# COASTAL INFRASTRUCTURE DESIGN: RESEARCHING SEA-WAVES AND TEXTURED SURFACES INTERACTION USING PHYSICAL AND VIRTUAL WAVE FLUMES

ROY KOZLOVSKY [1], YASHA GROBMAN [2] and HANNA LEVY[3]
*[1]Tel Aviv University, Tel Aviv, Israel; [2]Technion Israel Institute of Technology, Haifa, Israel; [3]independent scholar.*
*[1] rkozlov@tauex.tau.ac.il, http://orcid.org/0000-0003-4079-4637*
*[2] yasha@technion.ac.il, http://orcid.org/0000-0003-4683-4601*
*[3] hanny_levy@hotmail.com, https://orcid.org/0009-0001-6030-0588*

**Abstract.** Projected global rise in sea level and intensification of storms place the shoreline at risk, requiring extensive investment in coastal defence infrastructure. These structures are designed to efficiently dissipate wave energy at the expense of ecological and landscape values. The aim of the research is to establish a multifunctional approach to coastal infrastructure. Within this framework, it proposes a method for utilising simulation tools to creatively shape the interaction of sea waves with coastal structures for scenic and ecological benefits. It sets two primary goals: to establish that computational fluid dynamics tools can be used by architects to design the interaction of sea-waves with solid surfaces. This goal is explored by creating a digital simulation of a physical wave flume facility, and running physical experiments to calibrate the virtual simulation tool. Secondly, it uses these tools to systematically explore the range of possibilities latent in wave-structure interaction by initiating basic research into the flow properties of different types of textured surfaces to improve the aesthetic and ecological performance of such structures.

**Keywords.** Computational Fluid Dynamics, Coastal Infrastructure, Ecological Enhancement, Textured Surfaces, Physical and Virtual Simulations, Computational Design.

## 1. Introduction

Current forecasts of rising global sea levels and intensification of storms place the shoreline at risk, requiring extensive investment in new coastal defence systems and modifying existing facilities to protect urban development and critical waterfront infrastructure such as ports and power plants. The massive construction of seawalls and other types of protective coastal infrastructure may conflict with ecological and urban values, by employing materials and techniques that contribute to climate change, reducing public access to the shoreline and damaging sensitive coastal ecosystems (Hosseinzadeh et al. 2022). Mitigating these conflicts requires a multi-functional and

*ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024*, Volume 1, 445-454. © 2024 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

multispecies approaches in which defensive structures assume additional functions such as providing ecological services, parks and seaside promenades (Salauddin et al. 2023; Grobman et al. 2023). These approaches provide the opportunity to rethink the design of these structures, and especially how they interact with incoming waves.

The architectural, creative approach to designing these structures conceives sea waves differently than the defensive approach of coastal engineers. First, it would plan for moderate and calm sea states, which coastal engineers discount because their main design parameter are peak waves. Second, it would attend to the ways in which breaking waves flow back to the sea. This type of flow is of lesser interest to engineers, as it poses little risk to the stability of the structure or its resistance to overtopping. Third, it would attend to the texture scale of these structure, which is not an important factor for defensive design of marine infrastructure. To address these gaps in knowledge, the proposed research explores the ecological and experiential potential of coastal infrastructure by focusing on everyday sea conditions and the scale of texture.

The interaction of the sea with the built shoreline for both run-up and run-down flows is difficult to model because of the non-linear and turbulent behaviour of sea waves as they encounter a solid boundary and break. This complexity presents technical difficulties for developing methods for creatively shaping them through morphological and material interventions.

Until recently, the main method for studying the real-life interaction of sea waves with a solid structure without building it first has been to test a physical model in a wave flume facility. A major impediment to integrating wave flumes into architectural research is the high costs and time-consuming process of preparing and testing models in this highly specialized and expensive laboratory equipment.

Recent developments in digital computation and simulation technologies may facilitate design-oriented research into sea-wave flows (Chronis et al. 2017). Computational Fluid Dynamics (CFD) are being used by architects and designers to model and visualize airflows to design, healthy and energy-efficient buildings, as well as predict structural wind loads and environmental comfort around them. The aim of this paper is to expand the application of these tools to the design of coastal structures. This is possible because specialized CFD tools for simulating the complex interaction of sea waves with solid surfaces have advanced past the threshold of accuracy that enables architects to use them as substitutes to physical wave flumes, therefore removing a high entry barrier to this emerging field of design.

Previous research into multi-functional coastal infrastructure design utilized CFD simulation tools to explore seawall morphology as a means for creating different types of flow effects (Kozlovsky & Grobman, 2016; Grobman et al., 2017). Its contribution remained speculative since these tools were not empirically validated. This paper presents the next stage in the research program that addresses this gap. It sets two main goals: Validating the claim that currently available computational fluid dynamic tools can be reliably used to research the interaction between solid surfaces and sea-waves by comparing the virtual simulations with physical tests in a wave flume. Secondly, using these tools to systematically explore the range of possibilities latent in wave-structure interaction by initiating basic research into the flow properties of different types of textured surfaces. This stage of research contributes to CFD aided design the relatively unexplored scale of texture.

## 2. Methodology

The research combines analytical and experimental methods. It simplifies the infinite variety of textures and sea-wave conditions into basic parameters, and tests their interaction in a physical wave flume. The results are used to calibrate the virtual wave flume, and create systematic knowledge on texture-induced fluid motion.

The experiment is divided into three stages. In the first, it establishes simplified parameters for designing and fabricating textured surfaces such as geometry, density and extrusion, and standardized sea-wave flow variables for testing their performance in a physical wave flume, such as surface inclination and wave height. In parallel, the researchers utilize computational tools to construct a virtual wave flume based on the properties of the physical wave flume facility available to them.

In the second stage, the parametrically produced textures are tested in a physical wave flume. The results of the experiments are used to calibrate the computational tool and evaluate its capacity to achieve a reasonable degree of similitude.

In the third stage, the experimenters develop a set of criteria for measuring and assessing the flow characteristics of each texture, and used the comparative method to generate knowledge on the impact of geometry, density and extrusion on run-up and run-down wave motion. Based on the initial empirical findings, it proposes a method for systematically exploring the range of possibilities latent in wave-structure interaction and integrating this knowledge into the early stages of the design process.

## 3. Texture parameters

In architectural discourse, texture is defined as a formal category that accounts for the physical and visual qualities of surfaces. Modern architecture defined texture as subservient to primary categories of space, structure or form. Considered superficial, it is permitted if it adheres to the principle of material honesty, that is, exposing the material’s inner essence or the workmanship and tools applied to it. As an operative concept of design thinking, texture is considered a secondary artistic means for unifying or varying planes that enclose space, expressing the weight of a form, reflecting or absorbing light, and other compositional aims (Ching, 2007). In phenomenologically informed practice, texture's association with the sense of touch and tactile modes of perception informs its revaluation as a significant component of architectural experience (Pallasmaa, 2012). Digital technology and culture are reframing texture as an artifice of a new aesthetics that registers themes such as emergence, fluidity, animation, interactivity and differentiation (Schumacher, 2009).

Texture in coastal infrastructure has a functional rather than visual or experiential significance. It is assessed in terms of its performance, be it in dissipating wave energy or increasing biodiversity, suggesting that surface texture is not as a fixed, autonomous property, but a process that shapes and is shaped by external forces and programmatic requirements.

Hydraulic engineers consider texture in terms of its energy dampening effect on wave run-up. Increase in surface roughness is correlated with higher energy dissipation through friction and turbulence. This relationship, expressed in empirical equations, is used to determine the size of elements for building riprap revetments (van der Meer, 2018; Kreyenschulte et. al 2020).

The dimension of texture at its different scales has been explored by marine biologists, since it has a quantifiable impact on the ecological performance of coastal structures (Sella et al., 2022). Smooth surfaces that characterize modern concrete coastal structures have an adverse impact on biodiversity, since many species are adapted to naturally occurring textures. Increase in texture density enables more species to attach themselves to the surface or find shelter from predation, resulting in more abundant and diverse intertidal ecosystems. The practical application of biological research into the habitat properties of texture is the bioengineering of coastal and marine structures to recruit and sustain complex ecosystems. The texture may have aesthetic value, but it is incidental to its calculated effect on biodiversity.

The engineering and biological understanding of texture as a function of hydraulic or biological performance, can be transferred back to architectural thought, leading to the concept of the performative surface. The shape of the solid texture is a function of its effect on water flows. Since water is transparent, one can simultaneously observe both the texture of the solid surface in itself, and the emerging pattern of water flows during run-up and run-down. To begin exploring this unique condition, while insuring that the research into texture is not biased towards functional goals such as optimizing the structure's engineering and ecological performance, or humanizing texture by mimicking pre-existing culturally meaningful patterns, the research develops an analytical approach that sorts texture into basic morphological parameters.

## 3.1. BASIC TEXTURE PARAMETERS AND MANUFACTURING

In order to establish a basic understanding of how texture could be purposely applied to shape flows for practical and creative aims, the research simplifies texture into basic types of point-based and line based textures. These groups are tested for three elementary geometric forms, the circle, the triangle and the square.

The textured plates are of standard size that fits the width of the physical wave flume. Individual plates are designed to analyse one morphology. Using a parametric model in Grasshopper plugin for Rhinoceros design software, each plate includes a distribution of texture scale and roughness. Density of texture varies from highest to lowest value from right to left. Extrusion is distributed from lowest at the top to highest at the bottom according to a Voronoi grid which changes density of cells according to the texture density distribution described above (Figure 1). This setup is designed to study the minute variations in flow regimes and identify emerging flow patterns that are scale sensitive. Altogether seven texture pattern plates were constructed from birch wood plates using a CNC machine.

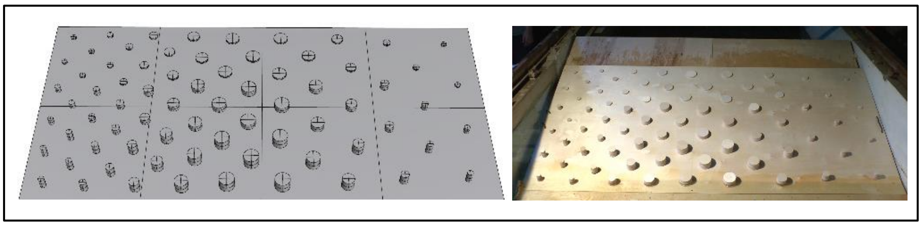

*Figure 1: Point-based circular texture plate.*

### 3.2 PLATE INCLINATION

The inclination of a textured surface is an important parameter for wave performance, both for run-up and run down flows. Due to gravity, run-up velocity is reduced by steep inclination, while run-down velocity is accelerated. Each inclination would produce a different flow regime for the same pattern. Minute differentiations in inclination angle may produce a qualitative change in flow regime. While digital simulation tools allow to test any inclination with a simple command, the practical constraints of time and costs posed by experiments in physical wave flumes limited the inclination parameter to two angles. The inclinations of 20° and 40° were chosen in accordance with the optimal inclination of maritime structures such as revetments and seawalls. Two demountable substructures with the mentioned above inclinations were built from wood to support the removable textured plates during the physical trial.

## 4. Wave flume experiment

The laboratory experiments were carried out in the Coastal and Marine Engineering Research Institute (CAMERI) at the Technion, Haifa. The facility's 45×2.45×1.5 meter wave flume is equipped with a wave generator, computerized control for real sea simulation, wave gages and high sampling rate pressure gages.

The water depth was set to 1 meter while the wave piston was set to move 10 cm back and forth, generating sinusoidal waves with height of 0.188 m and amplitude of 0.09. This type of waves imitates weak sea state level 2 according to the World Meteorological Organization scale. The simulations were recorded from three points of view simultaneously: from a top view, from a side view through a glass window to the side of the plate and from the back (Figure 2).

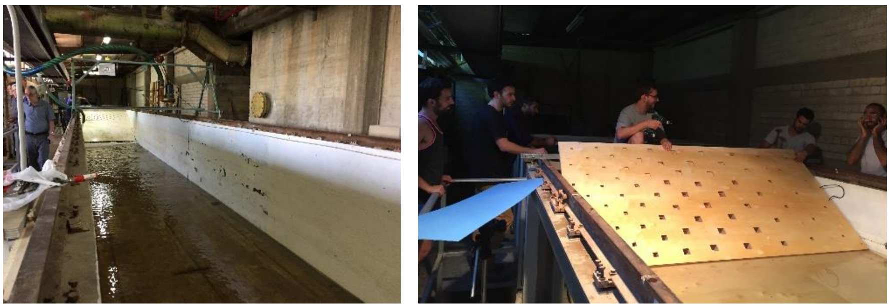

*Figure 2: CAMERI wave flume with demountable texture plate.*

## 5. Experimental Results

Initial examination of the results of the physical simulation showed that texture has a significant qualitative and quantifiable effect on water flow regimes, and that this effect can be analysed to establish a basic understanding of how texture could be purposely applied to shape flows for both practical and creative aims.

After observing the visual properties of run-down and run-up of flows on different texture types, it was decided to generate quantitative data on a series of parameters considered significant for understanding the relationship between texture and flow:

- Run-up and run-down flow times: the time it takes the wave to climb the textured plate, and the duration of the run-down flow.
- Run-up distance: the maximal distance reached by the wave during run-up motion.
- Flow wake width above and below: the width of the trail formed above and below the obstacle during run-up and run-down.
- Flow splash height: the height of the splash created by the impacting wave.
- Returning flow water jump height: the height of the jump of returning flow over textural elements.

Measurement were taken for three different waves. The outcomes shown below are the result of a mathematical average of the three sensitivity checks.

Parallel to the quantitative analysis, the observations identified qualitative flow patterns generated by specific textures, and analysed the parameters for their emergence.

## 5.1. QUANTITATIVE ANALYSIS OF TEXTURED FLOW

This section presents the most significant findings of the quantitative analysis.

### *5.1.1. Run-up and Run-down Time*

The run-up and run-down times for each dot-based texture placed with slopes of 20 and 40 degrees is presented in table 1 as percentage value to maximal time.

One first observation is the likeness of run-up time records of the plates with cavities and textures both with an inclination of 20, which variate only by 7%. The second observation is the likeliness between the run-down time of the texture plates with slope of 40° and that of the cavities plates with a 20° inclination.

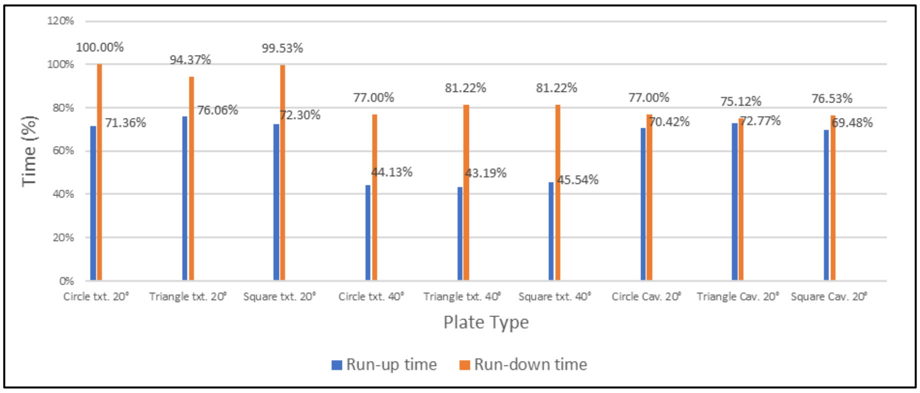


Table 1: Run-up and run-down time measurements for point-based textures.

The conclusion from the table is that the run-up time is almost the same for the circular texture and cavities plate (difference of 0.94%) while the difference slightly increases for triangle (3.29%) and square (2.82%) texture geometries. This happens because circles have a hydrodynamic shape in both directions of flow. In addition, the change in slope angle from 20° to 40° produces a stronger effect on run-down time, due to the effect of gravity.

### *5.1.2. Water Wake Width*

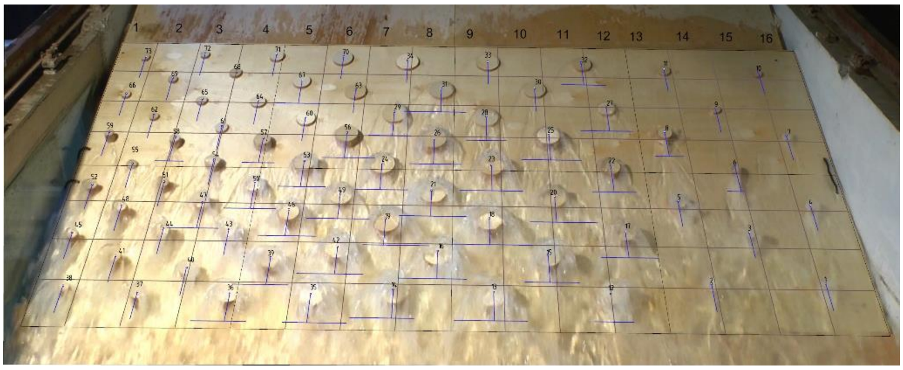

*Figure 3: wakes formed during run-down in circular texture at 20° slope.*

This set of measurements investigate the flow created after the run-down flows pass the textured field (Figure 3). The wake width measurement in Table 2 was taken at a distance of 80 mm below the obstacle. It presents an average of the three measurements. From the resulting trend line it is possible to conclude that, by average, the width of the wake on the y-axis is about 2.4 times bigger than the diameter, shown on the x-axis. This value can be used by designers to create a trail that has a desired width by playing with the diameter of the circular textures.

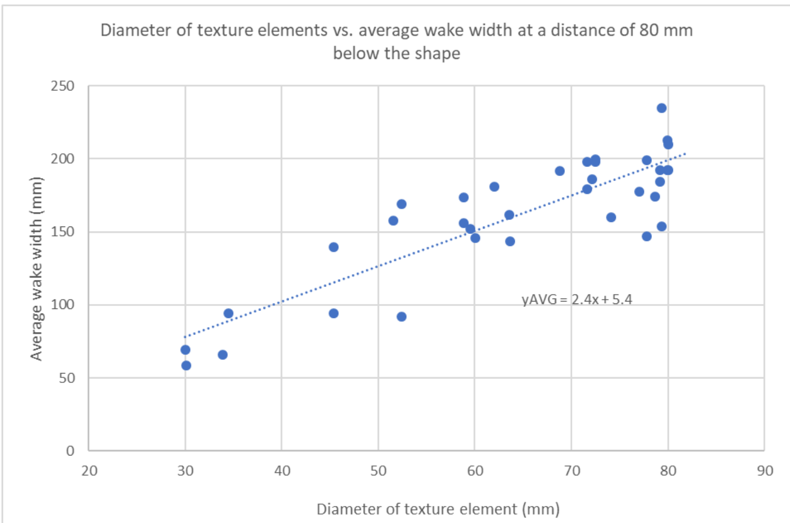


Table 2: Relation between texture diameter and wake width for circular elements.

### 5.2. QUALITATIVE ANALYSIS OF TEXTURE FLOWS

Concluding the catalogue of visual effects of texture are unexpected phenomena that may have aesthetic or educational value. These effects may be specific to a given texture geometry or flow condition such as the first, weakest run-up flow of a series.

One of these visual effects (figure 4) was a water jump created by the returning flow. The height of the jump could be calculated in relation to the texture extrusion height, surface inclination, and the position of the protrusion on the plate.

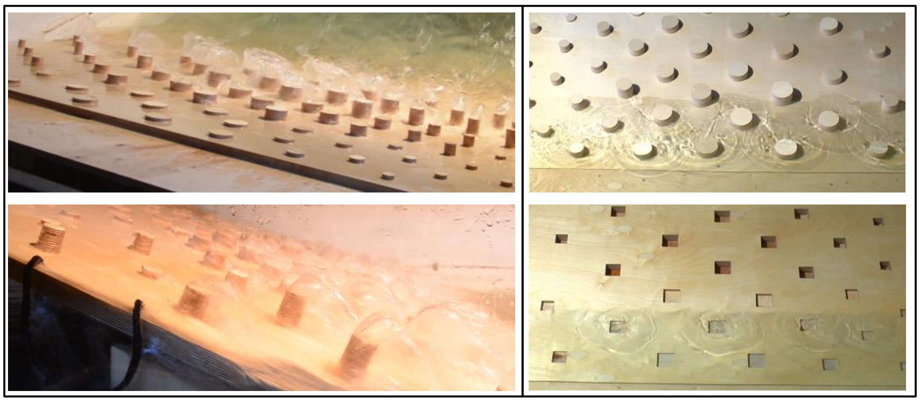

*Figure 3: quantitative effects: wake jump.* *Traces produced by cavities.*

Additional qualitative visual effects can be classified as echoes or traces left by the texture on the water surface (Figure 5). This delicate wave event was observed in the first, weakest wave of the series, for both protruding and cavity based textures. The visual interest in this wave taxonomy can be attributed to the tension between the texture's geometry and the circular movement of waves. As discussed in the introduction, this effect is limited to calm sea state, a relatively under-studied condition.

## 6. Calibration of Virtual Simulation Tools

The final step of the research dealt with the calibration of the virtual simulation. A digital version of the CAMERI wave flume was prepared according to its true measure, including the properties of its wave producing mechanism. The digital drawings of the textured plates were inserted into the virtual flume to run the simulation. The researchers used visual records and measurements from the physical wave flume to calibrate the digital tool by adjusting flow parameters such as viscosity, particle separation, and surface tension, as well as the movement of the virtual wave generator to reproduce the specified wave height of the physical experiment.

The initial computational set-up for the virtual simulation used Blender and its recent fluid simulator Mantaflow. Due to inconsistencies, it was decided to compute the simulation step with Houdini and then import it to Blender for final rendering.

The digital model of the wave flume and textured plates was imported into Houdini. Using the simulation of the triangular texture at 20° as a reference model, the flow simulation parameters of Houdini were adjusted in an iterative process until the final visual effect was close enough to the behaviour recorded in the physical wave flume experiment. To make the water more realistic, the element was composed of the actual fluid (made of FLIP particles) and white-water particles to recreate drops, bubbles and foam. Once the flip particles were simulated, little meshes were generated and located on each white-water particle to transfer their location to Blender.

As to the accuracy of the process, the calibration exercise shown in Figure 6 shows inconsistencies between the virtual version and the one obtained in the laboratory. However, there is a clear similarity between the run-up distance profile reached by the virtual and the laboratory wave. In fact, as in the real experiment, in the virtual version the wave reaches the maximal distance on the right side of the plate while it is minimal on the left side of the plate. The virtual tool therefore replicates the findings that higher texture density produces shorter run-up distance.

Our conclusion from the calibration process is that the tool can be used by designers to create textures and other features of coastal infrastructure, but it cannot at this stage of technical development substitute physical wave flumes for engineering and other purposes that require accurate simulation of fluid motion.

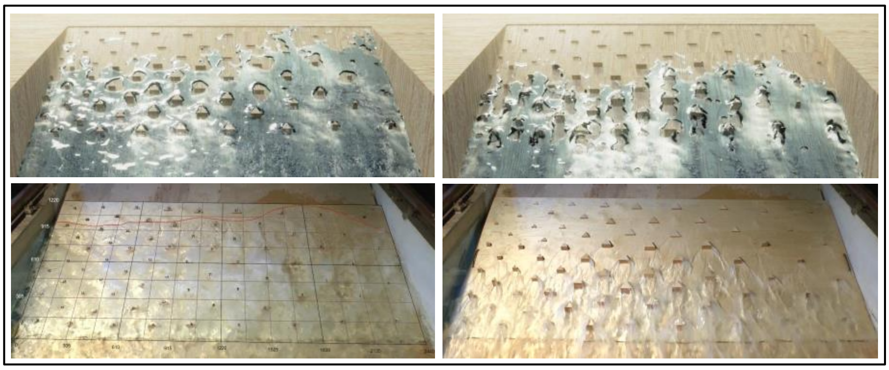

*Figure 6: comparison of virtual (top) and physical (bottom) simulations.*

## 7. Discussion and conclusions

The main aim of the research was to demonstrate the potential of CFD simulation tools to advance a multifunctional approach to coastal infrastructure. It initiated basic research into the capacity of surface texture to shape the ways in which waves break on the built shoreline for programmatic, ecological and experiential benefits. This was pursued by testing basic geometric textures and developing protocols for measuring and assessing flow regimes, as a first step in closing the gap in knowledge of textured surfaces-sea wave interaction.

The main findings of the experimental stage were the quantifiable impact of different texture morphologies on wave behaviour. Run-up distance is a function of texture density and geometry, while run-down time and wake length are closely correlated with the hydrodynamic characteristics of texture morphology, scale and density. Further investigations are required to assess the effect of texture on the ecological and engineering performance of waterfront structures.

The qualitative assessment of flow characteristics of the textures observed in the physical experiment foregrounded flow effects that have aesthetic and experiential value, mainly for run-down flows. This suggests that the otherwise overlooked phenomenon of wave run-down could be further developed for designing the experiential component of waterfronts and coastal infrastructure.

The research engaged with architectural issues beyond the expert domain of coastal infrastructure. The experimental use of digital simulation tools combined with digital fabrication to produce the textured plates may also open new ways of conceptualizing solid surfaces. Simulation technologies bring to awareness the dynamics of change, transformation and flux. This focus informs an epistemological shift from the object and its autonomous formal or structural properties to the complex, emergent interaction between fixed and fluid elements. Since water is transparent, the observer can perceive the material and fluid textures simultaneously as they enfold in time. Likewise, the process of designing such surfaces entails an iterative process of attenuation of the texture in relation to the feedback of the simulation. This dynamics expands the concept of parametric surfaces to include the dimension of performance, be it ecological, hydraulic or experiential.

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