

YEPPON SURF POOL: FULL-SCALE VALIDATION OF A CFD MODEL

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DHI has been supporting Surf Lakes in the design and optimization of their inland surf pool since 2017. This support has been primarily through providing CFD simulations of various aspects of the design. Whilst the CFD model was verified against basic functionality tests and qualitatively compared to the field data, no quantitative comparisons were available until February 2022, where our high-quality numerical model was compared with the field measurements. The results of that comparison and some details and challenges of the numerical model are addressed in this paper. The agreement between measured data and CFD results is excellent, demonstrating the ability to provide effective design support despite a range of numerical challenges.

Keywords: Surf Science, Wave Pool, CFD, Surfing Amenity, OptiSurf, Surf Lakes

INTRODUCTION

DHI has been involved in the study and design of multipurpose artificial surf reefs since 2009 (Mortensen and Henriquez, 2009, Mortensen, 2010). A successful example is the design of the submerged structure of Palm Beach to protect the shoreline and provide additional surfing amenity in Gold Coast, Queensland, Australia (Mortensen et al., 2015). DHI has subsequently played a significant role in the design and optimization of the Surf Lakes surf park (Mortensen et al., 2021). Early Computational Fluid Dynamics (CFD) simulations were verified against lab-scale experimental results, and the Palm Beach project has proven to be successful. Nonetheless, a quantitative comparison of full-scale surfable waves and the associated ride characteristics was not possible until early 2022, where a high-quality numerical model, used in the optimization of the Surf Lakes design since 2017, was compared with field measurements.

The Surf Lakes design is based on the heave of a symmetric cylindrical plunger in the center of a confined pool. Due to bathymetry variation in each direction, the plunger can generate up to eight different surfable waves. We use OpenFOAM®, the open-source 3D nonlinear multiphase numerical model to solve the Navier-Stokes equations on a complex geometry using a robust dynamic mesh algorithm and volume-of-fluid (VOF) solver. The results of OpenFOAM are postprocessed using OptiSurf, a numerical surf emulator developed by DHI. OptiSurf finds all surf pockets in the 3D free surface plots, then calculates the length and trajectory of the rides, the time series of the surfer speeds, barrel height, and the wave face height. In addition, surfer safety is considered by determining potential impact velocities and locations using another in-house tool, and then feedback into the bathymetry design process. This iterative process helps drive a comprehensive assessment of the wave quality from a surfer's perspective.

In February 2022, a set of field measurements were performed at Surf Lakes full-scale test facility at Yeppoon. A high-resolution camera was installed on the beach to capture the geometrical parameters of the breaking wave with the help of two survey rods installed in the pool. At the same time, a GPS was installed on the surfboard ridden by the former world champion surfer Mark Occhilupo on Occy's Peak, one of the breaks designed at the facility and named after himself. The GPS data presents the ride length, trajectory, and the surfer speed.

This paper outlines the numerical model that was developed, including early validation testing and ultimately comparison with field measurements at the Yeppoon full-scale prototype facility.

SURF LAKES, YEPPON

The Surf Lakes design is based on the heave of a symmetric conical plunger in the center of a confined pool. Due to bathymetry variation in each direction, the plunger can generate up to eight

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different surfable waves at the same time. This results in generating about 2000 surfable waves per hour, desirable for different levels of surfing skill. To the best of authors' knowledge, the technology is unique in several aspects: it is the only concentric wave generator and also the only concept that generates 8 different freely propagating gravity waves in comparison to the waves being forced by a foil or a current.

The full-scale prototype was built in Yeppoon, (QLD, Australia) in 2018, with several design guidance items using CFD results delivered by DHI the year before. Figure 1 shows an aerial view of Yeppoon pool in operation in August 2020 (Figure 1).



Figure 1. Aerial view of the Yeppoon surf pool (<https://www.surflakes.com>).

NUMERICAL MODEL

We use OpenFOAM®, the open-source 3D nonlinear multiphase numerical model to solve the Navier-Stokes equations for a fluid-structure interaction on a complex geometry. using a robust dynamic mesh algorithm and water-air interface was captured using VOF through the ‘*interFoam*’ solver. The plunger-style wave generator was moved based on the prescribed motion derived from actual full-scale plunger motions measured in the Yeppoon prototype facility. Our sensitivity study using various turbulence closure schemes found little impact to modelled surface elevations. An SST- $k\omega$ scheme was ultimately selected, predominantly because of increases in the computational efficiency due to a reduction of the maximum velocity. This occurred by dissipation of kinetic energy after wave breaking, which affects the minimum time step.

Preprocessing

To setup the numerical model, the bathymetry file was prepared in a format readable by OpenFOAM. STL format files are used for the bathymetry, plunger, pool perimeter, and central structure. These files define the solid boundaries of our CFD model.

For the Yeppoon Lake, the bathymetry surveyed by hydrometric equipment was mapped into a regular equal size grid mesh. The plunger was modelled as a moving rigid body that moves with a prescribed motion. The required motion time series were taken from the Yeppoon Lake operational records. It should be noted that this vertical movement is substantial – up to a 5.5m stroke at operational settings. All measurement tools (e.g., GPS and cameras) were synchronized with the plunger clock time.

In order to run an efficient model, horizontal mesh refinement was required. The refined zones were determined based on a uniform coarse mesh simulation, after which the surf zones were determined.

Meshing

To make the 3D numerical model in OpenFOAM, the snappyHexMesh mesh generator in combination with blockMeshDict was used. As the size of the pool is 230 by 270m and the water depth varies more than 10m, making an efficient mesh was a significant challenge. As will be shown later, our mesh convergence study indicated a mesh resolution of centimetre scale was required to capture the details of the plunging waves. As the plunger is a moving body, a dynamic mesh is needed to apply this

moving boundary condition. In the early phase of the project, we used the cyclic arbitrary mesh interface (cyclicAMI) to separate the refined zone from the rest of the model. For this model two separate meshes are made, one for the coarse area and another one for the refined area (the red rectangular region shown in Figure 2). Then the two meshes get merged and their interface is defined as a cyclicAMI boundary. This kind of boundary allows us to use different mesh sizes on the sides of the boundary, without the need to apply a mesh gradient to transition from coarse to fine mesh. The refined area covers the surf zone, so to try a new mesh size we simply take the area, refine it and merge it back to the rest of coarse mesh. While this method is promising for smaller operational plunger strokes, it fails at higher strokes because the dynamic mesh leaves some cells on one part of the cyclicAMI boundary without a pair on the other side.

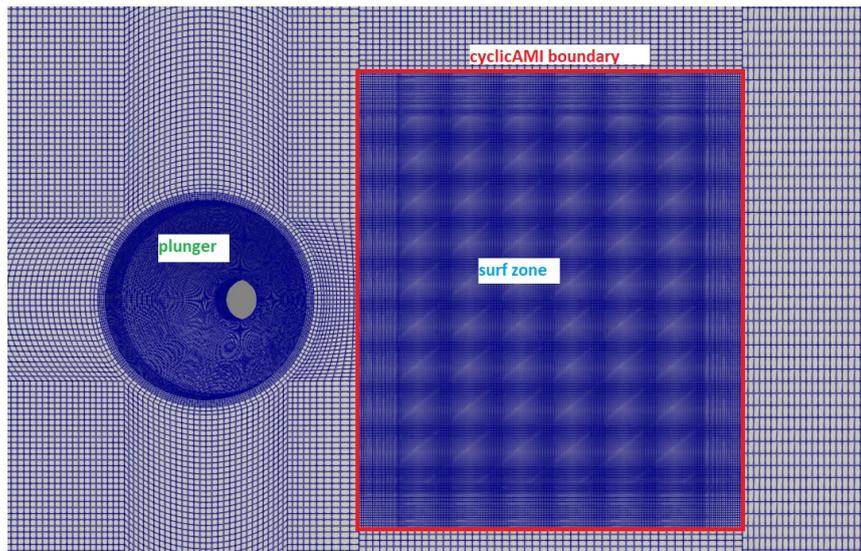


Figure 2. The application of cyclicAMI internal boundary to merged coarse mesh to the fine mesh.

Other methods were thus required. As an alternative, the whole mesh is continuous but refined at different orders, (i.e., 1, 0.5, 0.25, 0.125, and 0.0625m shown in different colors in Figure 3). To produce a stable mesh, we apply snappyHexMeshDict two times, first to refine the refined areas of a regular cubic mesh, then to snap the solid boundaries. The surf zone refinement can be any irregular shape defined by a *.stl file.

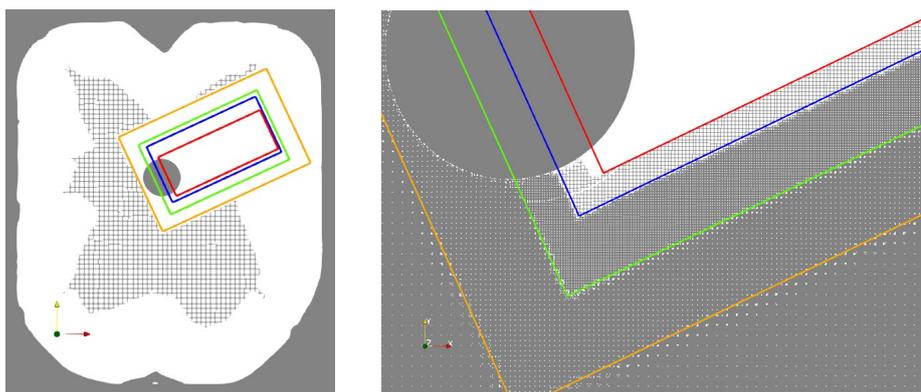


Figure 3. The continuous mesh refined at different levels of 1, 0.5, 0.25, 0.125, and 0.0625m.

Dynamic Mesh Solver

The problem we are solving is a complex fluid-structure interaction. In the older versions of the CFD model, “*sixDoFRigidBodyMotion*” was used. To apply a prescribed tabulated motion, we used “*displacementLaplacian*” where, mesh diffused with *inverseDistance* function from the plunger. We also tried *dynamicOversetFvMesh*, which was computationally less efficient and less accurate than *dynamicMotionSolverFvMesh* for this problem and configuration.

Mesh Convergence

A sensitivity study of our CFD model was performed by reproducing the regular deep-water wave generated by a plunging wedge-type wavemaker in a horizontal bed flume (Kashiwagi 1996, He et al. 2021). The wave gauge is a distance of $4.5L$ from the wave maker, where L is the wavelength. These tests showed that wave dissipation in the CFD model was about 20% larger than the experimental results, however mesh convergence was achieved for various settings and configurations (Figure 4). These results were taken forward to a further study that considered the shallow water conditions in Yeppoon.

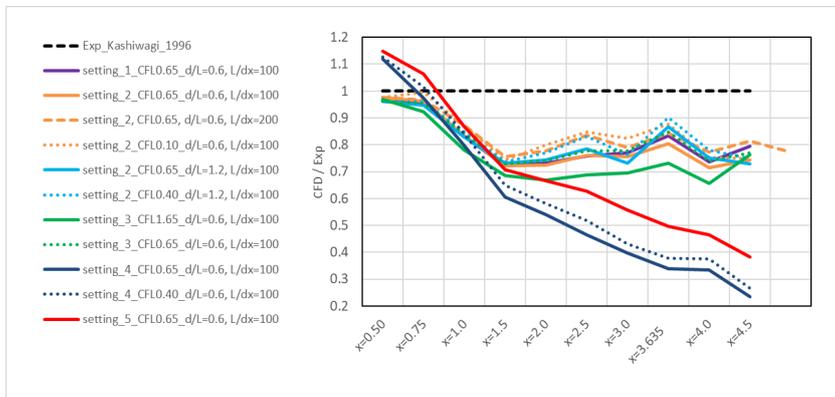


Figure 4. The effect of different CFD settings on the wave height at different distances from a wedge-type wavemaker.

For a typical operational plunger period of 6s, the ratio (d/L) of water depth (d) to wavelength (L) at Yeppoon is always less than 0.25 (Figure 5), indicating a simple shallow water wave flume is required to further test our numerical settings. We used the best setting found in the wedge-type tests (setting_2 in Figure 4) and made a piston-type wave maker in a 2D numerical wave flume of 0.25m depth, and simulated three different wave periods (1, 2, and 3s) to represent the shallow water conditions in Yeppoon.

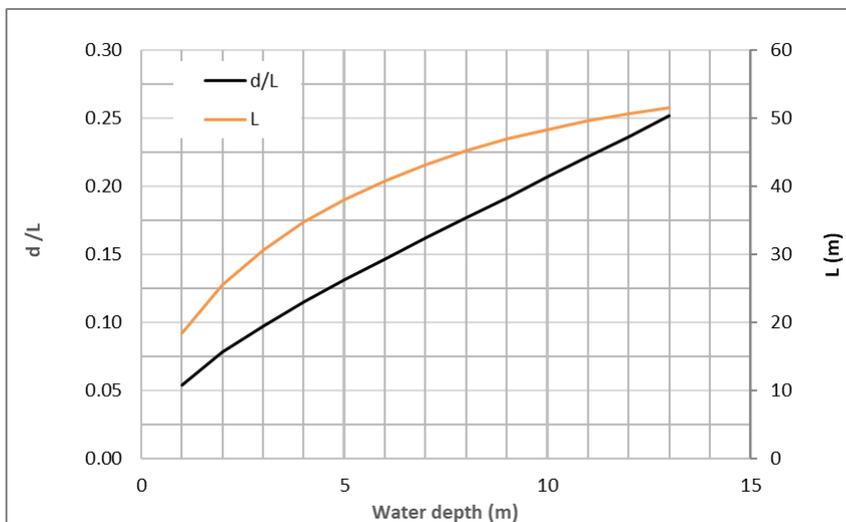


Figure 5. The wavelength (L) and water depth to the wavelength ratio (d/L) in Yeppoon.

These results show that in very shallow conditions ($d/L < 0.1$) the piston-type test overestimates the wave height by more than 10%, while for $0.25 > d/L > 0.1$, the dominant condition in Yeppoon, the model is promising provided sufficient vertical resolution is considered (Figure 6). We conclude that setting_2 is sufficient for a shallow water case with the depth to wavelength conditions similar to Yeppoon, to be taken forward for further testing, provided the vertical resolution is sufficient.

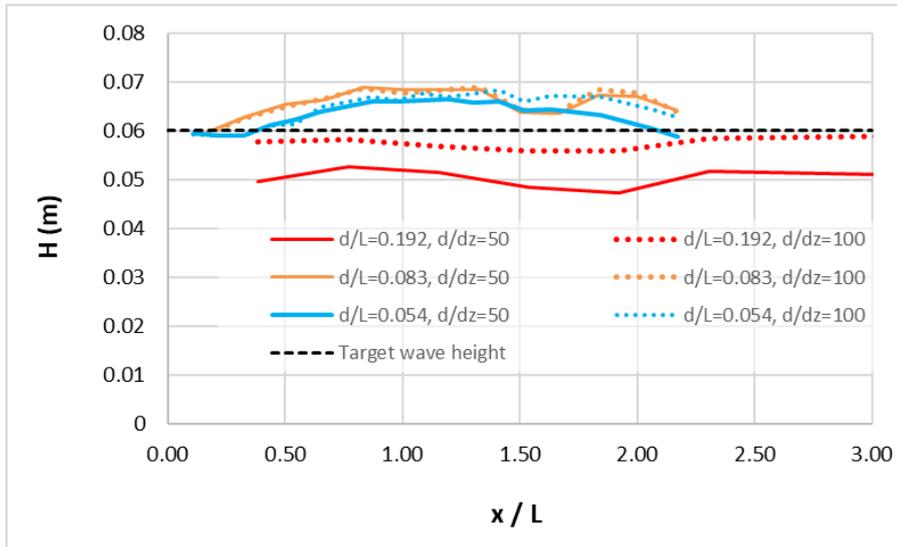


Figure 6. Wave height (H) at different distances (x/L) from a piston-type wavemaker for different depth-to-wavelength ratio (d/L) and vertical resolution (d/dz). The target wave height is 0.06m.

The final mesh resolution and time step study conducted was to apply these settings to the full-scale model of Yeppoon, where the plunger moves with operational strokes of up to 5.5m. The main mesh is uniform with 1m resolution, with the area shown in the red square (Figure 7) refined layer by layer. Wave height values measured at different locations inside the refined zone are compared for decision making. Most of the sensitivity study was done using mesh refinement A (right frame in Figure 7). The maximum wave height at different locations shown by their horizontal coordinates with respect to the plunger's center are summarized in Figure 9.

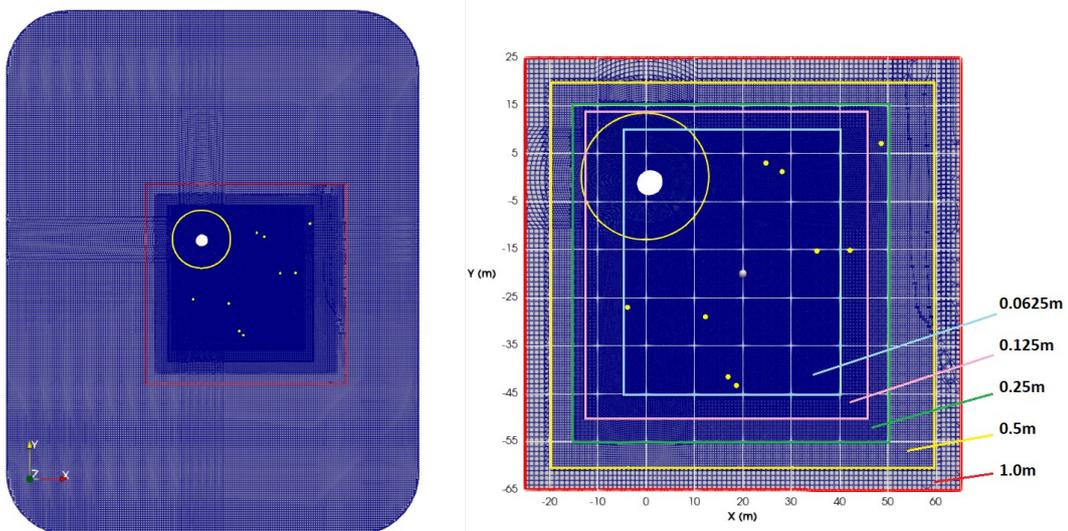


Figure 7. Mesh resolution used in the mesh convergence study for Yeppoon. The right frame is the blown-up region of the red box on the left frame which shows the top view of the whole mesh (mesh_A).

This study shows that a time step of 0.02s and mesh resolution of 0.125m represents a suitable compromise between wave height convergence and CPU cost. This, however, is not sufficient for this work - accurate barrel shapes are required, which necessitates the use of a mesh resolution of 0.0625m in the surf zone and a variable time step based on a small CFL number of 2.5 or smaller. Our results show that with a variable time step during wave breaking, the time step goes to as small as 0.001s. This is impractically small for engineering design purposes, thus applying a fixed time step is not recommended for wave breaking problems.

Application a refined mesh increases the number of cells, so we developed a different mesh which refines only the surf zones based on coarse mesh simulations. This mesh (mesh-B) is shown in Figure 8. We added two more simulations with mesh-B to the convergence study that confirm a reduced mesh with an irregular customized refinement zone is as good as the original regular mesh.

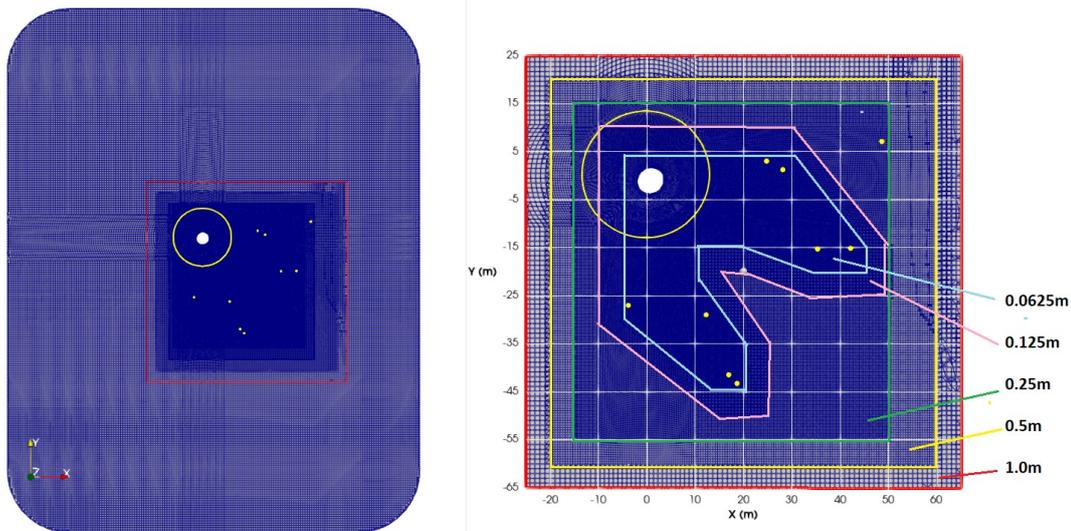


Figure 8. Mesh resolution used in the mesh convergence study of Yeppoon. The right frame is the blown up of the red box on the left frame which shows the top view of the whole mesh (mesh_B).

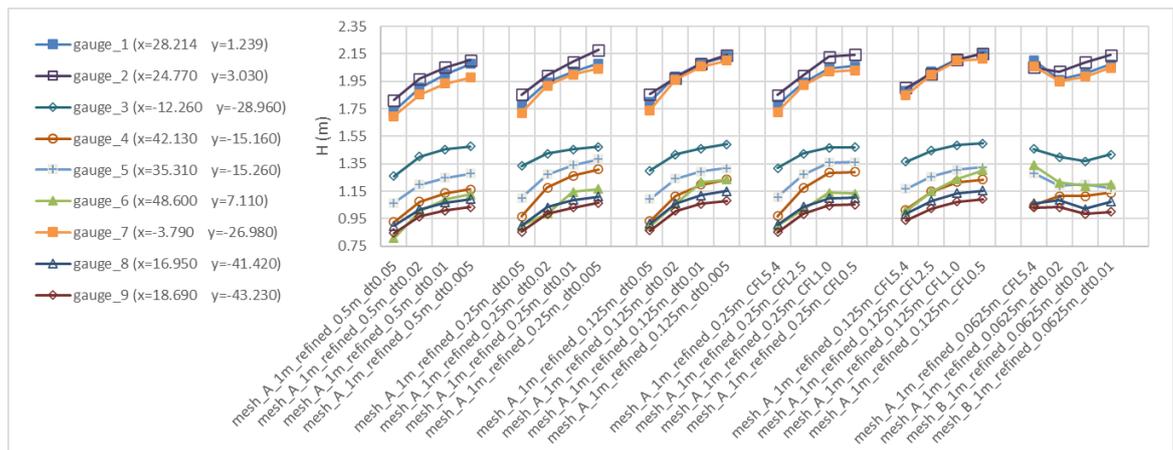


Figure 9. Wave heights at different (x,y) locations inside Yeppoon pool (yellow dots in Fig. 7, 8) for different meshes, spatial and temporal resolutions.

Post-processing

Outputs of our OpenFOAM model result in a number of different files. The free surface iso-surface plots which show the wave elevation are produced at 10 Hz. These files can be easily visualized in ParaView, a free-license tool, despite their huge size. Animations can easily be made to show the wave propagation. For high quality videos, we use Blender in the combination with our Python/MATLAB codes. Time series of water elevation, velocities, can be calculated at pre-defined probes during the simulations or can be derived from the free-surface plots in post-processing. Vertical cutting planes at

pre-defined locations can also be used to evaluate the vertical view of the simulations. These cutting planes are also used for surfer safety studies. In addition, forces (including pressure and shear stress forces) on the plunger, caisson, pool bed, are calculated for civil design purposes.

OptiSurf. A Lagrangian type surf emulator, capable of analysing all surfable sections of the break wave and stitching them together into surfable rides. The tool also analyses surfing quality and performance metrics taking surfer ability into consideration. The details of this tool can be found in Mortensen et al. (2021). OptiSurf results are post processed to provide the length and trajectory of the rides, the time series of the surfer speeds, barrel height, and the wave face height.

Surfer Safety. Surfer safety is considered by determining potential impact velocities and location using another in-house tool, and then fed back into the bathymetry design process. The model takes vertical wave-generated current velocities on the vertical planes, separated by 0.5m, then assumes an adult body falls off the surfboard and is advected by the flow using appropriate drag formulations. The model checks to see if the fallen surfer hits the pool bottom, and if so at what impact speed. This information is used in the civil and bathymetry design.

All these post-processing studies applied in an iterative process helps drive a comprehensive assessment of the wave quality from a surfer's perspective.

RESULTS

We present results from Yeppoon over two campaigns: the first includes the application of two pressure-transducer wave gauges on 20 and 21 August 2020, supported by video records during the measurements. The second test was on 19 Feb 2022, where experience from the first test campaign led us to return to the pool with more equipment including GPS sets, high-speed cameras, and survey bars to do more accurate real time recording of the surfer and wave motions.

August 2020

The time series of pressure measured by four pressure-transducers was translated to water elevation. The gauges were in an offshore part of the pool, where wave was non-broken. While the results were consistent, they were not showing the right wave elevation. The conventional understanding is that CFD models result in a smaller wave elevation than measured due to numerical dissipation. However, this was not supported by the wave gauges. From four measurements during two similar tests, one gauge showed the measured wave height to be 8 percent smaller than the CFD results, while the other three gauges showed on average 50 percent smaller measurements than the CFD. Further investigation was done through simple image processing of the recorded videos for those tests. A snapshot of the wave at the breaking point was scaled based on the surfer's height. The measured wave height at different locations on the wave front are shown in Figure 10. The average wave height is 2.46m, comparable to 2.33 calculated from CFD simulations, with a 5 percent difference. This confirmed that wave gauge data were not reliable. Having determined this, and inspired by our simple image processing, we were looking for the next possible test campaign to do more accurate field measurement with the help of the digitized images. Due to the Covid lockdowns, this opportunity only became available in February 2022.

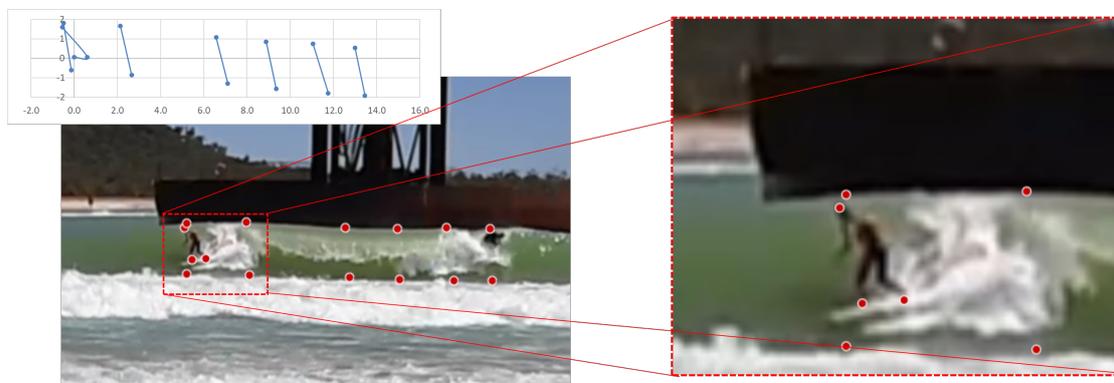


Figure 10. Finding wave heights from video records.

February 2022

In February 2022, a set of field measurements at a 4.2m stroke were performed at Surf Lakes full-scale test facility at Yeppoon. A higher resolution camera was installed on the beach to capture the geometrical parameters of the breaking wave with the help of two survey rods installed in the pool. At the same time, a GPS was installed on the surfboard ridden by former world champion surfer Mark Occhilupo on Occy's Peak, one of the breaks designed at the facility and named after him. The GPS data presents the ride length, trajectory, and the surfer speed. In the right frame of Figure 11 the location of camera and survey rods with respect to the plunger (shown in red circle) are shown. The left frame of this figure shows the survey rods in the surf zone of Occy's Peak.

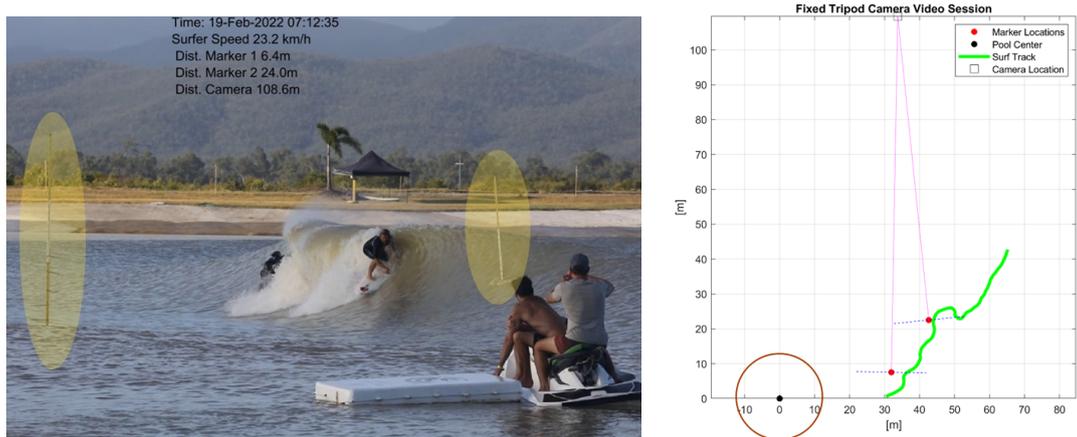


Figure 11. Location of the camera and survey rods in measuring wave characteristics during one of Mark Occhilupo's measured rides.

GPS-based results. The CFD results of the surfer trajectory, computed assuming different riding speeds (i.e., 22, 30 and 31 km/h), were compared with 3 of Occy's measured rides. The riding speed is the speed over the ground that a surfer can attain, with more skilled surfers able to attain a higher speed.

This comparison shows that surfer's trajectory, for design purposes, is predicted by the CFD model extremely well (left frame in Figure 12). The measured and numerical ride lengths are also compared and show excellent agreement (middle frame in Figure 12). Furthermore, the surfer's speed time series for four rides are also shown in the right frame of Figure 12. While the average speed of ride number 6 is around 22 km/h for the whole ride, the other rides start with a high speed of 30km/h and reduce to around 22km/h or less in the second part of the ride as the surfer modifies their position to maximise the ride length. So, the assumption of 22km/h and 30 km/h applied in the calculations is reasonable.

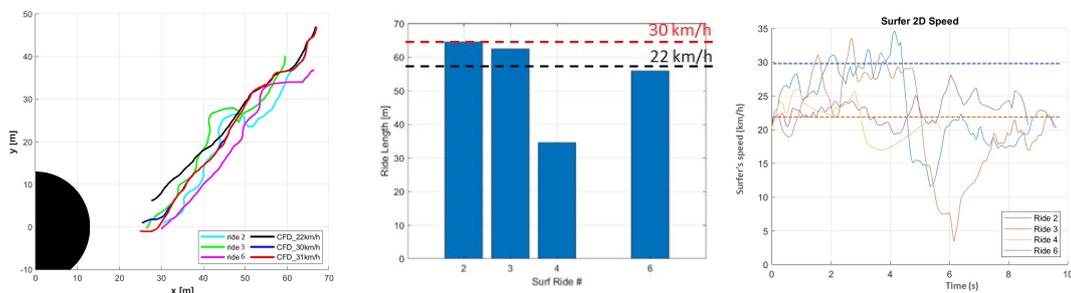


Figure 12. Comparison of CFD results to the pool measurements. Left) 2D surfer's trajectories middle) maximum ride length (dashed lines are from CFD results), and right) surfer's speed time series.

Camera-based results. Combining the GPS information on the location of the surfer at each time with the snapshots captured by the camera, we were able to determine the distances (Figure 11), and from that measure the wave and barrel. In Figure 13 one of these snapshots is compared to one slice of the CFD results. An ellipse is used to show the barrel size on both frames. Although putting a 2D graph

on a picture that shows a 3D view is not satisfactory, we can still see the general agreement of these two snapshots (Figure 14).

The most valuable part of this study is the comparison of wave characteristics measured in the pool to the numerical model results. This detailed comparison is summarized in Table 1 and shows the wave height (H) is in outstanding agreement and the barrel height (Barrel H) is also predicted well. The largest difference, still less than 20%, is for barrel width (Barrel W) and lip thickness. These parameters are illustrated on the right frame of Figure 13. The maximum ride length shows only a 5% difference. It is our view that those few centimeters of difference are in the order of both the model and measurement accuracies and the engineering judgment used in the evaluation of these parameters.

It is also useful to compare these results with those from other artificial wave pools. Feddersen et al (2023) take detailed measurements at the Kelly Slater Wave Company Surf Ranch and show barrels of similar dimension to those measured and simulated here (barrel aspect ratio 0.3 – 0.4). This indicates our model potentially has broad applicability to the simulation of surfable waves.

The conclusion is that our CFD model is well-calibrated and verified to support the design and optimization of Surf Lakes surfing pools, where shallow water conditions apply, and the travel distance of the waves is much less than their wavelengths.

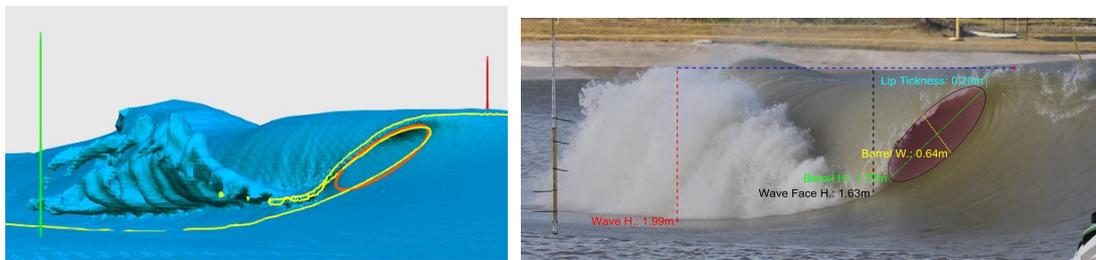


Figure 13. Snapshots of wave and barrel: left) CFD right) Field. Wave characteristics derived from image processing are shown.

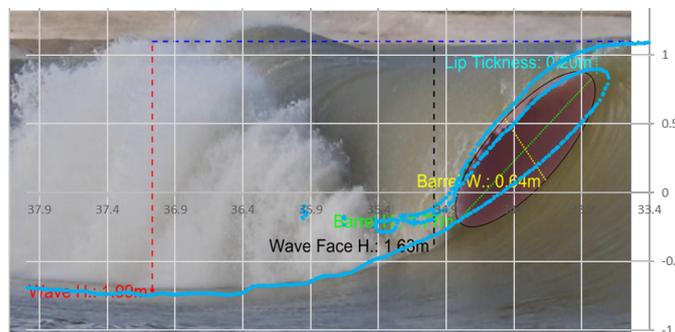


Figure 14. Snapshots of wave and barrel from CFD (blue dots) are shown on top of the barreled wave captured by the camera.

Table 1. Wave parameters: CFD vs. Field measurements. All measurements in metres.			
Parameter	Field	CFD	Difference %
Wave H	1.99	1.98	0.7
Barrel W	0.64	0.52	18.9
Barrel H	1.77	1.73	2.3
Wave Face H	1.63	1.77	-8.6
Lip Thickness	0.2	0.24	-19.0
Max Ride Length	60.7	63.9	-5.3

SUMMARY

In this paper, a summary of the validation of our state-of-the-art CFD model was presented. The model is used in the design and optimization of different artificial reefs and wave pools for improving

surf amenity. One of the main projects that DHI has been involved in for several years is Surf Lakes wave pool, with the full-scale prototype built at Yeppoon. We used the field data measurements from GPS connected to the surfboards and high-speed cameras with the support of survey rods to validate our numerical model. Several numerical validation tests (in deep and shallow water) and meshing techniques, used prior to the field validation, were also discussed in this paper. A systematic and quantitative CFD method for optimizing wave pool quality has been generated. Comparison to measured data has been well within the tolerance required for effective and quantitative design support.

Ongoing work is assisting the development of a new generation of diverse and high-quality Surf Lakes surfing experiences worldwide. At the same time, the continuous development of our CFD tools to improve the computational efficiency and adding new features is in process.

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