Sixth South African Conference on Computational and Applied Mechanics
SACAM08
Cape Town, 26-28 March 2008

NAVIER-STOKES WAVE MODELS FOR INVESTIGATIONS OF BREAKWATER CHARACTERISTICS

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Key words: Navier-Stokes, CFD, Volume of Fluid, wave model, dolos

Abstract

The protection of coastal structures is important to South Africa. The dynamics of breakwaters is a topic that is becoming amenable to numerical study, in terms of the motion of multiple interlocking structures under wave action. In this preliminary study, plunging waves and the loads they exert on semi-submerged structures are investigated with a Reynolds-Averaged Navier-Stokes model using a Volume of Fluid approach to surface modelling. Qualitative comparison of wave properties with experimental observations, including turbulence in surging and plunging waves, is encouraging, but quantitative comparisons are still to be made. Loads on a semi-submerged beam are modelled in preparation for studies of the dolos geometry.

Introduction

The dynamics of full breakwater stability are of importance in coastal engineering, and numerical models are some of the tools that can be applied. Given the work that exists worldwide in numerical models of breakwaters and armour units, it appears that a reasonable contribution can be made by models which take into account appropriate wave generation and spectra, 3D hydrodynamics and turbulence, and interaction with dolos structures. This contribution is made in conjunction with a wider project which examines spectral wave diffraction and refraction, dolos contact dynamics, and experimental breakwater modelling.

Wave interaction effects and turbulence effects on the stability of armour unit and rock beds have been investigated widely. Shallow-water models are used with success in harbour design and assessment of rubble mound structures in coastal engineering. Some numerical modelling in 3D has been undertaken, and has been directed primarily at breakwaters modelled as porous media [1] or to study waves and overtopping on solid shoal-seawall structures [2, 3, 4]. The influence of turbulence on the stability of single armour units and the stability of mounds has been studied by Hofland (2005) [5], whose methods can be applied to provide results from numerical models. It appears that insight into the interaction of waves with single and multiple dolosse remains to be investigated by numerical models.

Dolosse and similar fluked armour units differ from rubble in that they interlock, and forces propagate through a breakwater in modes different from those in a rubble mound. It is the interlocking and long-range interaction nature of the breakwater which is the focus of the long-term project. The interlocking particle bed offers different modeling challenges from beds constructed largely of convex shapes. We propose a multi-model approach to this complex system (Figure 1) in which a fluids team, with

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background in Reynolds-Averaged Navier-Stokes (RANS) modeling, provides fluid boundary conditions for waves, works toward turbulence model choices, and models forces on fixed structures, while a structural model team performs an investigation of many-body interactions in breakwaters (reported in a companion paper [7]). The intention is to bring the joint knowledge to a Fluid-Structure interaction or Discrete Element model in the next phase of the project.

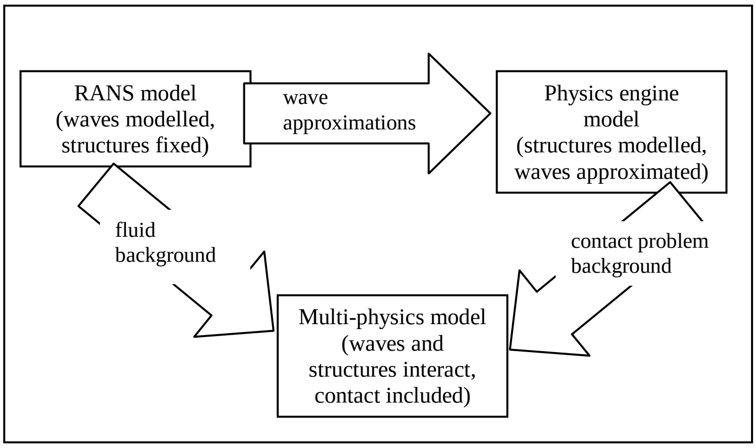


Figure 1: Relation of RANS, physics engine and DEM models

In considering the dissipation of wave energy by breakwaters, an understanding of porous and poroelastic media is valuable. A characterization of the geometry of various breakwater states may be able to contribute to parallel work on breakwaters considered as porous media [10].

Modelling considerations

The problem is 3D in nature, but initial models are independent of the third dimension. Reynolds numbers are known to be in the turbulent range. Free surface dynamics and aeration are dominant factors. The irregular geometry of one dolos, or a breakwater bed of dolosse, is important. Since many software numerical models of 3D turbulent flow on irregular grids are in existence, we do not propose to duplicate existing work, but to use an existing turbulent numerical solution of the Reynolds-Averaged Navier-Stokes equations with a Volume-Of-Fluid (VOF) approach to free surface dynamics and turbulence models.

It appears that useful progress in the field can be made by undertaking the following tasks in RANS models:

- Wave generation and non-linear wave tests,
- Submerged single dolos, forces in steady flow,
- Submerged single dolos, wave interaction, and
- Single dolos, non-linear surface wave interaction.

This work addresses non-linear surface wave interaction with a 2D structure as a task preliminary to the 3D simulation.

Geometry

For these purposes, a flume, which allows both 2D and limited 3D flow patterns to be explored, is ideal. The CSIR Built Environment flume of 20 m length and 1 m depth is the model chosen, to match experimental work. Numerical models are carried out at full scale for this flume. Two geometries were used. In the first (Figure 2) the shoal has no toe.

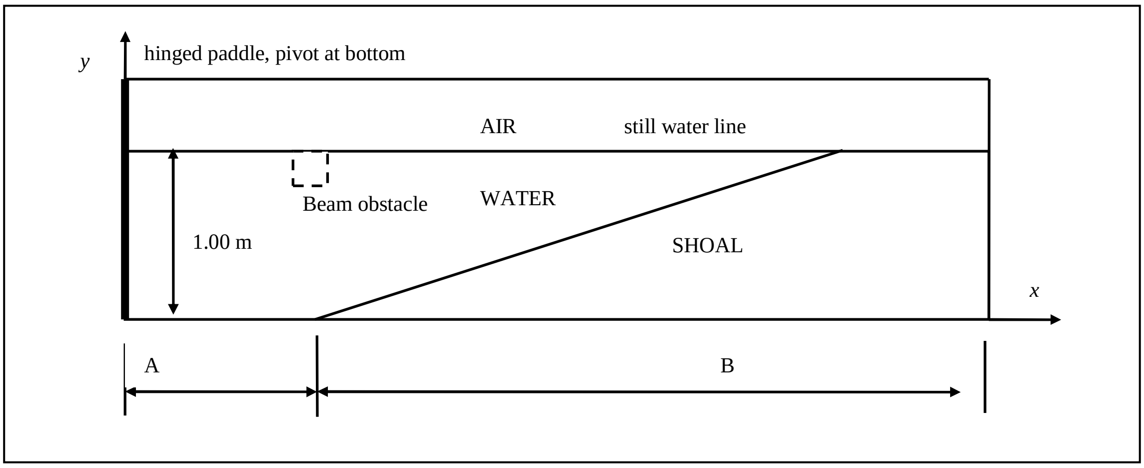


Figure 2: **Simple geometry**

In this simple geometry, the slope is 1:20, and a beam obstacle extending the full *z* width can be inserted.

Govender (1999)[7] provided measurements of wave height, velocity fields, vorticity fields, and turbulence in this flume on a 1:20 shoal. The geometry is shown as adapted in Figure 3. In cases used here A = 7.3 m.

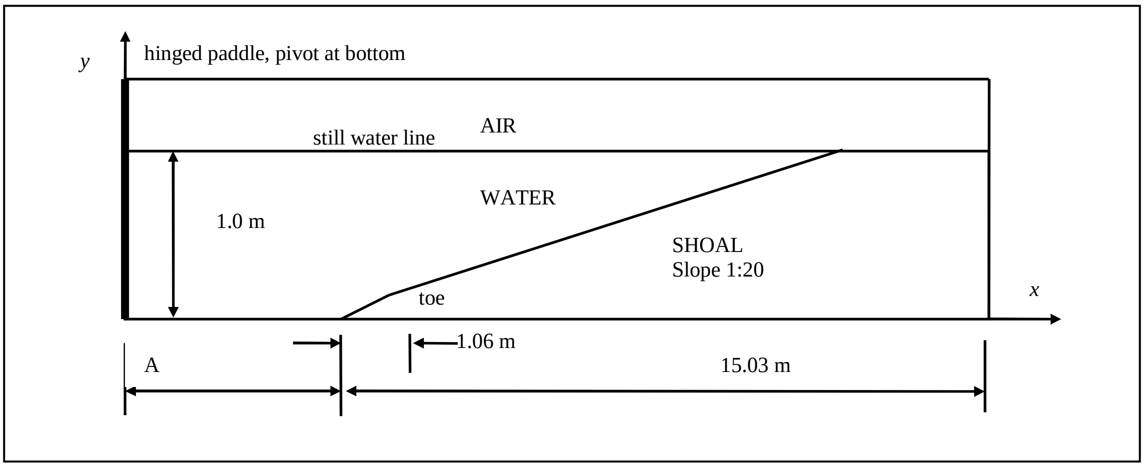


Figure 3: **Flume geometry after Govender [7], with coordinate system indicated.**

Boundary conditions

The shoal and floor are modeled as non-slip walls. A pressure boundary condition is applied at the top surface and at the air boundary at minimum *x* and maximum *x*. The model is 1 m wide in the third dimension *z* and symmetry boundary conditions are applied at constant *z*.

Waves were generated in two ways: by a collapsing water column, and by an oscillating boundary condition modeling model hall wave generation paddles. The collapsing column of water was initiated with a height of 1 m.

The wave generation paddles are hinged at the flume floor and oscillate as shown in Figure 4. The solid boundary formed by the paddle moves and produces water height, velocity and pressure changes in the water. In the numerical model, the paddle boundary is approximated by an oscillation of velocity only (Figure 4 (b)) (details below). The production of the velocity profile varying linearly with height has been verified by inspection of the flow field at the boundary.

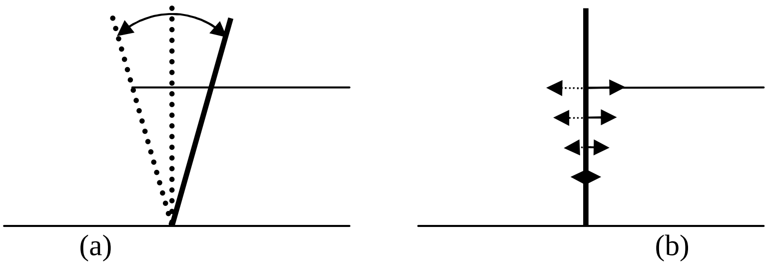

(a) (b)

Figure 4: **(a) Displacement oscillation of solid paddle boundary in flume (b) oscillation of velocities without displacement of boundary in numerical model; arrows represent horizontal velocity components**

Only the velocity in the x direction, u, was subject to oscillation. Velocity oscillations were given by $u = u_{\max} \sin 2\pi ft$ for $t_1 < t < t_2$. For most cases only one period is modeled with $t_1 = 0$ s and $t_2 = 1/f$ s.

Paddles are known to create free harmonics [7], which make water level measurements in the flume more difficult. Measurement of the spectrum of the numerically modelled waves should reveal whether free harmonics are propagating. Govender [7], in experimental models of the surf zone, absorbed the energy of propagating waves by placing a porous rock band on the upper part of the beach to reduce reflection. Measurement and control algorithms in the wave generators are used at present at the mechanical paddles in the flume to remove reflections by interference. Absorption or control of reflected waves is a consideration for numerical models, and has also been addressed by Liu (2006)[1] by placing an unphysical absorbing layer adjacent to the boundary condition, while Zhou *et al.* (2005)[3] developed conservative oscillating boundary conditions in the momentum equation.

A regular grid of 0.02 m in the x and y directions was used. Refinement at the fluid interface will be considered as future work and may well influence the capture of aeration effects.

Fluid model

Air is modeled as an incompressible gas, and water as an incompressible fluid. In a Cartesian coordinate system x_i, $i = 1, 2, 3$, the momentum conservation equation for incompressible fluid flows is derived from the following [9]. Buoyant forces are included as source terms. Repeated indices imply summation.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j - \tau_{ij}) = -\frac{\partial p}{\partial x_i} + g_i(\rho - \rho_0)$$

where t is time, x_i is coordinate i, u_i is velocity component i, ρ is density, and τ_{ij} is the stress tensor. The piezometric pressure p is defined as

$$p = p_s - \rho_0 g_m x_m ,$$

with p_s static pressure, ρ_0 reference density, x_m the displacement from a datum point where $\rho = \rho_0$, and g_m the components of acceleration due to gravity. Constant temperature is assumed.

Turbulent forces are known to influence particle stability and it is not yet known how sensitive the results will be to choice of turbulence model. In this project we propose to use the simple, well-known, $k - \varepsilon$ model for exploratory work, and refine the choice of model as the flow physics becomes clearer. The Reynolds stress is given in this model as follows.

$$-\bar{\rho}\overline{u_i'u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\mu_t\frac{\partial u_k}{\partial x_k} + \rho k\right)\delta_{ij}$$

$$k = \frac{1}{2}\overline{u_i'u_j'}$$

$$\mu_t = f_\mu \frac{C_\mu \rho k^2}{\varepsilon}$$

Here μ_t is turbulent viscosity, k is turbulent kinetic energy, σ_h the turbulent Prandtl number, C_μ an empirical constant, and f_μ a damping constant.

The free surface between immiscible incompressible fluids is modeled by the Volume Of Fluid approach. Surface tension is not modeled. A scalar α is defined as the ratio of heavy fluid (water) volume to light fluid (air) volume in a computational cell. Note that aeration is important in roller waves and the applicability of the VOF model has not been clearly established, although aeration will be modelled in an improved fashion as the mesh size decreases, and smaller bubbles or droplets are individually resolved. It is considered that the VOF approach will provide a better model of an aerated roller than an interface-tracking algorithm, for which fine resolution of drops and bubbles would be envisaged.

Initial numerical experiments qualitatively demonstrated features associated with monochromatic wave trains and with the formation of rollers in plunging breakers [6]. The following step shown here is the application of the wave forces to a semi-submerged beam. Further work will characterise the loads on a dolos, and in the larger project scope these will be integrated with the physics contact model.

Wave generation and propagation results

Unless otherwise mentioned, v_{max} = 50 ms^{-1} and f = 1 s^{-1} in the following. Because no absorber has been included at the still water line on the shoal, or at the wave generation boundary condition, waves reflect from the shoal and propagate back in the $-x$ direction, reflecting again from the wave generation boundary at time t_r. The following observations were made over time scales shorter than t_r.

For continuous oscillation of the boundary paddle for $t > 0$ s, with the simple shoal, a wave train is generated (Figure 5). By tracking the crests it is possible to deduce a phase velocity, which decreases from 3.3 ms^{-1} for the first crest to 2.6 ± 0.1 ms^{-1} for the following crests in the linear offshore and shoaling range. A first-order approximation from shallow-water theory [7] assuming that the wavelength is very much longer than the local water depth d is

$$(f\lambda)^2 = gd\,.$$

Unfortunately, in this early test the still water line rose slightly with time, but with d corrected accordingly the phase velocity is seen to be a reasonable order of magnitude in Figure 5(c).

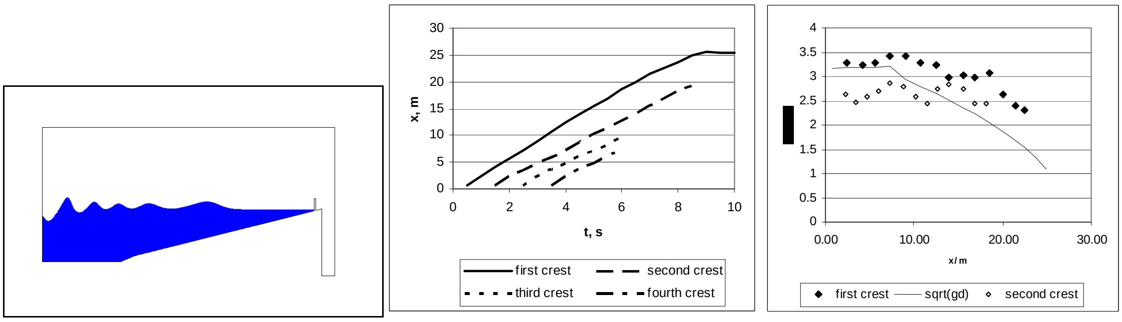


Figure 5: **Continuous wave train (a) surface (note that the horizontal and vertical scales of the figure have been changed for emphasis) , (b) crest propagation, (c) phase velocity.**

In the simple geometry, the collapsing water column initiated surging waves which propagated to the shoal and make the transition to plunging waves, in which most of the front face overturns and a prominent jet falls near the base of the wave, initiating further waves and jets. An aerated region, the roller, is formed. The VOF method appears to capture the events in qualitative terms; careful comparison with measurements is required. Plunging waves were also initiated with the hinged paddle method ($t_1 = 0$ s, $t_2 = 1$ s).

Contours of turbulent energy k (Figure 6) for the surging waves compare qualitatively well with the Particle Image Velocimetry (PIV) measurements of Govender [7]. It was noted that very high turbulence levels were associated with the hinged paddle boundary, and that with time turbulence features associated with the boundary conditions propagated into the region of wave study.

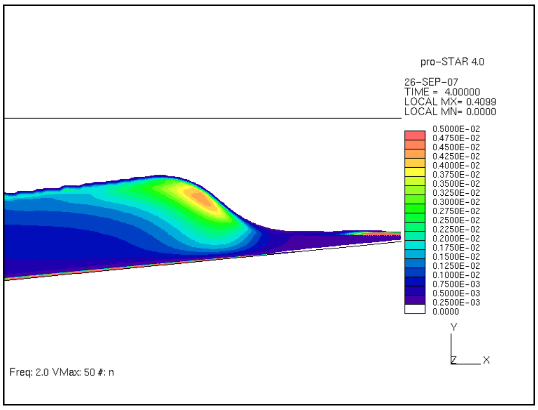
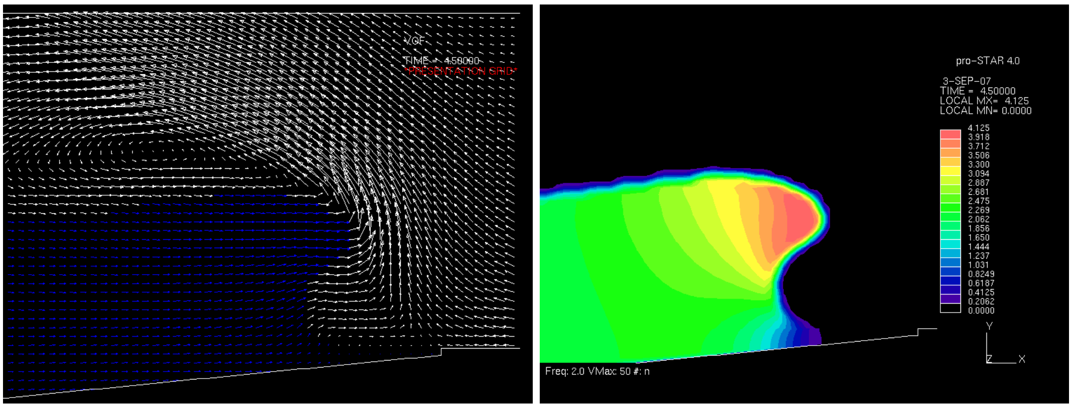


Figure 6: **Surging wave, contours of turbulence energy *k***

Figure 7 shows velocity fields as the wave plunges, together with turbulent kinetic energy. These compare reasonably well with the PIV measurements of Govender but a quantitative comparison remains to be made.



(a) (b)

Figure 7: **Plunging wave development: (a) air and water velocity vectors and (b) turbulent kinetic energy *k*.**

Preliminary results for loads on an obstacle in a surging wave

The obstacle in Figure 2 is a beam that runs across z and has dimensions 0.30 m x 0.30 m. One wave cycle with $v_{max} = 50$ ms^{-1} and $f = 1$ s^{-1} was initiated at the wave generation boundary ($t_1 = 0$ s, $t_2 = 1$ s). Total forces were obtained from the sum of shear and pressure forces. Shear forces are negligible in comparison to pressure forces, being 3 orders of magnitude less than the latter.

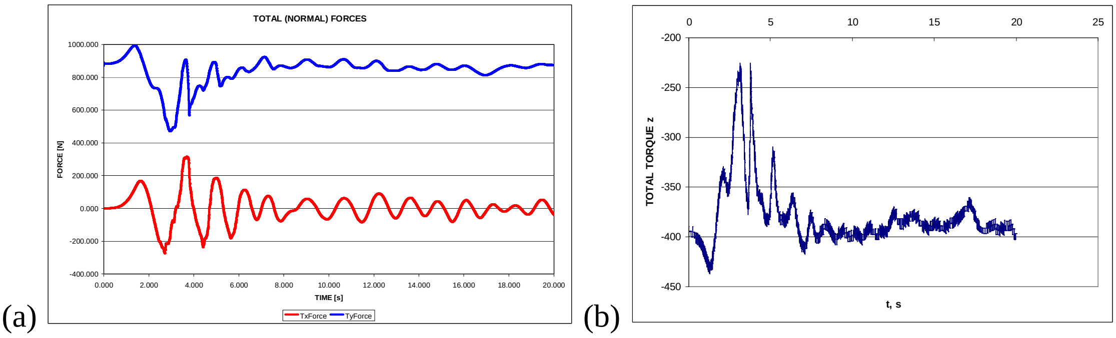


Figure 8: **Total loads on beam at surface: (a) forces (b) torque**

Buoyant forces are evident in the total force in the offset of the total vertical force T_y. Sloshing is observed after the passage of the wave. The maximum force on the beam at any time is approximately 300 N. Torques about the top centre of the obstacle are shown in Figure 8(b).

Conclusions and Recommendations

Forces on a sample breakwater element have been obtained. A qualitative study of the generation of waves using both collapsing water columns and hinged paddles has been performed. In shoaling geometry behaviour of the waves, in terms of propagation and plunging is reasonable, but quantitative comparisons should be carried out in conjunction with experimentalists (for example, a comparison with the Joint North Sea Wave Project spectra [11] and parameters could be undertaken). Turbulent features in waves about to break appear to be consistent with experimental results, but a detailed comparison is still to be carried out. Significant turbulent features are associated with the hinged paddle boundary, and further work remains to reduce this undesirable feature.

Only a preliminary model of forces on an object near the surface as waves approach the shoal has been demonstrated here, and it is clear that the study should be extended to the dolos geometry in three dimensions. It would be useful to characterise loads on the dolos in several attitudes and under several severe wave conditions, including any turbulent rocking effects as identified by Hofland [5], and it is an intention to quantify loads on a semi-submerged dolos subjected to incident plunging waves.

The larger scope of this project is directed at understanding failure modes of interlocked dolos units. The methodology includes three approaches: (1) Navier-Stokes models, to understand the modelling of wave dynamics and turbulent interaction with dolosse (restricted to very small numbers of dolosse), (2) physics models of the contact dynamics of the dolosse in order to understand their long range motion (without realistic fluid models), and (3) multi-physics models of large numbers of dolosse with realistic wave dynamics. A candidate for part (3) is Discrete Element modelling. In view of the computational expense of (3), (1) and (2) are incorporated to develop insight *en route*. For example, the geometric parameters of part (2) may contribute to study of the breakwater as a porous medium or a poroelastic medium, and an intermediate step in the project will be to apply typical forces generated by Navier-Stokes models to multiple dolosse in physics models.

References

1. Liu, H., “Numerical simulation of violent breaking and overtopping against seawalls”, Third Chinese-German Joint Symposium on Coastal and Ocean Engineering**,** Tainan November 8-16, 2006.
2. Lin, P. and P. L.-F. Liu, “A Numerical Study of Breaking Waves in the Surf Zone”, Journal of Fluid Mechanics, **35,** 239-264, 1998.
3. Zhou, Q.J., Wang, B. L., Lan, Y. M. and Liu, H., “Numerical Simulation of Wave Overtopping over Seawalls”, Chinese Quarterly of Mechanics, **26**(4): 629-633, 2005 (in Chinese).
4. Li, B., Fleming, C..A., “Three-dimensional model of Navier-Stokes equations for water waves”, Journal of Waterway, Port, Coastal and Ocean Engineering, **127**(1), 16-25, 2001.

5. Hofland, B., “Rock & Roll: Turbulence-induced damage to granular bed protections”, Thesis, Technische Universiteit Delft, 2005.
6. Peregrine, D. H., “Breaking waves on beaches”, Ann. Rev. Fluid Mech. **15**, 149-178, 1983.
7. Govender, K, “Velocity, vorticity and turbulence measurements in the surf zone”, Thesis, University of Natal, South Africa, 1999.
8. A. K. Cooper, J.M. Greben, F. van den Berg, I.M.A. Gledhill, B. R. Cannoo, W. J.v.d.M. Steyn and R. de Villiers, “A preliminary physics-engine model of dolosse interacting with one another”, SACAM08, Cape Town, March 26-28 2008.
9. STAR Methodology Manual, CD adapco Group, 2004.
10. G. P. J. Diedericks and J. P. du Plessis, “On tortuosity and areosity tensors for porous media”, Transport in Porous Media, **20** (3), 1573-1634 (1995).
11. K. Hasselmann, T.P. Barnett, E. Bouws, H. Carlson, D.E. Cartwright, K. Enke, J.A. Ewing, H. Gienapp, D.E. Hasselmann, P. Kruseman, A. Meerburg, P. Mller, D.J. Olbers, K. Richter, W. Sell, and H. Walden, “Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)”, *Deutschen Hydrographischen Zeitschrift Reihe* **A(8)** (12), 95 (1973).