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A Coupled DEM-CFD Simulation of Rip-Rap Revetments in Tidal Areas

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ABSTRACT: Rip-rap revetments are used as erosion protection for slopes on waterways and coastal shores. They are built to resist ship and wind induced waves, tidal and ship induced currents, tidally varying water levels and storm surges. In some areas the current basis of rip-rap design is inadequate for dealing with the complexity and variety of boundary conditions in tidal zones. A numerical model is developed, which is capable of simulating interaction of rip-rap and hydraulic loads holistically.
The numerical modelling of rip-rap is undertaken by using the Discrete Element Method (DEM). With the DEM, the armourstones can be modelled as autonomous objects, so that the movement of stones with six degrees of freedom is represented. In addition, the representation of the stones with a realistic size and mass distribution regarding the corresponding armourstone category is possible.
The DEM can be used to model rip-rap stones as autonomous objects with all degrees of freedom and realistic movement. The DEM code is coupled with a computational fluid dynamics code (CFD) to account for the influence of the hydraulic loads. Waves and currents acting on the rip-rap stones as well as tidally varying water levels can be generated realistically using time dependent boundary conditions.
Additional physical model tests in a laboratory flume, field tests and measurements with instrumented rip-rap stones serve as validation for the numerical model.

Keywords: Revetment, Rip-Rap, Discrete Element Method, Computational Fluid Dynamics, Model Tests

1 INTRODUCTION

Revetments are used to protect the banks of waterways and coastal shores against erosion. Because of the numerous advantages they offer, such as high flexibility and robustness against settlements, rip-rap revetments are used most frequently (fig. 1). Revetments have to resist manifold influences. The main parameters affecting rip-rap design on inland waterways are ship-induced waves and currents and excess pore water pressures due to ship-induced water level drawdown. On waterways in coastal zones additional influences specific to the coast play an important role as well. Larger, seagoing vessels with different geometries and increasing size instead of inland water vessels, different and irregular cross sectional areas of the waterway with varying slopes instead of a regular channel cross section, the influence of wind waves because of a larger, wind-exposed water surface, tidal currents in addition to ship-induced currents and tidal varying groundwater levels are just some of the factors that affect the rip-rap design for coastal waterways.

The present guidelines for rip-rap design are mostly based on small-scale model tests or experience data from inland waterways. This means that, in some areas, these guidelines are of only limited applicability in view of the complex and diverse boundary conditions in tidal zones. Therefore, it is the aim is to develop a numerical model in 3D which is capable of simulating the rip-rap-water interaction. By coupling different numerical methods, the model takes the hydraulic part (waves and currents) as well as the mechanical part (the rip-rap) into consideration. Hence, a holistic numerical analysis of the stability of rip-rap revetments in coastal zones is possible. The long-term objective of the research project is a suitable numerical tool for a safe and economic rip-rap design adapted to particular local conditions.

Figure 1. Rip-rap on the banks of Ems River (Germany) as a protective layer to prevent erosion of bank slope by hydraulic loads.

2 NUMERICAL MODELLING

The simulation of the rip-rap is undertaken using the 3D Discrete Element Method (DEM), the numerical modelling of the hydraulic part is done using a Computational Fluid Dynamics code (CFD). The holistic numerical modelling is carried out by a coupled computation of both codes. The numerical model is then validated by model tests in a laboratory flume, measurement data from instrumented armourstones and measurement data of waves and currents from field tests.

2.1 *Modelling of rip-rap with the DEM*

The Discrete Element Method (DEM) is a numerical method which simulates the movement and interaction of particles of a discontinuous medium on the basis of Newton's second law of motion and a contact law. The DEM was originally developed by Cundall and Stack (1979). Today it is widely used to examine engineering problems in granular and discontinuous materials.

The DEM allows rip-rap stones to be modelled as autonomous objects. The movement of stones with six degrees of freedom (three for translational and three for rotational movement) is represented realistically. In this research project the DEM part of the modelling is undertaken by using the three dimensional code "PFC" (Particle Flow Code) developed by Itasca Consulting Group Inc. (Itasca 2008a). This code is a simplified version of the general DEM because it utilises spherical particles (so-called balls) to make contact detection easier. However, arbitrary complex shapes can be produced by overlapping spheres (so-called clumps). This multi-sphere approach can be used to generate stone-like particles (fig. 2) and the whole rip-rap. Each clump acts as an independent object and cannot break during the calculation cycle (Itasca 2008a).

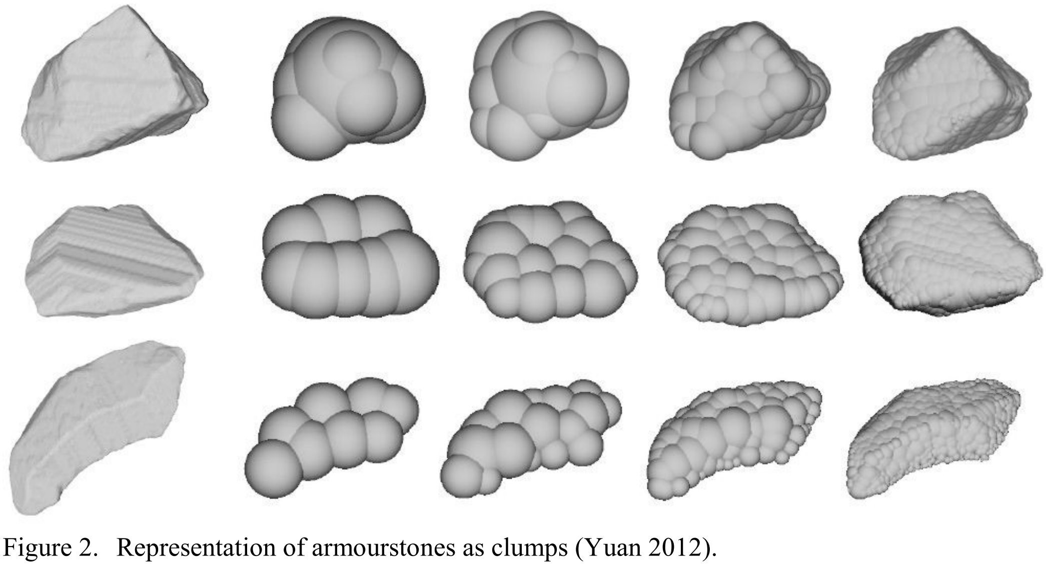

Figure 2. Representation of armourstones as clumps (Yuan 2012).

The numerical rip-rap should be realistic with regard to the representation of interlocking effects between the stones as well as with regard to the particular armourstone grading category. This results in two important issues: the realistic representation of the particle shape of the individual stones and the realistic representation of the whole rip-rap with respect to the size and mass distribution of all stones in the numerical model.

The research project is carried out in cooperation with the Chair of Rock Mechanics and Rock Engineering, Geotechnical Institute, TU Bergakademie Freiberg, Germany. To reproduce the rip-rap in a realistic way, the stones were divided into different shape categories (platy, longish, compact) and a mixture of stones from all categories was used for the numerical model (Herbst et al. 2010). The armourstones are generated with realistic shapes by the use of surface meshes from real stones (obtained by photo or 3D-Scan). With the help of a bubble-pack-algorithm contained in the DEM code the 3D surface mesh is filled with balls. The rip-rap can be represented realistically regarding the size and mass distribution of the corresponding armourstone grading category (fig. 3).

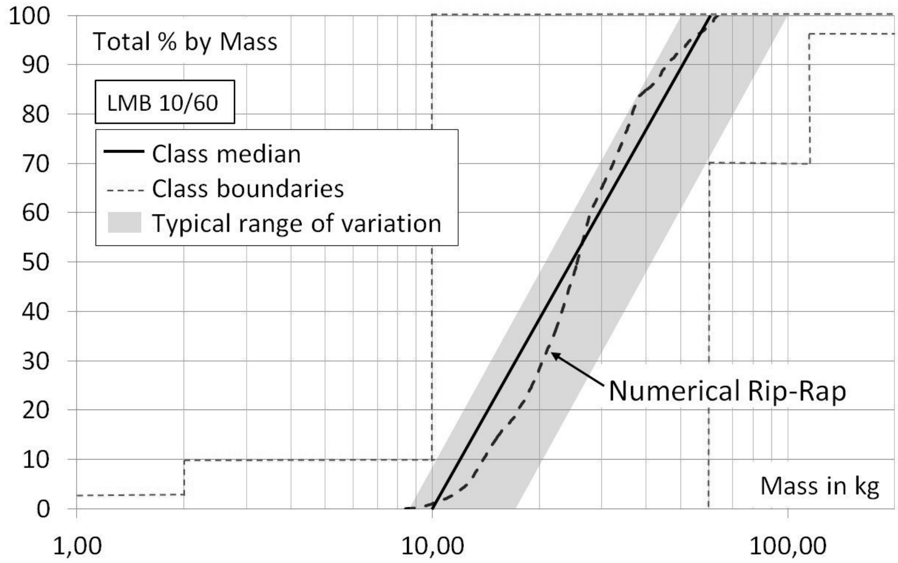

Figure 3. Typical range of variation of cumulative curve for armourstones class $LMB_{10/60}$ (BAW 2008), cumulative curve of corresponding numerical rip-rap.

2.2 *Modelling of hydraulic influences with CFD*

The modelling of the hydraulic part, such as waves and currents, is undertaken using a computational fluid dynamics (CFD) code. The hydrodynamic computation is done on the basis of the Navier-Stokes equations, which describe the motion of fluid substances. Together with the continuity equation they can be applied to solve all hydrodynamic problems.

In this research project the software "Coupled Computational Fluid Dynamics" (CCFD) is used, which is a product of ITOCHU Techno-Solution Corporation (Itasca 2008b). CCFD solves the simplified incompressible Navier-Stokes equations and the continuity equation with the help of a finite volume method in a 3D discretized domain (fluid element, hexahedron). The coupled computation of both codes – the mechanical DEM calculation in PFC and the hydraulic computation in CCFD – is possible. The CCFD-solver is embedded in a graphic modeller (pre/post-processor) which serves to specify the model geometry and the initial and boundary conditions.

In the numerical simulation the hydraulic loads can be generated by applying time-varying boundary conditions at the model boundary (fig. 4). Waves and currents are generated in the form of the water surface elevation and the horizontal and vertical orbital velocities described as a function of time. The data from field tests will then be used as input data for the waves generated in the numerical model. The measured water surface elevation (wave heights) and the deduced velocity field (development of horizontal and vertical velocity below the wave) are imported into the numerical model as time series for every time step. Hence, the measured wave is generated directly in the numerical simulation.

The reaction of the rip-rap stones in the DEM code due to current and wave attack from the hydraulic calculation in CCFD can be recorded by using so called "histories" in PFC.

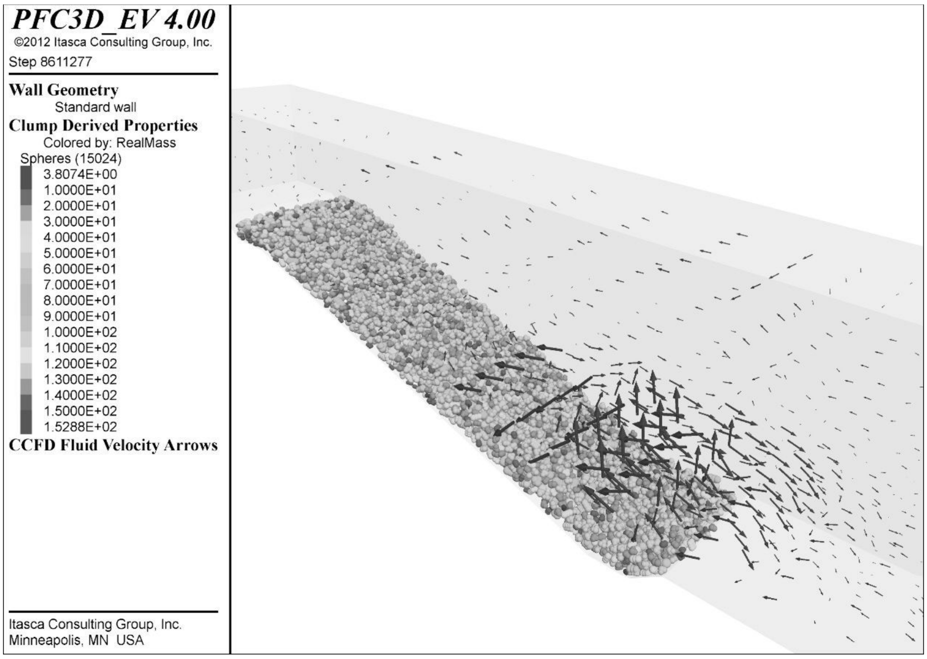

Figure 4. Rip-rap generated in PFC, coupled computation with wave impact.

2.3 *CFD-DEM coupling*

The numerical codes used in this research project allow the two-way coupled computation of the mechanical DEM calculation and the hydraulic computation (see example fig. 4). The displacement and the velocity of the particles are determined in PFC and the state variables of the flow in CCFD. During the coupled computation both programmes are executed with an additional data exchange at predefined time intervals. The DEM as well as the CFD code are formulated with additional terms to account for the fluid forces and the presence of particles in the flow.

In the DEM-part of the coupled computation a new term f_{fluid} is added to the calculation to represent the force applied by the fluid (Itasca 2008b):

$$\frac{\partial \vec{u}}{\partial t} = \frac{\vec{f}_{mech} + \vec{f}_{fluid}}{m} + \vec{g} \tag{1}$$

where u = particle velocity, m = particle mass, f_{fluid} = total force applied by the fluid on the particle, f_{mech} = sum of additional forces and g = acceleration of gravity. The force f_{fluid} consists of three terms: the drag force, the force applied by the fluid pressure gradient and the buoyancy (Itasca 2008b):

$$\vec{f}_{fluid} = \vec{f}_{drag} + \tfrac{4}{3}\pi r^3(\nabla p - \rho\vec{g}) \tag{2}$$

with

$$\vec{f}_{drag} = \left(\tfrac{1}{2}C_d\rho\pi r^2|\vec{u} - \vec{v}|(\vec{u} - \vec{v})\right) \cdot n^{-\chi} \tag{3}$$

where r = particle radius, p = fluid pressure, ρ = fluid density, v = fluid velocity, C_d = drag coefficient and $n^{-\chi}$ = empirical factor to account for the local porosity. The current fluid velocity v and the fluid pressure gradient ∇p necessary for this calculation are determined by CCFD and sent to PFC3D each time the coupling information are exchanged. The fluid force acting on the particles is applied to each particle (Itasca 2008b).

In the hydraulic part of the computation the equations of motion of the fluid and the continuity equation are formulated with porosity terms and an additional body force due to the presence of particles in the flow (Itasca 2008b):

$$\rho\frac{\partial n\vec{v}}{\partial t} + \rho\vec{v} \cdot \nabla(n\vec{v}) = -n\nabla p + \eta\nabla^2(n\vec{v}) + \vec{f}_b \tag{4}$$

and

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{v}) = 0 \tag{5}$$

with n = porosity, η = fluid dynamic viscosity and f_b = body force. The current porosity n in each fluid element and the body force fb is determined in PFC and sent to CCFD during the data exchange. The body force acting on the fluid due to the particles is given as an average value over one fluid element.

3 ARMOURSTONE EQUIPPED WITH SENSOR TECHNOLOGY

In the context of the research project a measurement device is developed to record the translational and rotational movements of armourstones due to current and wave attack. Several armourstones of different size, shape and density are bored and equipped with acceleration sensors and gyroscopes (fig. 5). The corresponding circuit board for measuring acceleration and rotational speed is an in-house development. Data can be registered by the stone for a period of up to one month and stored on a memory card. The displacements of the stone measured by the equipment in model or field tests can be compared to the displacements and the translational and angular velocities taken as histories from the particles in the numerical model. It is intended to determine the hydraulic loads and forces acting on the rip-rap from these measurements. Measurements with the equipped stones are carried out in the flume tests as well as in the field tests.

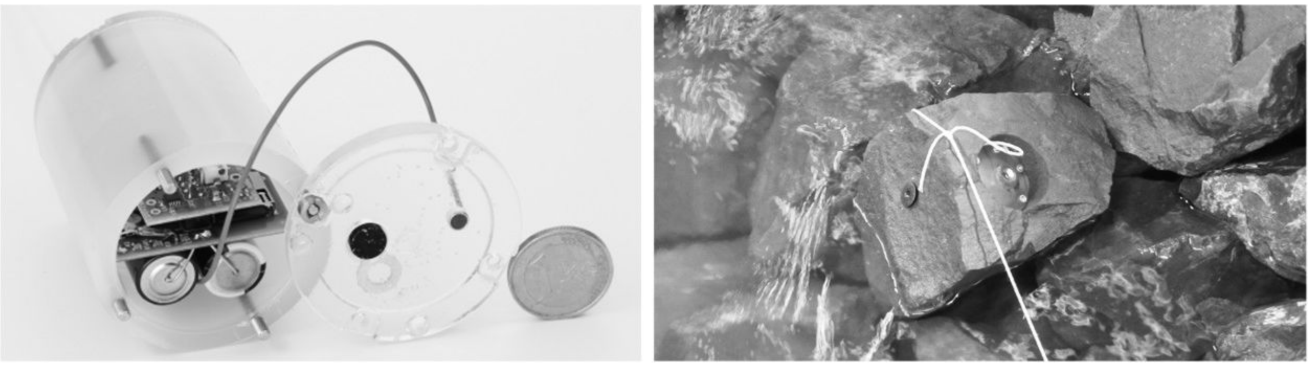

Figure 5. Example of armourstone equipped with sensor technology.

4 PHYSICAL MODEL TESTS

Physical model tests are used to validate the numerical model. The behaviour of the numerical armourstones depends primarily on the particle shape and the friction coefficient of the particle surface. Because a detailed representation of the stones raises the calculation time enormously, flume tests are performed to examine the extent to which these properties affect the accuracy of the numerical modelling and how the parameters should be chosen to achieve the best possible match with reality. The results of the physical tests with known boundary conditions are compared to an equivalent numerical model (fig. 6).

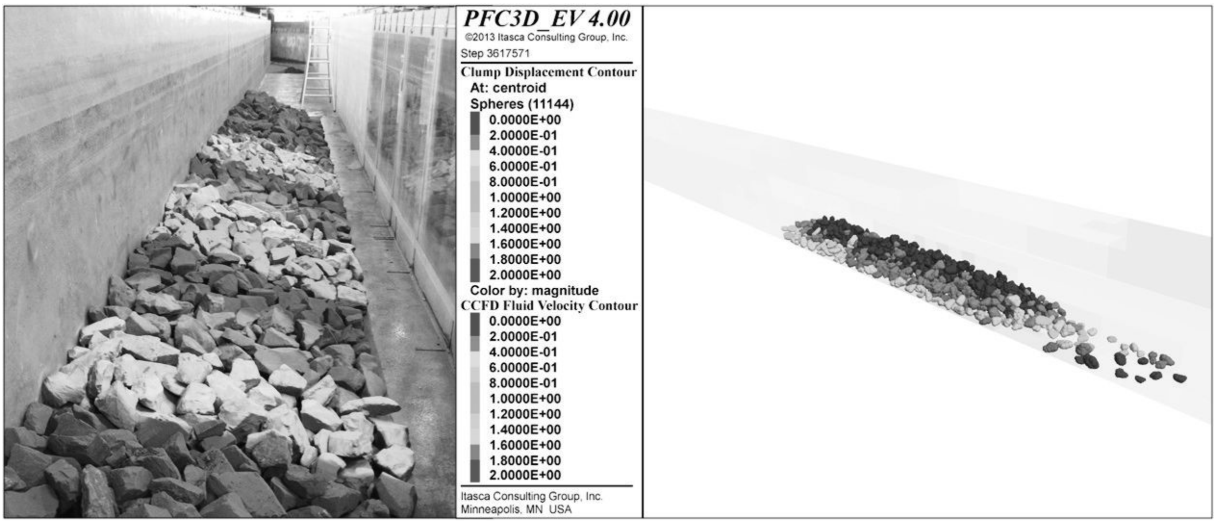

Figure 6. Rip-rap section in hydraulic flume and numerical simulation of physical model tests.

The physical model tests are carried out in a hydraulic flume of the Federal Waterways Engineering and Research Institute, Hamburg. A rip-rap section on a scale of 1:1 with stones of the armourstone grading category CP90/250 is built into the flume (fig. 6). There is an overflow parallel to the slope of the rip-rap section. The slope ratio of the rip-rap section is 1:1 respectively 1:3 in two different measurement campaigns. The flow in the zone of the rip-rap section is increased in four steps from about 1 m/s up to 2 m/s in several tests during one measurement campaign. The displacement of the stones due to the overflow is documented by a laser scan and a coloured surface of the rip-rap section.

5 FIELD TESTS

In addition to the physical model tests the numerical model is validated by field measurements executed as part of a project. Wave heights, flow velocities and to some extent pore water pressures in the subsoil are measured at an island in the Lower Elbe River. The measurements are carried out at two different monitoring stations in exposed positions with varying slope ratios and varying distances to the navigation channel of the Elbe. Stationary measurement systems and two flexible flow probes with independent power supply are applied. This equipment is placed at different positions over the entire slope of the bank and measures the acting hydraulic loads directly above the surface of the slope. Together with the measurement of the hydraulic loads, measurements with equipped armourstones are carried out as well.

Figure 7 shows the measurement results with the equipped armourstone in the field tests over a period of 42 hours. From top to bottom the figure shows the tidally varying water level of the Elbe (gauge at Lühesand), the ship passages respectively the occurring ship waves, the acceleration in x-, y- and z-direction and the rotational speed in x-, y- and z-direction. This example taken from the first measurements demonstrates that displacements of single rip-rap stones mainly take place when ships are passing in periods of low tide.

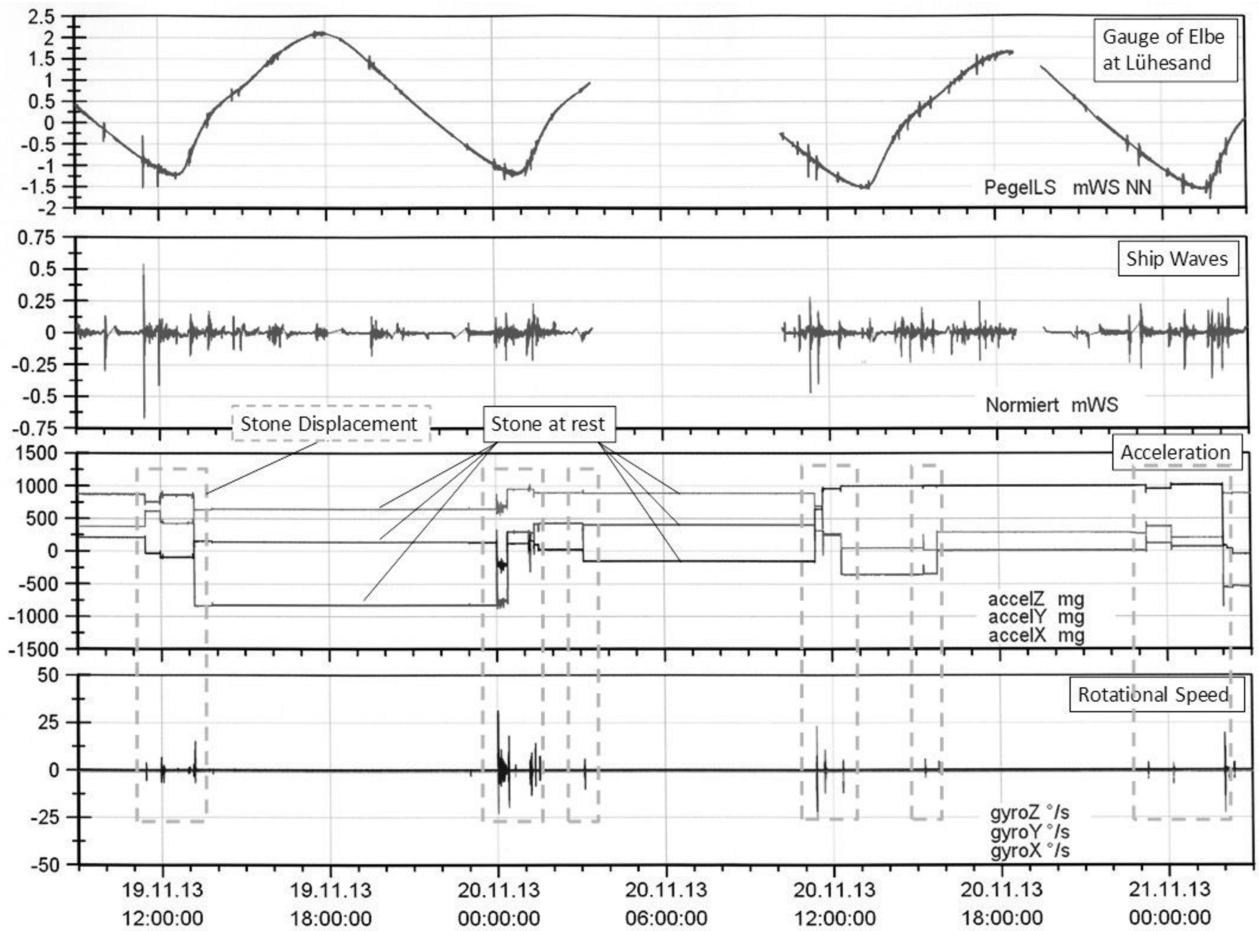

Figure 7. Example of measurements with equipped armourstones in field test.

6 CONCLUSION AND OUTLOOK

The Discrete 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 number of degrees of freedom. Together with a CFD-computation, the interaction of rip-rap and hydraulic loads is modelled holistically. The numerical particles representing rip-rap stones are calibrated using physical tests in a hydraulic flume and a measurement device for recording the movement of stones. The physical model tests and field tests will be continued and the modelling and validation of the numerical simulation will be adapted and improved to achieve the best possible match with reality.

NOTATION

m	particle mass
r	particle radius
u	particle velocity
ρ	fluid density
η	fluid dynamic viscosity
p	fluid pressure
v	fluid velocity
f_{fluid}	total force applied by the fluid on the particle
f_{mech}	sum of additional forces
f_b	body force
n	porosity
$n^{-\chi}$	empirical factor to account for the local porosity
C_d	drag coefficient
g	gravity acceleration

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