Large scale experiments in coastal and Ocean engineering A Review of 35 years of physical model tests in the Large Wave Flume (Grosser Wellenkanal, GWK)

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Abstract

The Large Wave Flume (Großer Wellenkanal, GWK) is the key facility of the coastal research center Forschungszentrum Küste (FZK), a joint institution of Leibniz University Hannover and Technische Universität Braunschweig. GWK is one of the few facilities of this kind worldwide allowing for physical model tests under well controlled conditions and with minimized or even negligible scale effects. The flume is in operation since 1983 and used to be even the largest facility of its kind until recently. This paper is intended to give a short overview of the capabilities of GWK and the experience gained over the last 35 years. Recent developments in measurement techniques allow for easier, more precise and more detailed measurements than in the earlier days of GWK and have increased the value of the experiments significantly. This will be demonstrated and discussed by typical examples from each of the four research topics at FZK: (i) coastal structures; (ii) sediment transport; (iii) marine energy; (iv) ecohydraulics.

Keywords: large scale experiments, measurement techniques, coastal structures, sediment transport, marine energy, ecohydraulics

I. Introduction

Physical model tests under well-controlled laboratory conditions are an invaluable tool for coastal and ocean engineering research since almost a century. Despite their power and capabilities laboratory experiments, like any other research and design tool, also have their limitations, which lie in particular in laboratory and scale effects (e.g. Oumeraci, 1984; Hughes, 1993; Oumeraci et al., 2014). Unavoidable laboratory effects like the neglect of processes (e.g. 2D vs. 3D), boundary conditions (e.g. wall effects) or discrepancies in wave generation will lead to inaccuracies in the representation of prototype processes, but are fairly well understood and can be avoided, minimized or at least assessed. Scale effects on the other hand are also understood in principle, but their exact impact on certain processes, like wave run-up and overtopping, breaking wave impact or sediment transport, can often hardly be assessed and only minimized or avoided, by using a large enough scale, i.e. a big enough laboratory facility.

Considering the significant effort and costs that are associated with the operation of a large scale facility, there is only a very limited number of such facilities existing worldwide and all are limited to flumes rather than basins. The first large scale wave flume that went into operation already in 1979 is the Delta Flume in the Netherlands followed by the Large Wave Flume (Großer Wellenkanal, GWK) of the coastal research center, Forschungszentrum Küste (FZK) in Germany, the Super Wave Flume at Tainan Hydraulics Laboratory (THL) in Tainan and a few others. Every institution operating such a large facility has gathered its own expertise and knowledge in preparing and conducting large scale model tests over the years. Many of the partly unique experiments have led to extremely valuable results for the scientific community as well as for practice.

The present paper reflects the last 35 years of experience gained with the Large Wave Flume (GWK), provides a short review of its origin and the experimental capabilities then and now followed by a short summary of exemplary past and present large scale experiments for coastal and ocean engineering carried out in GWK. Coincidently, the former director of FZK, Professor Hocine Oumeraci, gave a keynote lecture on December 10, 2010 at a workshop in Tainan to commemorate the 60th Anniversary of THL. His talk was later slightly extended and published as a paper with the title "More than 20 Years of Experience Using the Large Wave Flume (GWK) – Selected Research Projects" (Oumeraci, 2010). The present paper shall therefore not repeat what has already been published, but it is rather intended to be complementary to Oumeraci (2010) by focusing on recently emerging research topics and the capabilities of new measurement techniques like time resolving acoustic velocity and/or concentration profilers, laser scanning and video data analysis. Hence, the presentation and the paper shall serve as stimulation for an exchange of experience and research ideas as well as for a discussion about possible future collaborations at CGJoint 2018.

II. The Large Wave Flume (GWK)

The Large Wave Flume (Grosser Wellenkanal, GWK) in Hannover was planned and built within a 12 years special research project (Sonderforschungsbereich SFB 79 -"Hydraulic research in coastal areas") from 1969 to 1982 funded by the German Sciences Foundation (Deutsche Forschungsgemeinschaft, DFG). It went into operation in 1983 and was primarily used within another 12 years project (SFB 205 - "Coastal Engineering – Sea states and transport processes in coastal protection, offshore and harbor engineering") in collaboration between two universities, University Hannover – today Leibniz University Hannover (LUH) – and Technical University Braunschweig (TUBS).

In particular the two institutes for hydraulic and coastal engineering, Franzius-Institute – today Ludwig-Franzius-Institute (LuFI) – in Hannover and Leichtweiss-Institute (LWI) in Braunschweig, were involved in the research activities within SFB 205. The involved scientists carrying out experiments in GWK were supported by a permanent team of 7 engineers and technicians, directly located at the flume in order to help with expertise, knowledge and action during the experimental implementation and furthermore to constantly improve the facility services in terms of measurement techniques and experimental methodologies. After SFB 205 ran out the coastal research center Forschungszentrum Küste (FZK) was founded as a joint institution of the two universities to continue the well-established cooperation and to ensure the operation of GWK, which worked out very successfully until today.

With about 300 m length, 5 m width, 7 m depth and maximum wave heights up to about 2 m GWK used to be the largest facility of this kind worldwide until recently new flumes were built in the Netherlands (New Delta Flume) and in China (Large Wave Flume of Tianjin Institute for Water and Transport Engineering, TIWTE). Still GWK can be considered as one of the largest wave flumes worldwide, as illustrated in Figure 1, and the imminent upgrade with a new wave maker, a staggered deep section and a current generation system (Schlurmann et al, 2018), will make sure to give it a unique character back again.

The present dry-back piston-type wave maker is driven by a rack and pinion system powered by oil hydraulic pumps with a total power of 900 kW. The total stroke of the wave board is 4 m (±2 m) and the velocity and acceleration are limited to 1.7 m/s and 2.1 m/s², respectively. The wave board motion is controlled by in-house software allowing for the generation of any kinds of waves from regular and irregular waves to special waves like solitary or focused waves. The implemented active wave absorption works very efficiently and allows for long wave tests without spurious re-reflections at the wave board and for a fast calm down of the water surface after a test within a few minutes. The mechanical limitations of the wave maker limit the maximum producible wave heights to about 2 m for regular waves; 1.3 m (significant wave height) for irregular waves; 1 m for solitary waves and more than 3 m for focused waves. Typical wave periods are between 2 s and 8 s, but there is actually no limit at the upper end (with increasing period only the producible wave height decreases), but only a mechanical limit for the minimum period of about 1 s, which might be even lower for lower wave heights, as in the high frequency band of a spectrum.

GWK is equipped with two 5 ton gantry cranes and has a fixed 1:6 slope at the end in order to allow for easy access to the flume with heavier machinery and to assure an efficient model installation and de-installation. Measurement instruments are usually directly installed in the models to be investigated or at the flume wall at a fixed position, but a movable bridge with a vertical and transverse traversing unit also allows for a completely flexible positioning of instrumentation as well as taking profiles along the flume. The measurement equipment at GWK has been continuously extended and upgraded with the latest instruments in order to provide the best possible experiments. The current portfolio of instrumentation allows for traditional measurements of:

- Water surface (capacitive wave gauges)
- Flow (ADV-, EM-, propeller probes)
- Wave impact and pore pressures (pressure transducers)
- Forces (multidimensional force transducers)
- Displacements (1D displacement transducers)
- Acceleration (multidimensional acceleration transducers)
- Wave run-up/run-down (capacitive wire gauges)
- Bottom profiles along the flume (sensing arm at mobile bridge)
- Sediment concentration (Transverse Suction System (TSS))

With the growing capabilities of high-performance hardware and software technologies in the last 10 – 15 years there was a tremendous development in measurement techniques, which has led to unprecedented results, which could not be obtained in the past. While for example the Transverse Suction System (TSS) only allowed for measurements of time averaged sediment concentrations at a few sample positions, Acoustic Backscatter Systems (ABS) provide time resolved sediment concentration profiles in sub-centimeter range. The Acoustic Concentration Velocity Profiler (ACVP), which has been recently developed (Hurther et al., 2011; Revil-Baudard et al., 2015) and is still continuously improved, even allows for time resolved simultaneous measurements of flow velocities and sediment concentrations along a profile. Among the newer instrumentation at GWK are the following:

- Acoustic Backscatter Systems (ABS)
- Single beam echo sounders (in air and under water)
- Multi beam echo sounder
- 2D laser scanners
- 3D laser scanner
- Video camera system

In particular the last three instruments have been extensively used over the last years and software and procedures have been developed such that these techniques can be considered to be standard equipment today, which is continuously further developed and improved. Digital video data for example can be analyzed in several ways using standard image analysis methods. The synchronized video camera system at GWK has been mostly used for time stack analysis (Aagaard & Holm, 1989; Schimmels et al., 2012; Vousdoukas et al., 2012) to remotely and non-intrusively measure wave run-up and run-down, but also for determining the velocity and thickness of up-rushing jets due to breaking waves on a wall (Shiravani et al., 2014).

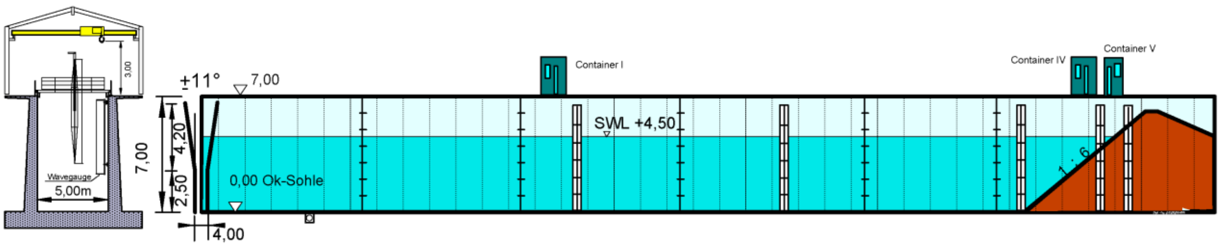

Figure 1. Cross section and longitudinal section of GWK.

2D laser scanners (or LiDAR) are also used for non-intrusive run-up measurements and provide cross shore profiles resolved with about 200 points in space at a sampling rate up to 50 Hz (e.g. Allis et al., 2011; Blenkinsopp et al., 2010). The advantage of laser scans over time stack analysis is that with the right post processing the cross shore profiles do not only provide the run-up height but even more the elevation of the underground as well as the water surface elevation of the incoming (broken) waves. This provides unprecedented information and possibilities for data analysis as exemplarily demonstrated in Figure 2, which shows one cross shore profile on top, a contour map presentation of all cross shore profiles over time below and the time varying elevation at certain locations across the beach at the bottom.

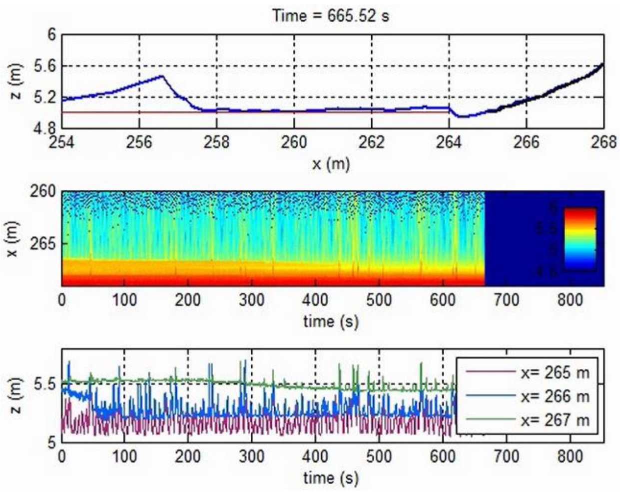

Figure 2. Data analysis possibilities from a 2D laser scan.

While the video data analysis methods and particularly the 2D laser scans provide information only along one profile, but resolved in time, a 3D laser scan is a stationary measurement, but in all spatial dimensions and with a very high resolution and accuracy down to sub-centimeter range. This can be of advantage in several aspects as exemplarily demonstrated in Figure 3, which shows a 3D laser scan of a dune before and after wave attack. The high resolution and the details of the scans are clearly visible and from their difference the eroded volume (in blue) can be accurately determined, while in the past only profiles from a sensing arm were available, which, apart from being slightly intrusive, are only representing one section, i.e. the determination of a volume has inherent uncertainties.

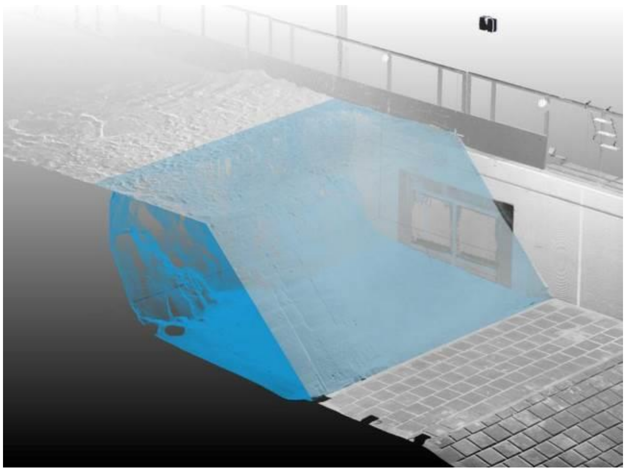

Figure 3. 3D laser scan of a dune before and after wave attack.

The latter also holds for a 2D laser scan, but this one on the other hand will provide detailed information of the incoming waves and allows determining the evolution of erosion over time, i.e. erosion rates, at least along the scanned cross section. Most benefit can actually be gained from a combination of all techniques as suggested by Vousdoukas et al. (2014) and therefore at least the synchronized video system and the 2D laser scanner are used today as a standard in almost all experiments and the 3D scanner is used at least for a scan of the model set-up and where appropriate also for other purposes during the experiments as in case of the dune erosion test shown in Figure 3.

III. Example projects

In the first years of GWK basically all model tests were done within SFB 205 "Coastal Engineering – Sea states and transport processes in coastal protection, offshore and harbor engineering" and were therefore almost exclusively dedicated to coastal structures and sediment transport. These two research topics still make a major part of the experiments in GWK, not at least because particularly sediment transport under currents and waves is far from being fully understood, but also new materials or designs for coastal protection always require model testing, often inevitably on a large scale. However, the scope of experiments in GWK has constantly increased since about 15 years. With the emerging offshore wind technology model tests were also frequently concerned with breaking wave impact as well as scouring and scour protection measures at offshore structures. Slightly later basic research and performance tests on wave energy converters became another field of investigations in GWK. Finally, due to an ever increasing political and societal awareness for the ecosystem there is a beginning paradigm shift in coastal engineering from "grey" to "green" protection measures, and the field of ecohydraulics, in particular the interaction between plants and waves, is becoming more and more important for experiments in GWK.

Today the portfolio of model tests in GWK can be categorized into four major research topics:

- Coastal structures
- Sediment transport
- Marine energy
- Ecohydraulics

which demonstrates that the demand and need for physical model tests in coastal and ocean engineering, particularly on a large scale, was probably never as big as today. This is also confirmed by the occupancy of existing facilities and even more by the planning and construction of new facilities, like the recently finished New Delta Flume (NL) and the Large Wave Flume of TIWTE (CHN) as well as the imminent upgrade of GWK (Schlurmann et al, 2018).

The following examples from the last 35 years of operation of GWK are structured by the four research topics mentioned above. They shall demonstrate the latest developments in laboratory technologies and the potential for future experiments in coastal and offshore engineering, underlining the above in terms of an ever growing necessity for physical model tests in particular on a large scale.

A. Coastal Structures

Coastal Structures, like breakwaters, dikes or revetments, are one of the key research topics in GWK from the very beginning, as there are many scaling issues involved depending on the type of structure (Oumeraci, 2010). Within SFB 205 for instance several different revetment types were investigated as shown exemplarily in Figure 4.

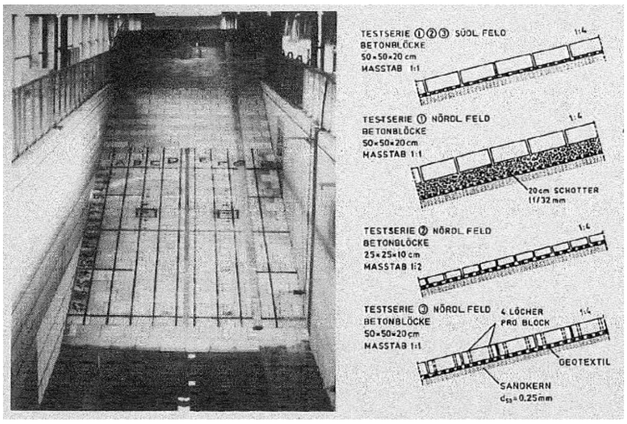

Figure 4. Different concrete block revetment set-ups tested in the early days of GWK within SFB 205.

The major goal of these experiments was the investigation of

- Run-up height
- Run-up velocities
- Impact pressures
- Pore water pressures / Soil mechanics
- Structural failure
- Scale effects

The hydraulic performance of costal structures and the interaction between waves, structure and soil is still a field of active research as illustrated by the many examples given in Oumeraci (2010). In particular our still remaining lack of understanding concerning the very complicated interaction processes requires more fundamental research and experiments on a large scale. On the other hand new materials or designs of coastal structures regularly emerge and require large scale model tests for approval of their stability and effectiveness. Figure 5 shows exemplarily tests in GWK with two new types of revetment, a polyurethane bonded aggregate (PBA) revetment and a concrete block revetment with specially shaped blocks, which gain more stability by interlocking.

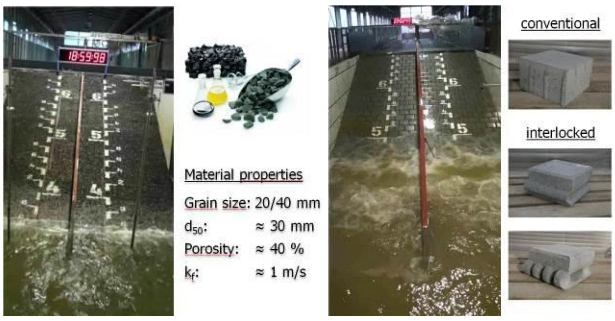

Figure 5. PBA revetment (left) and interlocked concrete block revetment (right) tested in GWK.

The tests were performed in 2009/2010 and 2010/2011, respectively, but the main objectives were exactly the same as two decades before, i.e. hydraulic performance in terms of wave run-up and reflection as well as structural stability up to the point of failure, if achievable. For the latter the measurement of wave impact and pore pressures is essential, which used to be and still is done with a significant amount of pressure sensors on top and underneath the revetment as comprehensively described for the PBA revetment in Oumeraci (2010). The measurement of wave run-up on the other hand used to be done with wire gauges adopted from traditional wave gauges that are mounted parallel to the slope or with specially designed run-up gauges with several electrodes placed some centimeters apart from each other along a board which is fixed on the slope. Both techniques come with certain drawbacks – in particular on uneven slopes or a non-rigid underground like a mobile sand bed – and are usually replaced today by video data analysis or laser scans.

In the above mentioned experiments on PBA revetments traditional wire gauges and video data were used for run-up measurements. A comparison of both techniques showed a better data quality with less scatter in maximum run-up values determined from time stacks (Schimmels et al., 2012). This allowed for a better assessment of a coefficient for porosity as shown in Figure 6.

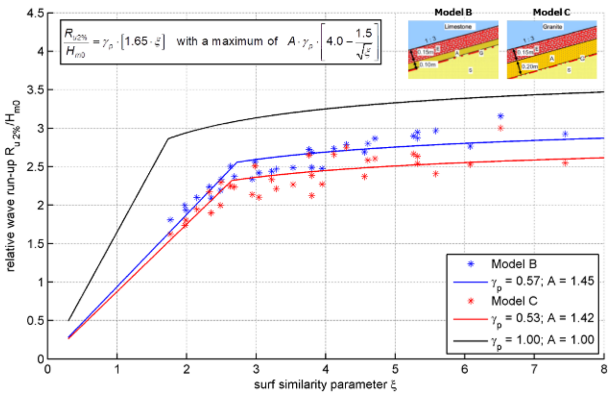

Figure 6. Wave run-up on porous revetments (PBA) compared to a plain smooth slope (adopted from Schimmels et al., 2012).

Another very recent experiment on stepped revetments (Figure 7) was also focused on wave impact and wave run-up, which is potentially significantly less due to the high turbulence induced by the steps. This is a perfect example where video data and 2D laser scans clearly outdate classical wave gauges, which are difficult to fix on the stepped slope and then might intrude the flow. Both non-intrusive techniques were therefore applied instead, but as the experiments were carried out in the beginning of 2018 data analysis is still ongoing and no results from these experiments are published yet. However, a general introduction to stepped revetments and results from smaller scale flume model test can be found in Kerpen et al. (2016), Kerpen et al. (2018) or Schoonees et al. (2018).

Figure 7. Model tests on stepped revetments in GWK.

B. *Sediment Transport*

One of the most challenging topics in coastal engineering is the understanding and prediction of coastal morphodynamics, be it on a long term when longshore transport dominates or even on a short term, during a storm when cross shore transport dominates. Therefore cross shore sediment transport under waves has been investigated in GWK since the very beginning. However, as measurements in the 1980s and 1990s were limited to cross shore profile measurements with a mechanical bottom profiler (sensing arm at mobile bridge) in between wave tests and average concentration profiles gained from water sediment samples with a TSS (Figure 8), the early experiments were focused on beach profile evolution and dune erosion in a more descriptive like manner. For example Figure 9 shows the influence of a foreshore on dune erosion and the evolution of the breaker bar.

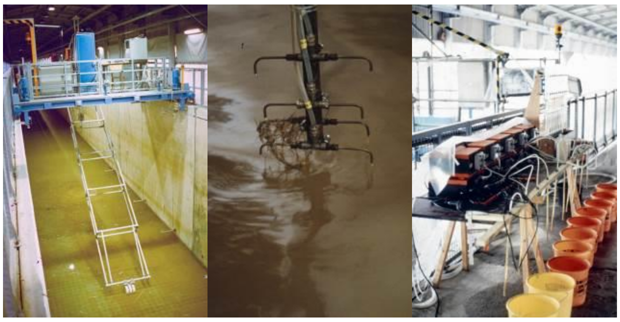

Figure 8. Bottom profiler in GWK (left); nozzles (middle) and pumps (right) of Transverse Suction System (TSS).

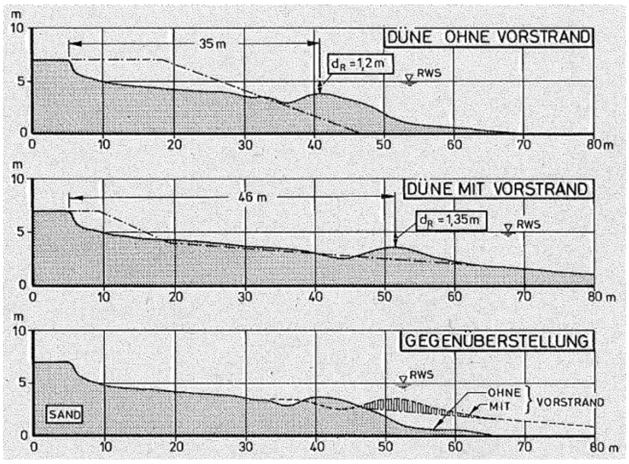

Figure 9. Dune erosion with and without foreshore.

With the development of acoustic measurement devices in the beginning of this century it became possible to obtain time resolved sediment concentration profiles and to look into the details of the processes. For instance in 2008, ABS sensors were deployed for the first time in GWK during experiments on a 1:15 sloped beach, and provided insights into the phase resolved sediment concentration profiles along the whole beach profile, i.e. under rippled and under plane bed regimes (Oumeraci, 2010; Ahmari & Oumeraci, 2011; Ahmari, 2012). Figure 10 shows one example result from an ABS measurement in terms of the sediment concentration profiles over a ripple under one wave. From the contour plot it can be clearly identified how the sediment gets into suspension when the flow velocity is at maximum or changes direction. In particular the latter is supposed to be associated with flow separation and vortex shedding over the ripple, but actually this cannot be derived from the pure concentration data but requires the corresponding velocity field, which today would be obtainable with an ACVP.

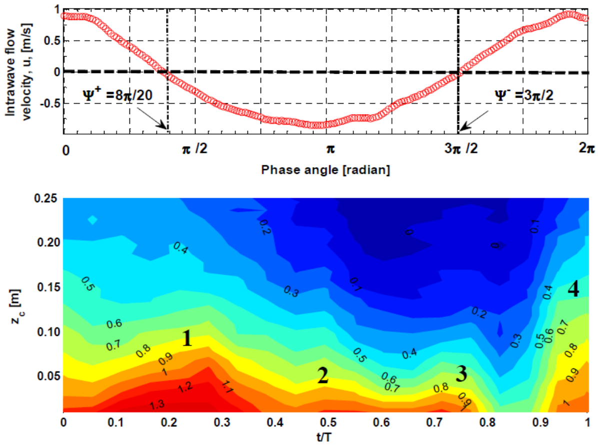

Figure 10. Phase dependent sediment concentrations over a sand ripple (Ahmari, 2012).

Video data as well as 2D and 3D laser scans also improved the investigation of detailed processes significantly. In 2013 experiments on a 1:15 sloped beach were carried out again, with a focus this time on the evolution of the beach face, which was observed with video cameras and 2D laser scanners, providing time resolved information of wave run-up and local erosion rates (Vousdoukas et al, 2014) as shown in Figure 2 In the same year the erosion of dunes on a German island was investigated in an applied research project. Here again 2D laser scans provided continuous erosion rates of the dune and 3D laser scans the corresponding exact erosion volumes (Figure 3) at certain times, which served to validate the rates.

Research on sediment transport made a huge progress within the last years not at least due to the analysis possibilities, which are offered by the new measurement techniques. Our understanding of the detailed processes improved a lot and helped in deriving better and more reliable sediment transport prediction formulas. However, due to the complexity of the processes in particular under breaking waves, we are still far away from a complete understanding and many more large scale experiments will be needed in the future. Furthermore, research efforts so far were more or less completely focused on simplified situations, i.e. beach and dune evolution on plain shore profiles with uniform sands. The interaction with structures, the transport processes of non-uniform sands (sand mixtures or graded sands) or the consideration of cohesive material are emerging topics, which will also have to be addressed. A first tendency in this direction is apparent from the latest experiments in GWK. In 2016 experiments were conducted on the interaction of a beach with a sea wall under storm conditions, in 2017 a “dynamic revetment” in terms of a mound of pebbles on a beach was investigated and in 2018 fundamental experiments on the transport of bi-modal sand mixtures ($d_{50,1}$ = 0.2 mm and $d_{50,2}$ = 0.6 mm) in different relations (100/0; 75/25; 50/50; 25/75) on a horizontal bed were carried out for the first time ever under real waves.

Owing to the uniqueness of the latter experiments, which were just finished in June 2018, the effort that was put into the measurements was extraordinarily high. As not all of the latest instrumentation is available at GWK, many researcher colleagues from France, Netherlands, Poland, Portugal, Scotland and USA joined the tests and provided their instruments. The additionally deployed instrumentation consisted of Capacitive Concentration Meters (CCM), Capacitive Concentration Profilers (CCP), Acoustic Concentration Velocity Profilers (ACVP), an Acoustic Ripple Profiler (ARP) and a LISST (Laser In-Situ Scattering and Transmissometry). Furthermore, overall transport rates can be derived from profiles of the sea bed taken with echosounders mounted on the movable bridge intermittently between wave tests and tracer sediments which were monitored by taking periodical sediment samples. The huge amount of data is currently analyzed and promises to provide exiting results.

C. *Marine Energy*

Marine Energy is one of the younger topics in GWK although first experiments on wave slamming forces on vertical pile structures were already conducted about 20 years ago (Wienke & Oumeraci, 2005). These fundamental experiments with focused breaking waves on vertical and inclined piles should bring more insight into the prediction of extreme loads on offshore structures and the derived loading formula was incorporated in international design standards for marine structures (ISO, 2007), but also for offshore wind energy devices (Germanischer Lloyd, 2005; ISO/IEC, 2009). Slightly later also the effect of pile groups has been extensively investigated (see Oumeraci, 2010 and references therein), but no comparable simple prediction formula could be derived yet. However, based on the results of the GWK model tests and additional tests on a smaller scale Bonakdar (2014) has derived a design approach using Artificial Intelligence techniques.

Since then several tests within commercial and non-commercial projects with different foundation types for offshore wind turbines, like monpile, tripod, gravity based, or jacket structures were done in GWK. Some examples are shown in Figure 11. Besides the wave loads also scour development and scour protection stability were in the focus of these experiments with the latter particularly profiting significantly from the development in measurement techniques in recent years.

Figure 11. Offshore wind turbine foundation structures tested in GWK; tripod, gravity based, jacket structure (from left to right).

While in the very first experiments on scour development in GWK in 2006 and 2007 the flume had to be drained after a test in order to do a very laborious and time-consuming manual levelling of the sand bed, similar experiments in 2009 could make use of a multi-beam echosounder (Oumeraci, 2010; Schimmels, 2010), which significantly reduced the effort and provided data with a much higher spatial resolution in the order of centimeters. However, also the multi-beam echosounder comes with some drawbacks, as the raw data require a significant amount of post-processing and the measurement uncertainty is only in centimeter range. This can be sufficient in certain cases in particular considering the rather large scale of the experiments in GWK, therefore the instrument has later been used in some other experiments on scour protection measures or scour development (e.g. Stahlmann, 2013; Stahlmann, 2014).

However, 3D laser scans outperform the multi-beam measurements in terms of resolution and accuracy by an order of magnitude and also require less post-processing effort. Therefore the multi-beam echosounder has quickly been replaced by a 3D laser scanner even if the flume has then to be drained for the measurements. In particular the high resolution and accuracy of laser scans are indispensable in certain situations, e.g. to determine the stability of scour protection measures or of armour material in general. The first time that a 3D laser scan was used in GWK was in 2013 within a project to investigate the stability of the scour protection and the ballast material of a special gravity based foundation (Figure 11, middle). An example for a 3D laser scan is given in Figure 12.

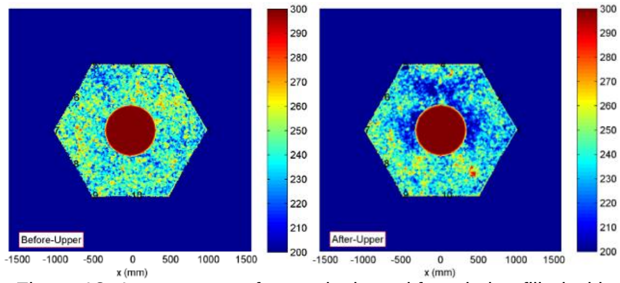

Figure 12. Laser scans of a gravity based foundation filled with ballast rock material before (left) and after (right) wave attack.

The comparison of the scans before and after a test clearly shows the rearrangement of the ballast stone material and the high resolution of the scans, in which each stone is well identified. Hence, from the difference of the two scans the erosion depth and volume, as stability measure can be easily and accurately derived.

Breaking wave loads on simple monopile structures are already complicated to predict, but the experimental efforts in GWK described above have significantly improved our understanding of the phenomenon and have even led to design approaches for practice. However, these approaches cannot be simply applied to typical jacket constructions (Figure 11, right), as the truss structure is comparably more complicated and it is not clear how individual members are loaded and how the load on one member affects the load of others. Therefore in 2013 experiments were carried with a sophisticated jacket structure model, in which a total of 22 specially designed force transducers were installed in order to measure the local breaking wave impact forces on the front legs and the front and side braces directly rather than deriving them from pressure measurements. Figure 13 shows details of the force transducers on the front leg and on one bracing, and Figure 14 shows the positions of all force transducers mounted in the model. The data is still being analyzed, but some results on the analysis of total and local forces on the structure have already been published (Jose et al., 2016; Jose et al., 2017 Jose & Choi, 2017).

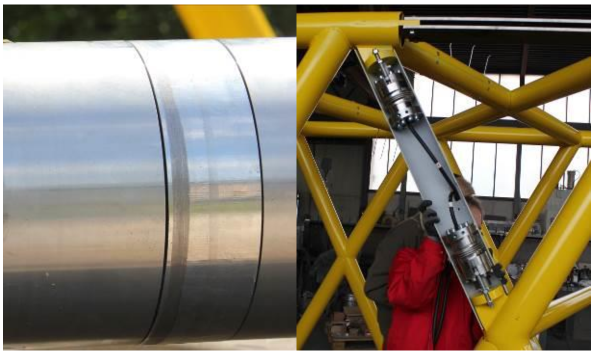

Figure 13. Details of the force transducers on the front leg (left) and one bracing (right) of the jacket structure model.

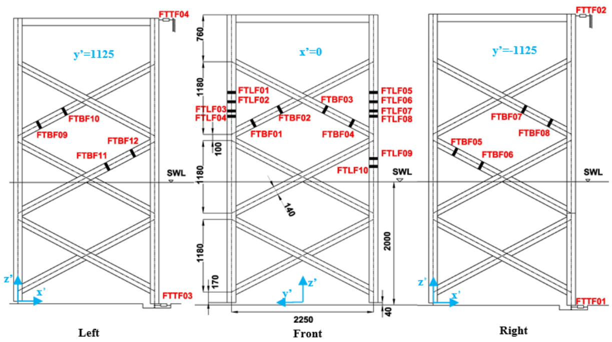

Figure 14. Positions of force transducers in the jacket structure.

Another part of marine energy and actually a more original one than offshore wind energy is wave energy. However, model tests in GWK related to wave energy are still in their infancy and for the most part concerned with testing of prototype devices before they are tested in the field. At the moment of writing these lines tests on a floating type device are just running next door in GWK and another prototype of a special Oscillating Water Column (OWC) device will be tested the week after.

The first real experiments on wave energy in GWK were carried out with an OWC model in 2014 and actually had a fundamental research background (Allsop et al. 2014). The objective was gaining more insight into the stability and performance of these kinds of devices in terms of the loads on the structure and the actual processes inside the wave chamber. Both strongly depend on turbulence levels and compressibility of air, which requires large scale experiments to minimize scaling effects. As almost all knowledge for the design of such structures is based on small scale experiments and simplified analytical considerations a further objective of the tests in GWK was to assess the impact of scale effects in order to verify or improve the existing design recommendations.

Figure 15 shows a sketch of the model setup and the instrumentation. The airflow in and out of the chamber is usually used for power production with a Wells turbine, but for the tests the turbine was simulated with an aperture with different width in order to consider different operating conditions. The flow rate through the aperture was measured directly with an impeller probe and by the pressure difference below and above the aperture. Wave impact on the front face was measured by pressure sensors and the process inside the chamber was monitored with a video camera, wave gauges and pressure sensors.

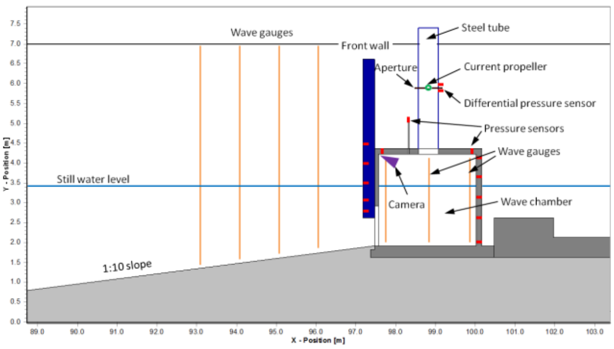

Figure 15. Model setup and instrumentation for OWC tests.

Figure 16 shows two snapshots from the videos inside the wave chamber for the same wave conditions, but different aperture widths in order to illustrate the complexity of the processes and the necessity for a large scale. With a small aperture width of 5 cm the air can hardly escape the chamber and is rather compressed and decompressed as seen by the light vapor in the image. With a large aperture width of 30 cm the air can easily get in and out of the chamber, which (depending on the wave conditions) may lead to significant sloshing and wave breaking inside the chamber

Figure 16. Snapshots from inside the wave chamber for same tests with different aperture width: 5 cm (left) and 30 cm (right)

D. *Ecohydraulics*

The field of ecohydraulics in the widest sense is dealing with the interaction between biota (plants and animals) and hydraulics and actually originates from river engineering where the importance of including biologically aspects in the engineering design has been recognized noticeably earlier than in coastal engineering. In costal engineering this field is rather new and therefore experience is still quite limited in general and so is the number of laboratory experiments, which so far were basically focused on interactions between plants and waves.

The general difficulty associated with ecohydraulic laboratory experiments is the representation of living organisms in an artificial laboratory environment in order to perform hydraulic model tests. In coastal engineering this can be particularly challenging as many organisms can only survive in salt water, while actually all wave testing facilities, including GWK, are using fresh water for the experiments. Sea grass for instance dies within a few hours in fresh water, but even if the species to be investigated are more robust and fresh water resistant, like for example salt marsh vegetation, it is still challenging to maintain their health in an enclosed laboratory environment (e.g. without natural sunlight) over the duration of the hydraulic model tests, which may easily last over several days or weeks.

It is definitely beneficial to use real organisms in an ecohydraulic experiment, as they inherently represent natural characteristics and heterogeneity, but very often it might just be unfeasible to provide the necessary environmental conditions, in which the health of species is maintained or the size of the species is just too big for the facility. An alternative could be the use of surrogates, which mimic the essential characteristics and behavior of the natural counterpart. However, finding a good surrogate of plants alone is another extremely challenging task, in particular if these are flexible and buoyant, like sea grass for example. In the European research project Hydralab IV a first attempt was made on a systematic development of aquatic plant surrogates (Paul & Henry, 2014; Johnson,et al., 2014), which was part of the work on guidelines for the performance of ecohydraulic experiments in the laboratory (Frostick et al., 2014). Still ecohydraulics is just in its infancy in particular in coastal engineering, and no matter if living organisms or surrogates are used in a hydraulic model test, the inclusion of biologists or other ecological experts is indispensable for successful experiments. Ecohydraulic research activities should therefore always be interdisciplinary.

The first experiments in GWK associated with ecohydraulics were performed in 2013 and are a prime example for interdisciplinary research and for the effort to be made when using real plants in the laboratory. The objective of these unprecedented experiments was the investigation of salt marshes under storm conditions in order to better understand and quantify their ecosystem services related to coastal protection. The key questions were the influence of the vegetation on the dissipation of waves and the response of marsh vegetation and soil surface to incident wave energy. 200 m² vegetated salt marsh with a thickness of about 30 cm were excavated at a site on the German North Sea coast, placed on 200 pallets and brought by trucks to GWK in Hannover. For logistical reasons the pallets had to be stored at GWK over winter and needed special treatment to let the plants recover over the following spring and summer in order to install them in GWK for the experiments in late summer 2013. The installation procedure of the 40 m long salt marsh stretch also required significant effort and man power and was finished after three weeks. Figure 17 provides some impressions from the excavation of the salt marsh blocks in the field to the final installation in GWK. Along the flume walls special lamps had to be installed in order to provide the plants with light, and to let the plants recover from the stress due to wave impact the flume was regularly drained in the actual testing phase. As mentioned before, this kind of experiments had never been done before and they helped a lot to better understand the interaction between soil, plants and waves (Möller et al., 2014; Paul et al., 2016; Rupprecht et al., 2017; Spencer et al., 2016).

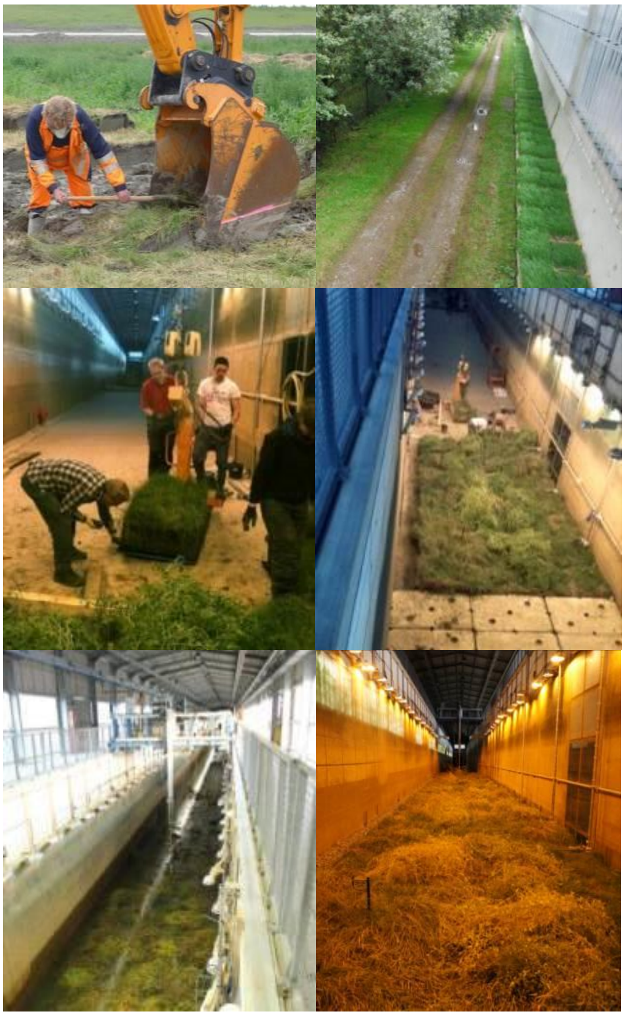

Figure 17. Impressions from the excavation, storage and installation of salt marsh vegetation in GWK.

After the very successful experiments in 2013 almost the same group of researchers very recently did another set of experiments in GWK, this time focusing on the salt marsh pioneer zone, i.e. the offshore margin of a salt marsh. The objectives were primarily to better understand (i) how extreme wave-forcing affects seedling survival of different pioneer species; (ii) how (and to what extent) vegetation affects erosion processes and rates under extreme forcing; (iii) how small clifflets at the seaward margin respond to high energy wave conditions; and (iv) what damage to the vegetation in terms of marsh plant breakage occurs under extreme conditions. The experiments were just finished by September 2018, so no results are available yet, but will probably be soon.

The two ecohydraulic experiments in GWK on salt marshes are supposed to be just the beginning as it can be expected that ecohydraulics will gain more and more interest in the near future and large scale experiments, like those in GWK, will play an important role. The emerging paradigm shift in coastal engineering from “grey” to “green” solutions requires a better understanding of water-soil-biota interactions and those can be investigated best under fully controllable laboratory conditions. Using surrogates in such experiments is often associated with simplifications and assumptions and sometimes even unfeasible. The use of living organisms on the other hand requires special care and effort as well as very often a large scale. In order to allow for further tests with living organisms in GWK the experimental methods are improved continuously and the imminent upgrade with a deep section and a current system (Schlurmann et al., 2018) will facilitate future GWK experiments in ecohydraulics even more.

IV. Conclusions

The demand and need for physical model tests in coastal and ocean engineering, particularly on a large scale, was probably never as big as today, which is confirmed by the occupancy of existing facilities and even more by the planning and construction of new facilities, like the New Delta Flume (NL) and the Large Wave Flume of TIWTE (CHN) as well as the imminent upgrade of GWK (Schlurmann et al, 2018). With a brief review of the history and the development of GWK over the last 35 years the present paper not only wanted to give an overview of past and present research activities at GWK, but much more intended to demonstrate the capabilities of new measurement technologies and show the opportunities for potential future experiments.

The “classical” coastal engineering research topics in terms of coastal structures and sediment transport will remain being an important factor in this context. For coastal structures new materials and designs will frequently emerge and will always require new investigations and physical model tests. New design approaches, i.e. deterministic vs. probabilistic design, will further require an understanding of degradation processes and failure development, which can only be explored realistically in prototype or large scale. In particular research on sediment transport has profited significantly from the development of new measurement techniques (e.g. video analysis, laser scans, ABS, ACVP) in the last 15 years. The new instruments allow for complete new and much more detailed insights into processes and will make the basis for future fundamental and applied research projects, which therefore have a tendency towards more complex phenomena like the transport of mixed non-cohesive and/or cohesive sediments.

Marine energy is another important topic for experiments in GWK since about 15 years now, starting with unique large scale experiments on breaking wave impact on slender cylindrical structures. Since then several fundamental and applied research projects in GWK have significantly improved the understanding of breaking wave impact, scour development and scour protection measures for different kinds of offshore wind energy foundation structures. The more complex structures (e.g. tripod, tripile, jacket) and the consideration of further important aspects like wave directionality or tidal currents will be in the focus of future studies. Experiments in GWK dealing with wave energy are comparably limited so far, but it can be assumed that with the growing political interest in renewable energy resources at the moment wave and tidal stream energy will become another important field for fundamental research and prototype tests of new devices in the near future, particularly when GWK is equipped with a better wave maker and a current system.

The latest of the current research topics in GWK is related to the coast again and also emerged from growing societal and political awareness for environmental concerns and interest in sustainable solutions. Recently suggested strategies like “Building with Nature” or “Nature-based Solutions” follow the concept of using ecosystem services for the design of coastal protection measures rather than just fighting against nature with coastal structures. Including natural features, e.g. wave attenuation by vegetation or mussel banks, in the engineering design necessitates a better understanding of the living organisms’ resilience against extreme events and in particular of the processes governing water-soil-biota interactions. Investigation of the latter is the objective of ecohydraulics and pioneer experiments in GWK on vegetated salt marshes in 2013 and 2018 proved on the one hand the high value of this kind of experiments and on the other hand the huge effort and challenges coming with them. Despite the latter it can be expected that ecohydraulic experiments in GWK will gain much more importance in the near future, therefore the experimental methods are continuously improved, with the forthcoming upgrade of GWK being one step in this direction (Schlurmann et al., 2018). We are convinced that new research topics, new measurement techniques and the new experimental possibilities will warrant another interesting at least 35 years of physical model tests in the Large Wave Flume (Grosser Wellenkanal, GWK).

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