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Title: NEW MODELLING AND ANALYSIS METHODS FOR CONCRETE ARMOUR UNIT SYSTEMS USING FEMDEM

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Corresponding Author: Dr John-Paul Latham, PhD

Corresponding Author's Institution: Imperial College London

First Author: John-Paul Latham, PhD

Order of Authors: John-Paul Latham, PhD; Eleni Anastasaki, MSc; Jiansheng Xiang, PhD

Abstract: Rubble mound breakwaters armoured with concrete units rely on collective behaviour between adjacent concrete armour units but existing largely empirical approaches have been unable to provide a detailed understanding of how these gigantic granular systems work. The problem has been that current methods cannot investigate the interdependence of hydraulic and structural stability at the scale of individual units. Numerical methods have the potential to provide such answers but there are many challenges to overcome. We present a solution to the first major bottleneck concerning the solids modelling: the numerical creation of a breakwater trunk section of single layer concrete units with geometrical and mechanical properties that conform to realistic prototype structure placements. Positioning of units is achieved with a new versatile software tool, POSITIT, which incorporates user-defined deposition variables and the initial positioning grid necessary to achieve the required design packing densities. The code Y3D, based on the combined finite - discrete element method, FEMDEM, solves the multi-body mechanics of the problem. First, we show numerically constructed breakwater sections with armour layers of 8m³ CORE-LOCTM units placed on rock underlayers. The numerically-generated packs are deemed acceptable when examined according to a range of criteria indicative of acceptably placed armour layers, as set by concrete unit designers. Breakwater sections with packing densities ranging from 0.59 to 0.63 are then created. Using a set of analysis tools, local variation in packing density as an indicator of heterogeneity, centroid spacing, unit contacts and orientation of unit axes are presented, together with mechanical information showing the variation in contact forces. For these five packs examined, an increasingly tighter pack was associated with a steady increase in coordination number and a more steeply and accelerating increase in average maximum contact force per unit. The force distribution results and discussion presented illustrate the potential of discrete unit FEMDEM modelling methods to address initial placement quality, armour layer design and future innovation in rubble mound structures.

Dear Prof Burcharth

As requested in your email of Feb 15th, below please find my detailed log of all the changes made to the paper according to the key reviewer, which I found understandable and instructive. I have only rebutted the elimination of the two real structure figures which are now better contextualised. There was a need for a new Appendix that makes the stereoplots much clearer. A discussion on friction values has been included and extensive changes to figures and text have been made. Textual changes in the manuscript are indicated in navy blue font colour to help readily assess my changes.

Best wishes

JP

Reviewer Comments and Revisions Implemented

Reviewer #1: General comment:

This manuscript describes the results of the application of advanced software tools (3D/FEMDEM and POSITIT) to model a solid granular system of 8m3 Core-Loc trunk armor. This software tools may be applied to other concrete armour units (CAUs) and are considered as a first step towards a realistic and precise numerical description of mound breakwaters, which could take into consideration both hydrodynamic as well as structural tensions within the units. The methods and tools, presented in the manuscript, are not much useful to design mound breakwaters today; however, some of concepts and tools may lead other methods which may have of practical relevance in the future.

This manuscript is interesting for publication; however, the manuscript is not acceptable (difficult to read) in its present form. It has many figures which should be eliminated, others should be transformed in tables and the paper needs additional figures and comments to clarify the text.

Specific comments to improve the manuscript:

1. Figures which should be eliminated:

Fig. 1, Fig. 2, Fig 3a, Fig 4a, Fig. 5, Fig. 6, Fig. 7 right, Fig. 9, Figs. 10 and 11 (transform them into tables), Figs. 18a, 18b, 18c, 18d.

We agree to delete Fig. 2, Fig 3a, Fig 4a, Fig. 5, Fig. 6, Fig. 9. Figs. 18a, 18b, 18c, 18d. We have now transformed Figs. 10 and 11 (into one table with a column for each direction).

The image presented before as Fig. 1 was not as good as the new one we propose for Fig. 1. By retaining Figure 1, with the new caption and text the aim is to lead the reader into one of the key issues of the paper - to consider the construction constraints applied to create such pseudo-random single layer structures with interlocking. It is important that real structures are presented in this paper to fully communicate the potential impact of the modelling methods. We hope the editor/reviewer can agree to the value of both Fig. 1 and Fig. 7 (right) being included as we now suggest but will understand whatever is their final preference.

2. Figures to be modified (suggestions)

Fig. 3b. One rock model is enough (the two rock models are the same)

The two identical rocks are still both shown in the figure to give a direct visual understanding of the two sizes that were used in the modelling of underlayer rock used to represent the size distribution (bimodal). The text now emphasises the ability to model a range of rock sizes and the use of the two

sizes chosen here helps to understand the model underlayer can be created in such a way to help ensure a more realistic roughness is generated.

Fig. 4b. OK.

Fig. 7left. OK. We believe the visual comparison/resemblance between real and modelled structure is in itself worthwhile for engineers with experience of using units and for criticism or confidence building in the future application of such numerical modelling. Therefore it is preferred to retain Fig 7 right, which is **a rare photo of a prototype structure taken nearly perpendicular to the armour layer**, which is a valuable addition to such photos (they are typically restricted to hydraulic model tests).

Fig. 8. Red rocks and red Core-Locs may lead to confusion.

The key is now amended to give the appearance of more discrete colours and a note in the text is given to explain the underlayer and container walls are represented as one solid body and thus this body has a coordination number > 10 , (probably ~ 500 !)

Fig. 12. It would be valuable to add the representation of three orthogonal planes (three curved lines): armour slope plane, vertical plane and third orthogonal plane. These three curved lines and the corresponding intersections would provide a clear indication of how the stereographic projection works.

An explanation is added in Appendix A that now negates the need to draw reference planes on the stereoplots.

Figs. 13 and 14. It would be better to include in the scheme all the variables involved $\{D_h, D_v, S_{ij}, Z_{ij}, \text{etc.}\}$ in the geometric description.

This has now been added to both figures.

Fig. 15. Is $S[\text{unit?}]$ the variable represented in X-axis? No, these are integer numbers identifying each unit showing here the first unit in row 2 to the last in row 19. Too many different symbols in the plot; I suggest to use only one symbol for even row indexes and other for odd row indexes. These suggestions have now been implemented.

Fig. 16. Contact number is discrete (0, 1, 2, 3, 4 and 5) while selected colours are not discrete. It would be better to use discrete black-white colours.

This is very difficult to achieve in our PARAVIEW post processing software but an attempt has been made which appears successful, using colour.

Fig. 17. Maximum contact force represented in Fig. 17 is dimensional. $F_{\max}$ could be referred to the weight of the unit ($F_{\max}/W$) to obtain a dimensionless $F_{\max}$.

The scale invariance of the force distribution when modelled at different scales has not yet been fully investigated. Therefore we show the absolute contact force values here. However, later when dealing with distributions, we normalise by dividing by Core-Loc weight (188.35kN)

Figs. 19a, 19b, 19c and 19d. It would be valuable to add the representation of three orthogonal planes (three curved lines): armour slope plane, vertical plane and third orthogonal plane (similar to Fig. 12) This has been addressed by addition of an Appendix.

Fig. 20. OK.

Fig. 21. OK

Fig. 22. Average contact force? Now made clear in text and caption, that this graph concerns the force of every single contact experienced by all the units (i.e. some 242 x 6 contacts for each model) which is then normalised to have unit area under the curve, i.e. it is the probability distribution function for the contact force of any single contact. $P = 1 - \text{cumulative frequency}$? P is thus different to $1 - \text{cum}...$ X-axis is dimensional. $F_{\max}$ could be divided by the weight of the unit ($F_{\max}/W$) to obtain a dimensionless variable. F has been divided by the weight of the unit (118kN) so that (F/W) is a dimensionless variable.

Fig. 23. X-axis is dimensional. $F_{\max}$ could be divided by the weight of the unit ($F_{\max}/W$) to obtain a dimensionless variable. $F_{\max}$ has been divided by the weight of the unit (118kN) so that $(F_{\max}/W)$ is a dimensionless variable.

Fig. 24. X-axis is dimensional. $F_{\max}$ could be divided by the weight of the unit ($F_{\max}/W$) to obtain a dimensionless variable. $F_{\max}$ has been divided by the weight of the unit (118kN) so that $(F_{\max}/W)$ is a dimensionless variable.

Fig. 25. $F_{\max}$ should be dimensionless (i.e. $F_{\max}/W$). Contacts with underlayer (approximately 2.0) could be represented to avoid all the points being represented in the same narrow band. These suggestions have now been implemented – is much better.

3. The manuscript includes several trademarks (i.e. CORE-LOC[TM], and ACCROPODE[TM]) with names in capital letters (also used for acronyms as FEMDEM) employed to promote products and services. Other registered trademarks (i. e. Xbloc®) are not written in capital letters, and the criterion is changed in page 8; you can read "CORE-LOC[TM] units, (hereafter referred to as Core-Loc units)". In my opinion, armor unit and product names should be correctly identified in a technical paper using the capital letter only for the first letter (Core-Loc, Accropode, Xbloc, Posibloc, Positit, etc). A technical paper full commercial trademarks in capital letters should be avoided. The opinion is welcome and the lower case system is now used sometimes after the Cap introduction. The other reviewer had similar points but there is a range of practice adopted in the CE journal

4. Introduction (1.1)-p.2-l.23. It should be re-written; the first sentence reads "Rubble-mound design is the principle design approach favoured for harbour breakwaters of substantial size". What does it means (compared to large caisson-type breakwaters)? Agree, caisson and rubble-mound design solutions should both be mentioned as two main options. Text now amended.

5.(1.3)-p.4-l.27. Fig. 1 and the phrase "Fig. 1 shows an example of a typical well-interlocked structure built with one of the class of single layer bulkier units, the CORE-LOCTM" should be eliminated. It does not show any interesting characteristic. The figure caption is introduced to point out the random appearance is in fact controlled e.g. by placement rules such as avoiding the contacts of adjacent units in the same row.

6. (1.5)-p.6-l.50. The phrase "There is a set of rules and sling techniques recommended by Artelia (formerly named Sogreah) to easily obtain the orientation pattern. These rules have been discussed by Verma et al. (2004)" should be re-written, i.e. "Verma et al. (2004) discussed the rules and sling techniques recommended for Core-Locs". This is one of the indirect phrases used in the manuscript involving secondary histories which are not relevant for the readers (a reference for details is the relevant point). The textual style has now been changed to avoid secondary histories – a useful distinction and easy pitfall for authors.

7.(1.5)-p.7-l.4. Should Table 1 be inserted here?. The authors should indicate where Tables and Figures should be inserted in the paper. [Suggested locations of tables and figs have now been included.](#)

8.(1.5)-p.7-l.15. The phrase "For example, to aid the subsurface placement of any unit type, POSIBLOCT V4 has been invented. It is a topographical 3D system jointly developed by Artelia Consultants (formerly Sogreah) and MESURIS for optimum placement control of armour units on breakwaters when using either land-based or marine equipment. VISIBLOCTM is an integrated software system for virtual imaging of the placement, specially developed for the POSIBLOCT system (Mouquet, 2009)" should be re-written. The readers need the reference paper (Mouquet, 2009?) for details, but not secondary histories about who develop what commercial product. [The textual style has now been changed.](#)

9.(2.1)-p.9-l.13. The phrase "A one way-coupled numerical model of the hydraulic performance of concrete armour layers (wave run-up, reflection) conducted by Maritime Engineering Division, University of Salerno, MEDUS (Dentale et al., 2009) using FLOW3D showed how geometric granular skeletons made up of various unit types performed reasonably well when compared with available experimental data." should be re-written to follow the general direct style used in the manuscript: Dentale et al. (2009). [The textual style has now been changed.](#)

10.(2.2)-p.9-l.50. Please, re-write the phrase focusing on key references. What reference is "early 1990's by Antonio Munjiza"? [Has been address, by removing this historical information completely.](#)

11.(2.2)-p.10-l.7. COBRAS reference? [Has been address, by removing the name as the important point is simply that it was a cfd code.](#)

12.(2.3)-p.11-l.5. The phrase "Fig. 2 shows the FEMDEM simulation of the normal stress component in the direction of sliding, colour-contoured red for low stress level, blue for high stress level." and Fig. 2 are not necessary. [Figure and text now deleted. Some text retained to reference the code validation paper by Xiang.](#)

13.(2.6)-p.13-l.4 and 37. "The introduction of a particular combination of four different reference orientations in four adjacent units in successive groups on the pattern grid was the key concept of the new placement method". "Two out of the six possible orientations were rejected". These four 3D orientations have a clear influence on the results, but they are not described in the text. What are those orientations?. What are the stereographic projection of those orientations?. Several obvious questions not answered in the manuscript. [This has now been fully explained in Appendix A together with a clear figure showing the four numbered configurations \(now Fig. 4\). The clustering in the stereoplot results figures is discussed in the text.](#)

14.(3.1)-p.14-l.31. What is unit axis orientation? [This refers to the Coreloc nose axis and will be used throughout text. However, it is now made clearer that this 2D feature when plotted on the stereonet, does not fix the attitude of the unit uniquely as the complete range of 180 degrees of rotation about the nose axis remains possible and is undefined on the lower hemisphere projection nose axis plot. What is unit plane face? The unit has three planes of symmetry; one of these is orthogonal to the nose axis. What is nose axis orientation?. We need a figure with a scheme to explain those Core-Loc geometric elements. A figure is now provided with better text and a brief Appendix is included.](#)

15.(3.2)-p.15. All the grid variables (S_{ij} , Z_{ij} , i , j , D_h , D_v , etc.) should be described in the corresponding figures (Figs. 13 and 14?). [The figures have been augmented with the \$S_{ij}\$ and \$Z_{ij}\$ etc](#)

16.(3.3)-p.16. The description of the stereographic projection is not clear. Only one reference (a book) is provided and it is not clear how this system can be applied for Core-Loc orientation description. Core-Loc is a solid which require three dimensions (angles) to be orientated in the 3D space, but Fig. 12 is planar (only two dimensions). A line plots as a point, so Fig. 12 represents line orientation no solid 3D orientation. Two very close points in Fig. 12 may represent Core-Locs with much different orientation. This is not clear in the text. Furthermore, Core-Loc has three orthogonal symmetric planes; thus azimuth {alpha} and azimuth {alpha+180°} is exactly the same 3D orietation. The effects of symmetries are not explained. At least, the three basic orthogonal planes (armor slope plane, vertical plane and the third orthogonal plane) should be represented in Fig. 12 (curved lines?) to facilitate the reading and interpretation of the Fig. 12. Same for Figs. 19a, 19b, 19c, and 19d. [All these points are now addressed.](#)

17.(3.6)-p.17-l.54. The maximum force must not be dimensional (Newtons) but dimensionless (F_{max}/W ?). When using the proposed software tools, the readers would like to know if the problem is scalable or not. [The problem scalability is the subject of current research. A further mention of this interesting point is now included in the discussion section.](#)

18.(4)-p.18-l.5. ". modern specifications." specify $\langle PHI \rangle = 0.63$ and give a reference. [The reference to 0.63 has been changed and we have included reference to designer information on CLI website: \$\Phi = 0.619\$ for 8m3 units, CLI website accessed in Feb 2011.](#)

19.(4)-p.18-l.55. ".Some clustering remains.four initial orientations.". What initial orientations? Are they represented in Figs. 12 and 19a, 19b, 19c and 19d?. [This is now much clearer in the revised text.](#)

20.(5.3)-p.21-l.38. "friction coefficient. was set to 0.9". Please, provide a reference to justify that friction coefficient for concrete-concrete and concrete-rock. It seems very high compared to frictions coefficients usually taken in other engineering applications (caissons on rock). What is the impact of a change in friction factor on the results shown in the manuscript?. Is it very sensitive or not?. [The issue of friction coefficients has been amplified upon in the new text. Most available data refers to caisson on rock and shows a range of results during a field trial pull test. This is a complex issue under further investigation and the results for force distributions are not very sensitive to friction values, but will clearly affect the predictions for stability under disturbance loading.](#)

21.(5.3)-p.21-l.52. ".. force is less than 0.1 MN". Please, force in dimensionless form (if the problem is scalable).. 50% of unit weight? [The dimensionless force is now referred to the concrete armour unit's weight \(188kN\)](#)

22.(Table 3). Please add, to the average values, columns with the Coefficient of Variation. [This statistical data \(std dev/mean\) is now added.](#)

Reviewer #4: I have reviewed the manuscript NEW MODELLING AND ANALYSIS METHODS FOR CONCRETE ARMOUR UNIT SYSTEMS USING FEMDEM by J.P. Latham, E. Anastasaki, and J. Xiang. The article is well written and clear. In addition, the methods promoted offer a significant advancement of technology for developing, evaluating, and designing concrete armor shapes. This review suggests that the paper be published with only minor modification. There are several comments made directly on the attached edited manuscript. [These have been found and the suggested changes made.](#) Suggest authors lighten the reference to VISIBLOC and POSIBLOC developers (only need one reference [now done](#)) and strengthen the references to Core-Loc (there are none). Suggest at least

one general reference for Core-Loc since most of the paper is focused on this unit. [Holtzhausen is one already and we have added a Turk & Melby and Melby & Turk papers.](#) A statement of the complexity of modeling real concrete surface forces would be useful. Most engineers are not familiar with the degree of frictional resistance generated by undamaged and spalled concrete. The range is significant. [A statement on the issue is now included but much more detail is not appropriate here we feel.](#)

Highlights

- We model Core-Loc breakwater armour layers with the finite–discrete element method.
- 242 armour units of 8 m^3 are placed on a rough underlayer of ~ 4000 angular rocks.
- Simulated armour layers meet acceptance criteria set by the concrete unit designer.
- Deterministic models generate spatial heterogeneity and contact force distribution.
- A packing density increase approaching 0.63 significantly increases contact forces.

NEW MODELLING AND ANALYSIS METHODS FOR CONCRETE ARMOUR UNIT SYSTEMS USING FEMDEM

John-Paul Latham^{i*}, Eleni Anastasakiⁱⁱ, Jiansheng Xiangⁱⁱⁱ

Department of Earth Science and Engineering, Imperial College London, South Kensington Campus,
London SW7 2AZ

ABSTRACT

Rubble mound breakwaters armoured with concrete units rely on collective behaviour between adjacent concrete armour units but existing largely empirical approaches have been unable to provide a detailed understanding of how these gigantic granular systems work. The problem has been that current methods cannot investigate the interdependence of hydraulic and structural stability at the scale of individual units. Numerical methods have the potential to provide such answers but there are many challenges to overcome. We present a solution to the first major bottleneck concerning the solids modelling: the numerical creation of a breakwater trunk section of single layer concrete units with geometrical and mechanical properties that conform to realistic prototype structure placements. Positioning of units is achieved with a new versatile software tool, POSITIT, which incorporates user-defined deposition variables and the initial positioning grid necessary to achieve the required design packing densities. The code Y3D, based on the combined finite – discrete element method, FEMDEM, solves the multi-body mechanics of the problem. First, we show numerically constructed breakwater sections with armour layers of 8m³ CORE-LOCTM units placed on rock underlayers. The numerically-generated packs are deemed acceptable when examined according to a range of criteria indicative of acceptably placed armour layers, as set by concrete unit designers. Breakwater sections with packing densities ranging from 0.59 to 0.63 are then created. Using a set of analysis tools, local variation in packing density as an indicator of heterogeneity, centroid spacing, unit contacts and orientation of unit axes are presented, together

* Corresponding Author: John Paul Latham, j.p.latham@imperial.ac.uk
Imperial College London, South Kensington Campus, London SW7 2AZ
Tel.020 7594 7327*

with mechanical information showing the variation in contact forces. For these five packs examined, an increasingly tighter pack was associated with a steady increase in coordination number and a more steeply and accelerating increase in average maximum contact force per unit. The force distribution results and discussion presented illustrate the potential of discrete unit FEMDEM modelling methods to address initial placement quality, armour layer design and future innovation in rubble mound structures.

KEYWORDS: Concrete armour unit; numerical model; FEMDEM; packing density; contact force; CORE-LOC™

1. INTRODUCTION

1.1. Importance of concrete armour layers

The two main design approaches favoured for harbour breakwaters of substantial size are rubble-mound and caisson. This paper is concerned with rubble-mound structures. Typically, the cover layers in first contact with storm waves will be gigantic granular systems of large blocks. If armourstone i.e. quarried rock, is not available or too small for the wave climate, concrete armour units with masses of tens of tonnes are used to make up the stable and porous armour layer that protects the rubble mound core by dissipating the wave energy. Here, we provide the context in which numerical methods can play an important role to support traditional understanding of concrete armour unit systems derived mainly from hydraulic model tests.

1.2 Structural stability of armour units

To select the type and size of unit for ‘hydraulic stability’ against wave action, designers, using the best available approach to date, implicitly accept scaled laboratory tests by generally referring to empirical formulae. They may consult best practice manuals (CIRIA, 2007; CEM, 2004), use the various unit designers’ guidance for size and placing methods, study laboratory scale research comparing type of unit performance (e.g. Van der Meer, 1999) and follow precedent practice from structures around the world. In simple terms, the empirical approach and inbuilt assumption is that when an armour unit system is placed according to the unit inventor’s guidance, it is designed so that units will have zero or insignificant movement for the design storm, so they should not break. Some movement on real structures is of course inevitable and designers dealing with probabilistic

1 occurrences understandably seek assurances of 'structural stability' in the most severe conditions,
2 something that cannot be easily imparted from laboratory tests.
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4 One problem for designers is that the two main failure modes for armour, namely (i) displacements -
5 hydraulic instability, and (ii) breakage - structural instability, are interrelated and must be studied
6 together (Burcharth, 1993). However, while the first can be studied conveniently in small Froude
7 scale models the second cannot because the stress levels are too small to cause any breakage of the
8 model armour units when made by mortar or other conventional model materials. Efforts to make
9 model units with strength-scaled methods (Timco, 1984) were partially successful but were not
10 taken up routinely as a reliable means to couple structural and hydraulic stability for prototype
11 structures. Although stress levels are small in model units, they can be measured by transducers.
12 Burcharth (1993) led investigations into stress levels e.g. using instrumented units within disturbed
13 packs, and carefully examined strength scaling laws to rescale dynamic and static results. Burcharth
14 et al. (1991, 2000) measured the stresses inside six model units under a suite of ramp tests and wave
15 structure conditions for randomly placed slender units (Tetrapods and Dolosse). The new design
16 formula obtained was a shift from the previous ones geared only for hydraulic stability. The formula
17 was designed to predict breakage conditions for Dolosse armour layers. However, it is widely
18 recognised that to validate predictions using stress information from site e.g. from instrumented
19 full-scale units which at best will give measurements only at the locations where sensors are placed,
20 and to understand breakage observations in the field has proved extremely difficult, see for example
21 discussions by Phelp and Zwamborn (2000), and Myrick and Melby (2005). Furthermore, designers'
22 attentions have now shifted from slender units to the bulkier single layer units that rely on
23 interlocking (as discussed below), and to the massive cube-like double layer systems. Current
24 research on unit systems is therefore turning more towards how to control the quality of placement
25 in these single layer interlocking unit systems and how to predict and limit stress levels.
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44 To tackle the issue of unit strength in such units, Muttray et al. (2005) applied overturning and free
45 fall drop tests as well as static and dynamic Finite Element stress analysis and compiled a comparison
46 of performance for three armour unit types of equal (4m^3) volume, [Core-Loc](#), [Accropode](#) and [Xbloc](#).
47 However, such stress analysis has only an indirect applicability to assessment of structural stability
48 and breakage probabilities since the distributions of local loadings affecting units may be very
49 different for interlocked multi-body systems of armour layers built on site or in model tests
50 compared with the two-body impact conditions.
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1.3 Interlocking of Armour Units

Hydraulic stability of armour systems when examined from first principles is generally attributable to number of waves, wave characteristics, armour slope, unit interlocking, contact friction, macro-porosity in the armour layer to provide space for turbulent energy dissipation, underlayer permeability for further dissipation, and appropriate armour to underlayer size ratio for filtering and shear key provision (e.g. Burcharth 1993). The term 'interlocking' invariably appears but it is a qualitative term. In granular systems it implies the degree of hooking and joining of particles so that movement behaviour of a particle or unit is increasingly dependent on its neighbours the greater the interlocking. Interlocking therefore increases for more concave-shaped particles or units and for unit assemblies arranged with higher packing density. However, although packing with regular pattern orientation of units can facilitate high packing densities, the regularity can introduce structurally weak directions in the pack. From experience, unit designers have therefore learned not only to set a target packing density or placing grid, but also to introduce construction rules to ensure sufficient randomness and to suppress conditions they consider are indicative of locally poor interlocking. A common optimisation problem in the design of armour units is the need to choose between hydraulic stability and structural stability. Armour units increase their hydraulic stability by interlocking but this usually requires significant reduction of the structural strength because high tensile stresses are developed in such slender 'concave' unit geometries, and hence the trend is to bulkier but still interlocking units. Fig. 1 shows an example of a typical well-interlocked structure built with one of the class of single layer bulkier units, the Core-Loc, (Melby and Turk, 1996). A detailed inspection indicates that the units are not entirely at random since a row-column structure is evident and, as will be discussed later in the paper, certain construction practices are implemented to achieve the best interlocking such as adjacent units in a row should not touch. High armour layer porosity is also desirable for energy dissipation, but for a given shape, tighter, i.e. higher packing density which implies a lower porosity, provides better interlocking. A big challenge, where researchers are turning to numerical modelling for future solutions, is therefore to numerically create such realistic interlocking structures and address this optimisation problem. Before introducing our approach to the numerical modelling of armour layers and the creation of different density packs, current understanding of armour unit packing and placement is briefly introduced.

[Suggest Insert Fig.1]

1.4 Packing density and terminology

Porosity in a granular system is the volume fraction of voids in a total volume, the volume fraction of solids being the packing density. With only one or two layers of granular material, the definition of the boundary of interest for the total or sampled volume is a well-known source of practical problems, especially in the case of rock armour (Latham et al. 2002). Clear guidance was given in CIRIA (2007) for layer thickness and porosity coefficients for different shape rocks and different surface survey methods. Medina et al. (2010) highlights the same problem for concrete armour layers. Here, we repeat the widely recognised formulae and symbols used for the geometry of armour layers. Placing density ρ_p [units/m²] which is controlled by the use of placement grids is given by the formula (CEM, 2004):

$$\rho_p = \frac{N}{A} \frac{V_u}{k_\Delta} \quad [1]$$

where N is the number of armour units placed on a reference slope with surface area A , k_Δ is the number of layers of units, V_u is layer coefficient, P is the nominal armour porosity and V_u is volume of unit. As mentioned by Medina et al. (2010) different layer coefficients k_Δ and different nominal porosities P may lead to the same placing density ρ_p .

A convenient parameter to measure the relative consumption of concrete in the armour layer associated with the armour porosity and number of layers, is the dimensionless packing density ρ_p which is the dimensionless placing density using the equivalent unit size, D_n as unit length:

$$\rho_p = \frac{N}{A} \frac{V_u}{k_\Delta} \quad [2]$$

Medina et al. (2010) suggest that it is better to refer to armour porosities $P = (1 - \rho_p)$ corresponding to a layer coefficient $k_\Delta = 1$, than to refer to nominal porosities P associated with a variety of specific layer coefficients $0.95 < k_\Delta < 1.10$. In the study of Medina et al. (2010) which focuses on double layer systems, dimensionless packing density, ρ_p , and related armour porosities P and number of layers in the armour k_Δ , are the preferred parameters used to characterize armour porosity and placing density of small-scale and prototype breakwater armour layers, i.e. a system that predefines k_Δ as 1. With the benefit of numerical tools, the volume fraction of void (or solid) within any rectanguloid sample window within a pack can be determined directly. However, as engineers focus quality control of their placement on numbers of units placed in a sample area, our

investigations will determine dimensionless packing density, D_p . As indicated below, this can be derived numerically both on a local and on a bulk survey basis.

In prototype surveys, especially for single layer systems, placing density is usually estimated by measuring the number of armour units in an area concerned and/or by measuring the distances between units (Oever et al., 2006):

$$D_p = \frac{N}{A} \quad [3]$$

where N is the number of units in one row and R is the number of rows, L is the length of row and W is the length upslope. Subtracting 1 from N and R prevents artificially over-counting perimeter units appropriate for the sampled area defined by L and W .

However, the placement of units is not always associated with a perfect row and column staggered or 'lozenge' placement pattern. Sometimes after placement and possibly because of settlement disturbance, the positions of units are less regular and significantly off-set from the theoretical pattern grid. Lines connecting units are not always straight parallel and perpendicular and they do not always form a rectangular area. Errors can become appreciable when attempting to apply Eq (3) to a sample area with poorly defined rows.

1.5 Armour unit placement

Although the hydraulic stability of armour layers has been extensively investigated by several researchers, the placement technique of concrete units is rarely discussed in the literature. In most cases the units are placed by hand on a model slope in a way that construction rules are satisfied and packing densities proposed by their inventors are achieved. In most experimental studies the hydraulic performance of the armour layer is examined, without focusing on the exact placement method of the units and without giving information about initial configurations of units. However, a general separation into a more regular or a more random placement of certain types of units has been found in some studies. The technique for the placement of single-layer random concrete units affects their interlocking and consequently the whole armour stability. The final average dimensionless packing density achieved is thought to play a large part in actual performance of these units, but is unlikely to be the only consideration that matters.

For each type of unit there is usually some guidance or a set of rules specified by their inventor to further encourage good interlocking. For instance, the local variability in the orientation of the Accropode unit is to be controlled for the proper functioning of the structure. Verma et al. (2004) discussed rules and sling techniques recommended to facilitate the desired orientation patterns for such units. Muttray et al. (2005) also discussed the placement of Accropode and Core-loc armour units, listing technical rules that were originally introduced for these units such as requirements for the positioning and criteria for the orientation of individual units. Table 1 provides an indication of such rules which have been used in practice for many years. The types of units invented more recently such as Xbloc and Accropode II are associated with a reduced emphasis on the need for such placement rules.

No matter what type of unit is being used; for hydraulic model tests the placement of units in the laboratory environment is relatively well controlled by training and use of grids, whereas the situation on site may prove less straightforward. Furthermore, the underwater placement of units typically requires final placing control to be assisted by divers, often with limited visibility, or continuous use of aids for the crane operator. For example, Mouquet (2009) described a topographical 3D system, Posibloc to aid the subsurface placement of any unit type. The system can provide optimum placement control of armour units on breakwaters when using either land-based or marine equipment. Furthermore, an integrated software system, Visibloc provides virtual imaging of the placement when using data from the Posibloc system (Mouquet, 2009). However, as far as the authors are aware, local placing density on a per unit basis, as introduced below, has not been presented in any software system or previous study whether for prototype, model or numerical armour layers.

1.6 Towards numerical placement of single layer systems

To numerically create single-layer random placed systems that have sufficient realism to provide reliable statistical force and stress characteristics as well as geometrical information is not straightforward for single-layer systems incorporating placement rules. To build software that mimics a crane operator, i.e. a 'numerical crane' is one approach. If successful, the software operator would manually carry out sequential placements in a visualizer environment much like the crane operator and the mechanics solver would need accurate high speed (real-time) execution to build a statistically representative layer (e.g. of >200 units) in practical timescales. To create such a

numerical crane constitutes a major software engineering task which would require fast and accurate physics solvers. An alternative approach - that we have adopted in this research - is to develop a placement method with no manual interventions necessary, but which incorporates constraints, randomness and physics-based operations. This approach has the advantages of repeatability, reasonable run times and importantly, it is hoped that different and new unit types can be the subject of more objective un-biased comparisons. It will be shown below that the results, in terms of the geometric skeleton's characteristics, are directly comparable with those of a system placed by contractor on site, or indeed, as placed by a model builder in the laboratory.

In the context of the long-term modelling aim within the coastal engineering community which is to build a virtual breakwater, the purpose of this paper is therefore to present the solid modelling component. We numerically create realistic concrete armour layers focussing here on [Core-Loc units](#). The geometric characteristics are demonstrated to be an appropriate match to those required for construction on site and in laboratory models. This enables models of Core-Loc packs with different packing densities to be built whereupon the distribution of forces and stresses can be examined and the implications of guidance on recommended packing densities investigated. In Section 2, previous numerical modelling research involving armour units is presented and the FEMDEM numerical methods for solving placement and equilibrium are introduced. Section 3 presents what is the central message of this paper: we probe the conformance of the numerically created layers. In order to both demonstrate that the adopted new placement procedures satisfy all technical criteria set by unit developers, and to interrogate armour layer properties and behaviour, a suite of new analysis tools was developed. One armour layer pack with a dimensionless packing density of 0.60, a value recommended when the Core-Loc was first used, is the subject of detailed analysis in this section. In Section 4, the creation of five different packing density armour layers is completed. Section 5 is a discussion comparing the statistical properties of each pack, in particular the contact force distribution. These early insights into the significance of initial packing density are placed in their broader context of on-going research before drawing conclusions in Section 6.

2. NUMERICAL METHODS

2.1 Previous research

Setting-up an experimental model can take a long time, give unreliable sensor measurements and be expensive, whereas numerical models can be quickly set-up, carried out on computers, or supercomputers if necessary and the degree of breakages inferred or modelled directly. One major advantage of the numerical methods introduced later in this paper is their ability to examine the distribution of contact forces with the potential to visualise the complete internal stress distribution within the solids, as well as track these during any further modelling of unit motion. The issue of scale effects and model effects, almost impossible to resolve in scaled flume and tank experiments are less severe or absent in numerical simulation.

The most significant effort in numerical modelling of coastal structures is currently being undertaken in the fields of numerical wave tank development, wave-structure interaction and more rarely, their combination. Until recently, there has been little work on numerical representation of realistic armour layers. However, achieving the numerical modelling of realistic concrete armour unit skeletons in which stresses can be examined (the solids modelling component) is a vital prerequisite to wave-structure modelling and progress in understanding rubble-mound designs.

Dentale et al. (2009) introduced a one way-coupled numerical model of the hydraulic performance of concrete armour layers (wave run-up, reflection) using FLOW3D and different granular skeleton geometries to represent armour layers of the various unit types. Hydraulic performance compared reasonably well with available experimental data. Their method of solid geometry pack creation is under further development so that non-overlapping and free-to-move unit packs can be represented to model breakwater performance and unit stability with greater realism, an objective shared with the present authors. Sakai et al. (2008) developed leading two-way coupled methods using particle-based fluids models and reported interaction of waves with packs of Tetrapod units that were modelled with a Discrete Element Method, (DEM) code. Several groups are employing DEM methods coupled to CFD codes, especially Lagrangian particle-based fluids codes to model wave structure interactions. Simulation results where armour units have been displaced from an initial position by wave action were presented by Onate, Iddelsohn and co-workers, e.g. Onate et al. (2012), using the new fully Lagrangian-based Particle Finite Element Method (PFEM). Greben et al, (2010) use a commercial code popular in the video games industry, PhysX (by Nvidia) to place packs of units such as Antifer Cubes and Dolosse, in the context of developing methods required to model wave-structure interactions for breakwaters. Blender, (Van Gumster, 2009) is a similar open source animation tool with certain physically realistic features used to introduce mechanical realism into computer animation visualisations.

2.2 The FEMDEM method

The Finite Element Method, (FEM) developed over several decades for modelling stress and deformation of solids was combined with the collision and motion tracking capability of the Discrete Element Method (DEM), to produce the combined finite–discrete element method (FEMDEM). Important for handling complex [deformable](#) shapes, FEMDEM solves the contact mechanics using a distributed contact force approach. All the [element](#) nodes local to a given contact and small overlap volumes are considered during collisions. A penalty function method delivers the contact forces (Munjiza 2004). FEMDEM was later extended to a 3D higher order and large strain formulation by Xiang et al. (2009a), in a code named “Y3D”. FEMDEM applications in the coastal engineering context were first proposed by Latham and Munjiza (2002). However, other techniques to combine FEM with DEM have been commercialised to produce the codes “UDEC” (see Itasca, 2004) and “ELFEN” (see Rockfield, 2004). [Recio and Oumeraci \(2009\) partially coupled UDEC to a CFD code to study hydraulic stability and deformation of revetments constructed with geotextile-filled sandbags](#)). The feasibility and early progress in applying FEMDEM to concrete armour layers was discussed in recent years, (see Latham et al. 2008a, 2009, 2011; Latham and Xiang, 2009 and Xiang, et al., 2011). It was shown to have many key attributes with which to investigate inter- and intra-block mechanics within a concrete unit armour layer, such as arbitrary shape and the ability to handle dynamic stresses. Before it can be exploited more fully in combination with wave-structure modelling, the first task is to numerically create rubble-mound breakwater sections with equilibrium conditions representative of full-scale units.

2.3 Introduction to the FEMDEM code, Y3D

Xiang et al. (2009a) introduced higher order large strain improvements in their FEMDEM code, named “Y3D”. This, the first reference to the fully deformable 3D FEMDEM code, includes many dynamic validation cases and the application of FEMDEM to stresses in armour units for the simple case of a flat-on-flat drop test. Y3D handles the transient dynamics of complex shaped multi-body behaviour and can support a vast range of alternative e.g. non-linear constitutive or internally fracturing properties. If stresses are sufficient to propagate cracks and initiate failure in the particles, they will fragment and the DEM formulations will continue to track the fragment motions. Hence, the potential exists to model breakup of units and the damage done by broken unit pieces in a storm.

In this paper we apply a simple friction law based on Coulomb friction. In this respect and considering other simplifying assumptions, it is very important the reader understands that the results do not represent the real behaviour of units and that this is a model with various assumptions and we are reporting a work in progress. If the tangential force F_t is larger than the friction force F_f given by a Coulomb type friction law, $F_f \leq \mu F_n$, where μ is the coefficient of sliding friction, the bodies slide over each other and the tangential force is calculated using the total normal elastic contact force, F_n . When bodies are in a state of rest, the tangential force for each contact may take any value between zero and μF_n . By comparing the tangential force being mobilised at each contact with the maximum tangential force that could be sustained at that contact, it is simple to derive a safety factor for each contact as discussed in Xiang et al., (2011).

Xiang et al. (2009b) investigated stopping distance predicted by the FEMDEM code implementation of the Coulomb friction law and showed the simulation was in excellent agreement with the analytical solution. Verification results for simple flat-on-flat sliding were also reported for velocity-dependent and pressure-dependent Coulomb friction laws by comparing the simulated bulk tangential and normal force ratios with the friction coefficients imposed as material properties at element level.

For certain multi-body applications, the material properties giving stress transmission through a body i.e. deformability, can be adequately represented by a rigid interior approximation. The contact interaction can still be solved with features of the FEMDEM approach such as distributed contact force interaction so that complex shapes can be handled. However, for the rigid case, new contact stiffness and damping coefficients need to be assigned and features of conventional DEM need to be implemented. This rigid implementation is very similar to that used for the cube packing tests reported in an early presentation of the FEMDEM method (Latham and Munjiza, 2004) and requires the moments of inertia and centre of gravity to compute body motion. The rigid version, named Y3D-R, has the advantage that it executes the simulation faster than the general deformable version, Y3D-D. For the work reported in this paper on simulation of realistic placements, we use Y3D-R to simulate deposition of units into the armour layer. Preliminary results using Y3D-D, for systems with relatively few loosely packed units where dynamic and static stresses were examined at full scale were presented by Xiang et al. (2011) and for model scale units, by Latham et al. (2011).

2.4 POSITIT - a new tool for depositing rocks and units

“POSITIT”, is a code written by Dr J. Xiang for introducing particles into a computational domain (Xiang et al. 2012). In this paper we briefly outline how it has been used in the context of armour unit placements and creation of realistic armour layers. However, the program is designed to be a versatile i.e. generic depositing tool, which can be used widely for industrial applications such as in powder and mineral technology. The program is used in combination with a FEMDEM solver. Here, we use the rigid FEMDEM code, Y3D-R code, a faster mechanics solver than the deformable version. Given time, particles settle towards a state-of-rest, i.e. into packs, with force equilibrium between neighbours and bounding ‘container’ walls.

POSITIT/Y3D-R allows the user to select multiples of any rock or armour unit shape and to position their centres on a 1D, 2D or 3D grid in a container of predefined geometry. Any initial non-overlapping particle position and velocity can be pre-set. The material properties become important when contacts are detected and the motions are computed using the mechanics solver in Y3D-R. The particles begin to pile up mechanically as they are caught in the container. The mechanical algorithms are exploited efficiently. If required, as units exit the array, new ones refresh the vacated positions so that a continuous stream of particles can be added. At the end of the run, if the particles have come to rest, the particles are touching and in static force equilibrium. These static configurations of meshed solid elements can be set as a checkpoint for further simulations by Y3D.

2.5 Rock Underlayer Placement

A rock particle with appropriate shape that was angular but with an acceptably low aspect ratio was selected from the VGeST shape library, see Latham et al. (2008b, 2010). This rock particle (Fig. 2) was resized to provide two alternative sizes ($D_n \sim 0.9$ and 1.0 m) and hence a bi-modal distribution was used to approximate the narrow grading appropriate for this rock underlayer. The underlayer was designed in accordance with engineering practice to conform to a mean size that gives a typical rock volume one tenth of the 8 m^3 armour units to be placed on top. More complex shape and size distributions could be modelled if required. To speed up the simulation of the deposition process, a compactor was applied. The simulation result for the final underlayer consisted of 3436 rocks. Fig. 3 shows details of the surface roughness. Note that the underlayer surface topography was checked and found to be within typically specified underlayer tolerances.

[Suggest Insert Fig. 2, Fig.3]

2.6 Concrete Unit Placement

After conducting many tests where model units were physically placed by hand on a smooth model slope, it was concluded that rules for positioning could be achieved provided that a suitable predefined placement grid was used. The main difficulty was to obtain sufficiently 'random' orientations for adjacent units. On completion of many placement tests, it was discovered that by pre-defining each orientation of adjacent units within successive groups of four units, the desired interlock with the appearance of a randomised final pattern could be achieved. The introduction of a particular combination of four different reference orientations in four adjacent units in successive groups on the pattern grid as shown in Fig. 4 was the key concept of the new placement method.

In using Positit, placement of units involves no manual interventions. In this sense, it is considered automated and repeatable. However, the user is required to input an appropriate placement grid. A pattern grid is theoretically designed in the plane of the slope 3:4 (V:H) considering both the technical recommendations and the target placement grid (Fig. 4). For Core-Locs with volume equal to 8m^3 and height $H=3.31\text{m}$ (in physical dimensions) the distance between the centroids of two adjacent units on the same horizontal row (D_h) and distance between the centroids of units upslope (D_v) was $1.10H$ and $0.55H$, respectively. Since the array read into Positit must not allow overlapping or touching particles, the units should also not be in contact with the slope in their initial configuration. An additional distance normal to the slope is added to redefine the target centroid positions of the units clearly above the slope.

[Suggest Insert Table 1]

According to the technical specifications (see Table 1), each unit should not have the same orientation as adjacent ones when positioned according to the target grid. In order to achieve better interlocking, alternative combinations of orientations of adjacent units were systematically considered. Taking orthogonal reference directions parallel and normal to the slope and aligning the axes of the units with these directions, it is found that six different configurations are possible (see Appendix A where stereographic projection methods for 3D orientation representation are summarized). Two out of the six possible configurations were rejected as these were the cases where the legs lie in the vertical plane but in parallel contact with the slope (either up-slope or

along-slope) i.e. at maximum risk of sliding on the underlayer base as there is no possibility of keying of Core-Loc unit noses or legs with the underlayer, (see Appendix A).

[Suggest Insert Fig.4]

An extensive series of deposition experiments was conducted to optimise the combination of the four initial orientations of Core-Loc units, their initial placement grid spacings, friction coefficient and the deposition velocity during their non-contacting phase. Units are placed using POSITIT/Y3D-R in a row by row sequence as shown in Fig. 4 where the non-contacting phase, as units descend onto a layer, is apparent for the upper two rows. The final average packing density can be predicted to a reasonable accuracy from the placement grid while other factors are set to ensure conformance with the construction rules for good interlocking. To ensure good contact is made between units and the underlayer rocks, a final procedure is added. This involves gentle vibration. The final numerically-placed pack is brought to equilibrium under conditions where the friction coefficient is 0.9 (Fig. 5, left). The value of 0.9 was chosen as a preliminary estimate for the friction coefficient of concrete against concrete, (see also discussion in Section 4). The final pack shows many of the attributes considered necessary for realistic initial builds. Furthermore, the simulated pack geometry shown in Fig. 5 (left) was examined and endorsement by this unit's developer. The numerically placed pack and the real world pack of a coastal protection structure in Chile, viewed nearly normal to the layer are shown side by side in Fig.5.

[Suggest Insert Fig.5 left and right]

3. CONFIRMATION OF NUMERICAL PLACEMENT REALISM

3.1 Introducing analysis tools for placement criteria

As discussed above, the focus of this work is on making a layer system that has the characteristics of layers built with current engineering practice. A suite of tools has been developed to fully analyse packs of armour units such as shown in Fig. 5 (left) and Fig. 6:

- Spacing between and relative displacement of unit centroids
- Stereographic projection analysis of the nose axis orientations of Core-loc units
- Accurate packing density calculations on a local and global basis
- Unit coordination number, as contacts only with underlayer or for all contacts

- Maximum contact force magnitude per unit (to generate force distributions)
- All contact forces between units and with underlayer

In this section we apply these tools to analyse a pack of 242 Core-Loc units (21 rows, 11 of which have 12 units and 10 of which have 11 units). The numerically created pack with a dimensionless packing density of 0.60 is presented in Fig. 6.

[Suggest Insert Fig.6]

3.2 Position of Centroids of units

The basic concept of placement pattern for a straight (trunk) section of a concrete armour layer is a staggered grid. In this staggered grid, each unit is in contact with two other units, two below and two above. Adjacent units in the same row are not in contact with each other. For any placement procedure, a target spacing grid is calculated for the unit centroids with both horizontal spacing D_h and upslope spacing D_v expressed as a multiple of H , the unit height. For example, the approximate grid and non-contacting neighbouring units of the same row can be seen in a prototype structure to the left of Fig. 1. For the current pack a theoretical square grid with $D_h=1.10H$ (where for a Core-Loc unit of 8m^3 , $H=3.31\text{m}$) and an upslope placing distance of $D_v=0.55H$ has been applied as the target grid.

In reality, the 'as placed and at rest' centroids cannot be expected to coincide exactly with the target centroids. The placement of units can often best be assessed by statistically checking the spacing between neighbouring pairs of units compared with the recommended target distances for both the horizontal and upslope distances between adjacent units. The coordinate reference frame adopted as follows: Z horizontal along the shoreline with positive Z towards the left when observed from the sea; Y vertical with positive upwards; X horizontal with positive directed into the slope and away from the sea, with the origin, $X=Y=Z=0$ at the start of the base of the slope. The reference axes directions are shown in Fig. 4. The positions of centroids of units can be output at any time.

In the pattern grid after placement, each separate unit can be identified by its sequence position in the grid. Where i = the sequence number of each unit in each row and j = the sequence number in each column, it is possible to check statistically, the degree to which the final positions of units satisfy the technical target placing requirements which are as follows:

- Positions of units in the same row should ideally have a distance $Z_{i,j} - Z_{i+1,j}$ equal to D_h
- The upslope distance of units $S_{i,j} - S_{i,j+1}$ should ideally be equal to D_v
- Since a unit must rest on two units of the row below, the horizontal distance $Z_{i,j} - Z_{i,j+1}$ should ideally be equal to $D_h/2$

The average spacing between neighbouring pairs of units in their final positions divided by their theoretical target spacing is presented in Table 2. Their distributions are presented in Table 3 the interpretation that there is greater upslope spacing variability than horizontal variability is clear. Having captured the coordinates of the centroids of units, other statistical values can be extracted from these distributions. However, these are outside the scope of the present paper.

[Suggest insert Tables 2 and 3]

3.3 Orientation of unit axes

A useful method to examine whether unit axes (e.g. the axis direction of the nose of the unit) have been placed with or later adopt a preferred orientation is to use the stereographic projection method (e.g. see Lisle and Leyshon 2004). The method is introduced briefly in Appendix A. A stereographic projection approach has already been adopted in the Visibloc system (Mouquet, 2009). Fig. 7 provides nose axis orientation data which can be readily interpreted with reference to Appendix A, Figs. A1, A2, A3 and Fig. 4. It is apparent that the relic of configurations number 2 and 3 can still be detected in the large but dispersed clusters with nose axes dipping $\sim 40^\circ$ upslope or $\sim 40^\circ$ downslope with numbers 1 and 4 more often tending to retain axes near to horizontal with alignment near to the direction representing the breakwater trunk.

[suggest insert Fig. 7]

Whereas in real armour unit systems, with the Posibloc system there exists a means to measure and tracked directly the principal orientations or symmetry axes of units, the numerical simulation system requires a means of deducing these from the coordinates of the finite element representation of the units. The axis of the nose of a Core-Loc unit can be calculated at any point in time in the simulation by computing the vectors that describe the 3 Principal Axes of the three moments of inertia. The least of these moments of inertia is associated with the unit nose axis direction. This is computed and all results are transformed so that the Reference Slope plane parallel to the armour layer becomes the horizontal for the purpose of plotting stereographic projection data (see Fig. 4). Note that the nose orientation does not uniquely describe how the unit lies on the slope as the legs can be pointing in any direction normal to the nose axis. In the Visibloc system

(Mouquet 2009) this extra degree of freedom is characterised by colour coding the points plotted on a stereonet according to rotation about the nose axis.

3.4 Packing density

A rigorous approach based on individual units is proposed for the accurate estimation of packing density with reference to the plane of slope. The main concept is based on the placement pattern with a staggered grid, where each unit is in contact with four other units, two below and two above, the unit to the left and right and straight above and below are not in contact (Fig. 8). In practice, the final placement may be more random such as the general case presented in Fig. 9. For each unit the area formed by these four surrounding units can be calculated, see Eq (4). However, this area will in general not be square or rectangular.

[suggest insert Fig. 8, Fig.9]

This area, associated with unit i can be expressed by the following equation:

$$A_i = \frac{1}{2} \left((Z_{i+1} - Z_{i-1})^2 + (S_{i+1} - S_{i-1})^2 \right) \quad [4]$$

where Z and S are the coordinates of the centroids of units in the horizontal and upslope directions, respectively. The number of units corresponding to this unit area is 2. The packing density is then equal to $2/A_i$. In Fig. 10 the packing density which corresponds to each unit is presented in dimensionless form where the x-axis is the index number of each unit for which an area can be calculated from its neighbours, starting from unit 1 in the toe row and ending with the unit 242 at the end of the top row. There are units next to the side walls as well as at the upper last row which are not connected with four units. The same is true for the lower units which are in contact with the toe units. For those units a corresponding area is not calculated.

[suggest insert Fig. 10]

[suggest insert Table 4]

In Table 4 the average dimensionless packing densities per row as well as the average packing density of the whole structure are presented. Calculations have been made including (and excluding) units close to the side walls.

Calculations have been verified for the theoretical as compared with the target area of each unit. In this illustrative case, the target dimensionless packing density was 0.60, but with the considerable local variation i.e. pack heterogeneity, being thoroughly examined with the statistical tools developed.

3.5 Coordination number: contacts between units with neighbours and underlayer

The number of contacts each unit makes with its neighbours is known as the coordination number, usually given the symbol z and sometimes simply called the contact number in the figures. For the 242 units placed on the rough underlayer, results shown in Fig. 8 with a colour coded key are as might be expected. The red underlayer and container walls are represented as one solid body and thus have coordination number > 10 (i.e. ~ 500). Two units have very high z ($= 8$) and close examination was able to verify this as being correct. Many of the units on the top row have $z = 3$, one with $z = 2$. Another analysis option exists to simply consider contacts between unit and underlayer (Fig. 11).

[suggest insert Fig. 11]

3.6 Contact forces

The magnitude of all contact forces experienced by each unit in the static pack has been extracted. The maximum contact force experienced by each unit is of particular interest and this is illustrated in Fig. 12 where there is a clear indication from these models that units near the toe are bearing higher contact forces, some well in excess of their own weight ($\sim 188\text{kN}$).

[suggest insert Fig. 12]

4. RESULTS: LAYERS CONSTRUCTED AT DIFFERENT PACKING DENSITIES

Achieving the packing density is considered essential for the effective use of interlocking single layer systems. For Core-Loc systems, the original recommended value (for 15 ton units) was $= 0.58$ (Holtzhausen, 1998) although the technical guidelines (Turk and Melby 1997) “suggest Core-Loc units should be packed as tightly as possible”. Tighter packs are recommended in more recent guidance, for example CLI (2011) presented a design table in which the recommended dimensionless packing density for 8m^3 units was 0.618. One of the first engineering applications of

the new layer-building methodology was to examine key differences between packs of different packing density. However, for numerical placement, further testing was required to examine the best initial setup to achieve a specific packing density. For example, a prescribed grid with an associated target packing density might not deliver the intended average packing density when a whole test section of more than 200 units is numerically placed.

In order to meet alternative packing densities different theoretical placement grids with horizontal distance $D_h \times H$ and upslope distance $D_v \times H$ between units were placed with the 'standard' pattern described in Section 2.6, i.e. that has a family of four adjacent units with four orthogonally arranged units. Extra freedom for units to slide and rotate was investigated by reducing the active initial friction coefficient of units while they are interacting with the rough underlayer and in contact with rocks and other units.

In this paper, in addition to Armour Layer (AL-601) analysed in Section 3, three denser (AL-607, AL-614, AL-629) and one looser armour layer (AL-589) have been numerically created. Packing density has been measured for each unit of the five packs using the new method of calculation of Local Packing Density introduced in this paper in Section 3.3. Average packing density of each row as well as of the whole structure has also been calculated. The characteristic grid pattern and friction coefficient settings for the five packs are presented in Table 5 together with the resulting total average packing density of each armour layer.

[suggest insert Table 5]

In all five cases the final placement of units is considered satisfactory in relation to the technical placement criteria (Table 1). The positions of centroids of units form straight columns and rows and orientations of adjacent units are different, while an acceptable degree of randomness of units' orientations has been achieved. Stereographic plots for AL-601 was presented in Fig. 7, while for the remaining four, the orientations of units are plotted in Fig. 13. (See Appendix A for an aid to stereographic plot interpretation). Some clustering remains as a relic from the original grouping into four initial orientations prior to unit interactions, but this was not considered to be a significant departure from the degree of randomness expected in prototype structures. The five patterns suggest some nose axis orientations survive from one creation to some of the others. This is to be expected in these examples as there are similar placement grids used to create the different final conditions. A greater dispersion of orientations (less clustering) is developed in the highest density pack.

[suggest insert Fig. 13]

5. DISCUSSION: COMPARISON OF ARMOUR LAYER PACKS

In this paper five breakwater armour layer sections, consisting of Core-Loc units of 8 m^3 , have been numerically created with different packing densities. The intention here is not one of providing precise predictions of the performance and properties to be expected of 8 m^3 Core-Loc armour layers, especially given that these structures represent force equilibrium in dry conditions. The purpose of this discussion section is to investigate heterogeneity and statistical trends arising when average packing density is varied and to illustrate the insights that a new numerical modelling approach can deliver.

5.1 Row-by-row packing density

Packing density is the most important parameter for the characterization of a concrete unit armour layer pack. It can be treated as a local or global property of an armour layer, depending on its associated region. The new method of calculation of local packing density on a per unit basis, as presented in this paper, allows the calculation of average local packing density in any sampling area and this can be on a per row basis.

Concerning the total average packing density of the whole structure, there are wall effects, just as found in laboratory tests. Including units close to the boundary side walls from the calculations leads to under-estimations of only 0.1% to 0.2% compared to when all units are included. Unless otherwise stated, packing density results are based on the analysis of Armour Layers with units close to the side walls included.

It is confirmed that the concrete armour layers placed in this investigation are heterogeneous in structure and this can be quantified in terms of local packing density. Fig. 14 compares the row by row average for all five Armour Layers. Average packing density per row is decreasing and increasing almost every 2-3 rows. Maximum local per row of 0.669, is found in the densest pack, AL-629, in Row 11. The middle rows 11, 12 and 13 are also the densest rows for AL-589, AL-614 and AL-629, with values of average local packing density per row equal to 0.619, 0.633 and 0.637,

respectively. In AL-601, the maximum local packing density, equal to 0.632, is found in the middle row 8.

[suggest insert Fig. 14]

If we consider the two halves of the structure, the lower part includes rows 2 to 10 and the upper part includes rows 11 to 19. In all five packs, the average local of the lower half structure, has been measured and found to be slightly larger than the average of the upper half structure. The average local packing density of the lower and upper half of the structure for each Armour Layer is: AL-589: 0.593 and 0.586; AL-601: 0.604 and 0.597; AL-607: 0.606 and 0.608; AL-614: 0.618 and 0.612; AL-629: 0.635 and 0.609. In AL-607, the lower and upper parts of the structure have almost the same packing density. In the rest of the Armour Layers the lower half part of the structure is tighter than the upper half part by between 1 and 1.2% except for the densest case, AL-629, the lower half of the structure is significantly tighter than the upper by 4.5%. The density achieved is therefore relatively even all the way up in most builds, but for the densest pack a greater density occurred lower down. Further effort is needed to assess whether equal density is achieved in construction practice and whether the model building procedure adopted can be modified to create more equal density in the upper and lower halves.

There is a trend described in the previous paragraph when analyzing the upper and lower halves of the layer separately. But when the whole structure is examined, there are two other obvious trends. One is the consistently looser packing in the upper three to five rows which is especially noted in AL-629. The other is that maximum forces have been measured in the lower rows. This first effect is explained by lower down-slope forces, the weight of units above being more in-active when the packs are created. Assuming that breakwater armour layers of 22 rows, (which according to unit developers is actually the maximum recommended number of concrete unit rows considered for standard structures) are designed for significant wave heights greater than 7m in deep sea water levels and for minimum to zero wave overtopping, these upper three to five rows will most probably be found above the sea water level. In real sea conditions, this is the part of the breakwater that is most exposed to the wave action and therefore to displacements of units. In real conditions an above water placement with extra effort may mitigate against this trend.

5.2 Coordination number

In contrast to 'crystallised' regular particle structures typical of sphere packs, irregular packing structures are normal in granular systems. The randomness of the packing required for the interlocking of the concave shaped Core-Loc units has the consequence that the number of unit contacts that each unit experiences is far from constant. Even though it is stated that each unit must touch four units – two in the row below and two in row above, and make contact with the underlayer slope, (see Table 1), the coordination number has a wide variation; contacts with neighbouring units or rock underlayer ranging from 3 to 13 in the five packs examined. Different packing conditions result in a different average coordination number and different spatial distributions of coordination number. Fig. 15 shows the variation of coordination number in a cumulative frequency plot for the five different packing density packs. For packing density equal to or below 0.607, the plots are almost identical. For further increases in Φ above 0.607 the cumulative curve shifts to the right, resulting in a larger average coordination number. The median value of z increases systematically from 5.5 with Φ less than or equal to 0.607, to about 6.7 for the tightest pack with Φ equal to 0.629.

[suggest insert Fig. 15]

5.3 Contact forces

The contact forces experienced by each unit are considered very important to a fundamental understanding of rubble mound structures since they affect the stability of units as well as of the whole structure. Before examining contact forces, it is appropriate to recall several simplifying assumptions affecting the behaviour at contacts and thus contact forces being modelled. For example, inelastic contact behaviour expected for sharper contacts on real structures is not included in the present model.

In this paper which examines the properties of placed unit packs, assigning the friction coefficient is important, but less critical than in future studies aiming to model unit and armour layer stability in response to disturbance forces (e.g. wave action or earthquake). Mobilised friction coefficients for shear of concrete to concrete depend on surface roughness and normal pressure. Whereas 0.5 appears to be an appropriate friction value for normal stresses of 0.5-2 MPa for smooth cast surfaces sheared as a flat-on-flat geometry; should the surfaces be rough such as the extreme case of a fresh fracture surface, as may be experienced by older units or at a contact of an edge or corner

1 against a flatter surface, a maximum mobilized value above 1.0 is supported by the experimental
2 data of Tassios and Vintzeleou, (1987). Data and guidance on concrete-concrete friction coefficients
3 tends to vary widely and particularly depends on whether a safe guidance limit or most likely value is
4 being proposed. It should by now be apparent that real concrete contact and friction forces are
5 complex and highly variable as a result of surface damage where concrete spalls and abrades and
6 aggregate is exposed. For sliding of concrete caisson on rock rubble, Hutchinson et al (2000) referred
7 to guidance for friction coefficient (0.6 in Japan and 0.7 in France) and presented large scale
8 experimental data giving a maximum mobilized friction coefficient of 0.78. For the models in this
9 paper, the friction coefficient is set to 0.9. To consider the sensitivity of this assumption to the
10 discussion on simulated force distributions, it was noted that the simulated pack geometry after
11 finding equilibrium does not change significantly when the friction coefficient is relaxed from 0.90 to
12 0.60. Although a small shift to higher maximum normalised contact force is noted, the effect is
13 significantly less than that associated with, for example, a comparison between force distributions
14 for packing density layers of 0.601 and 0.607.

15 [suggest insert Fig. 15]

16 Contact forces between units of an armour layer are captured here for the first time. The probability
17 distribution $P(f)$ of the magnitude of all contact forces f normalized by the number of contacts
18 (recall the differences in number of contacts noted for average coordination number for the denser
19 packs), and the weight of the unit itself ($W = 188 \text{ kN}$) is presented in Fig. 16. These distributions
20 further show the existence of a long tail, signifying the existence of many contacts with larger forces.
21 The trend is clearly seen in terms of the gradient of the approximately negatively exponential
22 distributions, where lower gradients and therefore greater numbers of high forces are experienced
23 by the packs with increasing packing density.

24 [suggest insert Fig. 16]

25 **5.4 Maximum contact forces**

26 Maximum contact force per unit yields a more log-normal type distribution than for forces at all
27 contacts where there are many instances with very small magnitudes. Such distributions are
28 considered likely to also yield log-normal distributions of maximum stress components, (tensile and
29 differential) as were observed for double-layer slender model units investigated by Burcharth et al.
30 (1991). For the looser packs, the simulated maximum contact force per unit was observed to vary

between 0.5 to 3 times W . For the densest pack, maximum contact forces of between 4 or 5 times W were noted (with a few higher maximum contact forces also observed). The high magnitudes of contact force for a relatively small proportion of contacts simulated here should be viewed with caution especially given our assumptions, as highlighted above, that inelastic crushing at sharp contacts is excluded. However, the trends learned from these simulations are of interest. The distribution of maximum forces per unit (shown with spatial variation in Fig. 12), presented in Fig. 17 shows a similar trend to the distribution of all contact forces shown in Fig. 16 but the increasingly significant number of maximum contact forces above $3W$ for packs with greater packing density (with Φ equal to or above 0.607) is clearly shown. The denser the armour layer, the greater is the number of larger maximum contact forces developed. The maximum contact force was found to occur in the densest pack, AL-629, which also has the most contacts. The cumulative plot in Fig. 18 picks out differences between the AL-607 pack and the less dense AL-589 and AL-601 packs somewhat better than the coordination number plot in Fig. 15, where these three packs are grouped together. Note that the forces are given here in normalised form, however the anticipated scalability of the force distribution is the subject of current work.

[suggest insert Fig. 17, Fig. 18]

5.5 Concluding remarks

Notwithstanding the limited number and range of simulated packs and the simplifying assumption of Coulomb friction with an assumed coefficient of 0.9, a summary plot for average coordination number and average normalised maximum force per unit for each armour layer pack is shown in Fig. 19. For all five packs, the average coordination number i.e. contacts made with the rock underlayer is two. The relation between average coordination number for all contacts, average normalised maximum contact forces and average dimensionless packing density is apparent. Both coordination number and maximum force become sensitive to increases in Φ above a threshold dimensionless packing density of about 0.60. However, the average maximum force increases non-linearly and at a greater percentage rate than average coordination number as Φ increases. The increase is greater for the armour layer with average packing density equal to 0.629 than for that equal to 0.614.

[suggest insert Fig. 19]

To address levels of stress in units at different packing densities, the FEMDEM Y3D-D code can be used as it provides dynamic and static stress information, and by inference, proximity to conditions

for failure. Although considerable discussion has been given to previous research efforts to obtain stress information for armour units in packs, this paper stops short of performing stress analysis, showing here the contact force distributions. Studies of armour unit stresses derived from simulations using Y3D-D will be the subject of future work.

In this paper, we reported the foundations of a modelling technique which can build armour layer systems realistically. We also presented (in Section 5) a snapshot of the type of insights into dry static systems that become readily available when applying these discrete models and analysis tools introduced in this paper. Modelling the response to loading disturbances is the next numerical modelling goal. Hopefully, the ability to examine heterogeneity and the statistical nature of armour unit behaviour will improve engineering understanding of movement, settlements and the dynamic and static loads and stresses. The hope is that numerical models based on FEMDEM will lead to improved design guidance, more optimised structures and possibly, novel design concepts.

History-dependent material properties such as fatigue are currently outside the scope of work, but preliminary research with FEMDEM modelling methods demonstrated that it is possible to examine the armour units' responses to loading disturbances. Early work on disturbance response was reported by Latham et al. (2011) and Xiang et al. (2011). The application of FEMDEM to armour layers disturbed by a range of time varying forces and velocity constraints is the focus of on-going research (Xiang et al., 2012).

6. CONCLUSIONS

The work combines a new deposition code, POSITIT with a multi-body mechanical FEMDEM code, Y3D. Pre-defined optimally oriented geometric arrays of 8 m³, 3.31 m high Core-Loc units are numerically deposited row by row onto a 24 m high model of a breakwater slope with a modelled underlayer surface made up of ~ 0.9 - 1.0 m sized angular rocks. The mechanical force equilibrium of units at rest is reached with contact interactions being handled explicitly employing the multi-body features of FEMDEM. Compared with previous work, we have for the first time, created a mechanical model representation of packs of concrete armour units with sufficient realism to provide preliminary insights into the heterogeneous properties of armour layers and the effect of looser and tighter layers. To demonstrate armour layer realism, and for future analysis of deforming armour layers, a range of statistical analysis tools were developed and illustrated. These include: (1)

spacing between and relative displacement of unit centroids; (2) stereographic projection analysis of unit axis orientations; (3) accurate packing density calculations on a local and global basis; (4) unit coordination number, as contacts only with rock underlayer or for all contacts with concrete units and rocks; (5) all contact forces between units and with underlayer rocks, (6) maximum contact force magnitude per unit. The main conclusions are as follows:

- (i) A reproducible algorithmic procedure has been developed that is fully automated and is capable of generating armour layers of single layer interlocking Core-Loc units of average packing densities specified by the unit designer (the tested range was from 0.59-0.63), and which meet their placement criteria. The procedure is general and therefore should be applicable to other shaped single layer bulky interlocking units.
- (ii) Five different armour layers with a range of average dimensionless packing densities from 0.59 to 0.63 were created where it was shown that above values of 0.60, an increasingly tighter pack was associated with a steady percentage increase in coordination number and a higher percentage increase in average maximum contact force per unit that is amplifying.

These models can be used in subsequent analysis of the behaviour of breakwater armour layers when subjected to disturbance forces, buoyancy etc. This is the focus of current and future research. With the new FEMDEM model code, Y3D, realistic concrete armour layers can now be created with average packing densities specified up to realistic values for constructed prototype layers. The stochastic nature of the granular structure and local mechanical details, including contact forces between units and the underlayer, are captured and presented here for first time.

Acknowledgements

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Appendix A.

This appendix presents a summary of the stereographic projection method applied in this paper to the representation of Core-Loc unit nose axis orientations on stereonet plots.

1 Stereographic projection using a Lambert Equal Area lower hemispherical projection is a method
2 widely used for presenting three-dimensional information on a two-dimensional plot, especially
3 useful in structural geology, e.g. see Lisle and Leyshon (2004). Line directions are represented by
4 points (poles) and planes are represented by curved lines (great circles) or straight lines (for the
5 special case of vertical planes). The stereonet represents a horizontal reference plane, the equatorial
6 plane through the sphere centre, onto which intersections with the lower hemisphere of lines or
7 planes passing through the sphere centre are projected.
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12 The Core-Loc has three axes of symmetry. The axis running through the two identical noses and
13 centre of the unit (the nose axis) is normal to the plane containing the four legs. It is possible to plot
14 the nose axis orientation uniquely (except when it lies exactly horizontally in which case the pole can
15 be plotted at either end of the two diametrically opposites points on the perimeter (see Fig. A3,
16 configuration 4). However, the attitude of the unit cannot be captured with the pole alone as the
17 unit has 180 degrees of rotational freedom about this axis. To further refine the usefulness of the
18 plotting system and identify separate units with identical orientation, a colour coding of the pole
19 from 0 to 180 degrees, to capture rotation about the axis is an option. However, simply plotting the
20 nose axes of Core-Loc poles, as adopted in Fig. 7 and Fig. 13 of the paper can readily give an
21 objective indication of spread or clustering of unit orientations.
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31 [suggest insert Fig. A1 and Fig. A2]
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34 A vertical line plots in the centre of the net and horizontal lines plot on the perimeter. A North-South
35 vertical plane plots as a straight N-S vertical line while an East-West vertical plane plots as a straight
36 E-W line. In Fig. A2, the units in configuration 1 and 2 are shown balancing on one another as their
37 nose axes poles plot as superimposed points at the centre of the stereo net. Horizontal nose axes
38 poles are plotted on the perimeter. Configurations 4 and 6 plot at positions pointing West-East, (e.g.
39 along the bench or along the trunk of a breakwater). Configurations 3 and 5 plot at the position
40 pointing South–North, (e.g. up and down the bench or up and down the armour slope of the
41 breakwater). A tilted reference frame is considered in the paper where the red lines in Fig. 4 show
42 the orthogonal reference planes.
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51 Figure A1 shows six configurations. Numbers 5 and 6 are not used in the initial pattern grid during
52 placement as they have the disadvantage of greater potential instability compared with 1 to 4. With
53 1 to 4, either the legs or noses initially point towards the underlayer rocks, providing the opportunity
54 for good keying, whereas with 5 and 6 there is a much larger flattish surface of the unit in contact
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with the underlayer i.e., less interlock with the rough underlayer, see further comment in the main paper.

The units in Fig. A3 have been carefully oriented and positioned to illustrate unit attitudes representative of the pole positions they occupy. They include non-unique three-dimensional attitudes of the Core-Loc units having nose axes that are horizontal, vertical and dipping at 45°, as described by these pole positions. Note, the nose axes shown dipping downwards at 45° to the cardinal directions N, S, E or W are positioned over the grid marking representing a 45° dip. Similarly, horizontal nose axes with NE, SE, SW, and NW azimuths are positioned over the equivalent grid markings.

[suggest insert Fig. A3]

The stereographic projection net can be used with the equatorial reference frame rotated to align parallel with a convenient reference frame. The stereographic projection plots of nose axes poles reported in this paper (Fig. 7 and Fig. 13) apply the equatorial reference frame to the plane of the armour layer with the cardinal points N-S in the up-downslope directions (S-axis direction) and W-E in the direction of the breakwater trunk (Z-axis direction). The standard X, Y, Z reference frame and the armour slope reference frame created by a rotation of $\tan^{-1}(\frac{1}{4})$ or ~37 degree about the Z horizontal axis are shown together in Fig. 4 of the paper.

REFERENCES

- Burcharth, H. F., Howell, G. L. and Liu, Z., 1991. On the determination of concrete armour unit stresses including specific results related to Dolosse. *Coastal Engineering*, 15, 107-165.
- Burcharth, H.F., 1993. Structural integrity and hydraulic stability of Dolos armour layers. Department of Civil Engineering, Aalborg University, Denmark.
- Burcharth, H.F., d'Angremond, K., Van der Meer, J.W., Liu, Z., 2000. Empirical formula for breakage of dolosse and tetrapods. *Coastal Engineering*, 40(3), 183-206.
- CIRIA, CUR, CETMEF, 2007. The Rock Manual. The use of rock in hydraulic engineering. 2nd edition, C683, CIRIA, London.
- CLI, 2011. Concrete Layer Innovations, <http://concretelayer.com/>, (website accessed 23.02.2011).
- Coastal Engineering Manual (CEM), 2004. Coastal Engineering Research Centre (CERC), US Army Corps of Engineers, Vicksburg, Mississippi, USA.

Dentale, F., Russo, S.D., Carratelli, E., 2009. Innovative numerical simulation to study the fluid motion within rubble mound breakwaters and the armour stability.

http://www.flow3d.com/pdfs/tp/wat_env_tp/FloSci-Bib01-10.pdf. Published online.

Greben, J.M., Gledhill, I., Cooper, A.K., De Villiers, R. 2010. Characterization and properties of breakwater structures modelled by a physics engine. 7th South African Conference on Computational and Applied Mechanics (SACAM10), University of Pretoria, Pretoria, 10-13, January 2010, 254-265.

Holtzhausen, A. H. 1998. The first Core-Loc breakwater. Proceedings of 26th International Conference on Coastal Engineering, Copenhagen, Denmark, 1998.

Hutchinson, S., Young M. and Macleod, A. 2010. Caisson breakwater design for sliding. Proceedings of 32nd International Conference on Coastal Engineering, Shanghai, China.

Itasca Consultants, 2004. UDEC Manual, 1 to 5, Minneapolis, U.S.

Latham, J-P., Munjiza, A. 2002 Porosity and Packing Simulations of Particles with any Shape or Size – Dynamic 3D results from Combined Discrete Finite Element Models, Proceedings of the International Conference on Coastal Engineering, ASCE, 1424-1435.

Latham, J-P., Newberry, S., Mannion, M., Simm, J., Stewart, T., 2002. The void porosity of rock armour in coastal structures. Proc. Water and Maritime Engineering, ICE, 154, 189-198.

Latham, J.P., Munjiza, A. 2004. The modelling of particle systems with real shapes, PHILOS T ROY SOC A, 362, 1953-1972.

Latham, J.P., Xiang, J. 2009. Application of the finite-discrete element method to dynamic stress development in armour units and armour layers. Coasts, marine structures and breakwaters. Adapting to change. Thomas Telford, 2009.

Latham, J-P., Munjiza, A., Mindel, J., Xiang, J., Guises, R., Pain, C.C., Gorman, G., Garcia, X., 2008a. Modelling of massive particulates for breakwater engineering using coupled FEMDEM and CFD. Particuology 6, 572–583.

Latham, J.P., Munjiza, A., Garcia, X., Xiang, J., Guises, R., 2008b. Three-dimensional particle shape acquisition and use of shape library for DEM and FEM/DEM simulation. Minerals Engineering, 21 (11), 797-805.

Latham, J.-P., Mindel, J., Xiang, J., Guises, R., Garcia, X., Pain. C., Gorman, G., Piggott, M., Munjiza, A., 2009. Coupled FEMDEM/Fluids for coastal engineers with special reference to armour stability and breakage. Geomechanics and Geoengineering, 4, Issue 1, 797-805.

Latham, J.-P., Xiang, J., Harrison, J.P., Munjiza, A., 2010. Development of Virtual Geoscience Simulation Tools, VGeST for irregular blocky rock applications in rock engineering using the combined finite discrete element method, FEMDEM. 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, Salt Lake City, UT.

1 Latham, J.-P., Xiang, J. and Baird, W.F. 2011 A numerical investigation of the influence of friction and
2 vibration on laboratory scale armour unit layers. Proceedings of the International Conference on
3 Coastal Structures, Yokohama, Japan. September 6-8, 2011.

4
5 Lisle R. J., Leyshon P.R. 2004. Stereographic projection techniques for geologists. Cambridge
6 University Press, New York.

7
8 Medina, J.R., Gomez-Martin, M.E., Corredor, A. 2010. Influence of Armor Unit Placement on Armor
9 Porosity and Hydraulic Stability, Proceedings of the International Conference on Coastal Engineering,
10 ASCE, structures. 41.

11
12
13 Melby, J.A, and Turk, G.F. 1996. CORE-LOC™ development as related to historical Corps concrete
14 armour unit performance. Advances in Coastal Structures and Breakwaters. Thomas Telford, 253-
15 267.

16
17
18 Mouquet, A. 2009. Armour unit placement and positioning in 3D real time. Coasts, marine structures
19 and breakwaters. Adapting to change. Thomas Telford, 437-447.

20
21
22 Munjiza, A., 2004. The Combined Finite-Discrete Element Method, John Wiley & Sons.

23
24 Muttray, M., Reedijk, J.S., Vos-Rovers, I., Bakker, P., 2005. Placement and structural strength of
25 Xbloc® and other single layer armour units. Coastlines, Structures and Breakwaters, Thomas Telford,
26 556-567.

27
28
29 Myrick, G.B., Melby, J.A., 2005. Monitoring of Dolos Armor Units at Crescent City, California. US
30 Army Corps of Engineers, ERDC/CHL TR-05-10.

31
32
33 Oever, T.E., Verhagen, H.J., Klabbers, M., Reedijk, B., 2006. Theoretical and experimental study on
34 the placement of Xbloc® armour units. Proceedings of the International Conference on Coastal
35 Engineering, San Diego, ASCE.

36
37
38 Oñate, E., Idelshon, S.R., Celigueta, M.A., Rossi, R., Marti, J., Carbonell, J.M., Ryzhakov, P., Suárez,
39 B., 2011. Advanced in the particle finite element method (PFEM) for solving coupled problems in
40 engineering, Book chapter: Particle-Based Methods. Computational methods in applied sciences. Ed.
41 E. Oñate and R. Owen, Springer, 25, 1-49.

42
43
44 Phelp, D., Zwamborn, J.A., 2000. Correlation between Model and Prototype Damage of Dolos
45 Breakwater Armouring. Proc. ASCE, 276, 120.

46
47
48 Recio, J., Oumeraci, H. 2009. Process based stability formulae for coastal structures made of
49 geotextile sand containers. Coastal Engineering, Vol. 56, No. 5-6. (May 2009), pp. 632-658.

50
51 Rockfield, 2004. ELFEN 2D/3D Numerical Modelling Package, Rockfield Software Ltd., Swansea

52
53
54 Sakai, T., Harada, E., Gotoh, H., 2008. 3D Lagrangian Simulation of Compaction Process of Wave
55 Dissipating Blocks due to High Waves, ICCE, Abstract 212.

56
57 Tassios, T. P., and Vintzeleou, E. N., 1987. Concrete-to-concrete friction. Journal of Structural
58 Engineering, 113: 832-849.

Timco, G.W., 1984. On the stability criterion for fracture in dolos armoured breakwaters. *J. Coastal Engineering*, 8, 161-170.

Turk, G.F. and Melby, J.A., 1997. CORE-LOC™ Concrete Armor Units: Technical Guidelines. USACE Miscellaneous Paper, CHL-97-6. 23 pages.

Van der Meer, J.W., 1999. Design of concrete armour layers. *Proc. Coastal Structures '99*, Santander, Spain, 213-221.

Van Gumster, J. 2009. *Blender for dummies*. John Wiley & Sons, 424 pages.

Verma, V., Varghese, K., Seka, A.L., 2004. Evaluation of physical modeling and 3-D simulation for planning accropode placement. *Isarc-2004*, www.iaarc.org/publications/fulltext/isarc2004-IS-02.pdf. published online.

Xiang, J., Munjiza, A., Latham, J-P., 2009a. Finite strain, finite rotation quadratic tetrahedral element for the combined finite-discrete element method. *Journal for Numerical Methods in Engineering*, 79, 946-978.

Xiang, J., Munjiza, A., Latham, J.-P, Guises, R., 2009b. On the validation of DEM and FEM/DEM models in 2D and 3D. *Engineering Computations*, 26, 673 – 687.

Xiang, J., Latham, J.-P., Zimmer, D., Baird, W.F., Fons, M. 2011. Modelling breakwater armour layers and the dynamic response of armour units. *Proceedings of International Conference on Coastal Structures*, Yokohama, Japan. September 6-8, 2011.

Xiang, J., Latham, J-P. Vire, A., Anastasaki, E., Pain, C.C. 2012. Coupled Fluidity/Y3D technology and simulation tools for numerical breakwater modelling. *Proceedings of the International Conference on Coastal Engineering*, Santander, July 2012, (in press).

Positioning	The acceptable deviations from the placement grid are typically limited to less than 10% of the unit size.	
Orientation	(i)	adjacent armour units shall have different attitude
	(ii)	armour units must not be in contact with units of the same row
	(iii)	each armour unit must be keyed into two armour units of the row below
	(iv)	less than one third of the units shall have the plane face parallel to the slope
	(v)	armour units with this orientation (plane side parallel to the slope) must be distributed throughout the slope and must not be found in groups
	(vi)	armour units shall rest on three points (two neighbouring units and the slope)

	$(S_{ij}-S_{i,j+1}) / D_v$	$(Z_{i,j}-Z_{i+1,j}) / D_h$
average	0.968	1.009
max	1.446	1.184
min	0.504	0.813

Number of occurrences per bin		
spacing interval (bin) given as proportion of theoretical spacing D_v, D_h	Upslope direction	Horizontal direction
	$(S_{ij}-S_{i,j}+1) / D_v$	$(Z_{i,j}-Z_{i+1,j}) / D_h$
0.4-0.5	2	0
0.5-0.6	3	0
0.6-0.7	15	0
0.7-0.8	15	1
0.8-0.9	31	27
0.9-1.0	38	76
1.0-1.1	44	73
1.1-1.2	32	38
1.2-1.3	19	6
1.3-1.4	9	0
1.4-1.5	1	0

Row	for all units	excluding units close to side walls	coefficient of variation for all units	coefficient of variation excluding units close to side walls
2	0.630	0.626	8.19%	9.03%
3	0.592	0.585	6.99%	7.24%
4	0.565	0.564	4.31%	4.53%
5	0.588	0.586	5.98%	5.75%
6	0.612	0.608	6.64%	6.84%
7	0.620	0.621	10.18%	11.30%
8	0.625	0.635	8.13%	8.24%
9	0.604	0.601	4.79%	5.20%
10	0.598	0.600	9.78%	10.99%
11	0.614	0.614	6.96%	7.77%
12	0.622	0.624	9.08%	9.11%
13	0.619	0.625	8.83%	9.49%
14	0.592	0.596	9.24%	10.08%
15	0.593	0.588	7.59%	7.25%
16	0.592	0.586	7.18%	7.63%
17	0.591	0.588	9.98%	6.42%
18	0.593	0.593	8.37%	8.28%
19	0.557	0.551	7.25%	7.12%
Total average	0.601	0.599	7.75%	7.91%

Test	Dh	Dv	Initial friction coefficient	Resulting total average packing density	Armour Layer
1	1.1H	0.55H	0.3	0.589	AL-589
2	1.1H	0.55H	0.25	0.601	AL-601
3	1.1H	0.54H	0.25	0.607	AL-607
4	1.1H	0.53H	0.25	0.614	AL-614
5	1.1H	0.53H	0.15	0.629	AL-629

Table Captions

Table 1 Single layer armour unit placement rules for Accropodes and Core-Locs (Muttray et al., 2005).

Table 2 Spacing between the final positions of units normalized by target spacing

Table 3 Data for frequency analysis of upslope spacings between adjacent units in consecutive rows and horizontal spacings between adjacent units in the same row

Table 4-3 Average dimensionless packing density per row with coefficient of variation and average dimensionless packing density of the whole structure (row 2 to 19)

Table 5-4 Characteristics of tests run in order to numerically create armour layers with different average dimensionless packing densities (for Core-Loc unit of 8m³ the height H=3.31m).

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Figure Captions

Figure 1 Single layer concrete armour system, an example using Core-loc units with discernible row column structure in lower left corner.

Figure 2 Mesh of two identical rocks used to build bimodal size distribution model of rock underlayer

Figure 3 Close-up of toe region of rough underlayer created using numerical deposition tool POSITIT and FEMDEM code, Y3D

Figure 4 Units descending row by row onto a smooth slope with POSITIT coupled to Y3D, showing breakwater trunk horizontal - vertical reference frame and slope reference frame.

Figure 5 Placed Core-Loc units in armour layer. Left: numerical placement at full scale, Right; San Vicente, Chile.

Figure 6 AL-601: Placement of 242 Core-Loc units of volume 8m^3 to create a layer of dimensionless packing of 0.60. The different colours indicate contact number (or coordination number), as described in Section 3.5.

Figure 7 Core-loc model AL-601 with 242 units. Stereographic projection of poles to nose axis orientations of units after numerical placement on top of the rough underlayer (lower hemisphere projection, see text and Appendix A).

Figure 8 Layout between units on a theoretical placement grid (i :row, j :column).

Figure 9 Random positions of units not forming a square area (κ : row, λ : column).

Figure 10 Dimensionless packing density, Φ , calculated on a per unit basis

Figure 11 AL-601: Coordination number indicating only contacts with the underlayer slope

Figure 12 AL-601: Maximum contact force exerted on each 8m^3 unit (Newtons).

Figure 13 Stereographic plots of nose axis orientations of units as placed in a. AL-607, b. AL-614, c. AL-629, d. AL-589. Stereographic plot of AL-601 has been presented in Figure 7.

Figure 14 Variation of average local packing density calculated on an average per row basis from row 2 to 19, for the five different Armour Layers in this study.

Figure 15 Coordination Number including contacts with underlayer rock – CN per unit for all five Armour Layers.

Figure 16 Probability density function, P of normalised contact force, F_c/W for all contacts experienced by the 242 units, illustrated for all five Armour Layers

Figure 17 Frequency distribution of the maximum contact force normalised by the concrete armour unit's weight, $F_{\max}/W$, for each of the 242 units, illustrated for all five Armour Layers

Figure 18 Cumulative frequency plot of the maximum contact force normalised by the concrete armour unit's weight, $F_{\max}/W$, for each of the 242 units, illustrated for all five Armour Layers

Figure 19 Relation between average coordination number between units, average number of contacts between unit and underlayer rocks, normalised maximum contact force, $F_{\max}/W$ and average dimensionless packing density, Φ .