Numerical modelling of structures of dolosse and their interaction with waves

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Abstract

We have applied various numerical techniques to describe the stability of breakwater structures under the exposure of waves. These studies are intended to get a better understanding of the parameters playing a role in breakwater stability and to complement the experimental studies in physical model halls, such as the one operated by the CSIR in Stellenbosch. On the one hand we use advanced computational fluid dynamics to model waves, on the other hand we model the different configurations of breakwater structures (e.g. dolosse) using a physics engine called PhysX™. Our aim is to integrate the two approaches so as to generate a powerful tool for the studying of breakwaters and thereby contribute towards the enhancement of the security of our coastlines and harbours.

In this paper we present new results from the PhysX™ engine simulation that demonstrate our ability to model great numbers of dolosse (up to 350 currently). We review our work on breakwater stability and demonstrate the power of PhysX™ to calculate relevant parameters.

1. General introduction

A variety of armour units (such as dolosse) are used to protect breakwaters, piers and other harbour infrastructure in South Africa, serving both to absorb the impact of violent seas and to reduce the likelihood of overtopping (i.e. waves breaking over into the protected areas of harbours) – see Figure 1. The CSIR coastal engineering group operates the Stellenbosch model hall, where it builds three-dimensional physical scale models of actual or planned harbours, which help to understand the dynamic processes caused by waves, tides, currents and storms and help with designing breakwater structures – see Figure 2. However, these models are expensive and time-consuming to build and complex to use, and they also have a limited predictive ability, because of the imperfect scaling of various effects in model halls (e.g. the impossibility to scale Reynold's number) and because of unavoidable side effects, such as reflections in the model basin reducing the correspondence with real harbors.

Figure 1: Dolosse protecting Cape Town's harbour

Numerical models are not affected by such scaling errors and by undesirable physical modeling side effects. Also, it is possible to analyze the behaviour of covered breakwater components that are not visible in experiments. However, the numerical models are limited by other simplifying theoretical assumptions which are needed to make the theoretical calculations feasible. The licences for the software platforms for numerical models can also be very expensive, particularly when run on multiple processors simultaneously.

Figure 2: *CSIR's physical model hall*

The current theoretical project is aimed at the development of analytical techniques to apply to numerical modeling of breakwaters to determine the characteristics of breakwater structural stability and to generate associated numerical simulation and modelling technology. Various approaches are followed and the ultimate goal is to integrate these into an advanced analysis tool. On the one hand we model armour units (especially the dolosse developed in South Africa, but also coreloc and antifer units), their contact dynamics, and their packing. This work is carried out using the physics engine PhysX[TM] [1], which handles most of the rigid body mechanics – see Figure 3. The current work is an extension of work reported at the SACAM conference in Cape Town [2]. Structures of up to 350 dolosse can now be studied and various characteristics, such as the number of contact points and the porosity of the structure, can be calculated. The aim is to derive the stability of these structures by expressing the stability in terms of these structural properties.

On the other hand we have to model the waves and their interactions. The wave forces cannot be directly introduced in the physics engine, but must first be generated by fluid dynamic models. These models require different approaches, such as Reynolds-averaged Navier-Stokes (RANS) models, Discrete Element Methods (DEM) and smoothed particle hydrodynamics (SPH) models. Ideally, these tools will provide approximate, but appropriate, inputs to the physics engine with the right physical calibration. Development of the fluid dynamics RANS program is underway and described elsewhere [3], and one of the challenges is to combine the wave and structural approaches.

We are also contemplating the usage of the SPH method, which has been proposed recently and is inspired by astrophysics [4]. In this method, the water continuum is modeled by discrete particles, an important advantage being the ability to treat free surfaces. For recent applications involving solid structures, we refer to [5].

The calculations will in future also be tested against specific tests with physical hydraulics models. If reliable predictions can be made with the developed numerical toolset, then the software can assist in supplementing the physical model breakwater studies for current or future harbours. In order to avoid some of the limitations of the theoretical approximations it may be necessary to carry out very sophisticated calculations that will require the usage of special computing facilities, such as the CSIR's Cluster Computing Centre (C4) or at the Centre for High Performance Computing.

2. Stability of breakwater structures

Two notions of stability are common in this field [6]: static stability and dynamic stability. The latter is of importance for rock slopes, rubble mounds, rock and gravel beaches, where the profile of the breakwaters adapts dynamically to the exposure of waves (i.e. 'settles'). Such exposure may lead to a more stable structure (profile) that does not significantly change in a global sense after further wave exposure.

Static stability refers to the permanent movement of structures. Such permanent movement is usually defined in terms of damage, rather than by (a changed) profile. Big armour units, like dolosse, should not really move under the exposure to waves. Hence, they are characterized by static stability, although in exceptional cases a "stable" profile change may take place after the units have been placed. Hence, their movement can be defined as damage. Quantitatively, damage is defined as the number of units that are displaced per unit of characteristic length along the longitudinal direction. The unit of length is then defined in terms of the nominal length of the armored unit, which equals the inverse cubic root of the volume of the dolos. Other definitions of damage are also popular, in particular, one can express the damage as a ratio of areas, namely the eroded area versus the nominal cross section [7].

This variation in the definitions of damage and stability emphasizes the phenomenological nature of this field. Extensive studies of damage, as related to various wave and structure parameters, have been carried out by Van der Meer [6]. The relationships were deduced from damage experiments in physical halls and therefore are of a purely experimental nature. Various curve fitting procedures were used to represent the phenomenological formula. The relevant wave parameters are wave height, wave length, spectral shape, groupiness of waves, water depth, angle of attack, storm duration, etc.; while the structure parameters are nominal length, grading (D_{85}/D_{15}), relative mass density, permeability of the armour units, and profile. Van der Meer [6] defines various dimensionless quantities that are combinations of the previous parameters. Such dimensionless parameters have distinct advantages, when characterizing stability properties, since different circumstances correspond to different characteristic ranges of dimensionless parameters. For example, the ratio of water height to the product of nominal length and relative density (the dimensionless water height parameter $H_S/\Delta D_{50}$) is about .8 for our breakwater structures, while it is much larger (1-4) for the typical dynamically stable structures considered by Van der Meer.

Since we want to study large breakwater units we have to extend the work by Van der Meer to this lower range of height parameters. Work along these lines has already been undertaken in Ref. [7], although the formula used are still largely based on Van der Meer's work. However, in contrast to these investigations we want to base our results on physics engine PhysX[TM], rather than on physical hall experiments. By exposing the breakwater structures developed in PhysX[TM] to waves of different strength and duration we can evaluate the damage theoretically. This should enable us to extend and improve the phenomenological formulae for stability. Naturally, we should validate certain aspects of our models with physical hall experiments, however, the main thrust of our work is theoretical modeling.

3. Wave models

Our main challenge now is to model the waves and to incorporate these forces into the PhysX[TM] engine. Since PhysX[TM] is primarily a games engine, whose source code is not available, the possibilities to model these waves are currently limited. The buoyancy of the armour units can, in principle, be introduced by replacing the density by the reduced density (subtracting the specific density of seawater). However, such replacements should only be performed for those parts of the dolosse which are under water. We have been able to define a water level in the physics engine, and can now calculate the proportion of dolosse under and above water.

We have also been able to calculate porosity of the breakwater structure. The definition of porosity is not unique for a finite structure, and we have defined it as the ratio between the minimal convex body encompassing the whole breakwater structure, and the combined volume of the individual enclosed breakwater structures. We have also defined height dependent porosity functions, that compare the volume of the breakwater structures under a plane to the total volume between the plane and the breakwater base. The plane can either be parallel to the sea level (horizontal) or parallel to the slope on which the armour units have been packed. The idea is to relate these porosity functions to (static) stability and determine which porosity functions are most suitable for characterizing the stability. The porosity (permeability) may play an important role in the modeling of the internal water movements, in contrast to the external water movements. Although the latter wave motion is expected to be mainly responsible for the resulting damage, the receding water movement and the internal water movement are of significant importance, as they exert forces that can pull armour units out of a breakwater structure. In fact, one of the main perceived advantages of dolosse and similar angular breakwater structures, is that they break the water movement and absorb the water waves. Naturally, such mechanisms only operate if the water has different waterways between the interlocked structures, i.e. it is sensitively dependent on the porosity.

Another quantity which can be calculated in PhysX[TM] is the number of contact points between the dolosse. Again, we think that this number, properly scaled and normalized, will correlate strongly with the damage parameter. An outstanding issue is the definition of a normalized contact parameter (e.g. with a value between 0 and 1). In atomic systems the pairwise interactions would represent such contact points and would clearly scale with N(N-1)/2 . In the case of a

breakwater structure such scaling properties have not yet been properly derived.

Since PhysX[TM] itself will not calculate the internal and external wave forces, one has to import these forces from calculations performed in other models on other platforms, such as Reynolds-averaged Navier-Stokes models and Discrete Element Methods (DEM). These models then have to distinguish between different types of waves, such as surging waves (low steepness) and plunging waves (high steepness). By limiting ourselves to situations that are most likely to cause damage we can limit this vast area of research. Our aim is not to give a complete description of the dynamics of water in a breakwater structure, since under normal circumstances there would be no damage to the structure. We are presently considering how this limited focus can help us to streamline the research.

Below we present some recent results from the physics engine. Shown in Figure 3 is an assembly of 351 dolosse, on a slope and contained by a toe. Currently, our setup limits us to a model with 351 dolosse, but this is more than adequate for our current requirements. With time, we intend modeling much larger arrays (physical models often include several thousand model armour units), using either the PhysX[TM] hardware accelerator (currently being incorporated into NVIDIA® graphics cards [5]) or a different platform. In the simulation, the dolosse are lowered individually by the physics engine at a specified lowering speed. Once touching another object, the dolos is released and will find its own position of stability. The order in which the dolosse are dropped for this example in Figure 3 is shown in Figure 4. A row of dolosse is placed along the bottom of the slope in one direction, followed by a row of dolosse in the other direction, higher up the slope. Then, the third row is placed above and between the first two rows, packing it in the same direction as the first row. The fourth row is packed on the slope above the second row and the fifth row is then packed between the second and fourth rows and on top of them, etc.
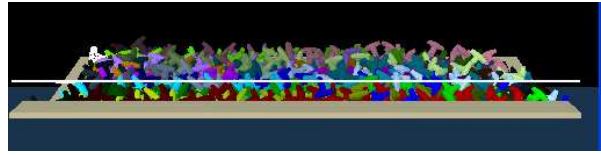

Figure 3: Assembly of 351 dolosse created by the physics engine PhysX[TM]. The water level is shown as well (as a line because it is in the plane)
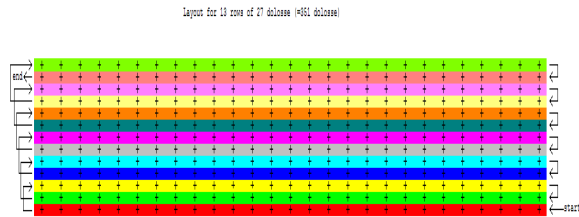

Figure 4: Order of releasing dolosse which has been used in constructing the assembly in Fig.3

In the simulations, the armour units are packed on a slope with a toe. We can now also design complex shapes for the slope and toe under the breakwater structures using PhysX[TM], which ability will be invaluable when we model specific harbours as opposed to purely theoretical models. An example is a round corner, which is displayed in Figure 5, with a sparse packing of dolosse to show the underlying structure.
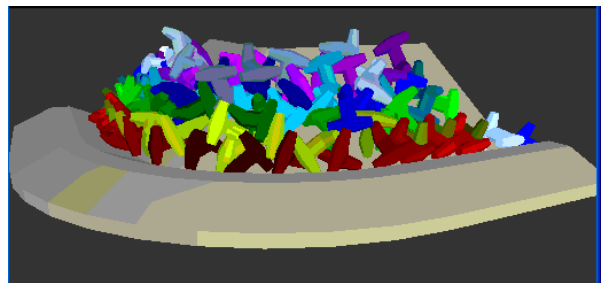

Figure 5: Example of breakwater structure consisting of dolosse with a round corner

These special shapes would seem of less importance in constructing phenomenological relationships between damage and wave and structure parameters. However, experience has shown that the exceptional points often suffer more damage than the straight portions of breakwater structures and the damage does not always occur where the waves strike the breakwater structure, as the wave energy can travel longitudinally along the structure to cause damage elsewhere at a

weak point. Hence, our ability to model these aspects theoretically, could be of great practical importance in the future.

Apart from theoretical placement structures we also are in the process of reproducing placement methods used in the field. To this effect we have taken videos of placement sequences in the physical hall in Stellenbosch. One of the difficulties with the reproduction of such sequences is that the packer uses his "artistic" freedom to exploit the actual packing result up to a certain point to place new elements in a strategic position. Since the actual packing result is sensitive to certain random aspects (e.g. unevenness in the underlying bed) his choices cannot always be reproduced in the numerical experiments. Clearly in each of the three cases (numerical calculations, model hall experiments and real breakwater structures) special properties play a role which cannot be fully reproduced in the other two cases.

4. Summary and Discussion

We have described our research programme to model theoretically breakwater structures and their interaction with waves under storm conditions. A combination of techniques is used. We are able to model the breakwater structures accurately, but the modeling of the interaction with waves is still rather crude. Our idea is to use a hybrid approach. We want to use a current profile of the breakwater structure to calculate the forces in fluid dynamic models. Hence, the checkpoint files of PhysX^{TM} (i.e. the records of the positions and orientations of all the structures in the PhysX^{TM} model) are used as an input to the CFD (computational fluid dynamics) calculations. Subsequently we introduce the calculated forces from the CFD calculations into PhysX^{TM}, and determine whether any damage is done. We then hope to continue the analysis of the internal and receding water movement inside PhysX^{TM}. Changes in the profile of dolosse will then be re-introduced in the CFD calculations. The real-time nature of the games engine limits the amount of calculations that can be performed between time steps and the amount of information that one can obtain about the underlying processes. These limitations still have to be clarified as we continue the integration of the two sets of calculations. By changing the wave and structure parameters in a systematic way we can investigate the damage characteristics as a function of these parameters. In this way we expect to get useful phenomenological relationships between wave and structure parameters and the damage potential. Ideally, such calculations and the associated assumptions are verified in tests with physical hydraulics models. The resulting relationships can then be usefully exploited in the effective construction and maintenance of breakwater structures. The ability to design improved breakwater structures is of particular importance in view of the expected future increase in sea water levels due to global warming.

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