DETAILED INVESTIGATION OF SURFING AMENITY USING CFD

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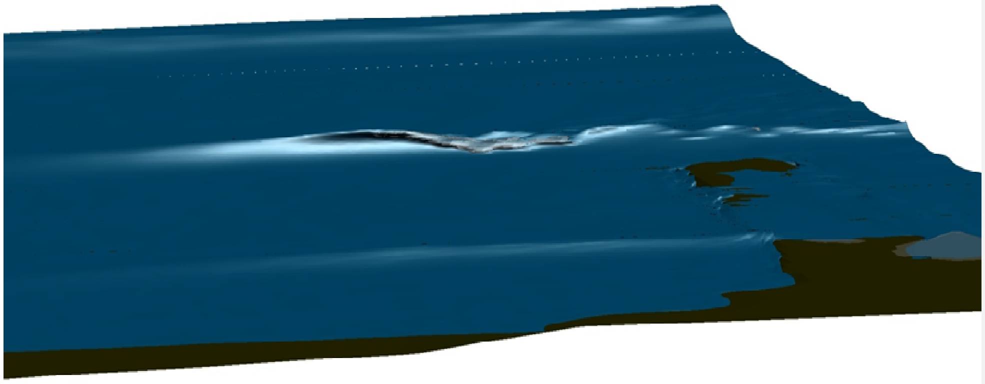

ABSTRACT

Recent advances in CFD modelling have now made it possible to adopt a new improved method to quickly and cost effectively integrate a detailed investigation on surf quality impacts into a wide range of coastal projects involving elements such as surfing reef design, dredging/by-pass operations and coastal protection.

Using a fully non-linear Volume of Fluid (VOF) wave model it is possible to model breaking waves explicitly and highly accurately, which allows for a much more detailed investigation of the performance of a surfing reef design or the impacts on surf quality in response to an altered bathymetry for an existing surf spot *(Mortensen 2009)*. By coupling with a Boussinesq wave model the influence of greater scale transformations to the incoming wave field such as from large headlands and offshore wave focusing bathymetric features can be included.

A world famous surf spot in Southeast Queensland was used as a case study to investigate the impact on surf amenity caused by a large scale changes in near shore bathymetry. It was found that the coupled CFD approach was a useful tool in quantifying and visualising the change in surf zone characteristics in response to the altered bathymetry.

INTRODUCTION

Incorporating the assessment of surfing quality into coastal management is a relatively new phenomenon, which has received growing attention following the gradual public acknowledgement of its importance and value to coastal communities (Lazarow, 2007). Previous studies have focused on developing a framework for assessing the socio-economic value of surfing amenity, while others have emphasized technical assessment of surfing quality itself. A comprehensive review of recent work is presented in (Scarfe, 2009).

Providing an efficient approach to carrying out coastal impact assessment studies with respect to surfing, requires a well developed toolset for accurate and cost-effective quantification of possible changes in surf quality in order to predict the associated socio-economic impact in response to proposed developments in the coastal zone.

Technically assessing surf quality has so far been established through a set of quantifying parameters that describe breaking wave characteristics that are important with respect to surfing. Among the most established parameters are wave peeling angle, peeling speed, surf intensity, wave height and length of ride (Hutt, 2001). The purpose of these has been to provide a measure of the difficulty and intensity of the surf ride thus linking surfing quality to the level of skill of the practitioner. An expert surfer will be able to generate more speed relative to the wave and thereby ride wave sections with low peeling angles/fast peeling velocity. He will also be better at negotiating sections with higher breaking intensity (surf. Term: riding inside the barrel) and be comfortable in larger waves compared to an intermediate surfer. In the extreme case of very challenging waves, the possible ride of the expert surfer might be long and extraordinary, while completely impossible by surfers of less skill. This leads to a spread in perceived surf quality and preference as also previously discussed in (Jackson, 2002).

In this paper a new tool for enhancing the assessment of surfing quality using a state-of-the-art CFD approach is introduced, where the 3-dimensional transformation and breaking processes of a surf able wave are resolved directly and a corresponding surf quality assessment matrix for multiple surfer profiles carried out explicitly.

NUMERICAL MODELS

A 3D coupling of the weakly non-linear Boussinesq wave model MIKE21 BW and the fully non-linear finite volume VOF model NS3 has been used to calculate the wave transformation and breaking across the domain.

MIKE 21 BW is a weakly non-linear time-domain wave model based on the enhanced two dimensional Boussinesq equations based on a depth integrated flux-formulation derived in Madsen et al. (1997) and presented below.

$$\frac{\partial \eta}{\partial t}+\frac{\partial P}{\partial x}+\frac{\partial Q}{\partial y}=0 \qquad (1.)$$

$$\frac{\partial P}{\partial t}+\frac{\partial}{dx}\left(\frac{P^2}{d}\right)+\frac{\partial}{dy}\left(\frac{PQ}{d}\right)+\frac{\partial R_{xx}}{\partial x}+\frac{\partial R_{xy}}{\partial y}+gd\frac{\partial \eta}{\partial x}+\psi_x+\frac{\tau_x}{\rho}=0 \qquad (2.)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{dx}\left(\frac{Q^2}{d}\right)+\frac{\partial}{dy}\left(\frac{PQ}{d}\right)+\frac{\partial R_{yy}}{\partial y}+\frac{\partial R_{xy}}{\partial x}+gd\frac{\partial \eta}{\partial y}+\psi_y+\frac{\tau_y}{\rho}=0 \qquad (3.)$$

MIKE 21 BW simulates the properties of propagation of irregular, directional waves into harbours and across regional coastal areas taking into account effects like wave-wave interaction, shoaling, depth refraction, diffraction, bottom friction, partial reflection from porous structures. Wave breaking is accounted for using a surface roller concept assuming that the effect of wave breaking can be modelled by imposing a volume of water (a roller) on the wave front (from the moment of breaking) travelling with the wave celerity. This change in the wave velocity profile leads to an excess in momentum, from which the radiation stress terms R_{xx}, R_{yy} and R_{xy} in the evolution equations can be obtained.

The fully non-linear hydrodynamic model NS3 was previously described in (H. Bredmose (2006). The model consists of a fully non-linear 3D Navier-Stokes solver with a Volume of Fluid (VOF) treatment of the free surface. The viscous forces are neglected reducing the Navier-Stokes equations to the Euler equations, which are given below.

$$\frac{\partial u_i}{\partial x_i}=0 \qquad (1)$$

$$\rho\frac{\partial u_i}{\partial t}+\rho\frac{\partial u_i u_j}{\partial x_j}=\rho g_i-\frac{\partial p}{\partial x_i} \qquad (2)$$

Here u_i are the three velocity components, g_i is the gravity vector, p is the pressure, and ρ is the fluid density. The free surface motion is governed by the kinematic boundary condition where a particle on the free surface follows the fluid velocity. The kinematic boundary condition is included by extrapolation of the velocities within the fluid domain to the surface and through the use of the Volume of Fluid method. The dynamic boundary condition in the case of an inviscid fluid is given as:

$$p_{surf} = p_{atm} \tag{3}$$

where the atmospheric pressure is set to zero in the computations. The hydrostatic pressure of the still water is subtracted from the pressure field, such that the excess pressure is the computational pressure variable. . This approach improves the numerical accuracy and removes the gravity term in (2). In terms of excess pressure, the dynamic surface condition for the free surface (3) becomes

$$\tilde{p}_{surf} = \rho g_i r_i \tag{4}$$

Where r_i is the position vector of the free surface relative to a fixed reference point on the still water level. The free surface is resolved using a VOF description. A scalar function F is assigned a value of 1 within the fluid domain and 0 in the void domain. This method was first described in (Hirt and Nichols, 1981) and with an improved scheme for the advection of the conserved quantity F cf. (Ubbink, 1997). The grid is fixed, while F moves with the fluid. F = 0.5 determines the position of the surface. The spatial discretisation is based on the finite-volume approach on a multi-block grid. The time-integration of the equations is performed by application of the fractional step method. The CFD-code solving the Navier-Stokes equations as sketched above has been used and validated in (Mayer, 1998), (Nielsen, 2001), (Christensen, 2006), (Bredmose, 2006), (Nielsen, 2008) and (Mortensen, 2009).

ASSESSING SURF AMENITY USING CFD

The numerical modelling approach was applied to assess the difference in surfing amenity at a world famous surf spot during the same large south swell in response to two difference layouts with regards to near shore bathymetry. Layout 1 represents a sediment starved stage of the near shore bathymetry while Layout 2 represents a highly nourished stage.

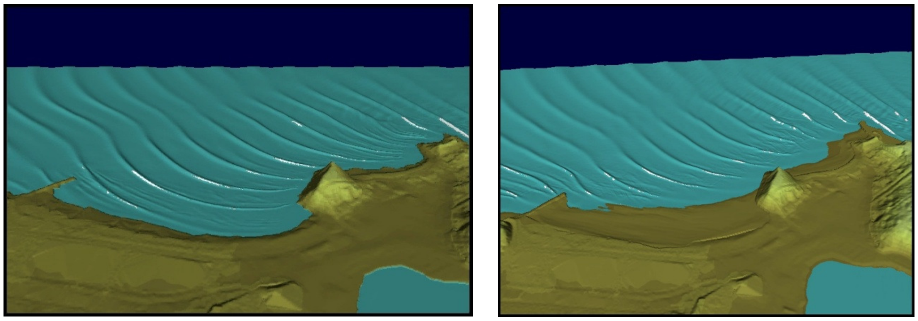

Figure 0-1 – Regional scale wave modeling using Mike21 BW for Layout 1 (left) and Layout 2 (right)

The Boussinesq wave model domain was set up for a domain of 10 square kilometres covering the greater coastal area in the vicinity of the surf spot, allowing the extensive wave refraction and shoaling processes around the nearby headland to be resolved. At the eastern and southern offshore boundary, a 3rd Order Stokes wave condition was applied. The wave height was 3 m, wave period 15 seconds and the wave direction was 165 degrees.

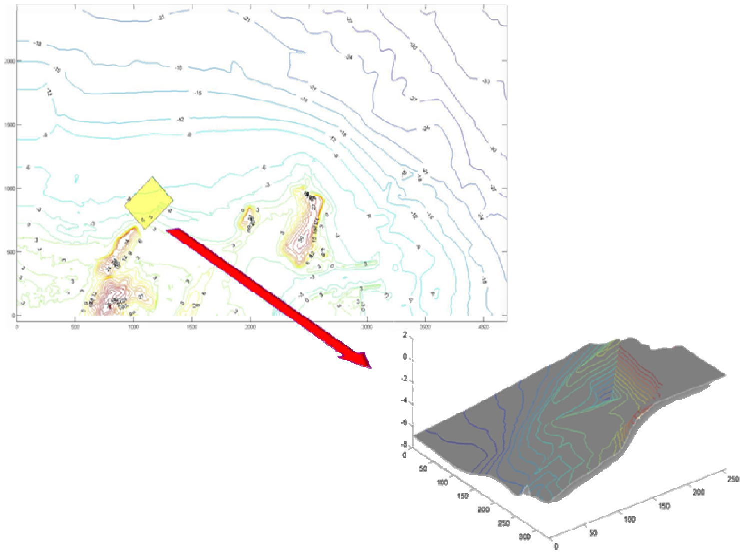

Figure 0-2 - Illustration showing the nesting of the two wave models.

From the Boussinesq domain bathymetry the detailed 3D model domain for the fully non-linear VOF model was extracted. The detailed model domain dimensions were 250 m wide and 420 long. The water depth at the detailed model offshore boundary extended from 5 m at the eastern corner to 7.6 m in the western corner. Based on a three-line output of surface elevation, u and v velocities obtained from the Boussinesq model, the 3-dimensional velocity field can be calculated using Boussinesq theory invoking a 9-point stencil central differencing approach.

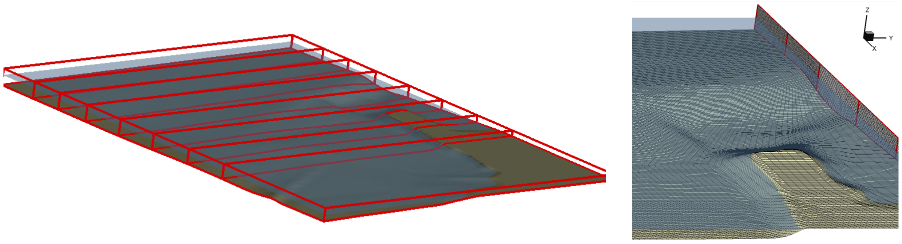

Figure 0-3 - The Multi-block grid used for the numerical simulation.

The computational domain for the detailed 3D model was divided into 8 rectangular block grids each with a cell resolution of 64 x 128 x 32 (longitudinal, transversal, and vertical) yielding a total number of 2097152 cells. Linear stretch functions were applied to assure a smooth transition in cell size between blocks and to increase the transversal grid resolution in the vicinity of the reef structure while allowing for a coarser resolution in the far field. The smallest computational cell measured 40 cm x 91 cm x 23 cm.
The maximum water depth was 7.6 m and the upper boundary of the computational domain was located 5 m above the still water line. The height of a nearby groyne was reduced to 0.5 m above MSL in order to improve computational run-time by preventing excessively thin cells in the domain.

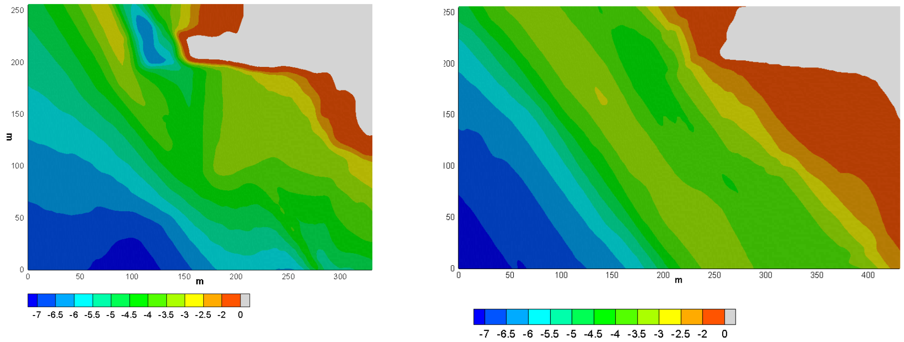

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Figure 0-4 – Differences in near-shore bathymetry at the surf spot location between Layout 1 (left) and Layout 2 (right).

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For each simulation, complete spatial surface elevation time-series are extracted which are used to analyse the 3D breaking wave characteristics with regards to surfing quality using the program OptiSurf. From the detailed wave model output, OptiSurf calculated the longest possible ride for each wave propagating through the domain based on a user specification of the skill level of the surfer.

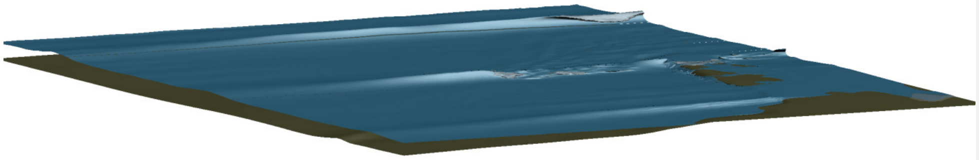

Figure 0-5 – 3D visualisation of wave breaking in NS3

One of the founding principles used in OptiSurf is that the possible ride length and intensity depends on the surfer’s skill level and the surf craft he is using. An expert shortboard surfer would be able to travel faster and place themself in more critical parts of the wave (e.g. the barrel) compared to a novice and thus maximum possible length of ride could be longer. If the surfer was riding a longboard, its extra bouyancy would allow the ride to start earlier in the wave-breaking cycle and sustain speed during smaller and less steep parts of the unbroken wave face, the resulting ride would be different and under some circumstances allow a less skilled surfer a longer ride compared to if a shortboard had been ridden. In OptiSurf the surfers skill and preference is quantified as his preferred steepness, the curl of the wave-face and his maximum possible speed, from which the longest possible ride for each wave is calculated and output time series of surfer position, speed and wave face height and steepness are produced.

RESULTS

The difference in surf quality at a world class surf spot has been analysed by assessing the respective response to a significant change in bathymetric layout when subject to the same large offshore swell condition.

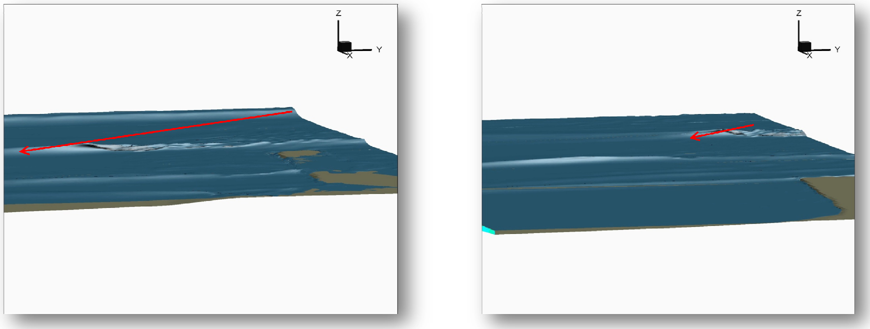

Figure 0-1 – Breaking wave propagation through the domain for Layout 1 (left) and Layout 2 (right)

From visual inspection of the model results alone it is easy to notice a difference in wave breaking pattern in response to the two bathymetric layouts. For both layouts the wave breaks from left to right (*surf term: right-hander*), with initial breaking occurring offshore the adjacent groyne. While the surf-able wave section, defined as the transition zone from non-breaking to breaking wave, occurs over a long continuous stretch for Layout 1, the respective surf-able stretch is significantly smaller for Layout 2. Additionally it was noticed that the initial breaking wave height is also smaller and the steepness of the unbroken wave face close to the break point is less compared to Layout 1.

An example of two surfer profiles quantified through their maximum possible speed, surf craft and required wave steepness is listed in the table below. The categorized values are to be taken as rough estimates and not based on detailed studies.

Table 1 – Surf profiles

Surfer Profile:	Surf Craft	Maximum speed relative to wave	Required wave steepness for take-off
Expert	Shortboard	18 m/s	50 degrees
Intermediate	Shortboard	9 m/s	50 degrees

Using OptiSurf the longest possible ride for an expert and intermediate surfer respectively was calculated for the two scenario runs. Analyzing the gradient and curvature of the surface elevation time series calculated by the numerical model, it was possible to establish a surfable time window across each subsection of the wave linked with a corresponding geographic location.

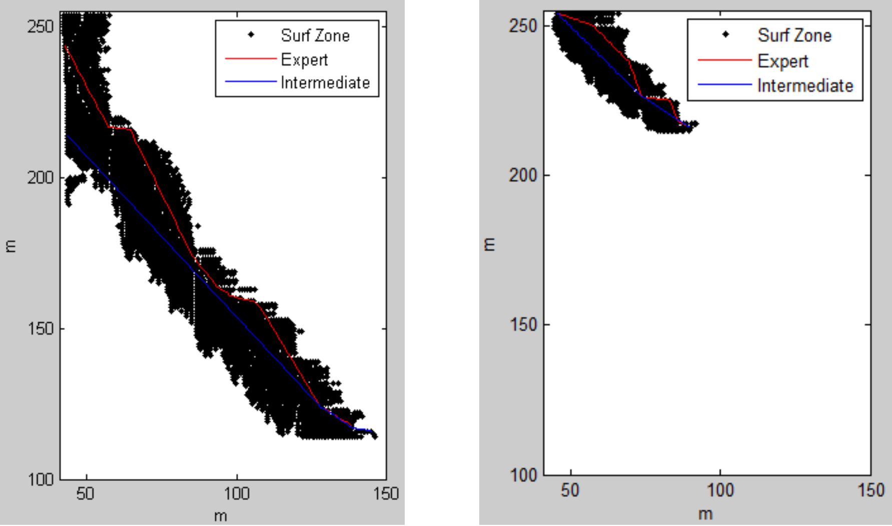

Figure 0-2 – Longest possible ride for layout 1 (left) and layout 2 (right)

Using an iterative vector-based scheme, OptiSurf calculates the longest possible ride based on the maximum possible speed of the surfer. In the first iteration the surf ride begins *(surf term. Take-off)* at the first section along the wave that becomes steep enough to be ride able. After the ride has commenced the surfer will go as slow as possible in order to stay as close to the break point as possible *(surf term. The Pocket)* which is the section of the wave allowing the surfer to carry out the largest range of manoeuvres. If the surfer reaches a wave section that is no longer ride-able, his speed in the previous section will be increased until the new section is passable. If it is found that the surfer cannot pass a breaking wave section even travelling constantly at his maximum speed the ride ends and a new ride is commenced starting 1 m further downstream from the initial break point thus placing him closer to the impassable wave section in the previous ride attempt. The iteration continues until the end of the surf able wave is reached.

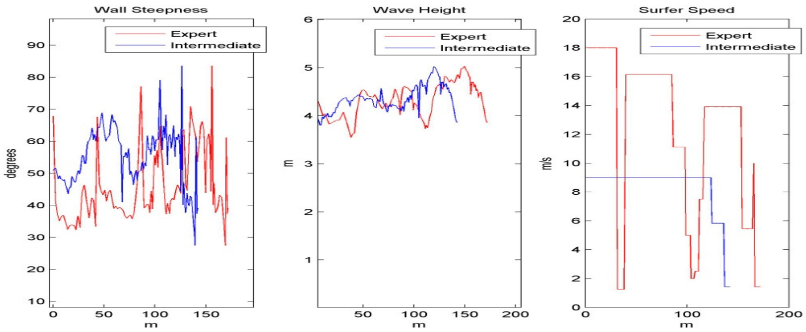

Figure 0-3 – time-series of wave steepness, wave height and surf speed experienced during longest possible ride (Layout 1)

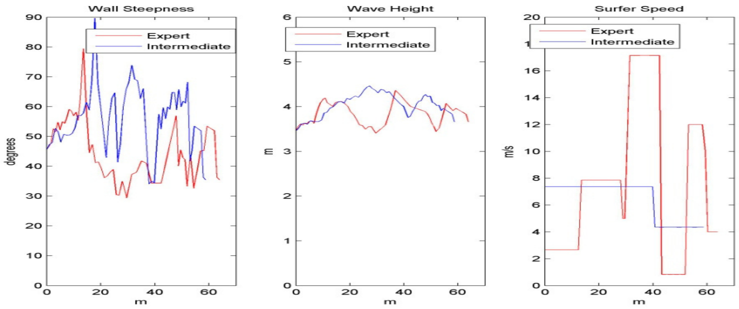

Figure 0-4 – time-series of wave steepness, wave height and surf speed experienced during longest possible ride (Layout 2

For each calculated ride, time-series of relative surf speed, wave steepness and wave height at the surfer's position are produced along with total ride time and ride length. The relative surf speed is defined as the mean speed the surfer has to travel in a direction parallel to the wave crest in a coordinate system moving with the wave celerity in order to make it past each breaking wave section. The wave steepness in this context only refers to the mean gradient of the unbroken section of the wave face under the surfer. The wave height is defined from crest to trough at the position of the surfer.

Table 2 – Comparison of maximum length of ride

Length of Maximum ride			
Skill level	**Layout 1**	**Layout 2**	**difference**
Expert	171 m	64 m	-63 %
Intermediate	142 m	59 m	-58%

Table 3 – Comparison of mean wave height

Mean Wave Height			
Skill level	**Layout 1**	**Layout 2**	**difference**
Expert	4.3 m	3.8 m	-12 %
Intermediate	4.3 m	4.0 m	-7 %

Table 4 – Comparison of mean wave steepness

Mean Wave Steepness			
Skill level	**Layout 1**	**Layout 2**	**difference**
Expert	46 deg	45 deg	-2 %
Intermediate	54 deg	55 deg	2 %

Table 5 – Comparison of mean wave speed

Mean Wave Speed			
Skill level	**Layout 1**	**Layout 2**	**difference**
Expert	10.8 m/s	6.2 m/s	-43 %
Intermediate	8.2 m/s	6.2 m/s	-24 %

From Table 2 through Table 5 it is observed how the longest possible ride length for both expert and intermediate surfers are between 58-63 % smaller for the Layout 2 domain compared to Layout 1. The average wave height is 7-12% smaller and the surfer speed is reduced by 24-43%. Only minor differences in wave steepness are experienced.

CONCLUSION

The purpose of the present work was to present an example case of how detailed CFD modelling could be used as an efficient tool in providing a thorough quantitative assessment of the changes in surfing amenity in response to changes in coastal morphology. This allows for efficient integration into greater scale coastal impact assessment studies, where surfing amenity is important.

A coupling between the Boussinesq wave model Mike21 BW and the state-of-the-art CFD model NS3 was used to numerically reproduce the complex wave field at a famous surf spot for a large south swell condition using two different bathymetric layouts. The program OptiSurf was used to analyse the surf characteristics based on the results of the numerical model and provide a framework for assessing the difference in surf amenity through a selection of representative surf quality parameters. The CFD analysis illustrated and quantified how the difference in bathymetry caused a significant variation in surf quality for both expert and intermediate surfers during a 3 m long-period south swell.

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