

## A PRELIMINARY PHYSICS-ENGINE MODEL OF DOLOSSE INTERACTING WITH ONE ANOTHER

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### Abstract

A variety of armour units are used to protect breakwaters, piers and other harbour infrastructure, serving both to absorb the impact of violent seas and to reduce overtopping. A common type of armour unit is the dolos. Coastal engineers use three-dimensional physical scale models of harbours and their surrounds to design harbours and their defences, and to understand the dynamic processes around them caused by waves, tides, currents and storms. However, these models are complex, expensive and time-consuming to build and difficult to use. We have begun a wide-ranging project aimed at developing advanced digital image processing and analytical techniques for application to breakwater structural stability and moored ship conditions, and the development of associated numerical simulation and modelling technology. A key part is being able to model armour units (especially dolosse), their contact dynamics, and their packing. We have developed a model of dolosse within a physics engine, which we report on here.

### 1. Introduction

Harbours play a vital role in the economies of most countries, both as nodes in trade routes and to provide shelter for ships and boats. Many harbours are subjected to severe storms, tides and/or currents, which can damage infrastructure and vessels and disrupt operations, such as loading and unloading ships. A variety of armour units are used to protect

breakwaters, piers and other harbour infrastructure, serving both to absorb the impact of violent seas and to reduce overtopping. The latter occurs when heavy seas flow over harbour defences into the supposedly protected areas of harbours, disrupting operations or damaging ships or infrastructure.

A common type of armour unit is the dolos, invented in East London in the 1960s. Made from un-reinforced concrete and weighing up to 20 tons, a dolos looks like the letter 'H' with one arm rotated through 90°. This allows dolosse to interlock with one another, forming a porous layer between the sea and the harbour infrastructure. Figure 1 shows dolosse protecting Cape Town's harbour. There are over 30 other designs for armour units in common use, with different properties.



*Figure 1: Dolosse protecting Cape Town's harbour*

The protection for harbours needs to be maintained, and its effectiveness assessed, on a continual basis. While much of this is done in the field, coastal engineers make extensive use of three-dimensional physical scale models of harbours to understand the dynamic processes around them caused by waves, tides, currents and storms, and their interactions with the harbour infrastructure and ships. They are particularly useful for planned new infrastructure. These models are then of the harbours and their surrounds (including the topography of the sea bed) and are used to design harbours and their defences. They are also used for artificial islands and other infrastructure in the coastal zone.

However, these models are complex, expensive and time-consuming to build and difficult to use, as the models and forces do not scale similarly. There are also very few facilities around the world capable of building such scale models. The CSIR has the only significant facility of

this kind in Africa, at its site in Stellenbosch, and it is also one of the six largest model halls in the world (see Figure 2). These facilities are generally fully utilized, yet there is increasing demand on their services because of the development of new harbours and artificial islands and the need to maintain or expand existing facilities, as the National Ports Authority is doing in South Africa.

During 2006, the CSIR initiated a wide-ranging research project to explore the possibility of developing digital image processing and analytical techniques for application to breakwater structural stability and moored ship conditions, and the development of associated numerical simulation and modelling technology. Our interest is in modelling the conditions in both scale models and in the field, building numerical models of packed arrays of armour units, to use these for developing simulations of the interactions between the armour units and waves, tides, currents and storms.



*Figure 2: CSIR's physical model hall*

We report here on one component of this research, a model of a packed array of dolosse interacting with one another, which was developed using the physics engine PhysX [AGEIA 2008]. Another paper at this conference reports on the work done on synthesising waves using Navier-Stokes equations [Canoo *et al* 2008]. Other parts of the project include examining spectral wave diffraction and refraction, quantifying changes in layers of armour units using digital photogrammetry [Van den Berg & Viera 2008] and an auxiliary vision system for monitoring harbours and models remotely [Phelp 2008].

## **2. Physical environment and the model hall**

The CSIR's model hall was built in 1968 and covers 11 000 m<sup>2</sup>. As well as being used for designing and assessing harbours and other infrastructure in the coastal zone, together with their protection by layers of armour units, the facility has been used for river and dam hydraulic research. The hall contains several model basins for three-dimensional studies (typically, at scales ranging from 1:100 to 1:40) and several flumes for two-dimensional studies, including one raised flume with glass sides (for viewing cross sections above and below the water line). These facilities are used for modelling structures in the coastal zone (in

whole or in part) to assess their effectiveness against various sets of wave patterns. This effectiveness is determined by the structure's stability – its ability to withstand the wave patterns (representing storms of a size specified by the client) without failing (eg: having armour units dislodged). They are also used for ship motion studies, to determine under what conditions ships may move around or load or unload in safety.

Unfortunately, these models are complex, expensive and time-consuming to build, because of their large size (eg: over 1000 m<sup>2</sup>) and the fine tolerances required for their construction, such as the cement floor shaped to model the bathymetry of the sea bed, the building of the rubble mounds with gravel of the correct grades, and the packing of armour units according to the design specifications (which vary for the different types). They are also difficult to use because the models and forces do not scale similarly, with the model armour units being far more robust than the real ones are, and the viscosity of the water becoming much more significant in the models, for example.

### **3. A short history of breakwater studies**

Breakwater stability can be assessed theoretically by exposing breakwaters to storms and storm sequences in model studies. In this context it is important to determine how many storms (and of what magnitude) breakwaters are likely to be exposed to in their lifetime. This is why some studies examine the frequency of storms and try to define a peak of a 30 or 100-year storm history [Kobayashi et al 2003a], in order to determine whether structures are of acceptable stability. This stability depends on the packing techniques when armour units are used and the nature of the armour units. The dynamics of rubble-mound breakwaters are known to be less sensitive to placement of rubble than, for example, to the ratio of higher to lower stone diameter [Kobayashi et al 2003b]. However, there are indications that interlocking dolos breakwaters which are “well-packed”, in contrast to those which are “indifferently packed”, show significantly less degradation over their lifetime [CSIR].

The ability to model the contact dynamics of collections of natural or man-made particles is relatively new, particularly when collective properties emerge above a threshold number of particles. One motivation to use such models is interest in behaviour that differs on the microscale (the interaction of two or three dolosse) from that on the macroscale (the systematic failure of an interlocked breakwater structure). A second aspect is the problem of understanding dynamics with different typical lengths in different directions, such as breakwater sliding, which may take place over a longshore distance many times that of the onshore dimension.

Over recent years, modelling of the contact problem for realistically-shaped particles has progressed (see for example the work of Peric and Owen [1992]), opening opportunities for the environmental sciences [Richards et al 2004] and providing a base of algorithmic development in contact detection, contact kinematics, discretised contact solutions, and fracture and fragmentation solutions [Munjiza & Latham 2004]. The necessary validation may be provided by very simple experiments [Latham & Munjiza 2004]. In this context, finite strain, finite rotation deformation of dolos-like armour units by contact forces using a combined-finite-discrete-element approach has been shown by Munjiza and Latham [2004]. An alternative approach has been made through poroelastic media [Chen et al 2002; Venkataraman & Rao 1998]. An analytic description of motion of a caisson under applied wave forces is part of the poroelastic model of Kuamagai and Foda [2002], which has the

advantage of avoiding long computation times while revealing some of the physics of the seabed, rubble breakwater and caisson interaction. Discrete element methods (DEM) can be used to simulate the interactions of submerged particles [Bierawski & Maeno 2006].

Different rubble mound models have been studied by Takayama et al. [2005]. The rubble elements were allowed to fall freely from a suspended matrix, the top surface was flattened to allow placement of a caisson, and the caisson was allowed to settle. The computed motion of the caisson and rubble caisson base was considerably larger than experimentally observed displacements. The stability of the caisson structure was improved after attack by large waves.

Noting the constraints imposed by computational resources on DEM, Araki and Deguchi [2005] simulated only the offshore and onshore sections of a spherical-stone breakwater with a 3D DEM, using incident wave parameters from a parallel experiment. Computed and experimental deformation and variation in the mass of rubble stone in the breakwater as stones are transported onshore showed more benefit from using denser stones than larger stones, but the necessity for 3D DEM, rather than 2D DEM, was demonstrated en route.

It may be noted that many specialist fluid models include 6 degree-of-freedom computations for moving bodies, but at present few also use contact models. A notable example is the use of contact models in the aerospace domain by Meakin [2006] in investigations of Space Shuttle Orbiter debris accidents. While a multi-physics approach is a desirable aim, possibly through DEM and turbulent fluid-VOF (volume of fluid) modelling, a simple contact approach can already reveal much about the interactions of many interlocking armour units.

#### **4. The physics engine modelling environment**

Since it is very time-consuming and difficult to write from scratch an object-oriented program that models the dolosse and their dynamics, we searched for a suitable games engine to implement our models and demonstrate the results via suitable graphics. We found that the PhysX tool, marketed by AGEIA, was most suitable for our purposes [AGEIA 2008]. The PhysX software development kit (SDK) has over 10,000 users. PhysX caters for key physics parameters (eg: gravity; static and dynamic friction; linear and angular damping; restitution and density), allows user-generated forces to be applied, uses OpenGL for the graphics and is available for free to encourage use of the PhysX dedicated hardware physics processor. PhysX has good documentation and tutorials and we were able to adapt one of the tutorials quickly and easily to prove the concept and feasibility of using PhysX.

The other serious contender was the Open Dynamics Engine (ODE), an open source, high performance library for simulating rigid body dynamics [ODE 2008]. Since we experienced problems with modelling collisions between different types of convex objects in ODE, we did not proceed with this software.

The dimensions of a model dolos were captured as part of the photogrammetric part of the project [Van den Berg & Viera 2008], but we subsequently obtained the design specifications for the dolos and other armour units, such as the Core-Loc and the Antifer cube. The dynamics of the dolosse are governed by a set of parameters: gravity (always reproduced faithfully as  $9.8 \text{ m s}^{-2}$ ); linear damping (values between 0 and 1); coefficient of restitution (i.e. the ratio of the magnitude of the after and before velocities of an object when hit, with 0 being

fully inelastic and 1 fully elastic); coefficient of static friction (ratio of the maximum force that can be applied to an object resting on the rubble without it moving to the normal force exerted between the two surfaces); and the coefficient of dynamic friction (the ratio of the force of friction between a moving object and the rubble or another static armour unit to the normal force between the two surfaces). Most dry natural materials have coefficients of friction between 0.3 and 0.6. The coefficient of dynamic friction should not be greater than the coefficient of static friction.

The density of each material also has to be supplied. We used  $1600 \text{ kg/m}^3$  for the rubble mound and  $2350 \text{ kg/m}^3$  for the dolosse. The coefficients for restitution, static friction and dynamic friction were fixed at (0.05, 0.5, 0.5) for the rubble mound and (0.8, 0.4, 0.4) for the dolosse. The breakwater is modelled as a sloping flat surface (slope .588 radians or 37 degrees), with a toe at the bottom to hold the armour units. We can represent a real harbour situation or the situation in the model hall in the Stellenbosch laboratory.

By dropping sequentially dolosse of specified orientation, size and colour from a specified height and at a constant velocity (imitating its placement in the field or physical model), we can construct a certain breakwater configuration. When each dolos strikes another dolos or the slope or toe, it is allowed to fall freely under gravity. The idea is to establish the breakwater's stability, "measured" by exerting a standard set of forces and seeing how the configuration responds. One of the problems is to define such a standard set of forces. In PhysX, the strength of the forces can be defined, however, the period over which the force is applied is more difficult to set. We do not expect any fundamental problems since PhysX allows the introduction of a lot of additional user defined capabilities. However, we have to calibrate the forces against more fundamental methods in which the forces are determined by fluid dynamic programs. The relationship of the forces to wave motion must also be developed in more detail.

We expect that the stability is related to the porosity of the structure and the number of contact points. The porosity is the ratio between the volume of water/air to the total volume, including the dolosse. We have explored three ways to define the total volume, given the irregular shape of the breakwater configuration:

- (1) The smallest convex body around the breakwater structure, providing a natural and unique definition of the porosity.
- (2) As the total volume bounded by the slope and a plane above it parallel to the slope.
- (3) As the total volume bounded by the slope and a horizontal plane expressing the sea level.

Future research must indicate which concepts are most useful to characterize stability. If we are able to establish a clear relationship between stability and porosity, then our program can be used to calculate the stability of any structure by simply calculating the porosity. This reduces the need to expose the structure to varied of wave conditions to determine the stability operationally. We expect that a low porosity (close packing) is more stable than a loose packing, however, a packing that is too close resembles a solid wall which is unable to absorb or deflect the energy of waves. The characteristics of stability will probably vary for different types of armour units.

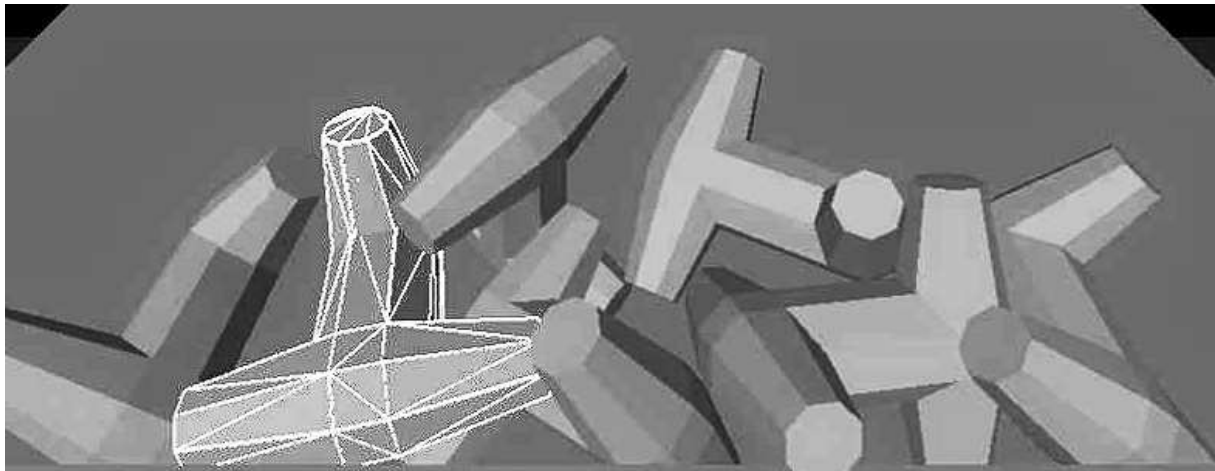
Another way of characterizing the stability is through the number of contact points between dolosse. These can also be easily calculated in PhysX. Since the number of contact points depends on the number of dolosse present a normalized definition has to be used. Again, the

irregular structure of the breakwaters may complicate the formulation of such a normalized contact parameter.

The further progress in our modelling work might be limited by PhysX being designed for games, rather than for scientific applications. It is not designed to record the history of certain dynamic processes. Since it is important to reproduce the same conditions, while varying selected parameters, one of the main functionalities we have developed is these recording functions. Also, it is preferable that input files can be constructed beforehand and read from a menu. Again, we have been able to progress considerably along this path, making PhysX into a powerful tool to model the dynamics of real breakwater structures.

## 5. The physics engine model of dolosse

We show here two pictures taken from the PhysX model. Figure 3 shows a close-up of several model dolosse. One of them is draped with a chicken-wire outline of its structure – this indicates that it is the active dolos, either because it is the most recently added, or because it has been selected to have specific forces applied to it. Figure 4 shows a packed array of 49 dolosse on a slope and toe. One can see the tight packing achieved along the bottom of the slope, though it deteriorates higher up the slope because the starting configuration was not designed by an expert packer! Several dolosse have “fallen off”, because the slope was too narrow for this packing configuration.

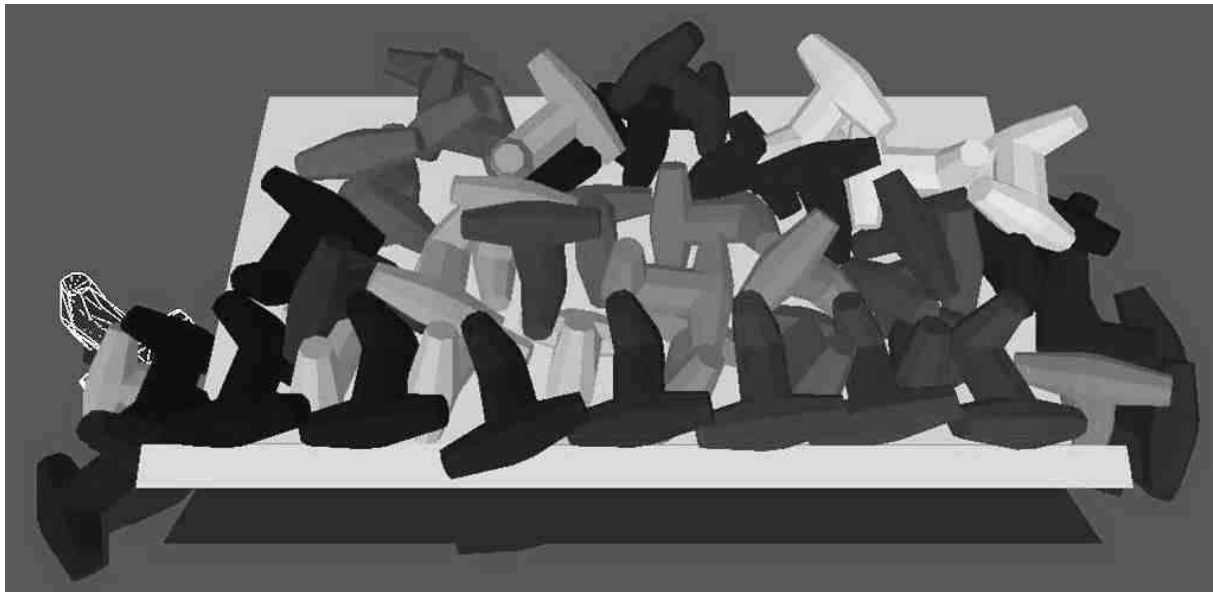


*Figure 3: Synthesised dolosse modelled in a physics engine*

## 6. Conclusions and the way forward

Using the physics engine PhysX, we have been able to model the construction of breakwater structures under ideal (dry) conditions. The porosity and contact properties of the resulting structure can be determined exactly. This opens the possibility to relate the stability of breakwater structures to these (or other) parameters. Since these parameters can be calculated exactly within the numerical model, such a relationship offers the possibility of assessing the stability of a wide range of breakwater configurations and breakwater objects, to supplement the physical model hall experiments. Our current study focussed on the dolos, but we have started modelling other armour units. We have tested the stability of these breakwater configurations by exposing them to massive forces specified within PhysX, without

calibrating these forces against real-world conditions. In future, we hope to exploit realistic wave models so as to test the model predictions against actual model hall results.



*Figure 4: A packed array of 49 dolosse*

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We dedicate this paper to the memory of our colleague, Brian Canoo, who was tragically killed in a traffic accident in February 2008.

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