Performative Coastal Textures: Integrating Computational and Physical Simulations for Seawall Design

Roy Kozlovsky[1], Yasha Grobman[2], Hanna Levy[2]

[1]Tel Aviv University, Tel Aviv/Israel · rkozlov@tauex.tau.ac.il
[2]Technion Israel Institute of Technology, Haifa/Israel

Abstract: The research examines the potential of surface texture to increase the experiential and ecological performance of coastal defence structures such as seawalls. It develops a method for utilizing physical and Computational Fluid Dynamic simulation tools to creatively design the interaction of sea waves with coastal structures. The experimental setup tests simplified textured surfaces in a physical wave flume, to develop a basic understanding of the parameters that shape texture-induced fluid motion. The test results are used to calibrate and validate a digital wave flume, with the aim of facilitating research into texture design in coastal environments.

Keywords: Computational Fluid Dynamics, coastal infrastructure, ecological enhancement, physical and virtual simulations, performative textures

1 Introduction

Hard coastal defences such as breakwaters and seawalls stress natural and urban environments by diminishing public access to the shoreline, blemishing the landscape and reducing biodiversity of coastal ecosystems (KOMYAKOVA et al. 2022). The solutions developed to address conflicts between civic, ecological and defence aims range from nature-based 'soft' solutions such as managed retreat and restoration of natural ecosystems, to the 'greening' of grey infrastructure (AIROLDI et al. 2021). Seawalls can be engineered to provide ecological services (SALAUDDIN et al. 2021) or designed as active elements of seaside parks and promenades (GROBMAN et al. 2017). These additional programs in turn have the potential to alter the design logic of these structures, including how they interact with incoming sea waves.

The engineering approach to seawall design is based on optimization and cost-benefit calculations. Engineers rely on physical wave flumes and Computational Fluid Dynamics (CFD) simulations to optimize the structure's performance in deflecting or dissipating peak waves. To reduce construction and maintenance costs, these structures are made of standardized precast modular units. From a landscape perspective, this approach results in structures that are at odds with the site's ecology and cultural identity. From a wavescape perspective, the engineering method is limited by its focus on peak waves, ignoring the interaction of the structure with everyday conditions such as calm and moderate sea states.

The presented research connects into a recent discourse that expands the role of CFD from an engineering optimization tool into a creative design instrument, bridging functional criteria (coastal protection) with ecological enrichment and aesthetic experience. Its main aim is to develop a design methodology for the design and evaluation of textured surfaces that shape wave interactions for aesthetic, ecological, and programmatic benefits, and expand existing knowledge on the interaction of marine landscape texture morphology and its connection to waterflows. Since CFD simulation is a medium that is epistemologically attuned to repre-

Journal of Digital Landscape Architecture, 10-2025, pp. 135-149. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-754-0, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537754013.

senting processes as they enfold in time, landscape architects can utilize this tool to develop immersive, embodied modes of experience, in effect redefining sea-waves as a visual, aural and tactile landscape material.

Previous research into multi-functional coastal defences by the authors focused on the potential of morphology to creatively shape wave flows (KOZLOVSKY & GROBMAN 2017). It proposed a basic design strategy that divides the seawall section into three zones, each with a different morphology and human activities, to match three types of waves typical to smooth, moderate and rough sea states (Figure 1). That research has remained speculative because the CFD simulations of wave interaction with different morphologies were not validated with physical experiments. While wave flumes are useful for testing scaled models, they do not provide accurate results for non-linear flow systems that are scale sensitive. These facilities can nevertheless produce reliable simulations of small-scale flow phenomena such as the movement of waves over textured surfaces. For this reason, the presented research focuses on the scale of surface texture, postponing the validation of morphological interventions to future research.

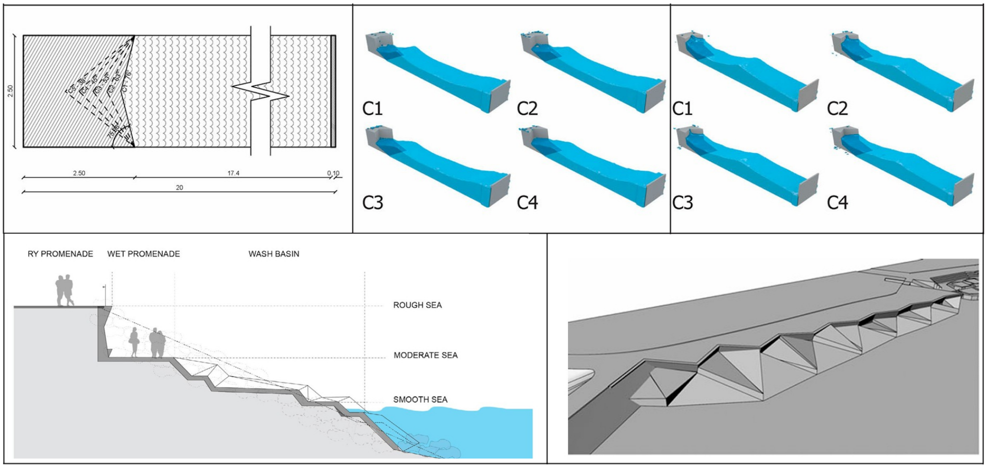


Fig. 1: Design for seaside promenade based on digital simulations of wave-seawall interaction under smooth, moderate and rough sea states (Source: GROBMAN 2017)

The paper starts with presenting an argument based on literature review for why and how texture can play a pivotal role in coastal design and why Computational Fluid Dynamics offers a promising way to harness that potential. In Chapter 2, the authors highlight the ecological and functional importance of textured surfaces on coastal structures by showing that texture supports marine biodiversity and influences hydraulic performance. Chapter 3 then connects these insights with CFD in landscape architecture. The methodology chapter (Chapter 4) presents a framework for a systematic testing and measuring methodology of the influence of texture parameters (geometry, density, scale, and slope) on wave dynamics, using both physical wave flume experiments and CFD simulations. This is followed by a results and conclusions and outlook sections that detail how different textural parameters affect wave flow metrics such as run-up distance, run-down timing, and wake widths and calibrate and assess CFD simulations against physical wave-flume experiments, demonstrating both the promise and current limitations of the suggested method and the tools it employs.

2 Texture in Coastal Environments

In design thinking, texture is treated as a secondary formal category that qualifies the visible aspects of a surface. Modern design theory treats texture as a creative means for achieving compositional aims such as unifying or varying planes that enclose space and expressing the weight and materiality of a form (CHING 2007). In landscape architecture, texture also has a signifying function, as when rustication and rough textures are employed to connote vernacular, rural modes of existence, or to signify the ideal of nature – a practice that landscape historians associate with the idea of the garden as 'third nature' (HUNT 2000). In coastal environments, however, textures are more commonly applied for functional aims, as they impact the structure's ecological and hydraulic performance.

Surface roughness and smoothness are critical parameters of hydraulic design. While most hydraulic structures require smooth surfaces to minimize energy loss, in seawall design, three-dimensional textures are used for dissipating wave energy through friction and turbulence. Hydraulic engineers use empirical experiments to determine the size and roughness of natural and prefabricated elements used in riprap revetments to improve their wave abating performance (KREYENSCHULTE et al. 2020, VAN DER MEER et al. 2018).

Texture has a quantifiable impact on the ecological performance of coastal structures. Because of their adaptation to naturally occurring textures, many marine species do not thrive on the smooth surfaces that characterize modern concrete coastal structures. Increase in texture density and complexity, on the other hand, enables more species to attach themselves to the surface or find shelter from predation, resulting in more abundant and diverse intertidal ecosystems (SELLA et al. 2022). Biological research into the habitat preferences of coastal flora and fauna informs the concept of 'greening grey infrastructure' in which coastal structures are bio-engineered to provide ecosystem services (AIROLDI et al. 2021).

Noteworthy engineering projects along water edges that employ texture to enhance intertidal marine life include the Seattle Seawall Project (2016), where the artist team Haddad & Drugan designed precast relief elements that represent the dynamics of ecosystem zonation; ecological tiles with three dimensional biomimetic patterns printed on octagonal tiles, developed by the Sydney Institute of Marine Sciences; and eco-tile cladding systems for seawalls in Hong Kong (BRADFORD et al. 2020). As they were developed for cladding existing vertical seawalls, none of these tile systems were designed to interact with sea-flows typical for inclined structures such as breakwaters and riprap revetments. The interaction of textured surfaces with wave flows in partially submerged conditions remains relatively unexplored as a potential factor in increasing the ecological and experiential performance of such structures. The aim of the research is to contribute to closing this gap in knowledge.

3 CFD in Landscape Architecture Research and Design

Computational Fluid Dynamics is a branch of applied science that studies the motion of gaseous and liquid fluids. In the field of architecture, the most common use of CFD is for modelling and visualizing airflows. Compatible with mainstream CAD software, these tools are used for designing thermally comfortable, healthy and energy-efficient buildings (STAVRIDOU 2015, HERSHCOVICH et al. 2021). In landscape architecture, CFD simulations of microclimate and air quality inform the design of urban spaces and outdoor environments

(BROOK-LAWSON & HOLZ 2020). In geomorphological analysis of landforms, these tools are used to calculate wind erosion and sediment transport dynamics (SMYTH 2016). They are also used to simulate liquid flows for modelling riverbank erosion and land loss in coastal environments (SPYROPOULOS & DARBY 2020).

This research calls to advance the application of CFD simulations of liquid motion in landscape design by capitalizing on the qualitative difference between liquid and gaseous flows: while in most situations, airflows are visually imperceptible, water flows are visible to observation and contemplation. CFD tools can be used to explore and assess the capacity of different morphologies and textures to generate flow patterns that can be experienced aesthetically.

Although extensive research exists in engineering, based on physical experiments and numerical simulations, regarding water flow behaviour over breakwaters and other obstacles (see for example MCCABE et al. 2013 and ZHANG et al. 2022), there is limited investigation into the design aspects of wave dynamics and no exploration of water interaction with textures. Some research exists on the broader application of CFD in architectural design, primarily focused on airflow (VALGER & FEDOROVA 2019), as well as on the potential regional-scale impacts of climate change on waterfront areas (Ackerman et al., 2019). However, no literature addresses the specific design aspects of form-texture-water flow interactions, apart from previous findings by the authors (GROBMAN et al. 2017, KOZLOVSKY et al. 2024).

A practical precedent for using computational tools to design the interplay between texture and water flows for aesthetic effects is the Diana Memorial Fountain in London. Its designers, Gustafson Porter + Bowman, leveraged advanced computational tools for its conception and fabrication (WALLISS & RAHMANN 2016). Another noted example of using texture to create aesthetic flows is the Marlene-Dietrich-Platz fountain, Berlin, by Herbert Dreiseitl. In this case, the designer used 1:1 scaled clay and plaster models to study the effect of texture on water flows (DREISEITL & GRAU 2009). Both cases are fountains, where designers exercise complete control over water flow characteristics. There are numerous other practical precedents that focus of seawall geometries such as the Econcrete's ecological waterfront and shoreline protection elements (see www.econcrete.com). The task of designing flows in coastal environments with unpredictable wave input requires a level of accuracy beyond the capabilities of conventional CFD tools. Hybrid programs that combine numerical and physical simulation methods with graphic animation programs provide a high degree of visual realism and physical precision in simulating the complex, turbulent behaviour of sea waves. A secondary aim of this research is to evaluate the accuracy of three types of currently available software: the grid-based model (Lattice Boltzmann method) used by Blender and Mantaflow, the smoothed particles hydrodynamics model used by the Blender-DualPhysics hybrid, and the Fluid Implicit Particles model used by Houdini. If validated by a physical experiment, designers could test their preliminary design in a virtual wave flume instead of relying on costly physical wave flumes, thereby lowering barriers to sea-wave design.

4 Research Methodology

Despite the foundational ecological and hydraulic principles informing the design of these installations, empirical analyses and optimizations concerning texture morphology vis-à-vis water flow dynamics remain sparse. Moreover, extant research has yet to ascertain empirical evidence establishing a correlation between water flow patterns and texture morphology.

The interaction of wave motion with a solid boundary is non-linear. Even minor changes in surface texture pattern, density and surface inclination on the one hand, and variations in wave force and direction on the other, may result in changes in flow regimes. As it is impractical to test all possible combinations of textures and waves, the research is designed to develop a basic understanding of texture-wave interaction by simplifying texture into basic parameters of geometry, density and scale, and testing them in a physical wave flume using simplified sea-wave conditions. Using the comparative method, the impact of each texture parameter on flow performance could be measured, and applying inductive reasoning, formulate observations into basic rules.

The physical tests are used to verify the reliability of different CFD programs for design purposes. This procedure follows the methodology used by aerodynamic engineers for validating CFD simulations of structural wind loads on high-rises, by comparing the results with physical wind tunnel tests (THORDAL et al. 2019).

The physical experiment was divided into two stages. The preliminary stage experiment devised a simplified test in which a textured plate interacted with a constant, unidirectional flow. This setup enabled a first categorization of water flow behaviour and the calibration of the CFD tools. In the second stage, a set of seven full-scaled texture plates was tested in a physical wave flume that simulated the up flow and down flow motion of sea waves. The results of the second stage enabled the development of flow taxonomies and design methodologies for working with textured surfaces in coastal environments.

4.1 Preliminary Experimental Setup

The preliminary simulation studies the influence of a single row of geometric patterns under constant, unidirectional water flow. The first aim of the simplified experiment is to verify whether existing CFD simulation tools can achieve a high degree of accuracy in replicating the physical experiment. The second aim is to develop the quantitative and qualitative parameters for assessing the flow of more complex textured patterns used in the second stage.

Using gravity, water stored in a reservoir is released over an inclined textured plate. Three plates were manufactured, each with a different geometry: circular, square and triangle. The sizes of the three protruding elements were set at 3cm, 5cm and 7cm. This range was considered optimal because larger elements behave as geometrical forms in their own right, while the effect of smaller values would be difficult to measure (Figure 2, left).

In parallel, the physical test was digitally recreated using the physical model in the animation software Blender. The physical simulation output was used to calibrate and validate the same set-up in the virtual simulation through an iterative process that stopped once the water flow patterns were visually identical (Figure 2, right).

The analysis of the flows characteristics from the preliminary test demonstrated that texture impacts flow in two distinct ways: the individual forms create a steady linear wake as water is forced to circumvent it by splitting into two streams. Secondly, after passing the row of obstacles, the flows overlap, forming a visible diffraction effect.

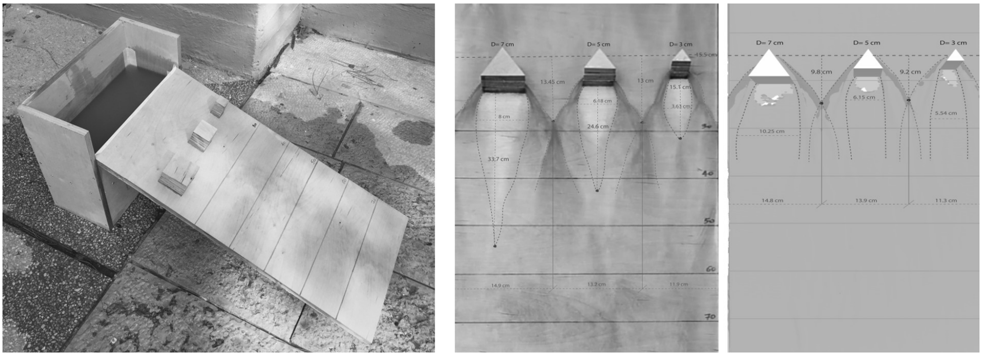


Fig. 2: Preliminary experiment. Left: mechanism for testing textured plates with constant down-flow. Middle: physical experiment. Right: CFD simulation.

The length and angle of the wake can be reliably measured from the virtual simulation. The digital tools therefore can be used to determine the distance between rows for different protruding forms to produce desirable flow effects. The next stage will further develop these principles to create more complex textured surfaces and patterned flows.

4.2 Wave Flume Experimental Setup

The second stage explores a series of textured surfaces in sea-like flow conditions recreated in a physical wave flume. Two types of basic textures were created: point-based and line-based textures. The point-based textures were based on regular geometries such as circles, squares and triangles. They were placed on the plates according to three parameters: the density of texture elements per plate area, their extrusion height, and their radius dimension. For each type of geometry, two plates were manufactured: one with protruding elements and another with cavities. Using a parametric model in Grasshopper plugin for Rhinoceros design software, the textured elements were distributed on the plate using a Voronoi grid. Texture density varies from highest to lowest value from right to left. Extrusion is distributed from lowest at the top to highest at the bottom (Figure 3, top). This setup is designed to study the minute variations in flow regimes and identify emerging flow patterns that are scale sensitive.

The line-based textures were created in a single plate organized in four columns with varying densities, extrusion height and depth. The right column has the highest density and lowest extrusion height and depth, and the left column has the lowest density and largest extrusion height and thickness. The tips of the extruded forms alternate between rectangular, circular and triangular geometries (Figure 3, bottom).

The inclination of the surface is an important parameter of wave performance, as even small variations in slope angle may produce qualitative changes in flow regimes. Digital simulation tools can test the performance of any inclination with ease, but due to time and costs constraints of operating physical wave flume tests, the number of inclinations was limited to two. The angles were derived from the optimal slopes of the most common types of coastal defence structures: 20 degrees slope which is the average inclination of revetments, and a 40 degrees slope that is typical to monolithic seawalls (DESTEFANO & ROBERGE 2004).

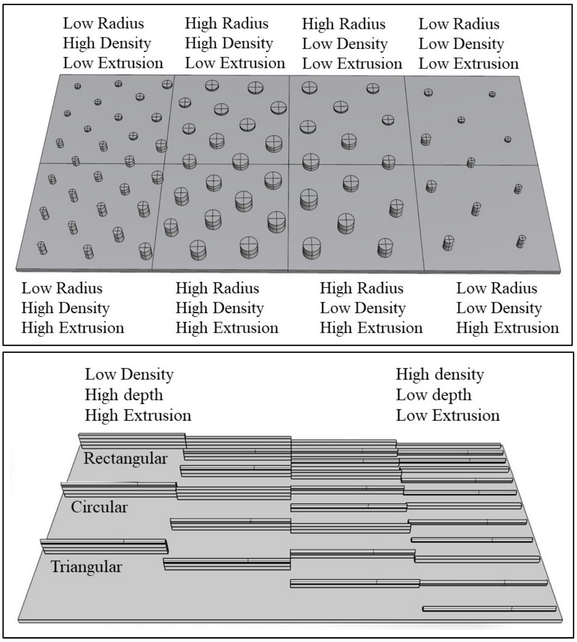


Fig. 3:
Basic textured plates for second stage experiment.
Top: Distribution of variations in density, extrusion and radius of point-based texture.
Bottom: Distribution of variations in density, extrusion and geometry of line-based texture.

The last variable of the experiment is wave input. Wave height and amplitude vary from season to season and even within a single wave packet. Due to practical considerations, the physical wave flume experiment simulated waves typical to a level 2 sea-state according to the *World Meteorological Organization (WMO)* scale.

The laboratory experiment took place at the Coastal and Marine Engineering Research Institute (CAMERI) at the Technion, Israel Institute of Technology. The facility has a 45×2.45×1.5 m. wave flume equipped with a wave generator, computerized control for real sea simulation, wave gages and high sampling rate pressure gages. The wave piston was set to move 10 cm back and forth, generating sinusoidal waves with height of 0.188 m., amplitude of 0.09 m., and wave period of 2.5 seconds. The experiment was recorded from three viewpoints: a top view, a side view through a glass window, and a back view (Figure 4). Measurements were taken for three successive waves. The results presented in the next section are the mathematical average of the three sensitivity checks.

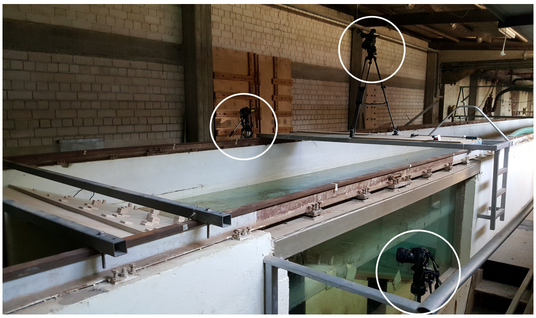


Fig. 4:
CAMERI wave flume with three cameras marked with circles

4.3 Parameters for Qualifying Flow Properties

After observing the visual properties of run-down and run-up 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 patterns:

- *Run-up and run-down flow times*: the time it takes the wave to climb the textured plate, and the time it takes to flow back into the channel.
- *Run-up distance*: the maximal distance reached by the wave during run-up motion.
- *Flow wake width*: the width of the trail formed above the texture by the upcoming wave, and below the texture by the returning wave.
- *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 above the texture elements.

In parallel to quantifying flow properties, the research identified qualitative flow patterns generated by specific textures and analysed the parameters for their emergence.

5 Experimental Results

5.1 Run-up and Run-down Flow Time

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

One observation is the likeness of run-up time records of the plates with cavities and with protruding textures. In 20 degrees inclination, the time variated by 7 percent. The second observation is the likeliness between the run-down time of the texture plates with slope of 40 degrees and that of cavities plates with slope of 20 degrees. It could be deduced that the parameter of texture height is significant only for run-down flows.

5.2 Run-up Distance

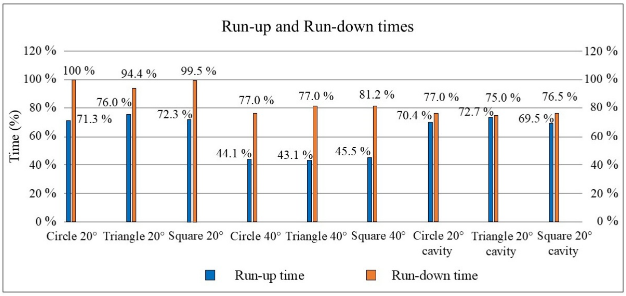
The run-up distance was calculated for all dot-based texture and cavities plates placed with slopes of 20 and 40 degrees. The interception of the maximal run-up profile with the vertical lines of the grid were recorded by calculating the distance of these points from the lower border of the plate and converting the values according to perspective proportions. The measured run-up distances were imported into Excel where the profiles were reproduced through graphs drawn over a corresponding grid (Graph 2).

A first conclusion based on these graphs would be that the average wave run-up distance is inversely proportional to the increase in surface area. This effect can be utilized to control how waves ascend the plate as a function of texture density.

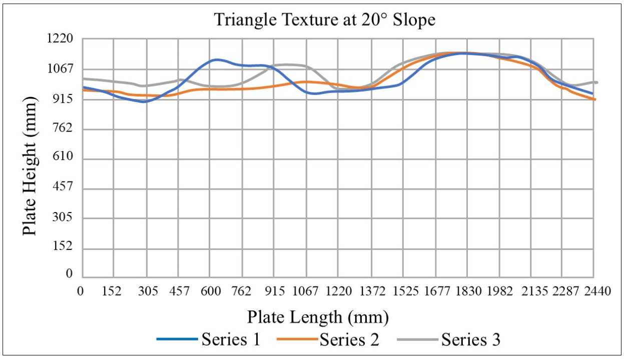
5.3 Wake Width

This last series of observations examines the wake created by the returning flow after it encountered the protruding elements. It measures the width of the wake that forms below the texture field at 80 mm below the obstacle.

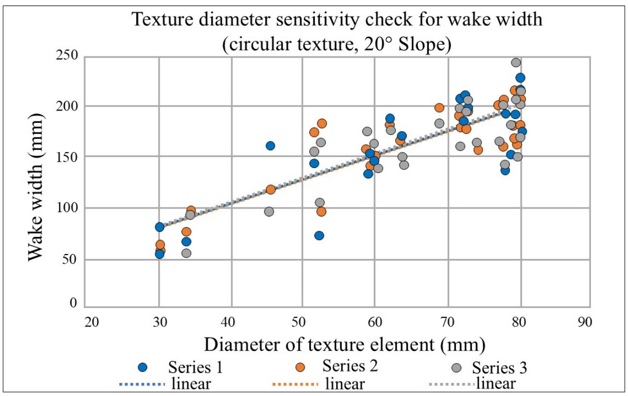
Graph 3 presents an average of the three measurements for circular texture on a 20 degrees slope. From the resulting trend-line it is concluded that, by average, the width of the wake on the y-axis is about 2.4 times wider than the diameter, shown on the x-axis. This value can be used by designers to recreate a trail with a desired width by attenuating the diameter of the circular texture. More experiments will be required to assess how changes in inclination alter the numerical relationship between wake width and texture diameter.



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



Graph 2:
Range of variation of run-up distance for triangular textures with a 20° slope



Graph 3:
Wake width as a function of texture diameter for circular texture at 20° slope

To conclude the quantitative assessment, we were able to isolate the impact of surface inclination, geometry, density, extrusion and radius on wave flows. For run-up distance, the main parameter impacting surface performance is surface inclination, and a secondary parameter is protrusion height. Wake width, in turn, depends mostly on the geometry of the protruding elements. Overall, we found that the physical forces governing texture-wave interaction in gravity-induced down-flows are the hydrodynamics of flows around solid obstacles, which are subject to inertial and viscous forces, resulting in the emergence of eddies, wakes and splashes. Wave physics in turn govern the interaction between the parallel wakes that form after encountering the obstacles.

5.4 Qualitative Analysis of Texture Flows

Concluding the catalogue of visual effects of texture are unexpected flows that affect the observers aesthetically. These effects may be specific to a given texture geometry or a flow condition. While it is possible to provide a physical explanation for their emergence, it is more difficult to define the parameters for controlling their emergence.

One such effect is the water jump created by the returning flow over the textural elements (Figure 5). This effect is highly scale sensitive: it varies in form and magnitude even for a single texture field. The height of the jump can be calculated as a function of the texture's extrusion height, the plate's inclination, and the distance of the element from the maximal run-up point, but it appears that the most important factor is the geometry of the protruding element, and especially its tip.

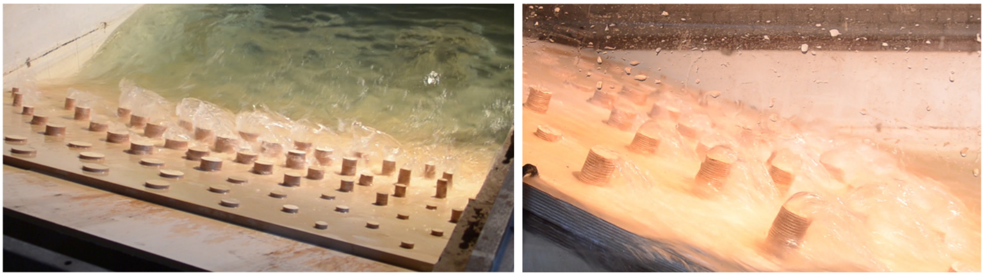


Fig. 5: Two views of the water jump created by returning wave for circular texture at 20 degrees slope

Fig. 6: Inverted trail created by upcoming wave for circular texture at 40 degrees slope

Another outcome observed is the ‘inverted’ trail created by the run-up wave when meeting the first line of textural elements. It would be interesting to investigate the properties the wakes as a function of the texture’s geometry and other parameters (Figure 6).

Additional qualitative visual effects documented in Figure 7 can be classified as echoes or traces left by the texture on the water surface. This delicate wave event was observed in the first, weakest wave of the series, for both protrusion and cavity-based textures. The visual interest in this wave taxonomy can be attributed to the dynamic tension between the texture’s rectangular geometry and the ring-like movement of ripple waves. This leads us to consider the reciprocal quality of performative textures: Since water is transparent, one may simultaneously observe both the solid texture and the textured flow it induces, bringing into reflection the emergent relationship between these two materials.

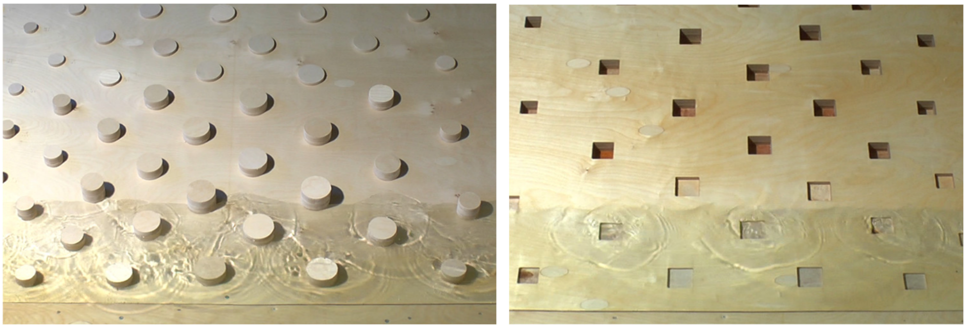


Fig. 7: Circular ‘echo’ traces created by upward flow of the first wave of the series

Fig. 8: Cascading effect by returning flow over a line-based texture plate

Lastly, line-based textures were observed to produce a cascading effect for returning flows (Figure 8). While this effect was intuitively expected, the geometric design of the plate, with four different texture densities and protrusion heights, provides empirical data for fine-tuning this effect. Designers can select among the variations the desirable flow rhythm and wake length. This flow effect appears to be most promising for enhancing the biological performance of the surface, since its upward facing side is shielded from the abrasive action of upcoming waves, while providing water circulation and moisture that fit the habitat requirements of intertidal organisms.

6 Calibration and Validation of CFD Simulation Tool

The final step of the experiment dealt with verification of the virtual simulation. A model of the CAMERI wave flume was built digitally according to its true measure and wave producing mechanism. The visual records and measurements from the physical experiment were used to calibrate the digital tool by adjusting parameters such as viscosity, particle separation, rest density and surface tension to reproduce the physical experiment.

A simulation using the hybrid program Blender and its fluid simulator Mantaflow was found to be inadequate, as a thin water film always formed on the plate's surface. Therefore, the digital model of the physical wave flume was set in Houdini. The flow simulation parameters were adjusted in an iterative process until the final visual effect was close enough, according to our standard, to the behaviour recorded in the physical wave flume experiment.

To make the water appear 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 information to Blender.

The rendering replicated the colours and the lighting at the CAMERI wave flume facility. The calibration process of the computational tool was performed visually, by observing the graphic similarity between the virtual and the real-life visual effect.

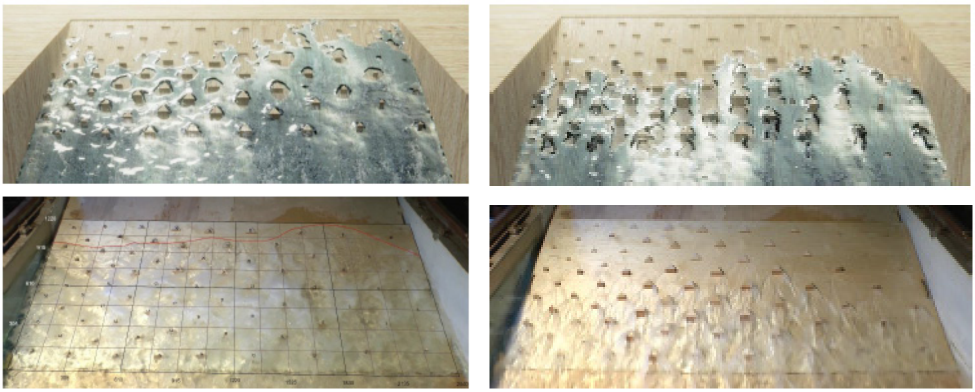


Fig. 9: Comparison of CFD simulations (top) and physical tests (bottom) for triangular texture. Left: comparison for up-flow. Right: comparison for down-flow.

As to the accuracy of the process, the calibration exercise shown in Figure 9 displays several inconsistencies between the virtual and physical simulations. Still, there is a clear similarity between the run-up distance profile reached by the virtual and the laboratory wave. The virtual tool succeeded in replicating the findings from the physical experiment that the higher the surface area of the plate, the shorter the run-up distance will be, and vice versa. As for the texture's impact on wake width, the calibration was done by imitating the distribution of foam and water flow volume on the two sides of the triangular textures (Figure 9, right). The most intense flow observed in the physical simulation, occurring in the central-left and lower part of the plate, was accurately recreated by the virtual simulation.

In conclusion, the calibration process reached an adequate level of similitude for design purposes. We verified that the computational tool accurately simulated the quantitative flow effects of texture, but it was less successful in simulating the qualitative visual effects observed in the physical experiment. Additional research is needed to ascertain if texture-wave interaction is beyond the capabilities of current CFD programs, or that the problem lies in the configuration of the digital wave flume.

7 Conclusion and Outlook

The main aim of the research was to develop a design methodology that examines the capacity of surface texture to shape the ways in which waves break on the built shoreline for programmatic, ecological and experiential benefits. The research created an initial taxonomy of basic geometric textures and developed basic experimental computational and physical methodologies for measuring and assessing different flow regimes. Its main finding is that the understudied phenomenon of wave run-down can be utilized to develop the experiential potential of waterfronts and coastal infrastructure.

In addition, the research touches upon theoretical issues beyond the specific domain of coastal infrastructure design. The experimental use of digital simulation tools combined with digital fabrication technologies may initiate new ways of conceptualizing textured surfaces. As Antoine Picon (2004) noted, simulation technologies bring to awareness the dynamics of change, transformation and flux. Since water is transparent, the observer can perceive both the solid and fluid textures simultaneously. Designing this dual effect involves an iterative process of attenuation and modification, in which the computational simulation provides a feedback loop for optimizing the texture's flow performance. Consequently, the surface changes its epistemic status from that of a finite object that exhibits stable, autonomous formal properties, to a relational entity, the complex, emergent result of the interaction between solid elements and fluid patterns of motion. By giving new data and method to design and evaluate textures the findings of the research have special significance to landscape architecture and especially to waterfront landscape design that is still in many cases led by engineers. The research also contributes to digital landscape design theory the concept of reciprocity, which brings to awareness and reflection the interdependence between forms, forces and processes. It therefore expands the meaning and efficacy of texture, a formal design category that has a subordinate, marginal status in digital landscape design.

Future research should expand the proposed taxonomy to encompass more complex geometries. A comprehensive taxonomy database could facilitate the development of machine learning–based tools for simulating water flow over textured surfaces, providing designers with near real-time predictive simulations. A deeper understanding of the relationship between texture geometry and water flow would also enable the examination of its implications for creating improved habitats for marine and waterfront organisms. Ultimately, these insights would contribute to the design of ecologically supportive, multi-species waterfront environments.

References

AIROLDI, L., BECK, M. W., FIRTH, L. B., BUGNOT, A. B., STEINBERG, P. D. & DAFFORN, K. A. (2021), Emerging Solutions to Return Nature to the Urban Ocean. Annual Review of Marine Science, 13, 445-477. doi:10.1146/annurev-marine-032020-020015.

BROOK-LAWSON, J. & HOLZ, S. (2020), CFD Comparison Project for Wind Simulation in Landscape Architecture. Journal of Digital Landscape Architecture, 5, 318-329. doi:10.14627/537690033.

DESTEFANO, J. & ROBERGE, J. (2004), Shore Protection Structures. Structure Magazine, August 2004, 10-12.

DREISEITL, H. & GRAU, D. (2009), Recent Waterscapes: Planning, Building and Designing with Water. 3rd Ed. Birkhäuser Architecture, Basel.

GROBMAN, Y. J., KOZLOVSKY, R. & LEVY, H. (2017), A Multifunctional Computational Approach to Waterfront Design. Architectural Science Review, 60 (6), 446-459.

HERSHCOVICH, C., VAN HOUT, R., RINSKY, V., LAUFER, M. & GROBMAN, Y. J. (2021), Thermal performance of sculptured tiles for building envelopes. Building and Environment, 197, 107809. doi:10.1016/j.buildenv.2021.107809.

HUNT, J. D. (2000), Greater Perfections: The Practice of Garden Theory. University of Pennsylvania Press, Philadelphia.

KOMYAKOVA, V., JAFFRÉS, J. B. D., STRAIN, E. M. A., CULLEN-KNOX, C., FUDGE, M., LANGHAMER, O., BENDER, A., YAAKUB, S. M., WILSON, E., ALLAN, B. J. M., SELLA, I. & HAWARD, M. (2022), Conceptualisation of multiple impacts interacting in the marine environment using marine infrastructure as an example. Science of the Total Environment, 830, 154748. doi:10.1016/j.scitotenv.2022.154748.

KOZLOVSKY, R., GROBMAN, J. & LEVY, H. (2024), Coastal Infrastructure Design. 29th International Conference on Computer-Aided Architectural Design Research in Asia. In: Singapore, 20-26 April 2024, Volume 1, 445-454.

KOZLOVSKY, R. & GROBMAN, Y. J. (2017), The Blue Garden: Coastal Infrastructure as Ecologically Enhanced Wave-scapes. Landscape Research, 42 (5), 439-454.

KREYENSCHULTE, M., SCHÜRENKAMP, D. BRATZ, B., SCHÜTTRUMPF, H. & GOSEBERG, N. (2020), Wave Run-Up on Mortar-Grouted Riprap Revetments. Water, 12 (12), 3396.

MCCABE, M. V., STANSBY, P. K. & APSLEY, D. D. (2013), Random wave runup and overtopping a steep sea wall: Shallow-water and Boussinesq modelling with generalised breaking and wall impact algorithms validated against laboratory and field measurements. Coastal Engineering, 74, 33-49. doi:10.1016/j.coastaleng.2012.11.010.

PICON, A. (2004), Architecture and the Virtual: Towards a New Materiality. Praxis, 6, 114-121.

SALAUDDIN, M., O'SULLIVAN, J. J., ABOLFATHI, S. & PEARSON, J. M. (2021), Eco-Engineering of Seawalls – An Opportunity for Enhanced Climate Resilience From Increased Topographic Complexity. Frontiers in Maritime Science, 8 (674630). doi:10.3389/fmars.2021.674630.

SELLA, I., HADARY, T., RELLA, A. J., RIEGL, B., SWACK, D. & PERKOL-FINKEL, S. (2022), Design, Production, and Validation of the Biological and Structural Performance of an Ecologically Engineered Concrete Block Mattress: A Nature-Inclusive Design for Shoreline and Offshore Construction. Integrated Environmental Assessment and Management, 18 (1), 148-162. doi:10.1002/ieam.4523.

SPYROPOULOS, E. & DARBY, S.E. (2020), Computational Fluid Dynamics (CFD) Modelling to Estimate Fluvial Bank Erosion – A Case Study. Journal of Geoscience and Environment Protection, 8 (7), 17-43.

SMYTH, T. A. G. (2016), A review of Computational Fluid Dynamics (CFD) Airflow Modelling over Aeolian Landforms. Aeolian Research, 22, 153-164. doi:10.1016/j.aeolia.2016.07.003.

STAVRIDOU, A. D. (2015), Breathing architecture: Conceptual architectural design based on the investigation into the natural ventilation of buildings. Frontiers of Architectural Research, 4 (2), 127-145. doi:10.1016/j.foar.2015.03.001.

THORDAL, M. S., BENNETSEN, J., KROSS, H. & HOLGER, H. (2019), Review for Practical Application of CFD for the Determination of Wind Load on High-Rise Buildings. Journal of Wind Engineering and Industrial Aerodynamics, 186, 155-168.

VAN DER MEER, J. W., ALLSOP, N., BRUCE, T., DE ROUCK, J., KORTENHAUS, A., PULLEN, T. & ZANUTTIGH, B. (2018), EurOtop: Manual on Wave Overtopping of Sea Defences and Related Structures. www.overtopping-manual.com.

WALLISS, J. & RAHMANN, H. (2016), Landscape Architecture and Digital Technologies: Reconceptualising Design and Making. 1st Ed. Routledge, Abingdon, UK.

ZHANG, J., ZHANG, N., ZHANG, Q., JIAO, F., XU, L. & QI, J. (2022), Numerical Simulation of Wave Overtopping of an Ecologically Honeycomb-Type Revetment with Rigid Vegetation. J. Mar. Sci. Eng., 10, 1615. doi:10.3390/jmse10111615.