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Numerical Simulation of Rip-Raps with the Distinct Element Method

Livia Mittelbach

Federal Waterways Engineering and Research Institute, WedelerLandstraße 157, 22559 Hamburg, Germany

Abstract. Revetments are used as erosion protection for slopes on waterways and costal shores. They have to resist hydraulic loads such as ship and wind induced waves, tidal and ship induced currents, tidal varying water levels and storm surges. The numerical modelling of rip-rap revetments is undertaken by using the Distinct Element Method in three dimensions. With the DEM rip-rap stones can be modelled as autonomous objects with any degrees of freedom. Typical shapes of stones are formed by using clumped spherical particles. A method for the generation of the rip-rap stones based on geometrical and probabilistic parameters has been developed in order to generate stones with a realistic size and mass distribution. The DEM program is coupled with a computational fluid dynamics program to account for the influence of the hydraulic loads on the rip-rap stones. The acting forces can be simulated realistically for waves, currents and tidal varying water levels. Field measurements and model tests serve as validation for the numerical model. Physical model tests are carried out in a hydraulic flume with an instrumented rip-rap section for the calibration of the numerical stones material parameters. The behaviour of the particles depends on properties such as density, friction coefficient, normal and shear stiffness as well as the accuracy of the numerical representation of the rip-rap stones. Influences on the accuracy of the modelling of rip-raps with regard to the variation of these parameters are examined by comparing the results of the physical flume tests and numerical model.

Keywords: Distinct element modeling, Rip-rap
PACS: 02.70.Ns, 02.60.Pn, 47.11.Bc

INTRODUCTION

Rip-raps are used to protect the banks of waterways and coastal shores against erosion. They have to resist different hydraulic loads such as ship and wind induced waves, tidal and ship induced currents, tidal varying water levels and storm surges. The current basis of rip-rap design is inadequate in some areas for dealing with the complexity and variety of boundary conditions, especially in tidal zones. The aim of the research project is to develop a numerical model which is capable of simulating the resistance of rip-raps to hydraulic loads. The rip-rap-water-interaction is modelled holistically by a coupled calculation of the software PFC3D based on the Distinct Element Method (DEM) and the computational fluid dynamics software CCFD.

NUMERICAL MODELLING

Rip-rap Stones

The simulation of the rip-rap stones is undertaken using the software PFC3D (Particle Flow Code in 3 Dimensions), which models the movement and interaction of particles on the basis of the distinct element method [1]. The distinct element method (DEM) is a special case of the discrete element method which uses an explicit dynamic solution to Newton's laws of motion. The advantage of using the distinct element method for the simulation of rip-raps is that the single particles can move independently from each other. The movement of the stones with any degrees of freedom can be represented realistically.

The fundamental particles in PFC3D are spherical (balls), however arbitrary complex shapes such as rip-rap stones can be produced by overlapping particles (clumps). Each clump acts as an independent object and cannot break during the calculation cycle regardless of the forces acting on it [1]. The clumps different properties are set, such as the normal stiffness, shear stiffness and the friction coefficient. The stiffness of the particles influences the overlapping of the single spherical particles and the calculation time. The behaviour of the clumps during calculation is mainly affected by the friction coefficient, stiffness and particle geometry.

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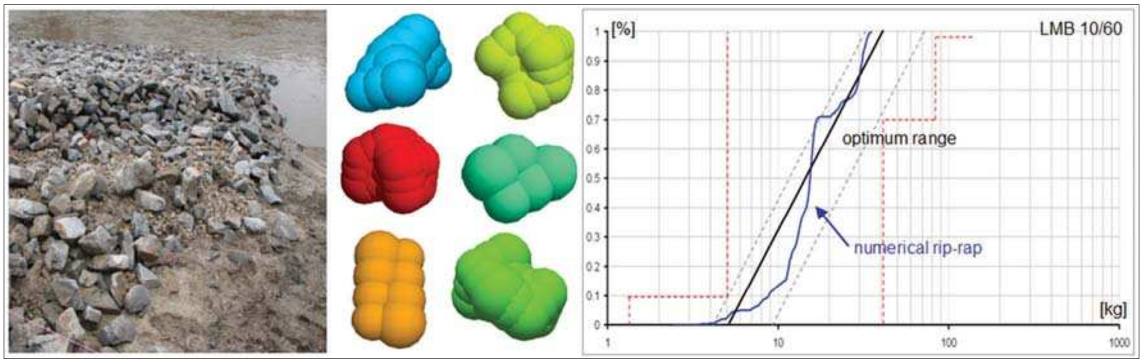

FIGURE 1. Real and numerical rip-rap stones, summation curve corresponding to armourstone category.

On the basis of the procedure of Lu and McDowell [2] an algorithm has been developed by the TU Bergakademie Freiberg to reproduce the rip-rap stones realistically regarding the shape and mass distribution of the corresponding armourstone category as shown in Fig. 1 [3]. As proposed by Lu and McDowell [2] the shape of the generated particles depends on six different parameters; the number of directions for ball generation, the probability of each direction, the number of balls generated in the chosen direction, the degree of reduction of radii and the degree of overlapping of balls. To reproduce the summation curve of an armourstone category the stones were divided into different size and shape categories (size: small to big, shape: platy, longish, compact) and a mixture of stones from all categories was used. The set of parameters for the generation of the different categories and the frequency of occurrence was derived by analysing pictures of real rip-rap revetments (Fig. 1) [4]. The representation of the rip-rap stones as numerical particles is possible in a detailed or simplified way, however the time required for the generation of the numerical rip-rap and the model calculation time increases exponentially when more detailed clumps are used. That's why stones with simplified geometries have been used so far.

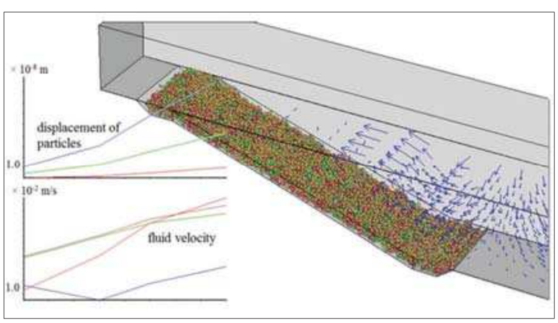

FIGURE 2. Numerical rip-rap (PFC3D) with wave impact (CCFD), histories of displacement and fluid velocity.

Coupled DEM – CFD Computation

For the holistic numerical modeling of the rip-rap-water-interaction the simulation of the hydraulic loads such as waves and currents is completed by the software CCFD (Coupled Computational Fluid Dynamics) [5]. CCFD is available as an add-on program for PFC3D to couple the mechanical DEM calculation with a computational fluid dynamics problem. The CCFD-solver is embedded in a graphic modeler (pre/post-processor) which serves to specify the model geometry and the initial conditions and boundary conditions. Waves and currents in the numerical model can be generated realistically with the help of time dependent boundary conditions. The reaction of the rip-rap stones due to current and wave attack is recorded by the use of so called "histories" in PFC3D (Fig. 2) [4].

The simplified Navier-Stokes-equation and the continuity equation are solved in a 3D discretized domain (fluid element, hexahedron) by the CCFD-solver. In the calculation an incompressible fluid flow and a constant fluid density are assumed. The equations are formulated with porosity terms to account for the presence of particles in the flow. The fluid forces acting on the particles are applied to each particle locally. The resulting body force acting on the fluid is given as an average over one fluid element [5]. During the coupled computation both programs are running in parallel with an exchange of data after a specified time interval. Each time the coupling information is exchanged, the current fluid velocity and fluid pressure gradient determined by CCFD is sent to PFC3D. In PFC3D the displacements and the velocity of the particles are calculated on the basis of the law of motion and the force-displacement law. Afterwards the current porosity in each fluid element is sent to CCFD.

A limiting condition for the coupled computation is the minimum porosity of 5% in each fluid element, in order to allow the flow of fluid. This means that a maximum of 95% of the volume of one fluid element can be filled with particles. This affects the mesh resolution of the flow problem and results in fluid elements larger than the generated rip-rap stones. In contrast a high resolution of the mesh would be necessary for a detailed reproduction of the flow regime [6].

MODEL TESTS AND FIELD MEASUREMENTS

Procedure and Measurement Systems

Physical model tests serve to validate the numerical model. The behaviour of the numerical stones (clumps) depends primarily on the friction coefficient of the particle surface and the particle stiffness. The accuracy of the numerical representation of the rip-rap stones (simplified, detailed) is also important. It affects the interlocking characteristics between the stones of the numerical rip-rap, however increased accuracy raises the calculation time enormously. To what extent these properties affect the accuracy of the numerical modelling and how the parameters should be chosen to have a best possible accordance with reality, is examined by the flume tests. Therefore the results of the physical tests with known boundary conditions are compared to an equivalent numerical model.

FIGURE 3. Model tests: hydraulic flume and rip-rap section with direction of overflow parallel to the slope.

The physical model tests are carried out in a hydraulic flume with a built-in rip-rap section with stones of about 9 cm to 25 cm in size (Fig. 3). In different tests the slope ratio of the rip-rap section is changed from 1:1.5 to 1:3. There is an overflow parallel to the slope of the rip-rap section. During one test the flow velocity is increased in several steps up to 2 m/s. The stones are coloured so that their movement due to overflowing can be easily seen after the test has finished.

The stones movement has been documented in photos. In addition to colouring the surface of the stones, they are scanned by a laser to register the surface geometry and therefore determine their displacements after the test.

Furthermore a measurement device has been developed to record the translational and rotational movement of stones due to current and wave attack. Stones are bored and equipped with acceleration sensors and gyroscopes (Fig. 5). The recording is started remotely and data over two weeks is registered and stored by the equipment. The displacement of the stone caused by the hydraulic loads is recorded with any degrees of freedom. These results can be compared to the displacements and the translational and angular velocities taken as histories from the numerical rip-rap stones in PFC3D. From these measurements the hydraulic loads and forces acting on the rip-rap can be determined.

A prototype of an equipped stone was tested in the flume tests. A group of equipped stones will be applied in field measurements as well. Once the numerical rip-rap stones are calibrated using the results from the hydraulic flume tests, the numerical model of the interacting hydraulic loads and rip-rap is validated by additional field measurements at the river Elbe.

Preliminary Results of Model Tests

During the flume tests an increase in the flow velocity occurred in the zone of the rip-rap section due to the narrowing of the cross sectional area. The maximum measured flow velocity in this zone was 2.0 m/s.

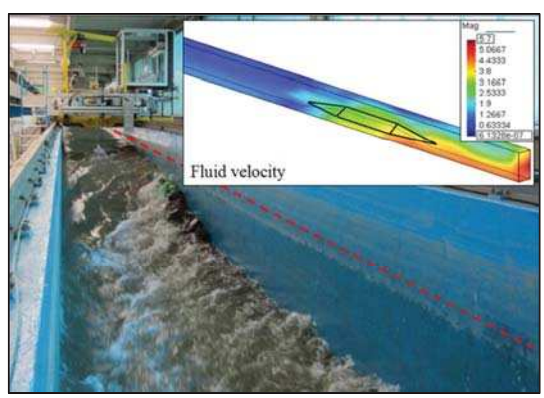

FIGURE 4. Water level decline in flume during test and numerical modeling of flume test.

As a result high turbulences and a water level decline could be observed (Fig. 4) . Both the increase in flow velocity and the water level decline is reproduced in the numerical model (Fig. 4). In the numerical model the particle stiffness was varied from 10^5 to 10^6N/m, and the friction coefficient from 0.35 to 0.7.

The numerical modelling of the hydraulic flume showed a good relationship with the physical tests using simplified numerical stones reproduced in a simplified way with only a few balls per clump.

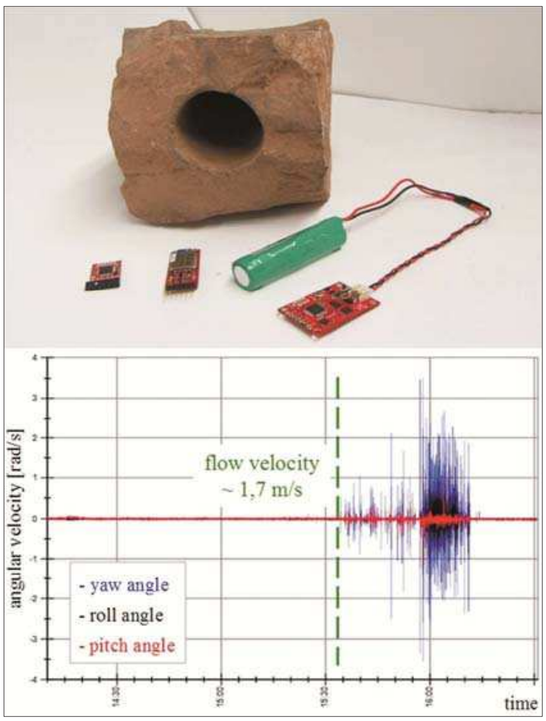

FIGURE 5. Rip-rap stone and equipment for recording rotational and translational movements, measuring result (qualitative).

Figure 5 shows a result of an equipped stone embedded loosely in the rip-rap section in the hydraulic flume [7]. The development of the angular velocity of roll, pitch and yaw angle during the test is shown. At the beginning of the stepwise increase of flow velocity there is no movement of the stone. With the help of the measured angular velocities it can be seen that the stone starts shaking at a flow velocity of about 1.7 m/s.

CONCLUSION

The Distinct Element Method is a suitable method for the simulation of rip-raps with complex-shaped particles. The movement of single stones can be reproduced with any degrees of freedom. Coupled with a CFD-computation the interaction of rip-rap and hydraulic loads is modelled holistically. By the use of tests in a hydraulic flume and a measurement device for recording the movement of stones, the numerical particles representing rip-rap stones are calibrated. Preliminary tests show a good relationship between physical model and the numerical modelling.

REFERENCES

1. Itasca, in *User's Manual Ver. 4.0: PFC3D – Particle Flow Code in 3 Dimensions*, Itasca Consulting Group Inc., Minneapolis, Minnesota, USA, 2008.
2. M. Lu and G. McDowell, *Granular matter* **9**, 69-80 (2007).
3. M. Herbst, M. Pohl and H. Konietzky, *Wasserbauliche Mitteilungen* **40**, 85-94 (2010).
4. BAW, in *Forschungskompendium Verkehrswasserbau 2011* (BAW, Karlsruhe, Germany) 2011.
5. Itasca, in *User's Manual Ver. 4.0: PFC3D – CCFD Add-on Ver. 1.0*, Itasca Consulting Group Inc., Minneapolis, Minnesota, USA, 2008.
6. GiD, in *Reference Manual Ver. 8.0.* International Center for Numerical Methods in Engineering, Barcelona, Spain, 2008.
7. BAW, in *Mitteilungsblatt* (BAW, Karlsruhe, Germany) 2012.