that of sparse forests, results in a greater reduction in tsunami flow pressure. Anderson, et al. [10] observed that field and laboratory investigations on the effect of coastal vegetation demonstrated the ability of plants to dissipate wave energy and decrease wave heights; however, wave attenuation was difficult to predict due to its contingency on plant biomechanics and wave characteristics.

The question addressed in the investigation reported here was: How does the *texture pattern* of artificial turf on the tsunami wave barrier affect tsunami wave amplitude at the shoreline? Three different tsunami barrier texture-patterns were tested to determine which was most effective in reducing wave amplitude: perpendicular, parallel, and diagonal were compared to the control (turf-covered). For simplicity, the patterns will be called perpendicular, parallel, and diagonal throughout this paper.

The perpendicular pattern was expected to result in the lowest mean wave amplitude because the parallel and diagonal patterns could produce a channeling effect toward the shoreline that results in wave amplification, as demonstrated in research on tsunami inundation and incised channels in fringing reefs [7]. Also, studies on the impact of large river debris demonstrated that linear debris oriented diagonally to flow (similar to the turf strips on the diagonal-pattern barrier) resulted in lower drag coefficients and less afflux when compared to debris oriented perpendicular to flow [5].

Materials and Methods

The research was conducted in a wave tank constructed from a glass aquarium (interior: 182.9 cm long × 45.7 cm wide × 73.7 cm high). The following constants were maintained for all experiments: shape of barrier; length of barrier; average height and width of barrier with turf; method of application of turf strips; spacing of turf strips; position of barrier in wave tank; water height in wave tank; position of wave measuring paper/board; method of wave generation; and method of wave amplitude measurement.

To maximize the efficacy of the wave generator, the functional length of the wave tank was shortened to 136 cm by placing a vertical board at the opposite end of the aquarium. The vertical board was designated as "the shoreline." A diagram of the wave tank is shown in Figure 1. Pre-cut wood boards and nails were used to build the bases for four rectangular prism-shaped wave barriers (40 cm long, 18 cm high, and 12 cm wide) (Figure 2).

The three different texture-pattern barriers were created by using marine adhesive to adhere 1 cm-wide strips of artificial turf as shown to the front (sea-side) and top of each barrier base. The texture strips were spaced 1.5 cm apart. To create the control barrier, a solid sheet of artificial turf was attached, using marine adhesive and staples, to the front and top of the fourth barrier base. The completed barriers are pictured in Figure 2. To prevent the barriers from moving inside the wave tank, each barrier was weighted by placing coins sealed in a plastic bag in the interior of the barrier.

To mark the water fill line, masking tape was applied to the outside of the wave tank at 15 cm above the tank base. The tank was filled with water to the fill line, and the water level was maintained at 15 cm for all tests.

The wave generator was built from two boards (each 40 cm × 60 cm × 1.9 cm) attached together along their short ends with three hinges (Figure 3). The wave generator was positioned hinged-end down at the near-end of the tank, with one (stationary) board placed against the tank wall and perpendicular to the tank floor. Two clamps were used to secure the stationary board of the wave generator in place, and one clamp was used to hold the front, moving board in the closed position. Two bungee cords (each 61 cm long) were hooked and permanently secured with duct tape onto the top-center piece of the aquarium. Immediately before generating each wave, the opposite ends of the cords were hooked to the moving board of the wave generator. The wave tank is shown in Figure 3.

To initiate testing, the control (turf-covered) barrier was positioned inside the tank at the far-end. The barrier back was placed against the wood, and the bottom of the barrier was flat on the tank floor.

For each barrier type, 30 pieces of construction paper were labeled according to specific upcoming tests (e.g., C1 for control test #1; C2 for control test #2; etc.). The first sheet of paper was taped to the back-board, between the barrier and the board, with the bottom of the paper touching the water line. Immediately after the wave crest crossed the barrier, the construction paper was removed and the water/wave height at its highest point was marked on the paper.

Prior to each wave generation, the water was allowed to settle so it was not moving. To produce the wave, the center clamp was removed, allowing the spring force of the bungee cords to pull the moving board of the wave generator out and down into the tank, producing a wave. At the point of generation, the amplitudes of the waves were observed to be relatively consistent but exact measurements were not obtained. This same procedure was repeated for 30 trials with the control, the perpendicular pattern barrier, parallel pattern barrier, and diagonal pattern barrier.

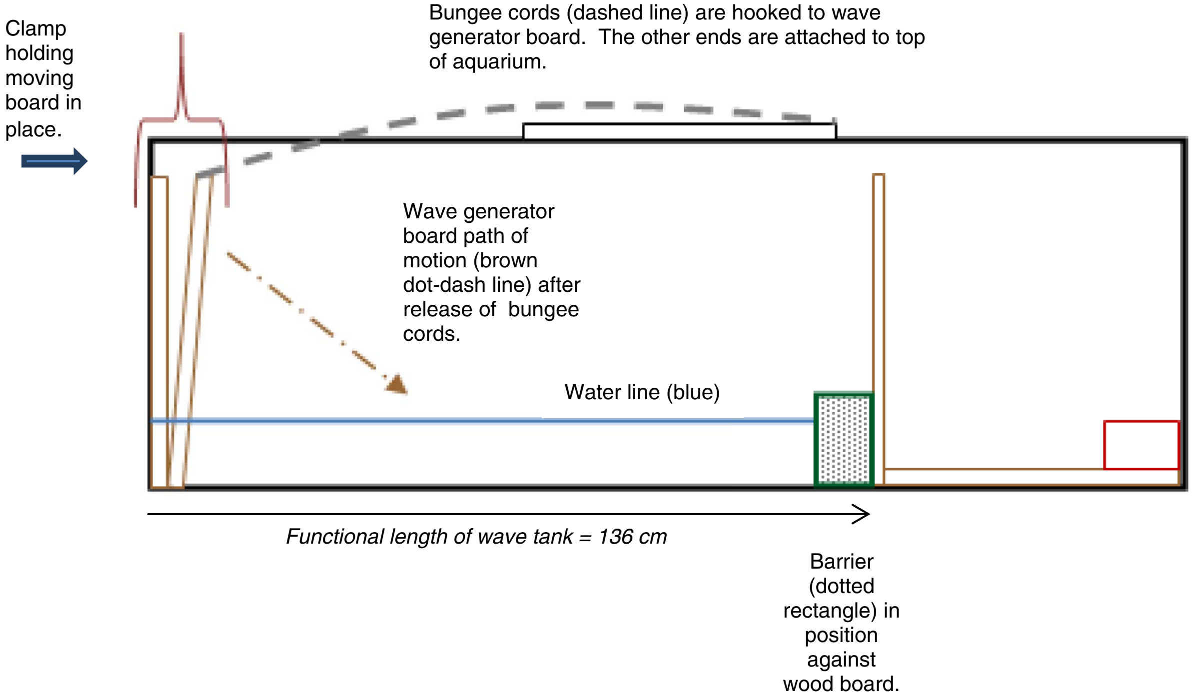

Figure 1. Diagram of wave tank illustrating features and how the wave tank worked.

Figure 2. Photographs of the various barrier designs (l to r): control barrier, perpendicular pattern barrier, parallel pattern barrier, and diagonal pattern barrier.

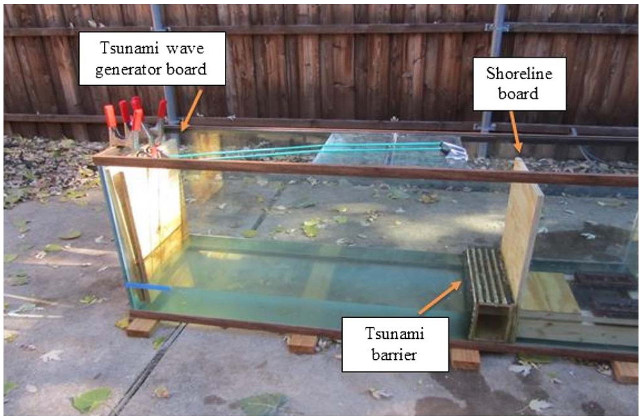

Figure 3. Photograph of wave tank with wave generator in closed position and perpendicular pattern barrier in place at far-end of tank. Bungee cords (blue) are attached to stationary top of tank and stretched to moving wave generator board.

For each trial, the wave amplitude was measured from the bottom of the paper to the wave amplitude mark. Wave amplitude data for each barrier type and for the control were recorded and entered into an Excel spreadsheet and graphed; the mean wave amplitude for each barrier type was then calculated. Statistical significance calculations (ANOVA and independent two-sample t-test) were completed using Excel and GraphPad QuickCalcs software. The mean wave amplitudes were graphed to facilitate comparison and evaluation of the means.

Results

The mean wave amplitude for each barrier type is listed in Table 1, with a graphic comparison of the means shown in Figure 4. Note that the perpendicular pattern barrier produced the lowest mean amplitude, 7.64 cm; the parallel and diagonal pattern barriers produced average amplitudes that were higher than the control amplitude. The mean wave amplitude produced by the perpendicular pattern barrier (7.64 cm) was 25% lower than the mean produced by the control (10.2 cm) and approximately

Table 1. Wave amplitude (mean ± standard deviation) following an artificial tsunami for each barrier texture pattern oriented with respect to the direction of water flow (n = 30 replicates for each).

Barrier type	Mean wave amplitude (cm)	Range
Control (turf-covered)	10.2 ± 2.269	7.1–15.4
Perpendicular pattern	7.64 ± 1.623	4.0–11.1
Parallel pattern	13.61 ± 2.574	8.3–18
Diagonal pattern	14.49 ± 2.227	10.5–18.6

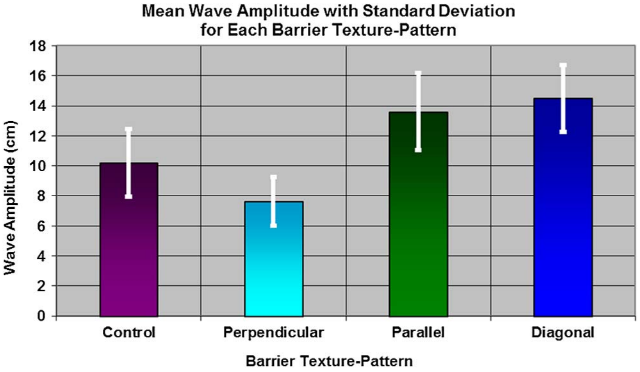

Figure 4. Comparisons of wave amplitudes using different barrier texture-patterns (mean ± standard deviation). Control barrier: 10.2 ± 2.269, perpendicular pattern barrier: 7.64 ± 1.623, parallel pattern barrier: 13.61 ± 2.574, and diagonal pattern barrier: 14.49 ± 2.227.

46% lower than the means produced by the parallel and diagonal pattern barriers, which generated the higher mean wave amplitudes (13.61 cm and 14.49 cm, respectively) than the control.

A one-way analysis of variance (ANOVA) was performed to compare the means of the control, perpendicular, parallel, and diagonal groups. There was a statistically significant difference between groups as determined by a one-way ANOVA ($F(3,116) = 61.92790419$, $p \leq 0.0001$).

Statistical analyses using an independent two-sample t-test were conducted to compare the amplitude of the control and perpendicular pattern groups, the control and the parallel pattern groups, and the control and the diagonal pattern groups. Analysis of the control and perpendicular pattern group revealed a significant difference in amplitude between the control (mean 10.2 cm, s.d. 2.269) and the perpendicular pattern barrier (mean 7.64 cm, s.d. 1.623), ($df(58) = 5.027$; $p \leq 0.0001$). A similar comparison of the control and parallel pattern groups showed a significant difference in amplitude between the control (mean 10.2, s.d. 2.269) and the larger mean amplitude with the parallel pattern barrier (mean 13.61, s.d. 2.574), ($df(58) = 5.443$; $p \leq 0.0001$). Analysis of the control and diagonal patter barrier revealed a significant difference in amplitude between the control (mean 10.2, s.d. 2.269) and the larger mean amplitude with the diagonal pattern barrier (mean 14.49, s.d. 2.2227), ($df(58) = 7.391$; $p \leq 0.0001$).

Although the physical scale of the experimental design was very small, it is believed that the comparison of mean amplitudes reflects results that could contribute markedly to the improvement of real-world tsunami barrier design.

Discussion

What is the effect of tsunami barrier texture pattern on tsunami wave amplitude at the shoreline? Channels or gaps in coral reefs can produce tsunami wave amplification, and in rivers, diagonally oriented debris is reported to generate lower drag in comparison with perpendicularly oriented debris [5]. Based on this information, the perpendicular pattern was predicted to result in the lowest mean wave amplitude when compared to the parallel pattern, the diagonal pattern, and the control. The comparison of the mean wave amplitudes showed that the perpendicular pattern barrier performed best in reducing wave amplitude.

The study's results show that the parallel and diagonal pattern barriers generated mean wave amplitudes (13.61 cm and 14.49 cm, respectively) that were higher than the control. These results align with the findings of Gippel et al. [5], who found that diagonally oriented, linear river debris generally produced lower drag and less afflux than linear debris oriented either perpendicular or parallel to flow. They also associate to some degree with the claims by Gelfenbaum et al. [7] and Fernando and McCulley [5] that channeling or water-jetting through coral reef gaps can produce wave amplification.

In the current investigation, the superior performance of the perpendicular pattern barrier in comparison to the control is not predicted by the skimming flow effect theorized by Morris [11] as discussed by Gippel et al. [5]. Applying the principle of skimming flow (which involves flow over a series of obstacles with only weak intrusion of flow into the obstacle-gaps) to the current study, it could be assumed the perpendicular pattern barrier would have performed similarly to the control (turf-covered) barrier. The data, however, do not support this assumption, suggesting the impact of more complex factors and the need for additional research.

The primary beneficiaries of the application of the current study's findings would be populated coastal areas that are vulnerable to tsunamis or large hurricanes. Real-world designs for tsunami wave barriers featuring natural or artificial vegetation, or a similar texture, in a perpendicular pattern could be created and evaluated. In a coastal setting, this type of barrier design could be advantageous due to its more natural appearance and increased effectiveness. The current investigation could also be relevant to research on how to optimize the performance of mangrove forests, coastal vegetation, and coral reefs as natural wave barriers.

Limited academic research on tsunami barrier design modifications and innovations has been conducted to date. Future experiments directly related to the current investigation could evaluate the effect of other independent variables including: artificial turf depth, artificial turf composition, texture density, pattern spacing, pattern placement on the barrier (e.g., top only), and artificial turf durability.

In the current study, research challenges were presented by limitations of the wave tank and wave generation mechanism. In order to maximize the effectiveness of the wave generator, the functional length of the aquarium (used because of its availability to the author) had to be shortened with a false back, thus reducing the length of the travel distance for the waves. Also, the amount of force produced by the wave-generation mechanism limited the power and amplitude of the tsunami waves. Improvements in methodology should include the utilization of a more powerful, mechanical wave generator in combination with a larger wave tank or laboratory wave basin that would more accurately replicate tsunami wavelength. To more closely replicate the bathymetry of coastal regions and to assess the impact of turbulent flow near the shoreline, a sloping and/or rough seafloor near the shoreline would be a useful addition to the wave tank. Future investigations incorporating these modifications could be highly informative.

Real-world applications of tsunami barrier research must take into account–and may be limited by–practical considerations. Such considerations include the barriers' cost and durability, environmental impact, and obstruction of view from the shore.

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