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A multifunctional computational approach to waterfront design

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ABSTRACT
Seawalls and other types of waterfront infrastructures are predominantly designed to counter natural forces and maintain structural stability. Consequently, their defensive and reactive design impedes other types of uses and users. As an alternative to the single-use paradigm, there have been attempts to develop a more ecological, performance-based and civic approach to coastal defence structures that would engage with the diverse needs of human and non-human stakeholders. This paper presents a theoretical and methodological framework for employing computational tools to creatively design the interaction between the sea and the man-made shoreline. The research developed and tested a computational design methodology for the early stages of the seawall architectural design process. The suggested design methodology relies on inputs from a wave and texture taxonomy that was developed using physically based fluid simulation tools. The methodology was tested in a case study design.

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Waterfront design; wave simulation; physically based animation; computational fluid dynamics; design methodology

1. Introduction

Seawalls and other types of waterfront infrastructure are predominantly designed to counter natural forces and maintain structural stability. Consequently, their defensive and reactive design impedes other types of uses and users. As an alternative to the single-use paradigm, recent concepts of waterfront and coastal design attempts to develop a more ecological, performance-based and civic approach to coastal defence structures that would engage with the diverse needs of human and non-human stakeholders (van Slobbe et al. 2013).

As research efforts in this field focused mainly on the defensive aspects of these structures, the potential to control the geometry of waves for creating visual, acoustic and cultural effects has not been examined (Kozlovsky and Grobman 2016). The paper presents a research that explores the efficacy of computational tools to the design of coastal infrastructure. It assumes that recent technological developments in computation and digital fabrication dissolve the limits in designing and constructing complex architectural forms. Therefore, it seems that these technologies have a potential to facilitate a design that goes beyond the static, defensive and single functional modernist approach to coastal infrastructure, which was limited in part by the incapacity to design and fabricate complex geometric structures, and to simulate their interaction with sea waves.

The new design approach and methodology are developed by examining the combined potential of physically based animation, computational fluid dynamic (CFD) and water channels to shape the interaction between solids and fluids, thus giving rise to a new type of 'animated form' that is generated by the combination of environmental and programmatic 'forces' it contends with (Lynn 1999).

The paper commences with a short historical overview of the integration of coastal infrastructure with public uses. It then discusses the theoretical and technical challenges of using physically based animation and CFD tools to simulate and control the non-linear behaviour of fluids in architectural design. This is followed by a presentation of the new multipurpose approach to design waterfronts and a suggested design process that is derived from this approach. The proposed approach and method are then tested in a case study design for an urban waterfront, in which an old mono-functional seawall is transformed into an ecologically and socially active environment.

2. Coastal infrastructure: public use and ecological performance

Seawalls and other coastal infrastructure in densely populated urban areas are often off-limits to the public, due to the way in which they are planned and built. To reduce labour costs and construction time, they are assembled from standardized precast concrete elements, such as the dolos and the tetrapod (Peters 1996; Takahashi 1996). Otherwise, quarried stone rubble is routinely deposited to form porous riprap seawalls. Modern seawalls are thus more cost efficient in terms of construction and maintenance, at the expense of their scenic value and pedestrian accessibility; for the same reasons, they also function as ecological sacrificial zones.

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Looking back into the history of such structures, one finds an alternative, less instrumental approaches: in the nineteenth century, for example, there was a conscious effort to integrate coastal infrastructure with public uses, such as promenades (Grobman and Kozlovsky 2014). Especially in resort towns, these structures became popular attractions in their own right, as they enabled an intimate, yet safe, encounter with powerful natural forces; their geometric simplicity and the use of labour-intensive craftsmanship construction processes also contributed to their majestic, civic appearance.

Nowadays, there are technological, social and economic forces that make it possible to revive this civic approach to coastal infrastructure. With the shift from industrialization to service economy, the design of urban coastal defences is undergoing revision. Contemporary projects such as Zadar's staircase promenade by Nikola Bašić from 2005, Sydney's pixelated Barangaroo Headland park (2015) and AECOM's 2013 biomimetic seawall for Blackpool are designed to endow coastal infrastructure with civic, environmental and cultural values by using different design and construction methods to avoid the modernist standardized appearance of seawalls (Figure 1).

A parallel development addresses the negative ecological footprint of modernist seawall structures. Recent reclamation projects for rebuilding the coastline following hurricane Sandy (Bisker, Chester, and Eisenberg 2015) put forward new ecological design concepts such as living breakwaters and dynamic floodplains to protect the shore in extreme weather conditions while offering new habitats for wildlife during normal weather.

The presented approach contributes to these developments an additional dimension that of treating sea waves as designable (Kozlovsky and Grobman 2016). It proposes to actively shape the pattern and rhythm of sea and wall interaction by utilizing a combination of physically based animation, CFD and the physical water channel test to model the pattern and intensity of water flows to generate perceptual effects that convey aesthetic and as well as educational values.

A precedent for utilizing digital technology to design water flow as an intrinsic, meaningful component of the landscape is the 2004 Diana Memorial Fountain in Hyde Park, London, by the landscape firm Gustafson Porter and the engineering firm Ove Arup (Walliss and Rahmann 2016). Its water flow has a range of meanings and uses intended to commemorate the princess's turbulent life and her accessibility to the public: it encourages a playful interaction of visitors with the water, and represents the Princess's effervescence and emotional intensity by making the water tumble, cascade, curl and bubble as it flows through the granite channel. The proposed research examines the prospects of transferring this technology to the design of urban waterfronts.

3. Physically based water flow animation and computational fluid dynamics

Computational fluid dynamics (CFD) calculates the motion of fluids and how it influences processes such as heat transfer and chemical reactions in combusting flow. Fluid motion can be of two main types: laminar and turbulent. Laminar flow is an ordered flow regime in which fluid particles do not mix laterally (Greenspan 2005). The behaviour of this type of flow is easy to predict since the simulations of fluids in a laminar regime are consistent with reality. Turbulence is the most common, yet least understood form of fluid motion. This kind of flow is three-dimensional, unsteady, diffusive and dissipative. Given the unpredictability of turbulent flow, there are no computer models that can compute the exact behaviour of such a complex system (Launder and Spalding 1974). Thus, comprehensive models

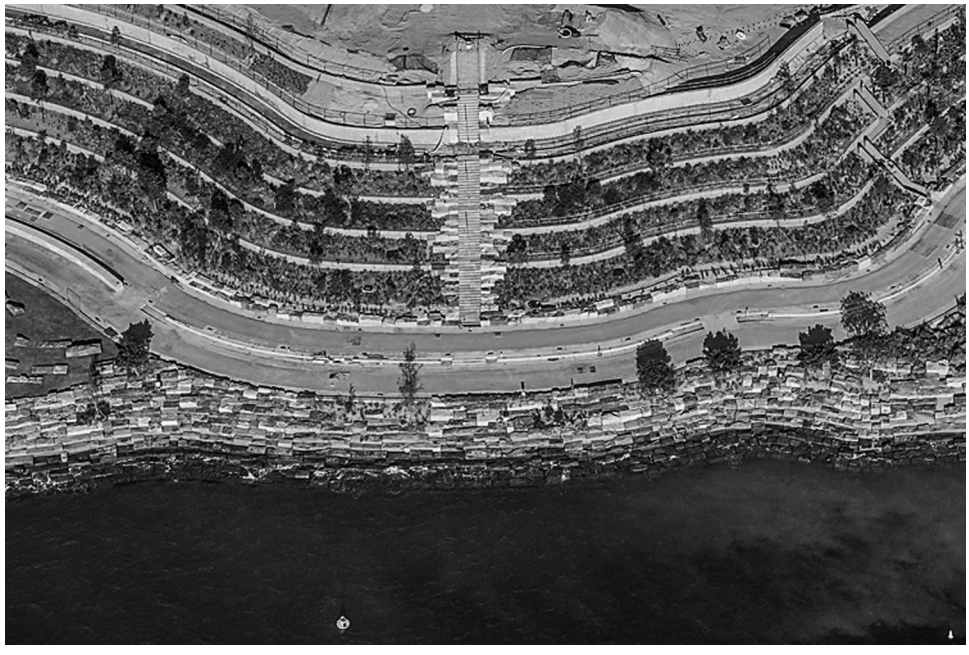

Figure 1. Barangaroo Headland park digitally controlled placement of sandstone blocks, Sydney, 2015. Source: http://www.barangaroo.nsw.gov.au/. Photo: Hamilton Lund.

of fluid motion simulate fluid motion by using approximation methods to laminar flow.

CFD has been used in the aeronautic and automotive industries since the late 1970s. It has been introduced to building design in the 1990s as a tool to simulate and help evaluating among others, internal ventilation, internal temperature, building insulation and external wind forces (Aynsley 1999; So and Lu 2001; Zhai 2006; Luther 2009). The use of CFD requires knowledge in fluid mechanics and its application is currently a relatively time-consuming process. The complexity of setting up the CFD model together with lack of knowledge in fluid mechanics and time constrains can account for the fact that CFD is rarely used by architects. It is seldom used during the initial stages of the design process, when the initial form of the project is generated. Nevertheless, CFD is increasingly used by experts in the later stages of the design process, usually when the project's design approach has already been determined. It is used for simulating the performance of systems such as ventilation, air-conditioning and the effect of external wind loads in order evaluate and optimize the chosen design approach (Zhai 2006; Kaijima et al. 2013).

In relation to wave simulations, the difficulty is even greater. The complexity of water flow and inherent inaccuracy of the results are probably the main reasons why common CFD software are seldom used even by experts (and researchers) for wave simulation. They are thus obliged to depend on physical wave flumes to accurately simulate wave behaviour. This situation was probably one of the main motivations for the development of specific CFD tools for simulating the dynamic behaviour of sea waves. Software programs such as DualSPHysics and REEF3D rely on variants of the Navier–Stokes equations to numerically compute in three dimensions the behaviour of sea waves. Extensive knowledge in the field of marine engineering is required to set the specific boundary conditions of the case one is simulating to forecast the expected output, yet even among marine engineers, not many experts are capable of using these software tools and interpret their numerical data output.

Besides the above-described CFD tools, another option to simulate water flow is a class of physically based animation programs that are intended for designers. These programs are mainly used to create virtual reality environments for architectural animations, films and games, and are otherwise unreliable for technical and scientific purposes. Recently, there have been efforts to further develop these softwares by exporting physical data from CFD simulations such as DualSPHysics, into animation programs such as Blender (https://www.blender.org). This hybrid computational tool can model not only the behaviour of a single wave, but also the dynamic interaction between a sequence of waves, including backflow, diffraction and refraction. The accuracy of the results of this type of simulation is questionable, and it seems that it could not be used in the near future to approach issues such as the structural design of breakwaters and marine structures. Nevertheless, this type of tools may offer great advantages for architectural and landscape research, disciplines that focus on the visual and sensorial effect of waves on the perceiving subject, rather than on their exact flow behaviour or structural impact.

One of the main aims of this research is to examine the potential of such tools to be used in early stages of the architectural design process by designers, and to develop a new design methodology that incorporates the use of these tools in the design of seawalls.

3.1. Physically based animation, CFD and wave mechanics

The shape of the wave is a function of the complex physical interaction of wave energy as it becomes constrained by a solid boundary, such as the rising seabed. In deep water, the wave is a forward motion of energy, while the water particles rotate in place. Once the seafloor rises above about half the wavelength, the surface begins to affect the wave's shape and celerity through friction. The inclination and materiality of the seafloor impacts the way energy accumulated in the wave is finally discharged on the shore. The actual form of the individual wave is singular, as fluid systems are non-linear and become turbulent with minor changes in scale or force.

Research of the interaction between seawalls and waves is currently limited to assessing the structure's protective performance, its structural stability, and its impact on natural sedimentation and erosion processes. The knowledge developed by engineers to decrease the probability of destructive phenomena such as standing waves and overtopping could be used for the opposite purpose, to intentionally engineer it for recreational or aesthetic purposes. But research into the shaping of seawalls to generate wave formations for other aims such as leisure, ecological enhancement or education is presently undeveloped, except for the use of CFD to enhance the surfing performance of existing beaches, or for creating artificial surfing facilities inland.[1]

4. Fluid simulation, architecture and artistic agency

Using computational tools to create, rather than merely test and optimize a preconceived design, raises the subject of artistic agency, as the emerging form is produced through the collaboration of human and non-human agents. Antoine Picon suggested that artistic agency in digital media is manifested mainly through the exercise of choice: 'While form can vary endlessly, choices have to be made; decisions have to be enforced in order to break with the theoretically reversible nature of digital manipulation' (Picon 2004, 118). Such mode of practice raises the issue of the interdependency of artistic intentions and the logic inherent to the computational tool, and especially the status of the criterions, both explicit and implicit, that are used for making choices and decisions during the design process. Marcos Novak pointed to a conceptual and phenomenological affinity between computers and fluid motion: 'the operations associated with the idea of the liquid suggest that parameterization leads to radical variability within a continuum implied by a thing and its opposite' (Novak 1999). The utilization of computational flow simulation tools to create varied sense impressions is in part related to what Bauman defined as the culture of 'liquid modernity' (Bauman 2000), in which observing processes as they enfold in time becomes in itself an object of self-reflection and aesthetic appeal. The epistemic status of animation as a time-based, dynamic process suggests itself to think of architecture and landscape in terms of performance rather than representation. This approach corresponds with performalism, a design

theory that integrates parametric technology into architectural culture:

> A performative perception of form would call for its optimization as a product of technical utilization, while at the same time it would aim to incorporate symbolic, perceptual, and behavioristic aspects of form as a figure that displays a visual and sensual appeal. Form in this case would be more flexible, adjustable, and free. (Grobman and Neuman 2011, 4–5)

The phenomenon for perception and contemplation is not the object, but rather its unfolding interaction with the environment. This entails conceiving landscape as a dynamic event, one that has aesthetic qualities that engage the spectator and create memorable time-scapes. One might conclude that simulation technology does not only have the potential to model the interaction between buildings and fluid systems in time; it also has the power to constitute the spectator's mode of experience and capacity to create meaning as part of the design process.

5. A new computational design approach for the early stages of the waterfront architectural design process

The suggested design approach to waterfront design proposes a twofold shift from the traditional approaches to waterfront design. The first change moves away from a vertical, defensive traditional design towards a more horizontal approach. This change is suggested for both the large scale (the main geometry of the seawall/waterfront) and the texture scale (Kozlovsky and Grobman 2016) (see Figure 2).

The second change, which is the focus of this section, focuses on the design process and allows designers to manipulate the breakwater/waterfront exterior geometry during the early stages of the design. Figure 3 shows a comparison between the traditional and the suggested design processes.

In the suggested design process starts with a new type of multifunctional brief that includes new aesthetical, cultural and other programmatic demands. The brief demands are translated by the designers into a set of sections. These sections are based on a combination of a structural section (from an existing traditional taxonomy of structural sections such as in Takahashi (1996)) and a new type of section based on a wave taxonomy (an example a taxonomy is presented later in this section). The numerous local sections are multiplied using a parametric model (in Grasshopper plugin for Rhinoceros design software), which generates behaviour variations by attenuation and amplification of the effect. The parametric model is also used to connect the various sections using morphing and lofting commands. The initial form resulting from this process is then tested by the designer in a calibrated physical animation tools. In an iterative process, the surface is altered and modified empirically, until an aesthetically and programmatically desirable wave formation is produced. After the initial form is achieved, a texture is added according to a texture effect taxonomy (according to programmatic and biological demands). This is followed by a similar iterative process by the designer in a calibrated physical animation tool.

A chosen alternative after the iterative process ends is further developed with the help of consultants into a final design proposal. The validation and evaluation of the final design proposal are performed in a water channel.

It is important to emphasize the need for calibration and validation of the computational tool results that are used in this process (Taşli and Özgüç 2001). The calibration of the computational tools that are used in the suggested process needs to show that the results of the computational tools' simulation tools used in the process resemble the results of the simulation in the taxonomy from which the initial section are taken. The taxonomy is based on simulation results that are calibrated and validated with a physical wave channel. A detailed description on the wave taxonomy is presented in the nest section.

5.1. *Wave taxonomy*

One of the main conclusions from the early empirical observations of natural wave behaviour is that the quantity and complexity of dynamic forces that act on waves make it very difficult to extract rules that could be later used in a design process. Therefore, in order to be able understand these phenomena from a designer point of view, it is important to start with a simplified fundamental wave conditions that can be understood and imitated by a designer. After this basic understanding is achieved, it will be possible to develop more complex geometric scenarios that will allow designers to imitate the dynamic natural phenomena in a new design.

To simplify the problem for the generation of preliminary taxonomy, we choose the initial wave conditions to resemble those prevailing at the location of the case study that will be described later in the paper. The dimensions of the virtual wave channel were modelled to resemble the actual physical wave channel that was used in the later stages of the design process to validate the virtual results.

The taxonomy of wave–surface interaction was developed experimentally, by running in a virtual water channel simulations

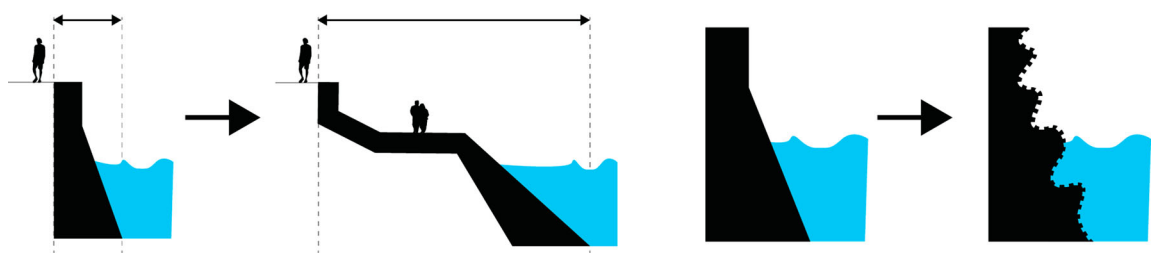

Figure 2. A shift from the traditional approach to the waterfront design: a shift towards more horizontal seawalls (left). Adding complex geometry to seawall geometry and texture scale (right).

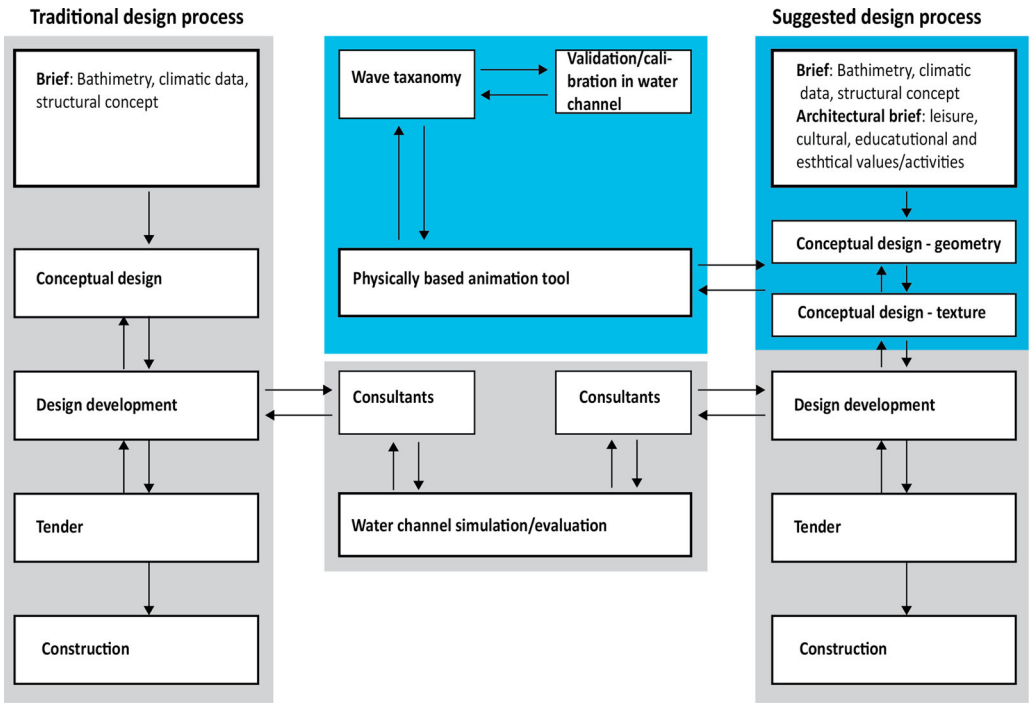

Figure 3. A comparison between the traditional and the suggested design processes.

of waves cresting on seawalls with basic geometric forms (Figure 4). Each basic form was tested in a series of variations, to study the effect of minor changes in geometric parameters on the non-linear behaviour of the wave in various conditions (wave height, wavelength and wave period).

The virtual wave channel was programmed to analyse the behaviour of a wave packet, including the interaction between an upcoming wave and the backflow of the preceding wave as it is deflected by the seawall. Figure 5 present a single simulation sequence of one of the examined geometries.

The evaluation studied the way waves break over the waterfront. It examined the concentration, direction, and the height of the water splashes and categorized it into basic (single splash, multiple splashes, water spray, etc.). Moreover, the analysis tried to lower the level of uncertainty of modelling wave behaviour by mapping wave events that could not be anticipated by designers due to the complexity of water flows. Figure 6 shows two examples of unforeseen wave formation.

Research into basic morphology revealed that just as wave energy can be superimposed to produce composite waves, so do forms: one can combine or subtract through Boolean operations different basic morphologies to create accumulating wave effects. These effects could be sequenced in time and thus become perceptible. This is possible because sea waves are slow enough that, for example, a wave travelling at 5m/s will begin to deform by the protruding element in Figure 3, and only after a second advance to the end of the 5-m-deep cavity, so the effect is delayed in time and the observer can perceive the dynamic effect of the form on wave motion. Thus, not only the dynamic form of the resulting wave could be considered as an object for aesthetic perception, but also the alternating submerging and surfacing of the structure itself. Moreover, because wave packets are composed from different wave intensities, the subject's perception of their interaction with the solid geometric boundary solids becomes attuned to this differential. This is of critical importance, since if simulation technology is a medium that brings to focus the perception of time, it may inform a design that seeks to manifest this dimension of experience.

As mentioned earlier the initial taxonomy results should be calibrated and validated in a wave channel test. The scope of the current stage of the research allowed performing a calibration of the results only on the small texture scale that is presented later in the paper. A further development of the taxonomy to include more complex seawall section and a calibration of the results in a wave channel is planned in the next stage of the research.

5.2. Wave input and seawall section

A major predicament of modelling the behaviour of the waves interacting with the seawall is that the input of the sea is varied and irregular. The force and direction of the wind, of underwater currents and surface waves, as well as tides, change from moment to moment, and from day to day, as well as according to seasonal cycles. There are also extreme weather events that statistically occur in 10- and 100-year cycles. The constraint this imposes on the design is that a section that is intended for calm water must also perform under rough sea conditions and, vice versa, parts that are designed for the most extreme swells occurring once a century must also support the usability and splendour of the promenade when the sea is calm.

Our approach to the dynamic nature of sea waves generalizes the broad spectrum of sea states into typical sea conditions according to the site and the brief. In the case study that will be presented later in the paper, we chose to define three typical sea conditions observed for the eastern Mediterranean coast following the World Meteorological Organization (WMO) sea state code scale: smooth (2), moderate (4) and rough (5). (As tidal flows in this region are insignificant, they were disregarded.)

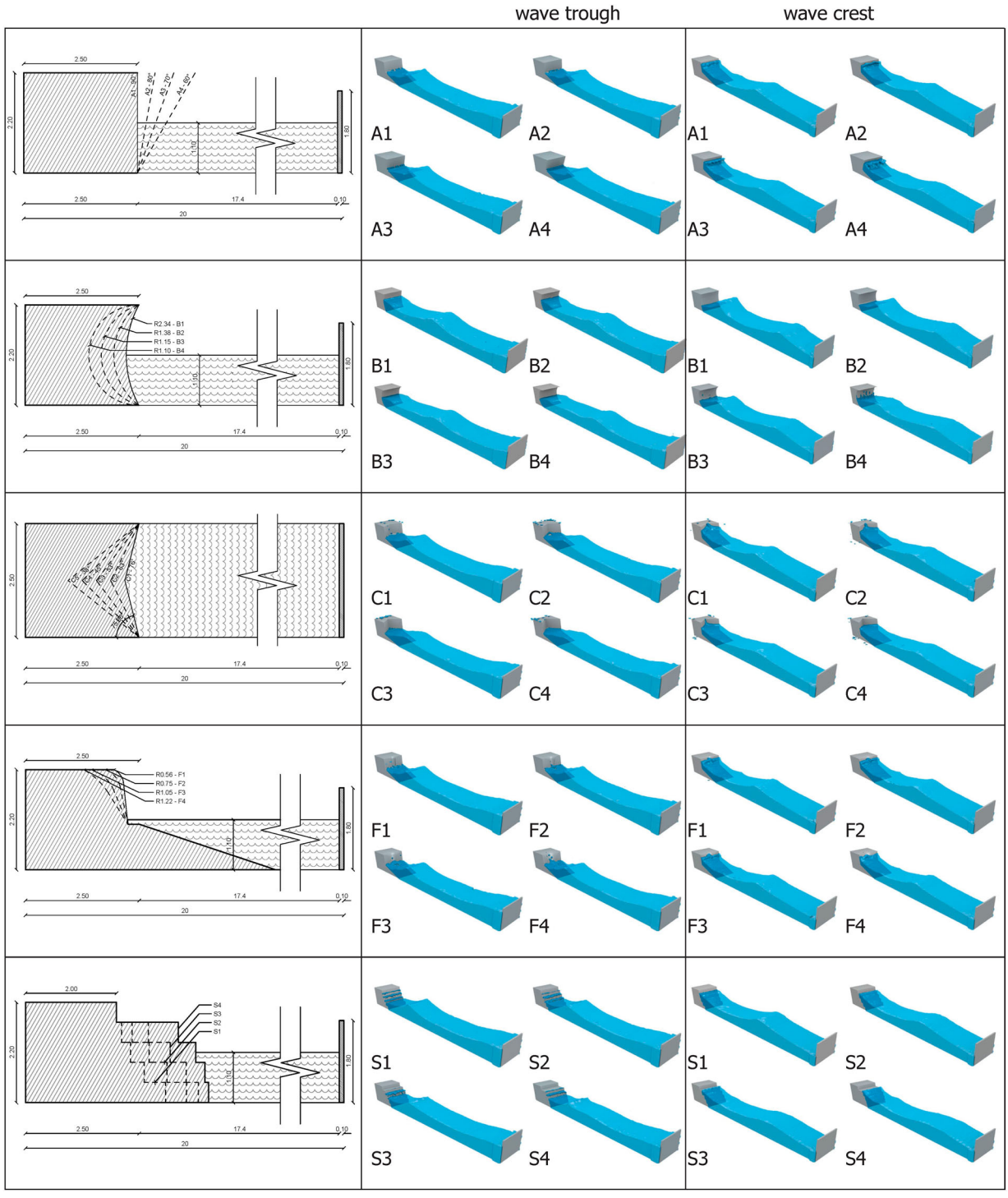

Figure 4. Selected basic geometries wave taxonomy catalogue.

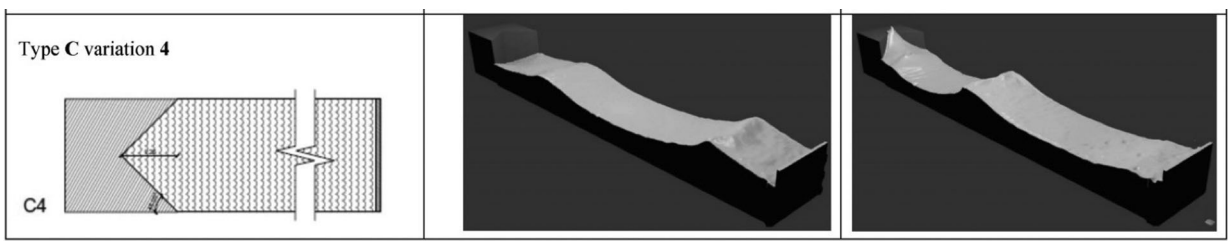

Figure 5. Behaviour of a single wave in a virtual wave channel.

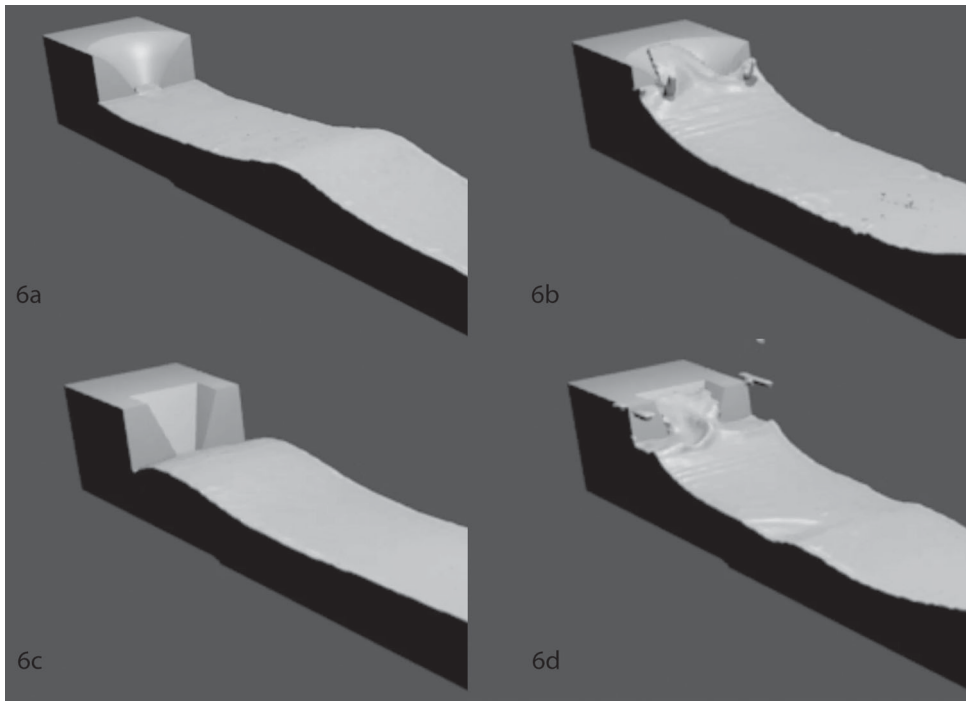

Figure 6. Unforeseen wave formations. (a) Initial condition. (b) Two splashes are created by the vortex in the entrance to the cavity. (c) Initial condition. (d) A single thin wave is created at the entrance to the cavity.

The design approach, therefore, suggests dividing the seawall accordingly into three zones (see Figure 7). The lower level is designed to engage with glassy and smooth sea conditions, making visible the forward motion of the faintest of waves, and exploiting the transparency of still water to disclose the marine life that thrives near the surface. The second level interacts with a moderate sea, using the section to deflect, rotate, uplift or dissipate the waves, and articulating the way they flow back to the sea. The middle section serves as the foundation of a 'wet promenade', a path parallel to the shoreline that allows for a sensuous encounter of pedestrians with the sea; this section can be made inaccessible during stormy weather for safety reasons. The uppermost zone is designed for rough sea conditions, using verticality to deflect the most powerful waves and protect the all-weather 'dry' promenade and other coastal structures inland.

The tripartite section has another advantage that it agrees with the principles of ecological design, as will be discussed in the next section.

5.3. Ecological input

An additional significant parameter for designing the interaction between the sea and the waterfront is ecological performance. Coastal infrastructure in urban and industrial areas has

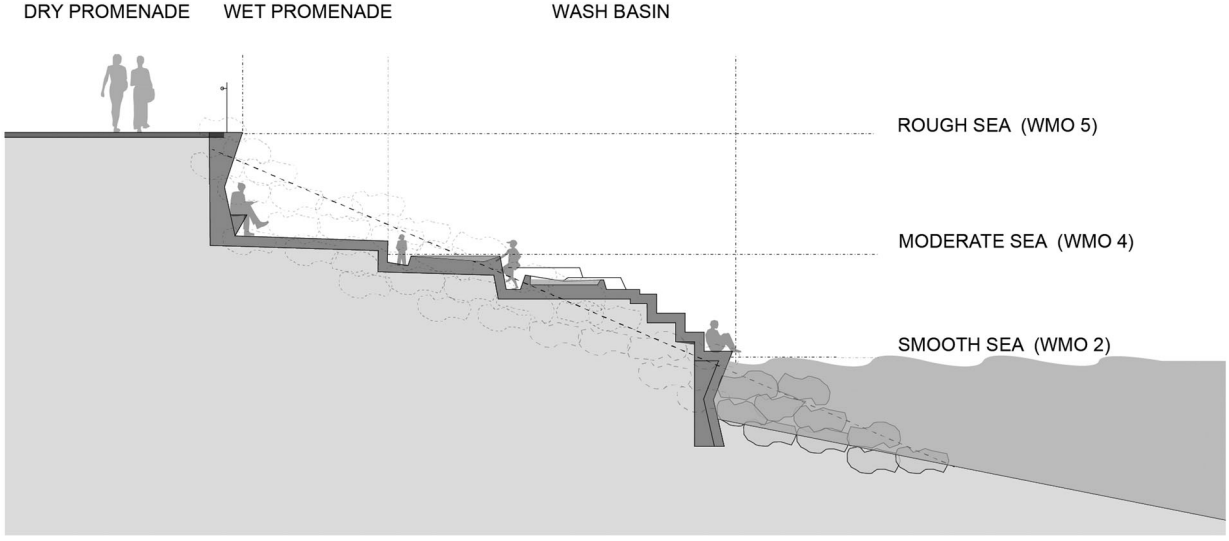

Figure 7. Division of seawall into three levels corresponding to sea states.

a significant environmental footprint, disrupting the ecological balance of coastal ecosystems through the destruction of natural habitats. By utilizing scientific knowledge of the habitat requirements of marine species, seawalls could be bio-engineered to increase their ecological value, thus transforming them into active ecosystem service providers (Chapman and Underwood 2011). Two promising approaches for enhancing coastal biodiversity focus on the morphological and material properties of coastal structures, and thus offer themselves to architectural thought.

Increasing the texture density of the surface is one parameter that raises the potential for sustaining more abundant and diverse natural assemblages. Smooth surfaces reduce the complexity of marine ecosystems, since they provide less traction for flora and fauna to attach to the surface (Moschella et al. 2005; Wiecek 2009). Thus, the texture could be considered as a performance parameter for enhancing the habitability of the artificial shoreline.

In parallel with texture, the surface inclination is found to be a significant factor for shallow water habitat creation. Inclined surfaces, by increasing the area with a favourable combination of sunlight, moisture, oxygen and flow of nutrients, are more hospitable for marine life than vertical walls (Figure 8). Thus, the performance of marine structures as biological habitats could be stated in geometric terms (Coombes et al. 2013).

Besides its important ecological contribution, the texture of the waterfront also influences the behaviour of water flows. This could be used by the designer to fine tune the design of the effect of waves over certain basic geometries by amplifying or reducing flows in certain areas.

5.4. Preliminary research into texture

This line of research focused on developing a research method to simulate and examine the influence of small geometries on a commensurable flow of water waves (WMO level 2). In this research, breakwater texture relates to two scales in terms of the dimension of the bumps and holes on the surface: micro-scale (0.5–3 cm) and large-scale texture (3–7 cm).

The first stage of this research focuses on the large scale, which can be fabricated in 1:1 scale using concrete (a common material for breakwater construction). Three mapping/simulation techniques were examined under equal flow conditions. The aim of this first preliminary simulation round was to study and examine the influence of a single protrusion on the water flow. This preparatory technique defined the boundaries for flow impact and enabled a first categorization of water flow behaviour in relation to different macro-textures.

Moreover, virtual models of the texture plates were simulated in the animation software Blender under corresponding flow conditions. The real-life simulation outputs were used to calibrate and validate the same set-ups in the virtually animated environment (Figure 9).

The second technique focused on examining the impact of simple spherical patterns using small (30 cm × 30 cm) tiles (Figure 10), and the third technique was based on large (100 cm × 100 cm and 120 cm × 240 cm) CNC-milled tiles (Figure 11), whose texture was created by a parametric model that created a continuous variation of size and geometry of forms.

The catalogue of chosen patterns is composed of basic types and arrangements of protrusions and cavities, whose aim is to inquire into the effect and affect of water flowing through them.

The initial morphologies are based on regular geometries manipulated according to three different parameters: the elements' density, their extrusion or depth and their radius.

Given the results of the first round of preliminary simulations, a special interest is placed on the relative influence of the different parameters on the impacted flow behaviour. For this, the catalogue of textures has been systematically developed to analyse the whole spectrum of parameters combinations (Figure 12). One of the constraints that guided the design of the textured plates is the ease of fabrication using readily available CNC machine tools; unit size was constrained by the ease of moving, lifting and mounting the plates into a wave flume. Thus, each plate is made of four parts and is mounted on a structure that can be adjusted to produce different inclinations, in order to test the performance of the textures at different water velocities.

Further examination is needed in order to assess the influence of the various type of texture on the development of marine life, and especially their recruitment value of desirable species. This issue is also dependent on the material from which the surface is made, as will be explained in the next section.

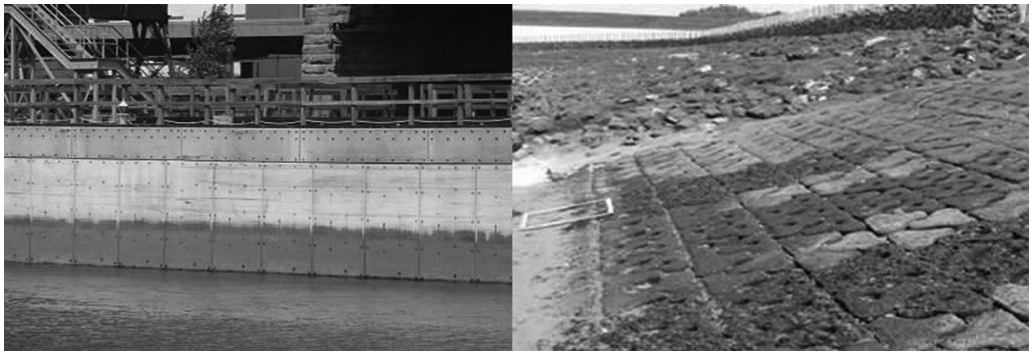

Figure 8. Impact of inclination and texture on ecological performance: (left) smooth, vertical seawalls with minimal biogenic build-up and (right) effect of inclination and texture on marine flora development.

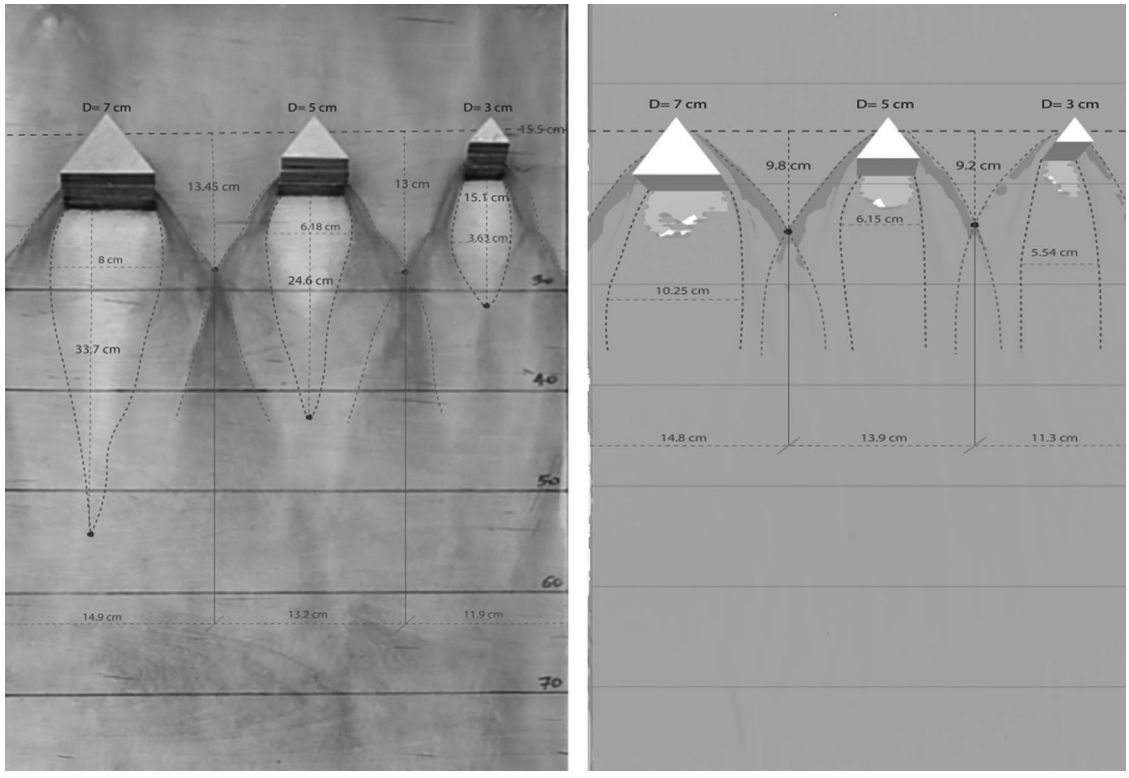

Figure 9. A comparison of the real (left) and computational (right) results of the preparatory simulations. The virtual simulation was found to provide a good degree of precision in simulating the real pattern of water flow.

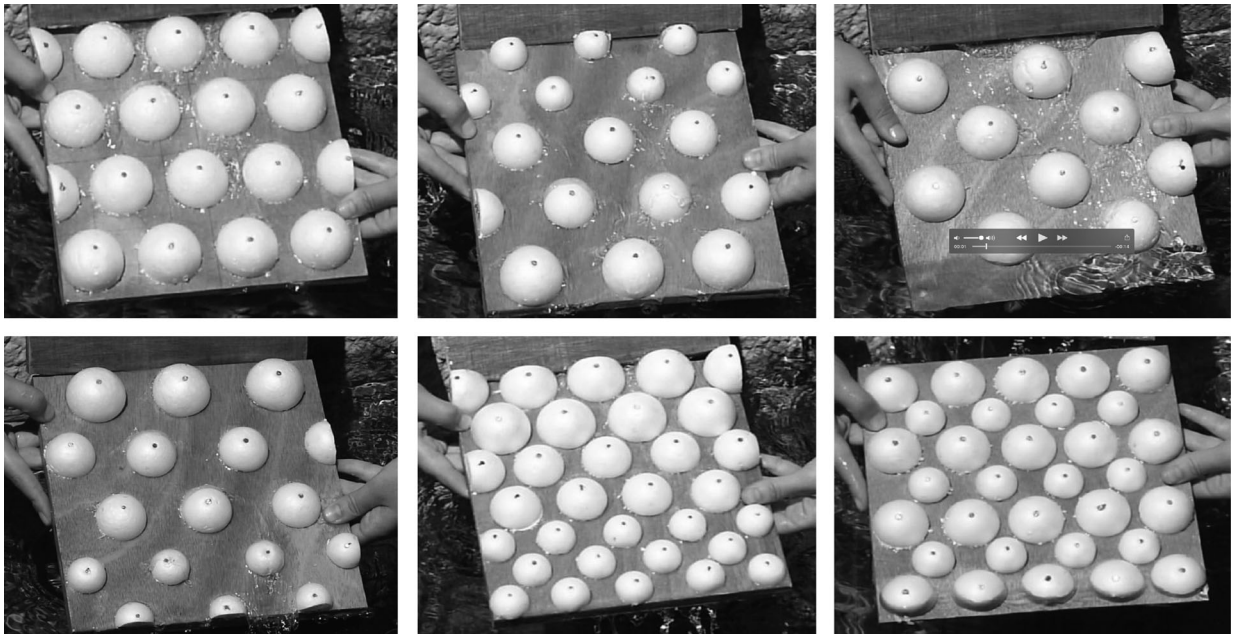

Figure 10. Selected tiles for mapping textures influence on water flow.

5.5. The material scale

Another parameter for sustaining diverse marine habitat, as well as for planning the life cycle of the seawall is material. In the case of concrete, which is one of the main materials currently used in the construction of waterfronts, it is possible to control its impact on marine organism and its weathering behaviour by altering the chemical composition of the concrete mixture, for example, by reducing its alkalinity which repels most forms of aquatic life (Sella and Perkol-Finkel 2015). Although the existence of marine organism is usually desired (biogenic build-up helps absorb wave energy and reduces surge impact on the structure), in some areas, such as pathways for pedestrians, it can cause slippery hazardous conditions. In these areas dark, high alkaline concrete could be utilized together with a good

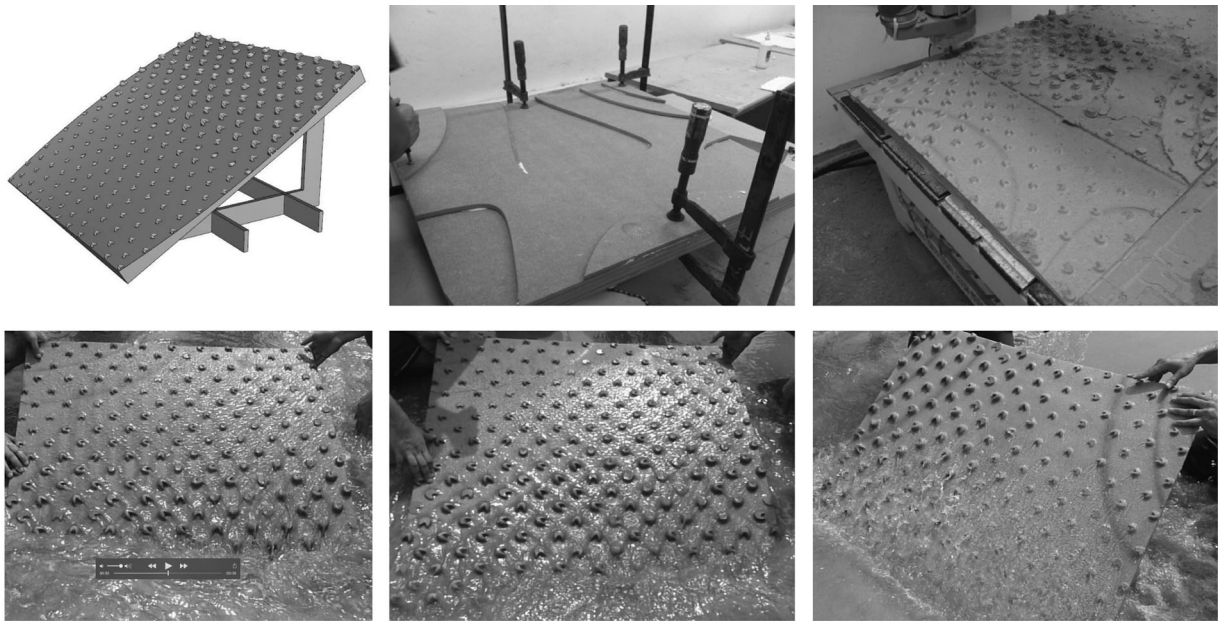

Figure 11. Fabrication process of a parametric tile (up). Water flow on selected parametric tiles (down).

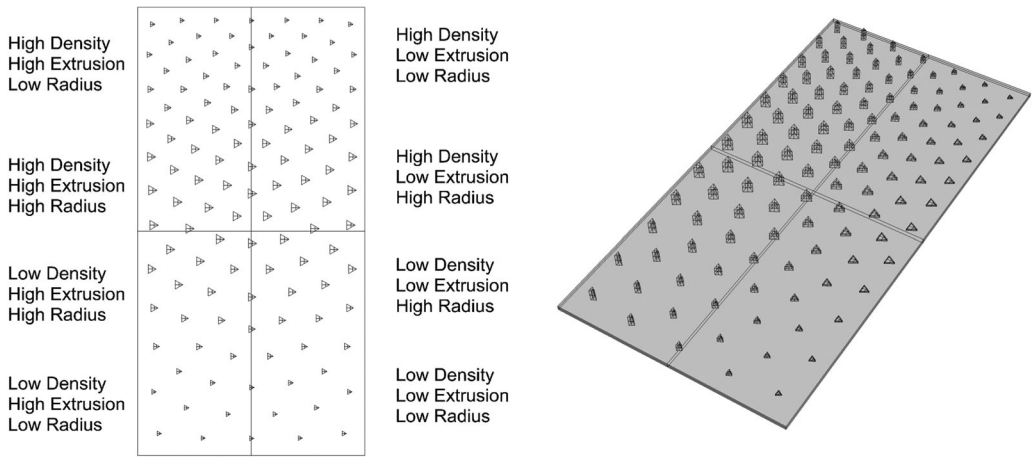

Figure 12. Example of texture geometry based on regular triangular prisms. On the left a plan view showing the parameters combinations; on the right a 3D view of the plate (120 cm × 240 cm).

drainage system to prevent the development of undesired flora and fauna.

Material properties and especially the number, type and dimension of aggregates in concrete also have a significant effect on the texture of the concrete. This can be used parallel to the more geometric approach to texture, which is determined by the design of the surface of the mould for casting the concrete. Lastly, material properties can be altered in order to create variation in strength in relation to a desired weathering variation of the structure.

Therefore, at the end scale of events design (after the duration of one wave, a pack of wave, etc.) is a longer timespan of the entire life cycle of the project, including its gradual disintegration under the abrading action of natural forces. Planning for the future introduces the problem of uncertainty, such as preparing for changes in climate and sea levels, but also the vicissitudes of long-term institutional commitment to maintenance and repair of the structure. Rather than opting for fail-safe design that seeks permanence through a fixed, resistant form, a more dynamic approach would work with such processes: the concrete elements could be manufactured and assembled in such a way that the seawall's inevitable disintegration will not be perceived as a failure: rather, its artificial, non-mimetic geometry would in time undergo processes of weathering, corrosion and fracturing, as an index of these geological, landscape forming forces. Therefore, the design approach at this scale can start with rather simple geometry that is based on orthogonal and diagonal surfaces, which are easier to fabricate, and design the material properties of the surfaces so that the forces of nature will smooth and round areas that interact with intense wave action.

6. Case study design – a new multifunctional waterfront

This section presents an application of the suggested processual approach in a case study designed for a specific site.

Figure 13. (left) Existing site conditions, aerial view of Charles Clore Park, Tel Aviv. (right) Riprap breakwater structure.

6.1. The site and the brief

The case study project was commissioned by the Tel Aviv Municipality as a proof of concept for the possibility to redevelop a mile-long stretch of the city's urban coastline with the suggested multifunctional approach. The project was developed as a collaboration of architects, marine scientist and coastal engineers.

The site runs parallel to the Charles Clore Park (Figure 13). It is reclaimed land that was used in the 1970s as a dumping ground for excavated material from an adjacent high-rise development and the demolition of a nearby neighbourhood. This specific area has been difficult to revitalize due to the method in which the breakwater had been constructed. Its riprap structure acts as a barrier that blocks pedestrian access to the sea, and the chemical composition of the rocks and concrete blocks have proven to be detrimental to local marine species, with the result that only a few invasive species have colonized it. As the purist option of restoring the site to its original pristine sandy condition by dismantling the seawall and clearing the landfill was deemed impractical, we chose to make the drawback of the site, its artificiality, into a conceptual advantage. The project limits itself to refurbishing the existing seawall and transforming it into an ecologically and socially active promenade. It is designed to offer active-use features such as a wet promenade, tidal and paddling pools for children, educational hotspots for learning about marine ecosystems, and places for contemplating the waves, a 'blue garden' equivalent of the land-based 'green garden' in its symbolic, perceptual, experiential and programmatic significance.

6.2. Design method

The design process described until now renders the form of the seawall as a function of the performance of fluid motion and biological processes, thus freeing form-making from any formal bias that favours shapes for their visual appeal or symbolism. This approach does not fully realize the landscape potential of the site, nor does it address the sheer material presence of the seawall and its role as an urban threshold. Yet, privileging only wave performance without an overall coherent organization would result in a project that would be perceived as a series of disconnected frills and attractions, a spectacle for visual consumption. To create a strong sense of place demanded by the client, we found it advantageous to use clear, distinct groupings of elements and bold horizontal strokes to provide the site with a legible, consistent identity. Consequently, the site has been divided into three segments, each with its own basic morphology (Figure 14).

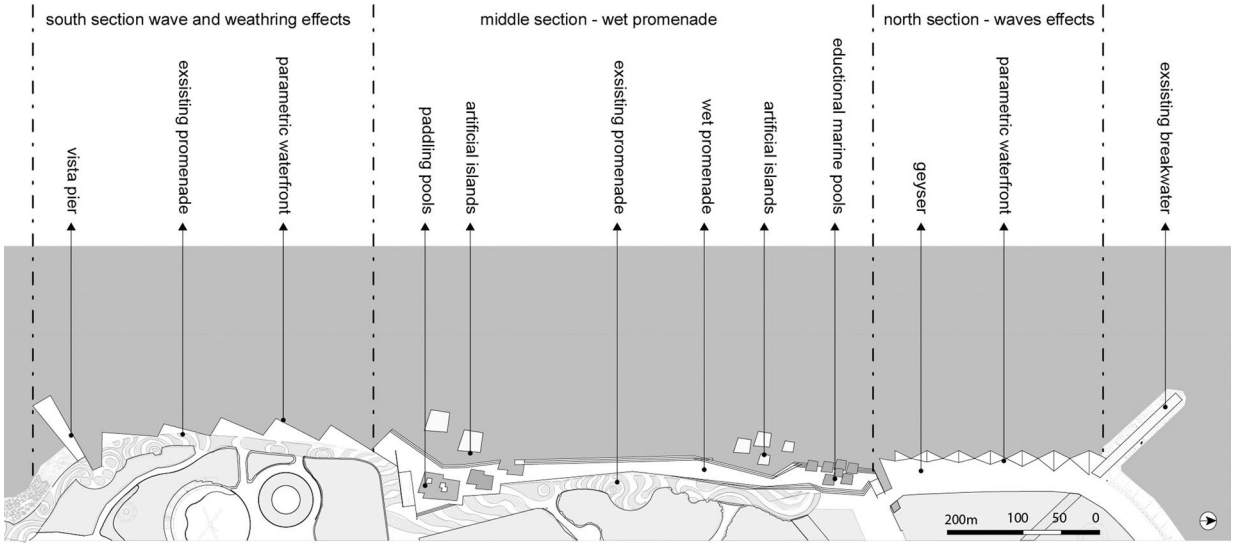

Figure 14. Case study project plan. Seawall is divided into three distinct areas.

The north part is made of partly submerged surfaces that protrude into the sea with an emphasis on creating mild visual and audible wave effects. The middle section is dike-like horizontal and diagonal section that includes a wet promenade and stairs for contemplating the sea, its basic section follows the recommendation of EurOtop II manual on wave overtopping of sea defenses and related structures ('HR Wallingford - Overtopping' n.d.). A series of small artificial reef islands at water level establish ideal marine habitats and function as protective breakwaters. The southern part of the project is more desolate and rough, with sections designed to intensify water action by inducing splashes, sprays and noises, and thus accelerate the rate of weathering.

These three basic zones are varied by changing the parameters controlling their basic sections in relation to the wave taxonomy presented earlier. Each zone is conceived as a series in time: as the wavefront changes, its angle towards the shore due to the daily wind regime of the site, the waves encounter the structure in an enfolding, gradual motion. When the wave is perpendicular to the shore, this effect is achieved by the jagged contour of the seawall.

Each section was then further developed by manipulating initial forms, which were taken from the wave catalogue and adjusted to the program in an iterative process, which was examined in a physical animation tool that would be calibrated to a water channel. Examples of this design process are presented in Figure 15, in which the form is modified according to the input of the wave simulation. The design was then further developed using a parametric model (in Grasshopper plugin for Rhinoceros). The parametric model was used to generate design alternatives by creating variations in the dimensions of the complex geometry of the waterfront sections according to programmatic demands, and connecting the generated results into a continuous waterfront surface. An example of design variations for two different alternatives is presented in Figure 16.

The new waterfront with the 'wet promenade' is designed to extend the area that could be used by the public and generate different experiences in multiple weather conditions and seasons. For example, the marine geysers embedded in the plan are designed to work under different sea/wave conditions (see Figure 17). One geyser will become active only during the strongest winter storms. It will thus express in a very dramatic way (10-m water column) the forces of nature, and will be a source of attraction for visitors during times when the waterfront is usually deserted.

The educational component of the project in the middle part of the project is directed towards first-hand experience. Besides the exposure to the visual and aural effects of the breaking waves, the design proposal includes special pools where children could watch and touch marine animals, and small artificial islands that would attract sea mammals and birds and thus bring them to closer views, to promote an understanding

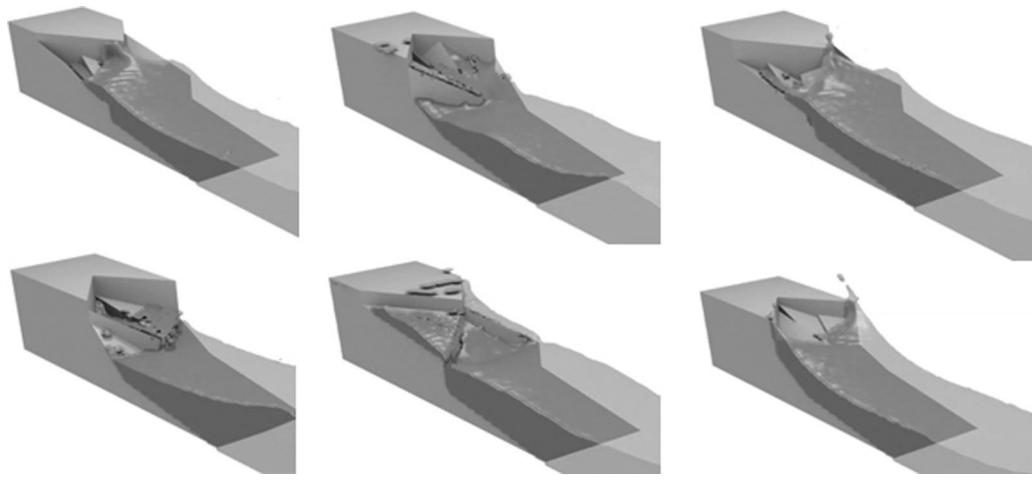

Figure 15. Examples of wave simulation results.

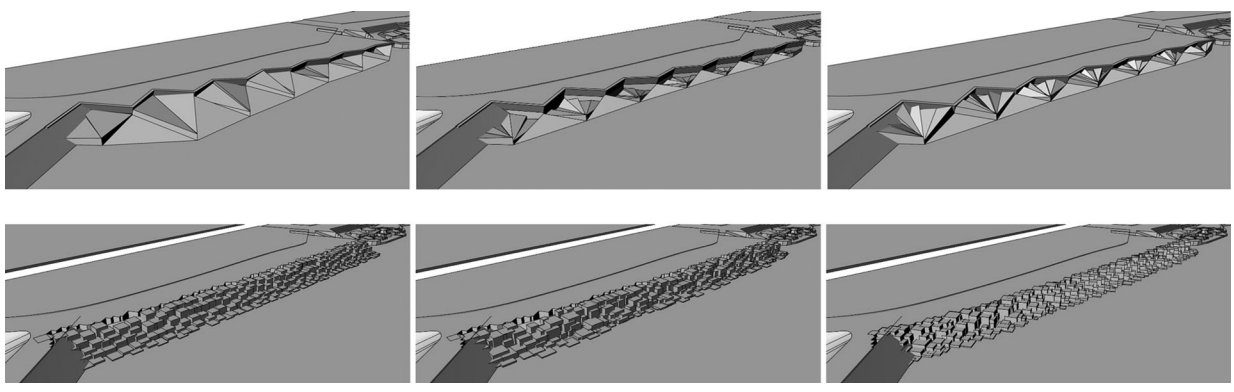

Figure 16. Parametric development of an alternative to the northern section.

Figure 17. Computer rendering of the waterfront preliminary design (a view from the north).

of the complexity and fragility of the Mediterranean coastal ecosystem.

The texture and materiality of the concrete that will be used for parts of the waterfront surfaces is designed in collaboration with marine bio-engineers. It employs ECOncrete, a material whose chemical composition is designed to accommodate marine life (Sella and Perkol-Finkel 2015). A different dark high alkaline concrete will be used for the surfaces in the wet promenade that are designated for pedestrians. By absorbing solar radiation, the dark colour increases the temperature of the concrete, inhibiting the growth of seaweed that is one of the main causes of slippery surfaces in waterfronts.

7. Conclusions

About 80% of all major cities are situated in a coastal or river delta zones. The increasing urbanization of the world population, the rising see waters and the changes in architects' abilities to design, simulate and construct complex geometries call for rethinking the traditional, single function and defensive approach for marine infrastructure. The presented research takes this challenge by developing a computational design method for seawalls that allows designers to utilize recent developments in computational fluid simulations technologies. The suggested design methodology helps designers to shape the interaction between sea and land and generate a seawall that, parallel to its defensive function, suggests an aesthetic and leisure experience, and supports a thriving bio zone for marine life.

The paper reviewed the current research on waterfront design and the use of computational tools for architectural design in general and for water flow simulations. The review showed that while computational fluid dynamics can simulate the non-linear, turbulent behaviour of water up to a certain extent, the complexity of urban waterfront conditions necessitates a simulation and a design strategy that simplifies these conditions into concrete steps that reflect important programmatic or performance criteria. Based on the insights from the literature review, a computational design methodology that focus on the early stages of the seawall design process was developed. The suggested design methodology is using inputs from preliminary wave and texture behaviour taxonomy that was conceptualized and developed in this research.

The suggested computation design methodology was examined in a case study design, which demonstrated that fluid physical animation tools could be implemented by designers as a medium for qualitatively designing the interaction of sea and man-made shoreline.

The researched showed that the combination of employing parametric design tools and fluid simulations allows designers to explore a large number of design alternatives prior to shifting to final validation with time-consuming and wave pools. Nonetheless, it is important to emphasize that due to the complexity of water flow and the limited accuracy of physical animation tools it is still imperative to validate the outcome design proposal of the suggested process with a physical wave pool prior to finalizing the design proposal.

The scope of the current stage of the research concentrated on developing an overall framework for the suggested design approach and an initial wave and texture taxonomy. Additional research is needed to expand the taxonomy to include more complex geometries and textures and to understand the effect of the complex textures and seawall section on the seawall structure. Additional research is also needed to quantify various effects of each geometry and to better understand the level of accuracy of the various computational simulation tools in relation to various waterfront scales, waterfront geometry and wave formations.

Note

1. The parameters for designing waves for surfing are based on the subjective preferences of surfers, which are translated into measurable parameters, such as the peel angle of the wave and its breaking intensity. Submerged V-shaped artificial reefs have been built to optimize the surfing experience of existing beaches; in closed onshore systems, it is also possible to control the wave generation. Commercial firms such as Wavegarden (www.wavegarden.com) employ computer modelling to design the bathymetry of the water channel to produce waves of different magnitude to match the skill level of the surfer.

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