Breaking wave uplift and overtopping on a horizontal deck using physical and numerical modelling

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Abstract

Wave loading and overtopping of a heavy-load wharf has been studied using two models. A 1:15 physical model of the deck, piles and under-slope revetment is compared with a CFD numerical model. Uplift pressure along the deck, flow in the impact zone, deck overtopping and air-water interface have been compared.

CFD modelling is a useful tool to evaluate several wharf design configurations, to reduce wave-loading uncertainties and to produce design innovation. The mathematical equation limitations, the computation power available and the numerical solution accuracy limit the numerical modelling quality. It is recommended that CFD model results be compared with scale testing and field observations to validate design choices and optimise the wharf layout.

1 Introduction

Xstrata-Nickel (Formerly Faulconbridge SAS) and SMSP (Sociètè Minière du Pacifique Sud) investigate the construction of a deep-water port at Vavouto, 250km north of Noumea, on the west-coast of New Caledonia (Figure 1) to service the Koniambo Nickel Project.

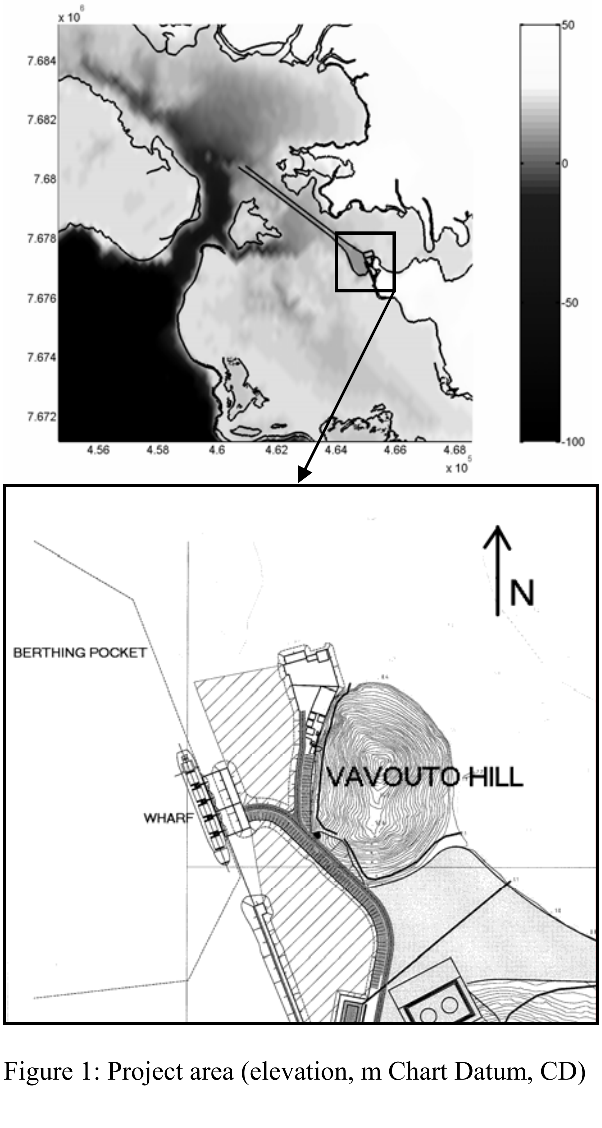

Figure 1: Project area (elevation, m Chart Datum, CD)

"Passe De Duroc" connects the Port area to the ocean. Vavouto Lagoon has mangroves in the river estuaries adjacent to nearby platform and fringing coral reefs. Previous investigations of the ambient environmental conditions provided details of the lagoon ambient hydraulic conditions (Colleter et al, 2003).

It is proposed to build a heavy-duty wharf to unload the Nickel process-plant construction modules. During exploitation, the wharf is to import and export general and bulk cargoes. The wharf is protected from ambient wave action by fringing reefs and shallow waters. New Caledonia is exposed to cyclonic events, causing storm surge and extreme wave conditions inside the lagoon. The wharf is to be designed for such extreme events.

2 Meteo-Ocean design criteria

The pre-feasibility study (KBR, 2002) estimated the "100-year Meteo-Ocean weather conditions" for the Vavouto lagoon. These weather conditions were used as design-criteria (Table 1). These design criteria are to be refined through cyclone, storm surge and Monte-Carlo modelling in the near future.

Table 1 Design Criteria

Design Parameter	
Highest Astronomical Tide (HAT)	1.80 m CD
Mean Sea Level (MSL)	1.0 m CD
Lowest Astronomical Tide (LAT)	0.11 m CD
Maximum Wave Height H_m *(m)*	2.9m
Wave Significant Height	2.2m
Wave Peak Period	4s to 6s
Storm Tide	+ 3.9m

(Source: KBR, 2002) Chart Datum =CD

The wharf deck level is +5.0m CD supported by steel piles. The wharf is 120m long by 34m wide, and five longitudinal beams 850(h)x1800(v) mm support the approximately 500mm thick deck.

The maximum design wave crest would reach the wharf deck and the interaction of the wave-flow with the wharf face (the seaward side of the wharf) may trigger significant overtopping. Slamming and uplift loads under the deck will be possible. Because the wharf is build at grade, overtopping would cause water to flow over the top of the wharf.

3 Anticipated wave load

When a wave hits the under side of the deck, the structure experiences an uplift force, followed by a negative force (downward) as the wave passes through the structure and the water exits the underdeck area. A brief peak-pressure or slamming pressure may also be recorded. This brief slamming pressure (0.01s-0.1s) involves predominantly fluid incompressibility and entrapped air and is closely associated with aeration and cavitation. The elastic dynamic response of the deck material is often involved in the absorption of this brief slamming pressure. The slamming load traditionally becomes critical for relatively small obstructions under the deck, since its persistence is brief and its effects are localised. Figure 2 shows a wave pressure recording from a deck structure being struck by a wave.

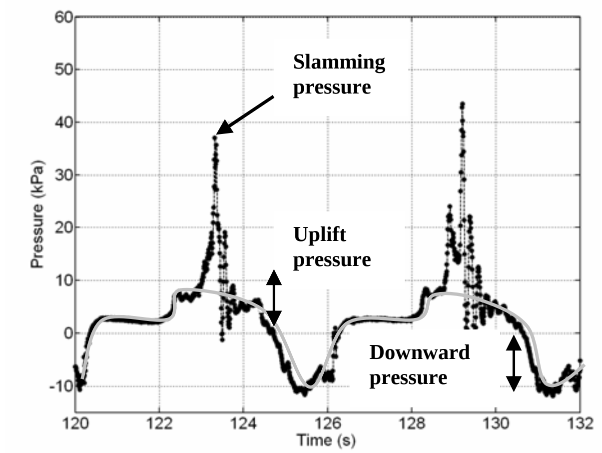

Figure 2 Definition of wave pressure parameters, from a pressure transducer record

The estimation of wave uplift, downward and wave slamming pressures on the deck requires empirical coefficients. These coefficients rely upon specific structural geometry and specific design storms.

Kaplan (1995) provides a detailed momentum and drag forces analysis for horizontal plates, that is applied to decked structures. This model provides an extensive theoretical procedure for the prediction of wave impacts on offshore platform decks, but does not specifically analyse aeration/bubble/diphasic flow properties.

Physical model testing at 1:25 scale of a representative exposed jetty (K.J. McConnell et al, 2003) has found that Kaplan's approach may underpredict wave loads on jetties and beamed structures. This study shows that the brief slamming load is between 1.5 and 4 times the uplift load. An uplift force prediction method is proposed, based on the testing, that accounts for underdeck beams. This method estimates uplift and downward forces within ±300%. The slamming load uncertainty would be 300% x 4 = 1200%.

The Coastal Engineering Manual (USACE, 2006) proposes the following slamming force model for emergent structures:

$$F_u = C_u A_z \gamma_w \left(\frac{w^2}{2g} \right) \tag{1}$$

Where C_u = laboratory derived slamming coefficient, A_z = projected area of solid body in the horizontal plane; γ_w = specific weight of water, and w = vertical component of flow velocity at level object.

Tickell (1994) reports a slamming coefficient between 2 and 20 for decked structures.

4 Numerical model overview

4.1 Numerical modelling objective

It was proposed to use a numerical model to investigate wharf uplift, estimate overtopping and study overtopping drainage. This model was used as a "concept design tool" only. As such, the model was setup to provide an approximate wave loading, to compare various wharf configurations and to select a preferred deck layout. This numerical model was not developed to detail the structural wave loading. Nevertheless, the modelling of wave action on the wharf involves the following challenges:

- Non-stationary boundary conditions (monochromatic waves),
- Complex water-air surface interface, partial wave reflection, wave breaking and air entrapment under the wharf; and
- Diphasic fluid (bubble, cavitation).

Generally, CFD modelling solves the equations describing fluid continuity, momentum, conservation of energy, and turbulence. Traditionally, CFD model application is limited to stationary or slowly varying flow. For instance CFD is routinely used to investigate hydraulic structure hydrodynamics such as dam overflow weirs. Increasing computation power allows the consideration of non-stationary flow.

4.2 Numerical model details

FLOW-3D was used for this non-linear wave model. It is a general-purpose finite volume model developed by Flow Science Inc (Flow3D, 2002). FLOW-3D allows the simulation of free surface flows, using true Volume-of-Fluid (VOF) technique, and models a range of external and internal fluid properties. An array of turbulence and fluid types is incorporated into the package. FLOW-3D provides the user with a number of numerical solver and grid definition options, as well as thermal, air entrapment and cavitation sub-models.

FLOW-3D uses an orthogonal, structured grid system, and also allows multi-block griding with nested and linked grids. The fractional area/volume method FAVOR is used for modelling complex geometric regions. FLOW-3D has a comprehensive track record of CFD modelling projects since 1985.

4.3 Numerical model tests

4.3.1 Shallow water wave propagation

First, shallow water wave propagation was tested. An oscillating boundary condition is set on the left side of the grid to reproduce the design wave case, that is a monochromatic wave train of 2.9m height and 6 seconds period in 16.9m of water. Figure 3 shows wave envelope and hydrodynamic currents calculated with the Fourier wave Approximation (Rienecker and Fenton, 1981) and calculated by CFD model.

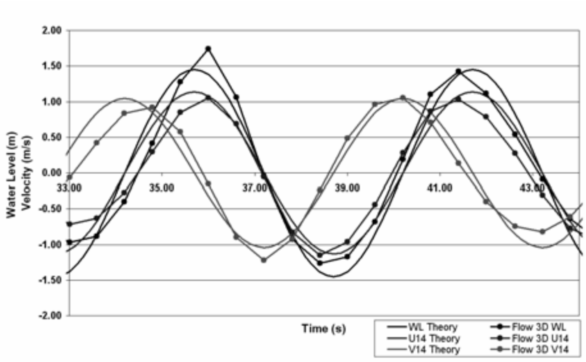

Figure 3 Wave parameters comparison

The CFD model and the algebraic solution provide similar wave envelope and currents within the water column. Also, the wavelength and wave celerity calculated by the CFD model match the theory well. This demonstrates that the CFD model produces monochromatic waves suitable for boundary conditions.

4.3.2 Breaking wave

Secondly, wave breaking on slopes was tested. The surf similarity parameter ξ_o is related with types of wave breaking:

$$\xi_o = \frac{\tan\alpha}{\sqrt{\frac{H_o}{L_o}}} \qquad (2)$$

Where α = slope angle, H_o = wave deep-water height; and L_o = deep-water wave length

If the surf similarity parameter is less than 0.5, waves are spilling, between 0.5 and 3 waves are plunging, from 3 to 3.5 wave collapses and if more than 3.5 waves are surging. The Kinematic wave breaking parameter (Hudspeth, 2006) states that the breaking wave crest velocity is equal to the shallow-water wave velocity. Table 2 compares these wave-breaking parameters. This simple test shows that the CFD model can approximate "realistically" wave breaking on slopes.

Table 2 Wave breaking test results

Slope	Surf similarity parameter	Model Breaker Type	Breaking wave Celerity m/s	Crest velocity m/s
1:3	1.45	Plunging	8.5	8.8
1:2	2.17	Plunging collapsing	9.5	10.2
1:1	4.35	Surging	N/A	N/A

4.4 Wharf model setup

The computation domain consists of a 2D cross section of the wharf, the grid is detailed on Figure 4.

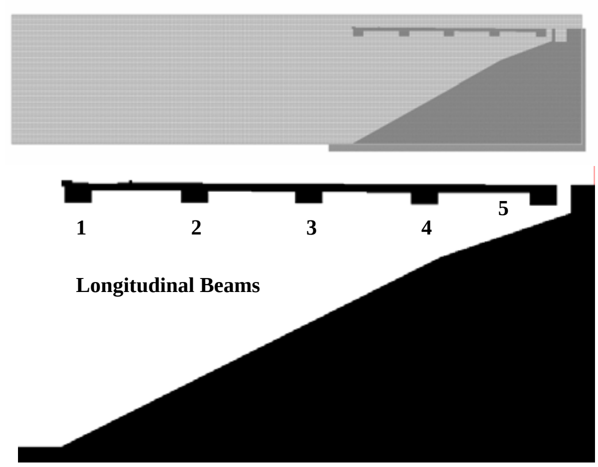

Figure 4 Koniambo wharf computation grid and details

The grid-size is approximately 300mm. In fact, the VOF interface tracking and the FAVOR geometrical description of the solid elements (wharf, underwater-slope) allows a much finer description of the free surface and of the structural arrangement.

The model physics includes the resolution of momentum and continuity equation for incompressible water in the gravity field (Navier-Stokes equations). The k-ε turbulence model is used to simulate sub-grid viscous flow turbulence. The numerical solver is set so that stability and convergence control the time-step. A third-order momentum advection scheme is used to reduce numerical diffusion. The fluid pressure was evaluated by iterating successive over-relaxation. The additional air entrapment and cavitation auxiliary models are setup to account for air-water interaction.

Seawater density, air density and viscosities are considered to be constant. Numerical parameters are provided in Table 3.

Table 3 Numerical model parameters

Numerical Parameter	
Seawater Density	1028 kg/m^3
Air Density	1.225 kg/m^3
Seawater Viscosity	1.07.10e^{-3} kg/(m.s)
Gravitational Acceleration	9.8 m.s^{-2}
Cavitation Pressure	-2840 Pa

It is anticipated that this numerical solver would provide a reasonable compromise between accuracy, numerical convergence and computation time for such a non-stationary model. It is noted that the numerical instabilities that develop at the model boundaries should grow with time and would allow only the testing of a few waves cycles. This is acceptable because "maximum wave" and "monochromatic waves" are considered for deterministic design.

4.5 Numerical model results

The wharf geometry creates a complex fluid flow pattern. Waves break on the wharf. Then, waves are partially reflected and overtopping flows on the deck.

Figure 5 shows a cross-section of the CFD-model when the design-wave breaks on the wharf face.

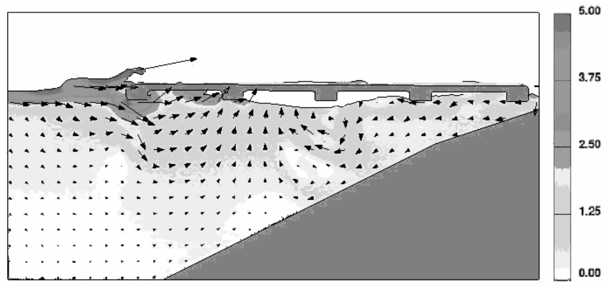

Figure 5 CFD model wave overtopping (H=2.9m, T=6s), shading indicates fluid velocity, m/s

Waves may overtop up to 3.0m above the wharf deck, at the wharf face, and flow depth on the wharf is approximately 300mm. The uplift pressure is stronger seaward of the wharf. Peak pressures (slamming) under the deck are below 60kPa, and the slowly varying positive pressure (uplift) is typically below 10kPa. The maximum peak-pressure (slamming) is typically 120kpa under the second longitudinal beam.

A few wharf modifications have been trialed. Following this desktop-investigation a grate has been proposed at the back of the wharf to reduce uplift pressure behind the wharf and overtopping flow over the reclamation area.

5 Physical model test

5.1 Physical model presentation

To confirm the design choices it was necessary to test a scaled model. This scale study was aimed at:

- Studying the wave uplift load in random conditions to provide realistic design conditions for the wharf;
- Investigating under-wharf revetment stability to wave attacks;
- Providing calibration data for the CFD-model; and
- Investigating if the CFD-model can be of use to undertake detail-design loading.

A 3D physical model of the wharf (approx. scale 1:15) was constructed at the University of New South Wales Water Research Laboratory in the 3-m wide flume. Recordings included:

- Uplift at 8 locations across the wharf using pressure transducers,
- Overtopping flow depth at two locations on the deck using ultrasonic gauge and
- Flow velocities under the wharf and in front of the wharf using Acoustic Doppler Velocimeter (ADV).

Both monochromatic waves (4s and 6s) and random waves (controlled spectrum and JONSWAP spectrum) are used. The physical model investigations have been detailed in a separate conference paper (Mariani et al, 2007).

5.2 Physical model results

In this section the monochromatic H=2.9m, T=6s test is compared with the above numerical model. Figure 6 shows the design-wave breaking on the wharf.

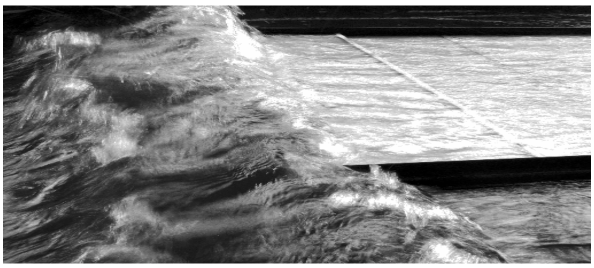

Figure 6 Scaled structure overtopping (H=2.9m, T=6s)

Similarities between Figure 5 and Figure 6 such as approximate breaking wave heights, reflected wave envelops and deck overtopping are observed. The scaled testing demonstrates that:

- Wave overtopping reaches 3.0m on the wharf face;
- Flow depth is typically 0.3m on the deck;
- Uplift peak pressure ("slamming") reaches approximately 60kPa in the vicinity of the second longitudinal beam;
- Uplift pressure is more intense in seaward of the wharf;

- Downward pressure is more intense seaward of the wharf; and
- Wave period significantly influences wave loading.

The overtopping of the wharf would be critical with green-water reaching 3.0m above the deck at the wharf face, while a steady flow (depth typically 0.3m) would develop on the deck.

The tests show that the wharf crossbeams influence the underdeck free-surface flow. The hydrostatic pressure at the back of the wharf is sufficient to lift the water table approximately by 1m while the grate captures the overtopping flow.

6 Model comparison

The physical model of the wharf has been built at approximately 1:15 scale, considers a –8.3m CD berthing pocket and represents the deck in 3D with its crossbeams. The CFD model wharf has been prepared at full scale, the berthing pocket level is -13m CD, and the model considers only a 2D section of the deck.

It was also noted that the CFD model diverges significantly from physical model measurements after 55 seconds of test. Boundary condition approximations and numerical model inaccuracies are suspected to be responsible for this behaviour. This reduces the performance of CFD model for probabilistic design, when random waves are considered.

Observed and modelled pressure variations along the wharf are plotted on Figure 7.

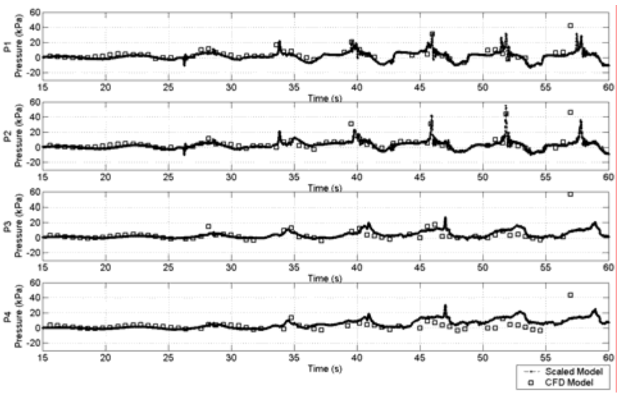

Figure 7 Hydrodynamic pressure under the wharf from CFD and Scale test

Both physical and CFD models detect the slowly varying uplift pressure; the downward negative pressure and the brief slamming pressure. It is significant to note that the pressure transducer load cell diameter and numerical model mesh size are of similar size: the recorded pressures originate from a similar "contact area". The slamming pressure was most intense in the near vicinity of the longitudinal beams. The numerical and scaled model show maximum slamming pressure reaching 60kPa, while slow varying positive pressure uplift was typically 10kPa and slow varying downward pressure was typically 10kPa.

The modelled currents under the wharf are relatively well correlated with ADP measurements, even though these records provide only single point verification. Laser optical Particle Image Velocimetry measurements have not been made under the deck structure to compare with the CFD model.

Globally, the scaled model corroborates with many of the "uncalibrated numerical model" tendencies.

7 Wave slamming load analysis

Assuming that the structure does not influence the wave flow field, and using the Fourier approximation wave theory, the maximum vertical flow velocity would be approximately 1.5m/s in the berth pocket. Considering that the recorded slamming pressure was approximately 60kPa and using equation (1), the slamming coefficient could be up to 50 for this wharf. The CFD model provides flow velocities under the deck that account for wharf and underdeck slope interactions. The CFD peak vertical velocity and the scaled model velocities at the second longitudinal beam were approximately 3.0m/s; the slamming coefficient becomes 13. Considering the whole deck the uplift pressure, 10kPa, is critical and the uplift coefficient becomes approximately 2.

Both the physical and CFD models show that pressure variations decrease landwards (towards beam 5) and that the underdeck beams significantly influence pressure distribution. This suggests that the use of an all purpose "slamming coefficient" for complex geometry and for all time-scale is questionable.

8 Conclusion and recommendations

CFD modelling is useful to compare several design configurations. It also reduces wave-loading uncertainties and produces conceptual design innovations. However, wave CFD numerical modelling accuracy is limited by the physics represented, computation power available and the numerical solution accuracy.

Overall, it is recommended to verify CFD model results at scale and to field observations in order to validate design choices and to produce detail design.

Project-wise, it is recommended also to complete the CFD model calibration. If the wharf is to be re-designed, CFD modelling could provide detailed deterministic design pressures, based on the maximum design wave, to the structural designers.

The estimation of detailed design criteria is essential. A cyclone, storm-surge, tide and wave Monte-Carlo study is proposed to ascertain design criteria. This should also consider wave set-up on reefs (Gourlay et al, 2005).

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