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Making Waves: Visualizing Fluid Flows

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Abstract

We explore the visualization of violent wave dynamics and erosion by waves and jets in laser-cut reliefs, laser engravings, and three-dimensional printing. For this purpose we built table-top experiments to cast breaking waves, and also explored the creation of extreme or rogue waves in larger wave channels. Surprisingly, there are nano-scale analogues of these wave patterns in surface engineering with ion beams instead of water waves. Insights in applied mathematics and fluid dynamics, materials, fabrication and aesthetics informed our explorations. The resulting patterns give us not only new ways to communicate to specialist and general audiences about mathematics and fluid dynamics on different scales, they also provide new, abstract imagery which can be used in architectural and design applications.

Inspiration

Wave patterns come in a range of scales: from water waves churning violently at sea, to nano-scale erosional wave patterns of Silicium and Germanium surfaces caused by ion-beam sputtering (in the optical semi-conductor industry). Water waves are also highly transient. A still photograph does not adequately convey the wave movement or character. To be able to capture the beauty of surface water waves, we built an idealized, table-top experimental version of breaking waves on an erodible and dynamic beach [1]. It enables us to both do science and cast the dynamic beauty of a miniature breaking wave into three dimensions. Our project shows experimental phenomena translated into wooden 3D laser engravings mounted together to form 3D relief images. This imagery inspires and aids further thinking about complex waves and the problems they sometimes present. Additionally, Perspex® models of the bore-soliton-splash and wave examples, which will be presented at the conference, function not only as a physical aid in presenting this work to specialist and general audiences, but form the basis for design and architectural motifs.

Breaking waves along our coasts are most prominent during violent storms. Violent wave action triggers strong coastal erosion, but also creates new land spits and beaches. Our table-top experiment is designed to capture the creation and destruction of sand, or shingle beaches (formed by pebbles), during storms.

Beaches, islands and sand dunes emerge as different bottom formations depending on the wave shapes. Strikingly similar patterns emerge elsewhere on very small, nano-scales in ion-beam sputtering of metal surfaces, a process used in the semi-conductor industry. While the purpose here is to create the smoothest surfaces for use as optical mirrors, ion-sputtering is highly sensitive to the beam angle, and non-smooth surface patterns regularly appear. What is visually striking about these patterns is that they resemble the sand ripples and sand bar shapes that we have all encountered on beach explorations. These, however, are unwanted patterns, despite their fascinating appearance. We explored how these images would be visually transformed, if lifted out of their usual two-dimensional form and recontextualised as laser-engraved patterns.

Our most dramatic and violent invention is the bore-soliton-splash, created for the opening of a public square (the Education Plaza) at the University of Twente, in September 2010 (see Fig. 3 to be discussed later). It is a man-made rogue, or ‘freak’ wave. A freak wave, at sea, is defined as an anomalous high wave among the ambient waves. It must have an amplitude at least two times higher than the average amplitude of the largest 33.3% of the waves surrounding it. This difference is measured by an amplification index: the ratio of the amplitude of the freak wave over this mean amplitude of the ambient wave fields. On the oceans, rogue waves occur with an index of 3 to 4. We created a freak wave with an amplification index of 10 in a wave channel of 40x1.8x0.5m^3, and also in a tank of 60x8x2cm^3. We aim to cast the subtle sensitivity of our rogue wave in layers of perspex.

Wave Breaking Reliefs

In 1897, Henry S. Hele-Shaw, FRS, [4] devised his most notable invention. He wished to show fluid flow past an object on a large screen for public presentations. He took two closely-spaced, rectangular glass plates, closed the two long sides and left the other sides open. The glass plates were placed at a slight angle on a table. Obstacles, like thin cylinders, were placed snugly between the glass plates and subsequently a (viscous) fluid, such as a transparent oil or water, was released on one side, entirely filling the gap between the glass plates. When the fluid flow was constant, and hence stationary, the streamline patterns around the obstacles could be visualized by adding small particles or streaks of dye at the side where the fluid entered. Because the fluid flow is nearly two-dimensional, as there is only a narrow gap between the two glass plates, Hele-Shaw's set-up lent itself well to flow visualization. The flow is regular or laminar when the glass plates are spaced sufficiently close together.

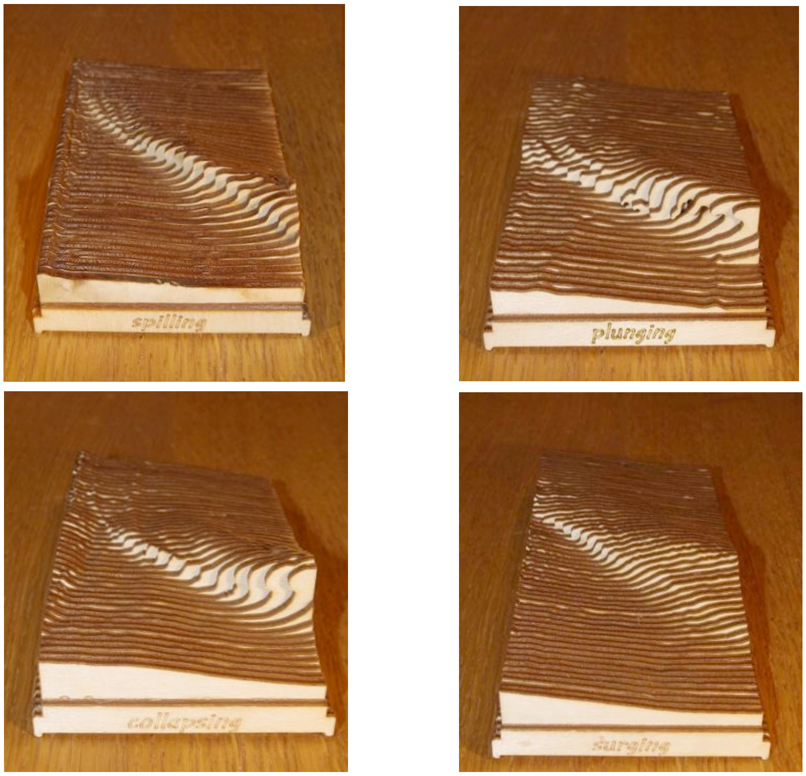

Figure 1: *Wooden reliefs of spilling, plunging, collapsing and surging breakers. Each slice in the wooden relief is 0.02s of real time. Each relief is approximately one wave period.*

In a similar spirit, we decided to vary Hele-Shaw's original experiment by placing a vertical ‘beach-slice’ with beach particles, water and air between the two glass plates. Our very narrow Hele-Shaw wave tank is closed at the bottom and sides, while the top remains open. The tank measures 1x0.3x0.002m^3, and contains a wave-maker in the form of two welding rods or a piston wave-maker on one side, with beach particles on the other side. The particles are only 1.8mm in diameter moving between two glass plates spaced two millimetres apart; this gap width guarantees very clear visualization of the movement of each particle, especially when lit from behind. Critical to our design was the calculation of the gap width using applied mathematics and analogue as well as modern simulation techniques [2,7]. The key insight arising from these calculations is that we needed to make the gap between the glass plates wide enough such that the flow is not entirely laminar, and small enough to ensure the flow is still largely two-dimensional. This made the flow simple to visualize. The desired gap width is about two millimetres. Aside from the scientific version, we built another Hele-Shaw beach experiment with a portable case, for public outreach purposes. Wave motion is generated by the wave-maker. Each wave lasts about one second, after which another wave reaches the beach. Wave breaking causes the ‘sand’ or ‘pebbles’ to move back and forth. We used Gamma Alumina particles because they have a diameter slightly smaller than the desired gap width and because their off-white colour allowed good imaging. Each wave animates the beach such that particles move back and forth. Yet it is only after many waves have been pounding for a long time, from some minutes to an hour, that a net movement becomes observable. Thus, land in the form of beaches, and even an island in some cases, is created from a starting state in which all land was covered by our table-top ‘sea’. The wave breaking in our experiment led us to explore how we could visualize and perceive these waves in a better way [5]. Breaking waves are classified into spilling (e.g. breakers at Dutch North Sea beaches), plunging (e.g. the famous curling Hawaiian breakers), collapsing (in which the lower part of a wave breaks down), and surging (a smooth wave that overturns only right at the beach) breakers. These wave types have been cast into laser-cut wooden reliefs, and are displayed in Fig. 1.

Sensing Nano-scale Ion-sputtered Surfaces

Our wooden reliefs of wave breaking and our results on beach erosion by breaking waves led Pepijn Pinkse (personal communication, University of Twente) to point out to us that similar erosional features are found on much smaller scales. Ion-beam sputtering of Silicium or Germanium surfaces cause these surfaces to erode in beautiful patterns. These patterns cannot be observed directly, but only with the aid of atomic force microscopy (AFM). To render these patterns appreciable, Wout Zweers scaled up the images from Frost's scientific article [3] to make the laser engravings in Fig. 2.

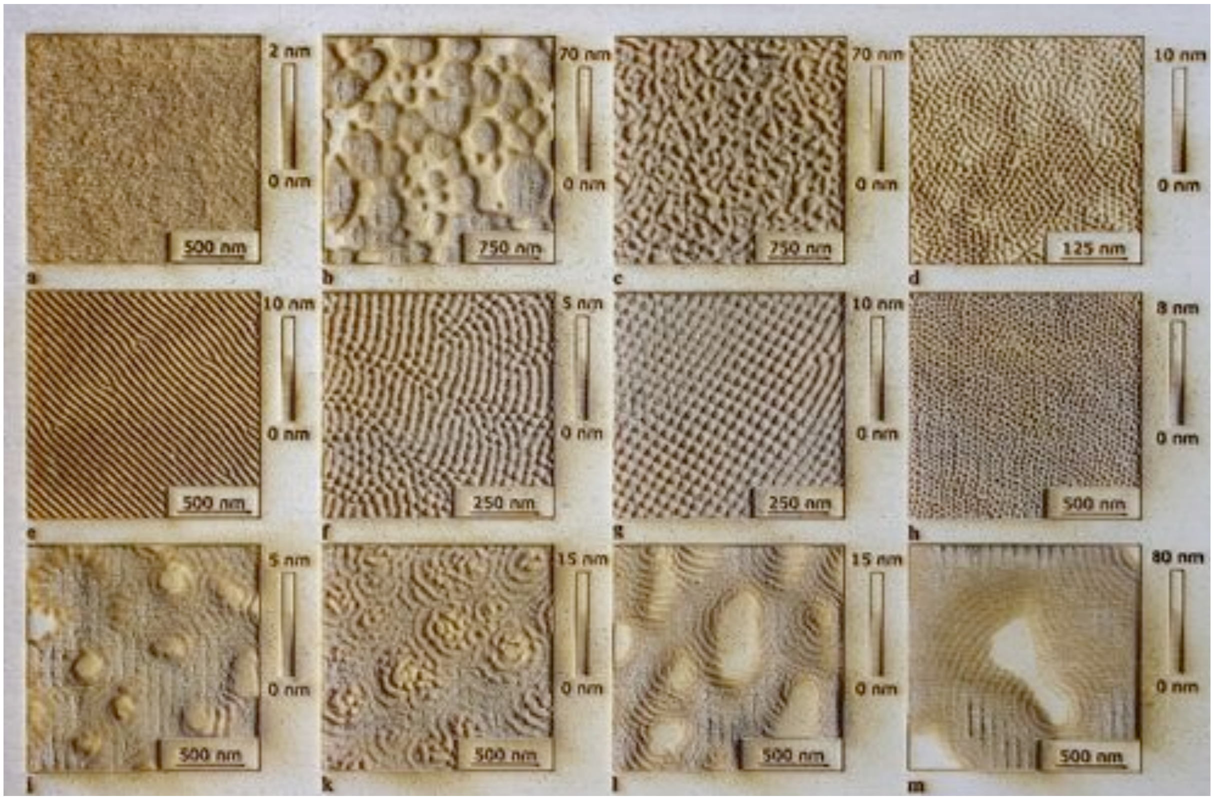

Figure 2: *A laser-engraved wooden relief of Fig. 2 in Frost et al. [3], showing the diversity of patterns on Si and Ge surfaces by low-energy ion-beam erosion.*

Bore-Soliton-Splash

In a 42m channel a wave of 35cm in height is created by pulling a sluice gate between two water levels, initially at-rest. A compound of partially-broken solitons (waves) travels towards a V-shaped channel end, the first and highest wave reflects with almost no splash, draws a deep trough in which the second and lower solitary wave precisely falls to create a 3.5m high splash. See the water channel and consecutive photos of events in Fig. 3.

After the sluice gate in Fig. 3(a) is pulled, the first soliton breaks and becomes a so-called *bore*, dissipating enough energy to become a smooth wave again at the V-shaped end in Fig. 3(b). A *soliton* is a single, isolated mass of water that can travel almost undisturbed along a uniform channel. The *splash* eventually collapses into droplets. The amplification index of this *bore-soliton-splash* is the ratio of the incoming wave height over the splash height: it is about 10. This is very high compared with freak waves observed in nature. If the V-shaped channel end had an inclined, initially dry valley or incision, the wave run-up would resemble tsunami dynamics. At Onawaga Bay in Japan, the 2011 Tohoku tsunami of 7.5 meters initial wave height ran for miles up a valley to reach a maximum height above sea level of circa 42 meters [6]. For Bridges 2013, our aim is to capture this wave motion with high-speed cameras in order to create a 3D perspex model of the bore-soliton-splash.

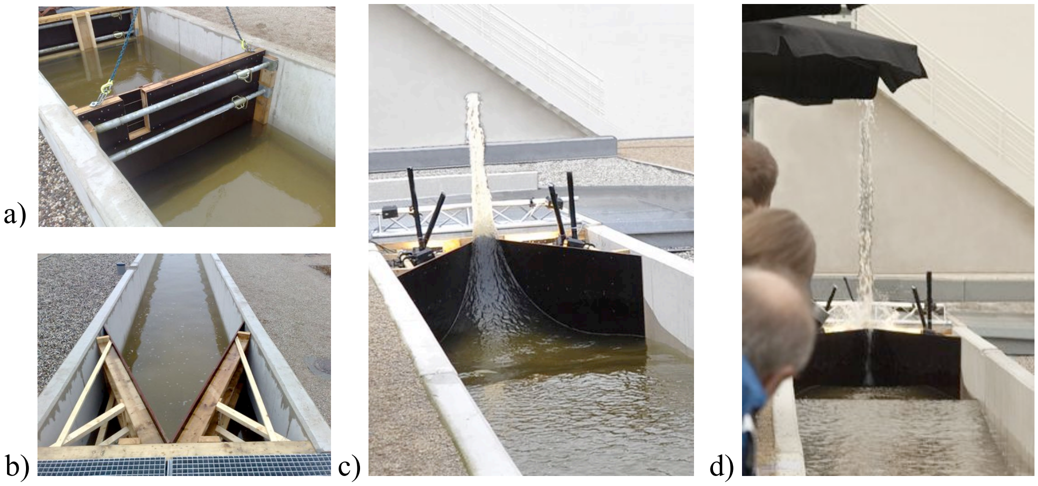

Figure 3: *The Bore-Soliton-Splash: a,b) channel before the sluice gate is pulled, and c,d) the splash.*

Conclusions

In addition to the obvious benefits as communication aids, our visualisations of nano-scale and real-world phenomena have resulted in abstract and organic motifs. These intrinsically beautiful patternings lend themselves to a wide variety of decorative, design and architectural applications. An improved understanding of dynamical phenomena, applied as a series of topographical rules, is creative work currently undertaken (independently) by Zweers and Zwart. Architectonic and design explorations, in the form of painting and sketches informed by the dynamical phenomena outlined here, will be presented. Our explorations of casting wave action in space and time are ongoing. We aim to continue these investigations through the applications of different materials, laser-cutting techniques, milling and 3D printing. For Bridges 2013, perspex versions of laminations of the four wave types are planned, as is a perspex version of the formation of the bore-soliton-splash. Additionally, the entire trajectory of the experiment's development, from initial calculations and laboratory videos and photographs through to the fabrication of the visualisations will shortly be available on a dedicated website.

References

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