Adaptation for Climate Change

Guidelines for physical experiments involving complex processes related to climate change impact and adaptation

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DISCLAIMER

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EXECUTIVE SUMMARY

Hydralab+ addresses the need for adaptive infrastructure within a dynamic land-water border under climate change conditions. This requires physical experiments conducted in hydraulic facilities under conditions that are outside the range of conventional hydraulic experiments. To tackle these conditions of increasing complexity there is a need to establish guidelines for proper conduct of such experiments.

This deliverable identifies and addresses four areas of complexity that are becoming increasingly important for hydraulics experiments.

1) Hydraulic mobile bed experiments involving mixes of sediments of different size.

2) Eco-hydraulic experiments involving vegetation and its interaction with hydrodynamics and morphodynamics.

3) Incorporating biofilm effects in hydraulic experiments.

4) Properly representing the mechanical properties of ice for wave-ice-structure interaction experiments.

For each area of complexity, the deliverable provides an account of experience from previous experiments, an overview of related experiments being conducted within Hydralab+, and practical guidance on how to address key issues associated with proper conduct of hydraulic experiments involving that complexity.

1 INTRODUCTION

The need for sustainable and adaptable hydraulic infrastructure for protection against flooding and loss of life and property, and the related need to predict climate change impact on fluvial and coastal environments, means that physical experiments conducted in hydraulic facilities are becoming increasingly complex. For example, recent increased interest in vegetation-based coastal defence requires the complex issue of correctly representing vegetation in wave flume and wave basin experiments to be addressed. Similarly, substantial reduction in the extent and thickness of Arctic sea ice, and the consequent increasing population of structures and vessels operating in ice-laden seas, demands better understanding and physical modelling of the complex mechanical properties of sea ice in order to conduct physically-realistic experiments in laboratory ice tanks.

In this report we identify four complex issues that are becoming increasingly important in the context of laboratory hydraulic experiments as a result of climate change projections, the move towards adaptive fluvial and coastal solutions, and increased activity in ice-laden seas: (i) conducting sediment dynamics experiments in which the sediment comprises a mix of diverse grain sizes; (ii) incorporating vegetation in physical experiments concerned with fluvial and coastal hydrodynamics and morphodynamics; (iii) incorporating biofilm effects in flume experiments, especially in the context of low-mobility hydraulic conditions; and (iv) modelling the mechanical properties of ice for wave-ice interaction experiments and experiments on ice loading on vessels and structures.

Section 2 of the report elaborates on the climate change context, particularly on the move from “grey” to sustainable and adaptive nature-based solutions, a move that requires deeper knowledge of three of the four complexities addressed in Section 3. For each of the four complex issues, Section 3 briefly summarises previous related experimental studies, presents an overview of experiments carried out within HYDRALAB+ that relate to the complexity, lists the main issues associated with the complexity in the context of hydraulic experiments, and finally provides practical guidance for dealing with these issues in order to conduct the best possible experiments.

2 THE CLIMATE CHANGE CONTEXT

Protection of human settlements against flooding and erosion is done since centuries, mostly following the concept of "fighting against" natural forces by building hard structures, for example, dikes, breakwaters, revetments, seawalls or groins. As most of these structures are made from stone or concrete, the approach is often described as a "hard" or "grey" measure. Based on long-term practical experience, with many lessons learned from failures, and the very large number of dedicated hydraulic model experiments conducted within the last century, well-established guidelines exist for such structures, which allow for economic design and construction with a very low risk of failure.

At first sight, the traditional approach might therefore be considered as a good solution to the societal challenge of disaster risk reduction in the face of climate change. However it also comes with certain drawbacks. Not all countries have the necessary knowledge or the financial possibilities to implement the expensive structures. In addition, hard structures designed to solve a local issue can create problems at neighbouring sites; for example, groins that reduce coastal erosion rates locally can lead to a sediment deficit at a downstream location. Artificial interference in the natural environment also has always a certain impact on the ecosystem, which in the best case is usually compensated by other ecosystem-promoting measures. Last but not least, hard structures are not easily adapted to changing conditions, meaning they cannot easily adapt to climate change impacts like rising sea levels, increasing wave heights or higher precipitation.

The negative issues associated with traditional engineering solutions were already realised since the introduction of the Integrated Coastal Zone Management (ICZM) concept in 1992. Since then there has been increasing awareness of the need to apply sustainable solutions to coastal management and coastal protection issues. In EC recommendations 2002/413/EC on ICZM (EC, 2002), it was already acknowledged that "community coastal zones are further threatened by the effects of climate change, in particular rising sea levels, changes in storm frequency and strength, and increased coastal erosion and flooding" and that this requires "adaptive management during a gradual process which will facilitate adjustment as problems and knowledge develop", which "[…] implies the need for a sound scientific basis […]". It is further recommended that future solutions should be "working with natural processes and respecting the carrying capacity of ecosystems, which will make human activities more environmentally friendly, socially responsible and economically sound in the long run."

Since the late 2000s this paradigm shift has become more and more acknowledged, emphasised by the initiation of different strategic programmes worldwide, all following the same goal to promote new solutions that integrate ecosystem services from the outset, rather than simply artificially modifying the environment. The most prominent concepts in this context are "Working with Nature" (PIANC, 2018), "Engineering with Nature" (USACE, 2018), "Building with Nature" (Ecoshape, 2018) and "Nature-based Solutions" (IUCN, 2018; EU, 2018). While the former three, all originating from engineering associations, are practically orientated, "Nature-based solutions" (NbS) is an umbrella concept that encompasses environmental and societal challenges, including climate change and disaster risk reduction. The NbS concept is still being shaped (Nature, 2017), but it has already developed to the point that its philosophy is now implemented in national and international policies and programmes supporting the development of new solutions. For instance, the EU is explicitly

supporting NbS projects through Horizon 2020, with a momentary focus on renaturing cities and minor emphasis on coastal protection or flood risk management (ThinkNature, 2018).

The concepts driven from an engineering perspective are all focused on coastal protection and have already provided many practical examples for adaptation measures following the new philosophy. To test and investigate their performance, several pilot projects have been realised, monitored and reported, in particular in the Netherlands within the scope of "Building with Nature" (BwN). Two representative examples are:

- Mega sand nourishments like the Sandmotor (www.dezandmotor.nl/en), where a very large volume of sand is dumped at one location and is allowed to respond naturally to the prevailing wave and current conditions over one to two decades, the eroded material being redistributed along the coastline by natural forces. At the same time, the peninsula created by the dumped sand may provide new ecological and social benefits. Detailed studies of the hydro- and morphodynamics of such mega nourishments, as well as the ecological and societal effects, are currently underway.

- Wave attenuation and sediment stabilisation by plants like salt marshes, sea grasses or mangroves. Vegetated foreshores are known to have a positive effect in terms of reducing incident wave conditions and trapping sediments, which enables the foreshore to develop over the long term in response to rising sea levels. However, the detailed processes and interactions between plant species and waves and currents need further study in order to fully understand and optimise this ecosystem service for implementation in coastal protection strategies.

Figure 1: Nature-based solutions: experiments on salt-marsh vegetation in GWK, Hannover

Traditional grey solutions will surely not become completely dispensable, particularly not for densely populated cities, but they might be combined with Nature-based Solutions, following the recently suggested concept of Adaptation Pathways (e.g. Haasnoot et al., 2013; Kwakkel et al., 2016). Very recently, Ecoshape, the consortium promoting the BwN concept, has also adopted the Nature-based Solution term, and together with other partners published a guideline on "Implementing nature-based flood protection" (Ecoshape, 2018b), in which five principles are postulated, one of which is "Adaptive Management". The implementation guidance given in the document also foresees the possibility of using "green" (NbS) or "grey" interventions alone, or combining them in a hybrid solution based on a risk analysis, which requires knowledge about the actual performance of individual measures or their combination.

Even for traditional engineering measures, a reliable risk assessment is challenging, but for the rather new nature-based measures it is almost impossible for many reasons. Apart from the difficulty in predicting future hydrological conditions, and perhaps even higher uncertainty in the assessment of ecosystem dynamics, there is also a lack of understanding of the physical processes involved, especially under extreme conditions. Learning from pilot projects is surely an important way of addressing knowledge gaps and gaining more experience on the practical implementation of NbS for flood protection and disaster risk reduction, but a comprehensive investigation of specific processes in order to better understand their details is only possible with dedicated laboratory experiments under fully controlled boundary conditions.

As indicated by the two examples given above, two major areas of focus for hydraulic experiments in support of nature-based solutions and adaptive measures are sediment transport and ecohydraulics. For the former there is already significant experience and knowledge available, but major challenges still remain, including, but not limited to, sediment flux under high-energy, sheet-flow conditions and the transport of sediment mixtures. Regarding ecohydraulics, the interaction of vegetation and biofilms with currents and waves represents a comparatively new area of research, and experience with hydraulic experiments is therefore rather limited. Besides the challenges of measuring the processes of interest, there are also challenges in terms of how to deal with living plants and organisms in a hydraulic laboratory experiment or using surrogates.

Besides accelerating the move towards adaptive, nature-based solutions, and the attendant need for hydraulic experiments to address complex issues, climate change also predicates a need for more and increasingly complex experiments involving ice. Climate change has decreased the extent and thickness of Arctic sea ice substantially, a consequence of which is a growing population of structures and vessels in ice-laden waters. Because of climate change therefore, there is increasing need for accurate physical models of ice in experiments on the complex interaction of ice with waves and with structures and vessels.

3 AREAS OF COMPLEXITY

In the following, four areas of complexity for future hydraulic model tests concerned with the challenges related to responses and adaption to climate change are presented and discussed: (i) sediment mixtures; (ii) vegetation; (iii) biofilms; (iv) ice. In particular the first three are directly addressing the necessary laboratory investigations for further promoting new adaptation measures following the NbS philosophy as discussed above. For each complex area a brief overview of previous experimental studies and experiments carried out within Hydralab+ will be given, followed by a summary of key issues to be considered and practical guidance how to deal with these issues.

3.1 EXPERIMENTS WITH SEDIMENT MIXTURES

3.1.1 Previous experimental studies on sediment mixtures

i) Grain-scale experiments

Small grains in sediment mixtures tend to fill the gaps between larger grains, thus reducing porosity and permeability of the sediment (e.g. Bear, 1972). Several grain-scale experiments with dry granular media (e.g. McGeary, 1961; Lade et al., 1998) have shown how the pore space of mixed sediment is affected by the grain sizes in a mixture. Similarly, the vertical infiltration and percolation of water into and through a sediment bed is affected by the grain-size distribution. For many decades experimental studies in the fields of groundwater research and petroleum engineering have investigated the relation between grain-size distribution and permeability of a porous medium (e.g. Kozeny, 1927; Carman, 1937; Krumbein and Monk, 1942).

ii) Unidirectional flow experiments

In fluvial geomorphology many experimental studies have focused on sand-gravel mixtures in a unidirectional current (Jackson and Beschta, 1984; Iseya and Ikeda, 1987; Sambrook Smith and Nicholas, 2005; de Linares and Belleudy, 2007; Venditti et al., 2010; Wren et al., 2011; Buscombe and Conley, 2012; Houssais and Lajeunesse, 2012; Wren et al., 2014; Kuhnle et al., 2016; Hill et al., 2017; Miwa and Parker, 2017), while few experiments have involved sand mixtures. The experiments of Grass (1970) showed that incipient motion of a sand grain mixture can be described via a statistical interaction process between the distribution of instantaneous critical bed shear stresses and associated individual grain instabilities, i.e. the distribution of the sand grain resistance. The latter is directly linked with grain size. Wallbridge et al. (1999) visually observed the entrainment of individual sand particles on a grain scale from uniform and heterogeneous beds, confirming the theoretical model by Wiberg and Smith (1987), which describes the selective entrainment of coarse grains from a mixed bed (due to protrusion into the flow), while fine grains remain stable (due to hiding in between coarser grains). For their grain-scale experiments, Wallbridge et al. (1999) used six different mixtures comprising grain sizes between 0.045 and 2.0 mm. The review paper of Blondeaux (2012) summarizes studies explaining the appearance of rhythmic morphological features in the coastal region in heterogeneous sediment mixtures and considering selective sediment transport. The study showed the significance of sorting phenomena, e.g. accumulation of coarse sediment at the crests and of fine sediment in the troughs of the bottom forms or vice versa depending on the parameters of the problem. Moreover, Blondeaux (2012) found that the presence of a sediment mixture has a significant stabilizing/destabilizing effect on the formation of the bottom forms and

that it affects their migration speed. Recently, Bartzke et al. (2013) and Staudt et al. (2017) used an annular flume to investigate at small scale the effects of grain-size distribution on the stability of various sand-silt mixtures (D_c = 0.30 mm, D_f = 0.06 mm) and glass bead mixtures (D_c = 0.37 mm, D_f = 0.09; 0.06 and 0.04 mm) respectively. Several other studies (e.g. Mitchener and Torfs, 1996; Torfs et al., 2001; Le Hir et al., 2008) have focused on sand-mud mixtures, but these studies are of less interest here since such mixtures are not found in high-energy surf zones, which is the focus of the HYDRALAB+ experiments.

iii) Oscillatory flow tunnel experiments

Van der Werf et al. (2009) provide an overview of large-scale laboratory experiments that have investigated wave-driven sand transport until 2009 (the so-called SANTOSS database). Only 4 of the 26 studies covered in the database have investigated the transport of mixed sand (Inui et al., 1995; Hamm et al., 1998; Hassan, 2003; O'Donoghue and Wright, 2004a, 2004b). Inui et al. (1995) investigated three different bimodal mixtures (25; 50; 75 % fines) of medium (0.2 mm) and coarse (0.87 mm) sand in the oscillatory flow tunnel at Tokyo University (TOFT). Hamm et al. (1998) tested fine (0.13 mm) and coarse (0.32 mm) sand in a 50/50 mixture in the Large Oscillating Water Tunnel (LOWT) of Delft Hydraulics (now Deltares) in Delft. Hassan (2003) and Hassan and Ribberink (2005) tested the following mixtures in the same LOWT facility: 70:30 mix of 0.21+0.97 mm; 60:20:20 mix of 0.13+0.34+0.97 mm; 50:50 mix of 0.13+0.34 mm. O'Donoghue and Wright (2004a, b) investigated various mixtures of 0.15 mm, 0.28 mm and 0.51 mm sands in the Aberdeen Oscillatory Flow Tunnel (AOFT). Besides the experiments covered in van der Werf et al. (2009), Ahmed and Sato (2003) conducted experiments in the TOFT for various mixes (70:20:10; 50:30:20, 40:30:30 and 20:40:40) of 0.21, 0.49 and 0.74 mm sands. The experiments have majorly focused on sheet-flow sand transport conditions and involved (to a greater or lesser extent depending on the study) measurements of sediment concentrations, velocities, net transport rates, bed cores and grain-size distributions in bed cores, suction samples and sand trap samples. Results include, again depending on the study, detailed sediment dynamics, net total and fractional transport rates and sorting processes.

iv) (Large-scale) wave flume experiments

Oscillatory flow tunnels reproduce the oscillating flow induced by orbital waves at the sediment bed. However, these facilities do not reproduce wave-induced vertical flow velocities and wave-induced net currents, both of which can be important for sediment transport, especially the transport of fine sediments. To account for all wave-induced processes, and to avoid scale effects, experiments need to be carried out in large-scale wave flumes such as the Large Wave Flume (GWK) in Hannover or the Canal d'Investigació i Experimentació Marítima (CIEM) at the Universitat Politècnica de Catalunya (UPC), Barcelona. However, to date, the only experiments in these facilities that have involved sediment mixtures are the beach evolution experiments conducted in the GWK in which the beach consisted of a mix of 0.3 mm sand and 21 mm gravel (e.g. López de San Román-Blanco et al., 2006). At smaller (but still relatively large) scale, beach evolution experiments have been conducted in the large wave flume at Imperial College London (Holmes et al., 1996) involving a 50:50 mixed beach of 1.5 mm and 0.5 mm sands. Like the GWK experiments, measurements were made of the surf-zone hydrodynamics (wave height, undertow), beach evolution and cross-shore sorting of the size fractions. We note that Holmes et al. (1996) mentions experiments involving a flat, bimodal sediment bed under non-breaking waves conducted by Mansell (1992); however, no further information about these experiments could be found in the literature.

3.1.2 HYDRALAB+ experiments on sediment mixtures

The following experiments on sediment mixtures are being, or will be, conducted as part of HYDRALAB+. These experiments will deliver new insights on the behaviour of sediment mixtures under waves and provide additional experience on dealing with practical issues associated with mixed sediment experiments.

i) Large-scale wave flume experiments: GWK Hannover

To date, no large-scale wave flume experiments have been conducted to investigate sheet-flow sediment transport processes and related near-bed hydrodynamics above a horizontal bed. Such experiments, with bimodal sand (D_c = 0.58 mm, D_f = 0.21 mm), will be conducted in the GWK in 2018. A horizontal sand bed (30 m length, 5 m width) will be prepared in the middle section of the flume which has a total length of 307 m. Various sediment mixtures (0% fine:100% coarse; 25:75, 50:50, 75:25, 100:0) will be tested under two regular wave conditions (H = 1 m, T = 7 s; H = 1.5 m, T = 7 s); each condition will be run for 5 x 20 min. The lower wave condition will be used to investigate transport processes in which the coarse fraction is tending to produce ripples while the fine fraction is tending to produce sheet-flow; for the higher wave condition, the transport regime is expected to be sheet-flow for all mixtures. In between the experimental runs with different wave conditions, the bed will be remixed in-situ using paddle mixers. Various high-resolution instrumentation (ABS, ACVP, CCM, SRP) will be used to measure the transport processes and the fractional sand transport rates.

ii) Large-scale wave flume experiments: CIEM Barcelona

Large-scale experiments to investigate mixed sediments under ripple regime conditions have been conducted in the CIEM in Barcelona in 2017. The test bed was horizontal with length 14 m and width 3 m width; the water depth over the bed was 1 m. The study involved three sand beds: (i) a unimodal bed with D_{50} = 0.25 mm, (ii) a layered bed comprising a 13-cm top layer of unimodal coarse sand with D_{50} = 0.55 mm overlying unimodal sand with D_{50} = 0.25 mm and iii) a bed with a homogeneous mix of the two fractions. The ripple formation on the horizontal section was tested under regular waves with T = 5–9 s and H = 0.18–0.40 m; wave conditions were adjusted to force the desired ripple conditions. Acoustic (ADV, ACVP) and optical (OBS) instruments were used to measure the flow velocities and suspended sediment concentrations. Ripples were detected using ARP, BASSI and a mechanical ripple profiler. The data analysis is in progress.

iii) Oscillatory flow tunnel experiments: AOFT Aberdeen

Experiments in the Aberdeen Oscillatory Flow Tunnel (AOFT) aim to investigate the dynamics and transport of sediment mixtures under large-scale oscillatory flows. The experiments involve various mixes of 0.21 and 0.58 mm sands and flow velocities up to 1.5 m/s with period approximately 6 s. The objectives are to determine the transport regime (ripple, transitional, sheet-flow), the dimensions of bedforms and the total and fractional net transport rates for given mixture and flow conditions, and to obtain insights into the underlying processes through detailed measurements of concentrations, velocities and sorting processes. Results from the work will be used to develop practical sediment transport models for sand mixtures, with proper account for sediment mixture effects. The experiments are conducted during 2018.

3.1.3 Key issues to be considered in experiments with sediment mixtures

Depending on the purpose and scope of the study, experiments with mixed sediments need to address some or all of the following practical issues:

(i) Sediment mixing
(ii) Bed laying
(iii) Bed coring
(iv) Particle size analysis
(v) Streamwise sorting
(vi) Measuring water surface elevation
(vii) Measuring sediment concentrations
(viii) Measuring velocities
(ix) Measuring bed morphology
(x) Particle tracking
(xi) Measuring net transport rates, including fractional net transport rates
(xii) Instrumentation deployment

Figure 2: Sand mixture in the Aberdeen Oscillatory Flow Tunnel, University of Aberdeen

3.1.4 Practical guidance

The following guidance is based on previous experience with mixed sediments in flow tunnel and wave flume experimental facilities. As indicated in the literature review, most of the experience comes from flow tunnel experiments, and mostly related to sheet-flow experiments; experience with mixed sediments in wave flumes is still quite limited.

(i) <u>Sediment mixing</u>

Sediment fractions should be rinsed (i.e. cleaned of finer material like silt or clay) when mixed. Mixing in a clean, dry cement mixer is a very effective way to thoroughly mix sediments; however, depending on the grain sizes segregation can occur if the sediment is rotated for too long (Thomas, 2000). Wet sediment is harder to mix, but the addition of water during the mixing process can reduce segregation. Mixing by hand is not recommended, as the degree of mixing is harder to control when mixing manually. For experiments in large-scale laboratory facilities like the GWK, for which vast amounts of sediment (and water) are needed, the entire mixing and bed laying operation requires detailed planning.

(ii) Bed laying

For relatively small wave facilities and large oscillatory flow tunnels, the sediment mixture can be placed in the test section in small quantities under a small depth of water, building the bed up in thin layers. The water ensures that air pockets are avoided. However, the water must be shallow and care must be taken to avoid separation of size fractions by moving water during installation. The bed should be levelled (or profiled) under water. Good practice is to screed the bed, turn it over at least twice with a small shovel, screed once more while slowly turning the sand in front of the screeder by hand with a corkscrew motion. Once a bed is laid, bed cores should be taken and analysed to check for uniform mixing through the depth.

Between experimental runs, or when the bed is deemed to need replenishing, the top layer of sediment should be replaced with newly-mixed sediment. How much needs to be removed will depend on the "active" depth during the run. For sheet-flow conditions for example, for which the active depth is typically less than 2 cm, removal of the top 5 cm may be sufficient. There is no experience of mixed sediments for rippled regime conditions; how much of the bed needs to be replaced between runs will depend on ripple size.

For experiments in very large facilities (GWK, CIEM) heavy machinery (e.g. wheeled front-end loaders or cranes) may be needed to move the mixed sediment into (and out of) the flume. In these facilities the mixture will need to be laid in the dry. The effect of machinery on bed compaction needs to be considered (López de San Román-Blanco et al., 2006). Care needs to be taken when filling the flume to prevent bed disturbance and separation of size fractions. The sediment bed must be given time to settle under the full water column. For their experiments in the GWK, López de San Román-Blanco et al. (2006) noted significant bed settlement following 1 day of filling and 1 day of waiting; the settlement was not measured but was sufficient to expose instruments that had been buried in the dry bed.

(iii) Bed coring

Bed cores are taken to check the constitution of the bed after laying and may be taken after experimental runs to measure bed sorting. For relatively small wave facilities and large oscillatory flow tunnels, bed cores can be extracted using a thin-walled tube. Wright (2002) used an 88 mm-diameter, 160 mm-long thin-walled stainless steel tube. The tubes are inserted while the bed is submerged, leaving 10 – 20 mm of tube protruding above bed level. The thin wall of the tube ensures that sediment disturbance caused by inserting the tubes are confined to the edges of the tube and the protruding tube ensures against disturbances from water flowing over the surface of the cores whilst draining. The water is then drained from the test bed and the cores removed by digging away the surrounding sand. If the sand mixture is fine enough, the core will not fall through the tube when the tube is extracted from the bed; if the mixture is coarse, the lower opening of the tube has to be closed (e.g. using a mesh, a membrane or lamellae) to prevent the loss of the core. The same procedure can be used for large-scale facilities but only when the water depth has been lowered to near-bed level. However, a regular procedure for bed coring under large-water depth in such facilities is not yet established (experience will come from the new HYDRALAB+ experiments); a more sophisticated field-type sampler (e.g. Beeker sediment corer) is one possible option.

To analyse the core, a rig is needed to hold the tube while the core is slowly pushed upwards through the tube, enabling slices of the core to be taken. Wright (2002) describes a core-extraction rig that enables 1 mm-thick slices to be accurately taken from a core.

(iv) Particle size analysis

Particle size analysis is required to establish the size distribution of the constituent sediments of the mix and of the mix itself. This is normally done by standard sieve analysis on dry samples. Size analysis may also be needed for bed core slices, samples of suspended sediments obtained using suction sampling and sediments transported to traps. Depending on the experiment, the volume of sediment transported to traps may be large enough for sieve analysis after oven drying. For small volumes, size analysis can be carried out using settling tubes (Kleinhans, 1998) or a laser-diffraction-based particle size analyser. Note that laser-diffraction PSAs measure the diameter of a sphere of equivalent volume to the sand grain being measured, while a sieve measures the particle's second smallest dimension. This means that sizes measured using the PSA tend to be slightly larger than the corresponding sieve sizes. In addition, some studies have reported that the laser-diffraction method tends to underestimate the fine fraction, especially in widely graded (bimodal) grain-size distributions, when compared to other techniques (e.g. Konert and Vandenberghe, 1997; Pieri et al., 2006).

(v) Streamwise sorting

Selective sediment transport mechanisms occur when a mixed sediment bed is subject to flow. Different size fractions are transported at different rates, and possibly in opposite directions. Unless the test bed is long and horizontal and the flow is uniform, selective transport will lead to a streamwise change in bed composition with time. The sorting will then impact on measurements of, for example, suspended sediment concentration and sediment flux. Experimenters need to be aware of this sorting and account for it in the interpretation of measurements.

(vi) Measuring water surface elevation

Various methods can be used to measure the water surface elevation. These include resistance wave gauges, pressure transducers and acoustic sensors. These instruments do not face any limitations or special considerations when used with mixed sediments.

(vii) Measuring sediment concentrations

Time-averaged suspended sediment concentration can be measured directly using transverse suction sampling. A bonus of the method is that samples can be analysed for sediment size. Guidance on suction sampling under waves and oscillatory flows can be found in Bosman et al. (1987). For mixed sediments, the design of the sampling system will need to consider the largest sediment size likely to be in suspension.

Acoustic (ABS, ACVP, UHCM), optical (OBS) and conductivity-based instrumentation (CCM) can be used to measure intra-wave suspended sediment concentrations. Acoustic/optical instruments are based on acoustic/optical backscatter from particles suspended in the flow, which depends not only on concentration but also on sediment size and mineralogy (Moate and Thorne, 2012; Downing and Beach, 1989). The acoustic/optical inversion therefore requires knowledge of the sediment size in suspension, which ideally comes from suction samples. In the case of mixed sediments, the inversion

may be more complex because of the possibility of different-sized particles being in suspension. Some acoustic instruments work around these issues by using different acoustic frequencies to distinguish the backscatter from different particle sizes and interpret them separately. Acoustic and optical measurements should be validated against suction sample measurements if possible. Note also that acoustic/optical measurements are strongly affected by the presence of air bubbles in the flow.

CCMs are used to measure high concentrations of suspended sand, usually within the sheet-flow layer produced by energetic flow-sediment conditions. The instrument is usually deployed upwards through the sediment bed. Precise vertical positioning is important because of high concentration gradients in the sheet-flow layer (O'Donoghue and Wright, 2004a). Calibration is straightforward: in-situ readings are taken of voltage with the CCM placed within the undisturbed sediment bed and voltage with the CCM in clear water. There are no calibration complications when using the instrument for mixed sediments.

(viii) Measuring velocities

Flow velocities in flume and tunnel experiments are measured using electromagnetic (ECM), acoustic (ADV, ADCP, ACVP, UVP) or optical (LDA, PIV) instruments. For experiments involving mobile sediments, all of these instruments can be used to measure fluid velocities where sediment concentration is very low, but only the acoustic instruments can measure where the sediment concentration is relatively high. In such cases the instrument measures the velocity of the particles (not the fluid, which may be slightly different) based on the Doppler shift in frequency of the emitted and received acoustic signals. No calibration is required for the velocity measurement; there is therefore no particular issue with applying the instruments to mixed sediments. Specifications and capability of acoustic instruments vary; examples of velocity profiles within high-concentration sediments include UVP measurements by O'Donoghue and Wright (2004b) and ACVP measurements by Revil-Baudard et al. (2015) and by van der Zanden et al. (2017). Note that the ACVP (Hurther et al., 2011) combines the advantages of other acoustic instruments to simultaneously measure the 2D flow velocity profile and the sediment concentration profile.

(ix) Measuring bed morphology

Morphology measurements are needed to measure bed profile changes in the case of morphological response experiments and bed profile change for net transport calculation. Techniques include mechanical profilers, 2D/3D lasers and acoustic ripple profilers or echosounders. There are no particular issues or limitations when applied to mixed sediments.

(x) Particle tracking

Particle tracking can be of particular interest in experiments involving mixed sediments as different grain sizes tend to sort streamwise (see v) and vertically under flow or wave action. Tracking individual size fractions and individual particles may help understand the transport paths of grain sizes in a mixture. Natural or artificial sediments can be coated with a fluorescent coating to distinguish them from other sediments in the bed. The coating can also be made para-magnetic to facilitate separation of the coated particles from a volume of sand (Black et al., 2007). Coating particles can be done using a concrete mixer. The coating process slightly changes grain size and density, which needs to be considered in the experimental design and interpretation of the results.

(xi) Measuring net transport rate, including fractional net transport rates

Net transport rate for mobile sediments in wave flume and tunnel experiments is measured by applying mass conservation to the measured masses of sediment collected from the two ends of the test section and the measured pre-test and post-test bed morphologies (e.g. Dohmen-Janssen, 1999). In the case of mixed sediments, fractional transport rates can be estimated based on a size analysis of the sediments collected in the traps (Wright, 2002). In principle, net total and fractional transport rates can be determined from combined concentration and velocity measurements through the water column, but such measurements may be difficult to realise over the full water column for reasons given in (vii) and (viii).

(xii) Instrumentation deployment

As for experiments with sediments generally, instrumentation used for mixed sediment experiments needs to be carefully positioned relative to boundaries and relative to other instruments to optimise performance and limit interference with the flow and sediment bed response. Experiments need to include means by which the exact vertical position of a measurement can be determined in the post processing, knowing that the bed level changes.

3.2 EXPERIMENTS WITH VEGETATION

3.2.1 Previous experiments with vegetation

Denny (1988) and Vogel (1994) are two main seminal works in the area of flow-biota interactions. Comprehensive reviews focused on vegetated channels at a range of spatial scales are provided by Folkard (2011a) and Nepf (2012). In the following a concise overview of the literature concerning experimental studies, organised according to the spatial scale of investigation is provided.

i) Leaf/blade scale experiments

Most studies at this scale have focused on marine vegetation (i.e. seaweeds or seagrass), because the size of leaves/blades make it possible to investigate the fundamental mechanisms controlling vegetation growth and survival at such a small scale. Koch (1994) studied the nutrient uptake and photosynthetic activity of blades from two seagrass species at a range of flow velocities in a microcosm, concluding that shear velocity on the blade affects seagrass productivity. A number of studies were conducted on seaweed blades to estimate the thickness of the diffusive boundary layer (DBL) (e.g. Stevens and Hurd, 1997; Hurd and Pilditch, 2011), which is a primary factor in mass transfer to and from leaves/blades. These experiments were performed at low flow velocities to prevent seaweed motion and allow measurements on the blade surface. Huang et al. (2011) further investigated mass transfer on seaweed blades considering DBL renewal associated with blade motion. Physical models of vegetation with a range of mechanical and morphological characteristics were used in studies performed in flume facilities to explore the hydrodynamic performance of vegetation: Rominger and Nepf (2014) measured the mean drag force experienced by a seaweed blade model and estimated the mass transfer across its DBL; Albayrak et al. (2012) investigated drag and motion of a range of leaf models; Vettori and Nikora (in press) explored drag and motion of seaweed blade models and their effects on the flow characteristics. An experimental study at several spatial scales was conducted by Albayrak et al. (2014) on leaves, stems and shoots of *Glyceria fluitans*, focusing on hydrodynamic performance.

ii) Organism scale experiments

Experimental studies at an organism scale have been conducted on both freshwater vegetation (e.g. Usherwood et al., 1997; Sand-Jensen, 2003) and marine vegetation (e.g. Boller and Carrington, 2006). The main focus of these studies has been on the mean drag force exerted by the flow on an organism (e.g. Schutten and Davy, 2000), either considering the mechanical properties of vegetation (e.g. Usherwood et al., 1997; Biehle et al., 1998) or accounting for its motion/reconfiguration (e.g. Sand-Jensen, 2003; Boller and Carrington, 2006). Interspecific comparison of hydrodynamic performance of vegetation was carried out by Boller and Carrington (2007) for seaweeds, and Bal et al. (2011), Puijalon et al. (2011) and Siniscalchi and Nikora (2012, 2013) for freshwater macrophytes. Additionally, Bal et al. (2011) estimated plant surface area exposed to light, and Siniscalchi and Nikora (2013) introduced the concept of dynamic reconfiguration as a means of drag reduction in vegetation. Several studies have focused on the drag force experienced by an organism within a patch, either for freshwater macrophytes (e.g. Plew et al., 2008), riparian trees (e.g. Armanini et al., 2005), or physical models of plants (e.g. Wilson et al., 2003) and seaweeds (e.g. Johnson, 2001). Physical models of seaweeds were also used by Stewart (2006) to investigate the effect of flexural rigidity and mass density on the hydraulic performance of a red alga (a type of seaweed). Wilson et al. (2008) found that foliage has a considerable contribution to the drag force experienced by branches of pine and stipes of ivy.

iii) Patch scale experiments

Fewer experiments have been conducted at a patch scale compared to smaller scale experiments. Riparian vegetation has been studied by Järvelä (2002), using willows and sedges to quantify flow resistance in a vegetated channel, and Righetti (2008), who explored the drag force exerted by the flow on willows and the vertical distribution of flow characteristics within a patch. The flow resistance of vegetated channels was also explored using wheat plants grown in containers located in a flume facility (Järvelä, 2005). Other researchers used artificial vegetation for studying the effects of a vegetation patch on flow characteristics. For example, Wilson et al. (2003) designed and manufactured physical models of seaweeds (i.e. stipe and blade) and explored how flow characteristics were affected by the presence of blades on the models. Siniscalchi et al. (2012) used artificial plants and studied the drag force experienced by multiple plants within a patch and the effect of vegetation on turbulence within the patch and downstream of it. Additionally, a series of studies by Thomas et al. (2000), Thomas and Cornelisen (2003) and Weitzman et al. (2013) are worth highlighting since the authors use a 'field flume' for exploring the effects of flow conditions on nutrient uptake of seagrass in a patch in-situ.

iv) Reach scale experiments

Nepf and Ghisalberti (2008) provide a comprehensive review of recent works at this spatial scale. The first studies on vegetation at canopy scale were conducted by Kouwen et al. (1969) and Kouwen and Unny (1973) who aimed to incorporate the vegetation flexibility into the roughness parameters typically used to estimate hydraulic conditions in open channels. In recent years, a number of authors have explored the flow characteristics either in emergent arrays of cylinders (e.g. Nepf, 1999) or in fully submerged canopies made of artificial vegetation (e.g. Nepf and Vivoni, 2000; Nezu and Sanjou, 2008; Nikora et al., 2013) or live plants (e.g. Carollo et al., 2005). The majority of these studies were conducted with a single canopy with uniform vegetation density at uniform flow conditions. Exceptions are represented by the works described in Folkard (2005, 2011b), who

explored the characteristics of the flow between patches of artificial seagrass, and Maza et al. (2015), who studied flow attenuation caused by a canopy of live saltmarsh plants, considering both current and waves. Further, some laboratory work has been carried out to explore the effects of riparian vegetation on the geomorphology of braided rivers by using alfalfa plants (Gran and Paola, 2001; Tal and Paola, 2007, 2010) or a mixture of bedding plants (Coulthard, 2005).

Figure 3: 10-day old alfalfa on sand bed in the Total Environment Simulator, University of Hull

3.2.2 HYDRALAB+ experiments on vegetation

The following experiments using vegetation have been, or will be, conducted as part of HYDRALAB+.

i) Organism scale experiments: Loughborough University

Two sets of experiments are carried out at Loughborough University: (a) mesocosm experiments to explore the effect of abiotic factors on plant health status and biomechanical properties; and (b) flume experiments to study the effect of selected environmental conditions on plant hydrodynamic performance and the effect of flow conditions on plant health status. Mesocosm experiments have been conducted in summer 2017 using three freshwater macrophyte species (*Potamogeton crispus*, *Callitriche stagnalis* and *Myriophyllum verticillatum*). Plants were exposed for five days to a range of environmental conditions (light irradiance, water temperature and water quality) typical of hydraulic laboratories. The health status of plants was monitored daily using a chlorophyll fluorometer. At the end of the experiments, plant biomechanical properties were measured by uniaxial tensile tests and three-point flexural tests. Further mesocosm experiments with *Potamogeton crispus* and seagrass species *Zostera marina* are planned for 2018. Flume experiments will also be conducted in 2018 with plants of *Potamogeton crispus*, the objectives being to determine the effect of flow conditions and abiotic stressors on plant health and hydrodynamic performance during laboratory experiments. Results from the work will be used to develop practical guidelines for the use of live vegetation in flume facilities, with proper consideration to vegetation behavioural integrity.

ii) Canopy-scale wave flume experiments using surrogate vegetation: Hull and Aberdeen University

Experiments on the effects of vegetation flexibility and density on wave hydrodynamics have been conducted in the Aberdeen University Random Wave Flume (20m long, 0.45m wide, 0.7m water depth). Surface waves, subsurface velocities and turbulence were measured for a range of vegetation blade flexibilities, canopy densities and wave conditions. The surrogate vegetation

comprised four 4mm-wide Polypropylene strips attached to a rigid PVC dowel inserted into a prefabricated 7.5 m-long baseboard. Eight surrogate vegetation canopies were tested, comprising four blade flexibilities (semi-rigid, low-flexibility, medium-flexibility, high-flexibility) and two canopy densities (142 and 566 shoots/m^2). Measurements were made for three regular wave conditions (T=1.6s, H=0.19m; T=1.6s, H=0.095m; T=1.1s, H=0.19m). Velocity measurements were made using two component LDA. The data will be used to understand velocities and turbulence within vegetation under wave conditions.

iii) Reach-scale flume experiments: University of Hull

Preliminary experiments were undertaken to understand the behaviour of surrogate vegetation used in reach-scale flume environments. These experiments attempted to mimic bank erosion in riverine environments at a small-scale. A 60 cm^3 block of sand was positioned at an angle to a steady flow and eroded over a period time. Alfalfa *(Medicago Sativa)*, a fast-growing vegetation commonly used in experiments as a surrogate for riparian vegetation (e.g. Gran and Paola, 2001) was seeded on the block of sediment. Two different seeding densities and three different growth periods were used as a proxy for vegetation density and age. The outcome of these experiments show that vegetation age has a greater impact on erosion rates than vegetation density, despite both reducing the rate of erosion.

Experiments were undertaken in the Total Environment Simulator (TES) at the University of Hull to characterise the response of vegetated braided rivers to flood sequence. The geometry of the experimental rivers (10m long, 2.5m wide) and their hydraulic parameters were selected to reproduce the morphodynamic processes that characterise a typical gravel-bed braided stream, using Froude scaling. During the experiments, once an equilibrium constant discharge and constant bed load is reached, the braided bed is subjected to a flood sequence that includes a combination of small and large floods in different sequences. Alfalfa vegetation was seeded in the flume and subjected to the same flood sequences. Four different growth periods for the alfalfa were investigated to understand the relative effect of vegetation of vegetation age (and therefore increased resistance to erosion) relative to the geomorphic impact of flood events. Laser scanning and digital photography have been used to quantify the development of channel morphology under different hydrodynamic and vegetation growth conditions.

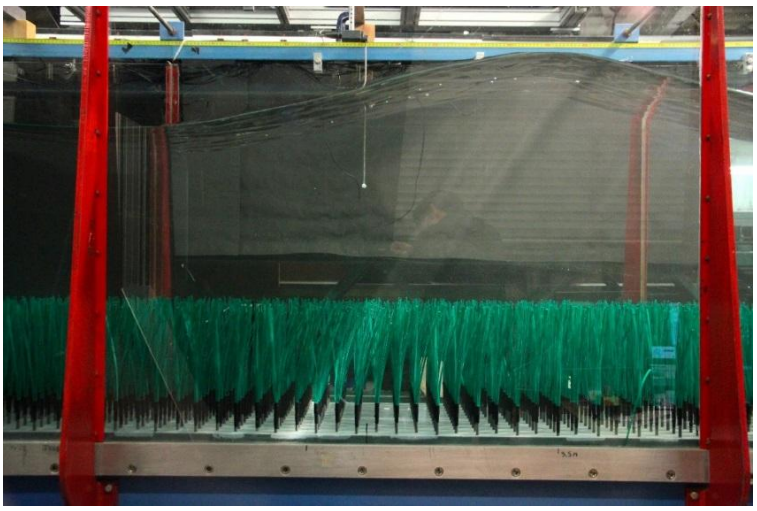

Figure 4: Surrogate seagrass under waves in the Aberdeen Random Wave Flume

3.2.3 Key issues to be considered for experiments with vegetation

Depending on the particular purpose and scope of the study, experiments with vegetation (live or artificial) need to address some or all of the following practical issues:

(i) Vegetation husbandry
(ii) Assessing vegetation metabolic activity
(iii) Characterising vegetation biomechanical properties
(iv) Installing and/or representing vegetation in flumes
(v) Down-scaling
(vi) Measuring flow velocities
(vii) Measuring water surface level
(viii) Measuring drag force exerted on vegetation
(ix) Monitoring vegetation reconfiguration
(x) Measuring nutrients and light availability

3.2.4 Practical guidance

The following practical guidance is based on previous experience using vegetation in flume and wave facilities.

(i) <u>Vegetation husbandry</u>

Husbandry of vegetation to be used in laboratory experiments is a particularly complicated issue to address, because optimal conditions for vegetation are species dependent. Additionally, vegetation can adapt to environmental conditions to which it is exposed, and its morphological and mechanical characteristics vary depending on these environmental conditions. To supply vegetation with sufficient light irradiance for its photosynthetic activity, vegetation should be exposed to natural light conditions, or fluorescent lights designed for plants grow should be used. Vegetation also needs a range of nutrients (e.g. CO_2, NO_2^-, PO_4^{3-}) readily available either in the substrate (for terrestrial vegetation) or in the water (for most aquatic vegetation). As a rule of thumb vegetation is generally resistant to temperature variations typically found in flume facilities, but this does not apply to tropical species and seagrass. Depending on the scope of a study, if vegetation is grown in an environment with conditions considerably different from those to which it is exposed during experiments, the experimenter should consider that vegetation performance will likely be affected by the change of environmental conditions. In such instances it is advisable to use the vegetation as soon as possible after it has been removed from its growing site. Lara et al. (2016) provides some comprehensive guidelines on husbandry of vegetation to be used in hydraulic experiments.

(ii) <u>Assessing vegetation metabolic activity</u>

Assessing metabolic activity provides indirect information on the health status, and light and nutrients uptake by vegetation. Metabolic activity can be assessed using chlorophyll content meters, chlorophyll fluorometers, or measuring gas exchange on a leaf/organism. These systems are non-destructive and non-invasive. Gas exchange systems are complex to use in flume facilities, because they are closed systems. Small sensors such as microoptode or electrodes that can measure the concentration of dissolved gases locally on the surface of leaves or blades are valid alternatives to gas exchange systems (e.g. Hurd and Pilditch, 2011). Chlorophyll content meters and chlorophyll fluorometers have broader applications: the first measure the amount of chlorophyll present in a sampling area (of a leaf or blade); the second provides an indirect measurement of the luminous

power absorbed by chlorophyll pigments in a sampling area to power photosynthesis. Chlorophyll fluorescence analysis has been found to be quite accurate at detecting vegetation stress caused by a range of abiotic factors. Excellent reviews of this technique are available in the literature (e.g. Baker, 2008; Murchie and Lawson, 2013).

(iii) Characterising vegetation biomechanical properties

Data on vegetation biomechanical properties are quite limited (especially for aquatic vegetation). Vegetation biomechanical properties are investigated using standard mechanical tests developed in mechanical and materials engineering. Methods developed for testing the mechanical properties of textiles have been found to work well enough for vegetation with low rigidity (e.g. Peirce, 1930). Standard tests require a benchtop testing machine or instrumentation with equivalent purpose (i.e. extensometer and load cell/dynamometer) to measure the deformation of a specimen under applied load. The most common tests are uniaxial tensile tests, flexural tests and torsional tests. The mechanical properties (e.g. Young's moduli) are determined from the applied load, measured deformations and the specimen geometry (e.g. Niklas, 1992).

(iv) Installing and/or representing vegetation in flumes

Vegetation can be installed/positioned in a flume facility in a number of ways depending on the scope of the study. If the drag force exerted by the flow on an organism is to be measured, the organism needs to be attached directly or indirectly to a drag sensor. This usually requires the organism being uprooted or cut in order to be attached to the sensor. In terms of vertical positioning, the organism is often located on the flume bed, but it can also be suspended in the water column when other setups are investigated. Vegetation is usually located in the central part of the facility where flow uniformity is achieved. If the facility allows it, vegetation can be moved into a flume together with the substrate in which it has grown (e.g. Lara et al., 2016). When investigating flow-vegetation interactions, instrumentation needs to be deployed strategically in such a way that instruments do not interfere with each other or with the vegetation dynamics, and the vegetation does not hinder measurement. Measurements of flow velocities close to vegetation require accurate positioning of instrumentation and consideration of the vegetation motion, as vegetation can obscure line-of-sight and interfere with sampling volumes. To investigate the reconfiguration (i.e. posture and motion) of vegetation, cameras can be used to measure the vegetation movement.

Vegetation can be represented using surrogates or mimics. The geometric and mechanical parameters of surrogate vegetation can be informed and dynamically scaled with respect to data from natural examples. Developing surrogate models with identical biomechanical properties to their natural prototypes is challenging. The focus should be on reproducing the dynamic behaviour of natural vegetation. For example, Ghisalberti and Nepf (2002) proposed biomechanical scaling methods which quantify the ratio of buoyancy to rigidity force of the blades ($\lambda_1 = \frac{(\rho_w - \rho_s)h^3}{Et^2}$) and the ratio of drag to rigidity force ($\lambda_2 = \frac{Et^3}{h^3 {U_c}^2}$), where ρ_w is water density, ρ_s is blade density, h is blade length, E is blade Young's Modulus, t is blade thickness and U_c is mean in-canopy velocity. Emphasis is often placed on λ_1 when calculating appropriate properties of the surrogate vegetation, due to the large variability in mean flow velocity in nature, a large influencing factor of λ_2. The development of appropriate surrogates requires a good understanding of the plant biomechanical properties and therefore requires field data collection prior to the main experiments. Johnson et al.

(2014) give examples of studies that use surrogates, but there are few studies that detail the surrogate design process, particularly for complex aquatic plants (e.g. Paul and Henry 2014).

(v) Down-scaling

Scaling is essential for replicating natural scenarios in a laboratory environment and, bearing in mind case-specific limitations, should be based on dimensional analysis so that all significant processes/phenomena are scaled correctly. Nikora (2010) provides an overview of the most important forces for maintaining dynamic similitude when investigating flow-vegetation interactions. Use of artificial surrogate vegetation is advantageous when biological processes concerning vegetation are not relevant to the study. However, this approach is likely to be limited to fixed flow conditions since real plants adapt to the imposed flow (e.g. Graba et al., 2013) and surrogates usually have fixed properties. This may present significant issues since the morphology and mechanics of aquatic plants can vary seasonally.

A key scaling issue identified in Baynes et al. (in press) is that timescales associated with vegetation growth in the field are considerably longer than the timescales normally considered in laboratory hydrodynamic or morphodynamic experiments. Therefore, when vegetation forcing (i.e. plant growth or decay) needs to be modelled on the timescale of an experiment, it may only be practical to use living surrogates at smaller scale (e.g. Gran and Paola, 2001). In this case, down-scaling is not straightforward since maintaining all similitudes is often impracticable (e.g. Froude and Reynolds similarities). For this reason, the design of a scaled model is to be addressed on a case-by-case basis, considering the main factors driving the phenomena and processes of interest in the prototype. In fact, rigorous dimensional analysis can seldom be applied to a model replicating flow-vegetation interactions, particularly when sediment transport processes are also investigated. Therefore, a trial and error approach is often used in practical situations.

(vi) Measuring flow velocities

Similar to other areas of complexity, flow velocities in experiments with vegetation are measured using acoustic (ADV, ADCP, UVP) or optical (LDA, PIV) instruments. The characteristics of both types of instrument should be taken into account when designing and conducting experiments. Acoustic instruments do not require calibration; the position of the sampling volume needs to be carefully selected to minimise the chance of the vegetation hindering measurement. Optical instruments are generally located outside the facility, with line-of-sight enabled by transparent side-walls. Again, measurement volume positioning needs to take account of vegetation reconfiguration under flow. Since vegetation is comprised of three-dimensional dynamic objects, instruments such as PIV and ADCP that can measure flow velocities at multiple locations simultaneously are advantageous to study flow-vegetation interactions. This is particularly relevant when focusing on the turbulence generated by flow-vegetation interactions at a range of spatial scales (e.g. from leaf scale to canopy scale). Additionally, the duration of the measurements should be set to ensure convergence of the turbulence statistics. Examples of studies that involve detailed velocity measurements in the presence of vegetation include Folkard (2005), Plew et al. (2008) and Siniscalchi et al. (2012).

(vii) Measuring water surface level

As for other areas of complexity, water surface level can be measured using a range of methods, including pressure transducers and acoustic sensors.

(viii) Measuring drag force exerted on vegetation

The drag force exerted by the flow on vegetation can be measured using spring balances or drag sensors with strain gauges. Spring balances were widely employed in the first studies of flow-vegetation interactions (e.g. Schutten and Davy, 2000). They measure the mean drag force on vegetation. Use of more sophisticated sensors such as drag sensors with strain gauges as main components allows drag force measurement at high frequency. Instruments used to measure the drag force require calibration and need to be selected based on their accuracy, resolution and maximum load applicable. This aspect is crucial in experimental design and setup, because strain gauges are very sensitive and can break easily if subjected to forces exceeding their maximum load. Measurements with strain gauges can be affected by external noise such as mechanical vibrations of the facility. The effect of external noise on the mean drag is usually negligible, but it can heavily bias drag fluctuations, therefore requiring the application of digital filters during post-processing. Also, it is of some relevance to note that the total drag force acting on an object is not the sum of the drag forces independently acting on its components (i.e. the system is not linear). Examples of studies that involve force measurements on vegetation include Usherwood et al. (1997), Albayrak et al. (2014), and Vettori and Nikora (2017).

(ix) Measuring vegetation reconfiguration

Vegetation reconfiguration (both posture and motion) can be measured using image analysis applied to photographs or video records. Corrections need to be applied to images taken with cameras with distorted lenses, or when the interrogation window does not lie in a plane parallel to the (projected) surface area of interest. The light setup is of primary importance for monitoring reconfiguration, as increasing the contrast between the background and vegetation facilitates image processing. In cases in which not enough contrast is available, bright objects may be attached to selected parts of the vegetation. Standard HD cameras can be used for monitoring vegetation reconfiguration, they can either be positioned on the side of a flume, to have a side-view of the vegetation, or on the flume bed upstream of vegetation, to extract vegetation projected surface area against the incoming flow. These methods allow tracking vegetation projection in two-dimensional planes. Current technological limitations constrain the ability to monitor reconfiguration in three-dimensional space. Examples of studies that involve reconfiguration measurements include Sand-Jensen (2003), Huang et al. (2011) and Siniscalchi and Nikora (2013).

(x) Measuring nutrients and light availability

Light availability can be measured using PAR (photosynthetically-active radiation) sensors, which measure the light irradiance in the ranges of the light spectrum absorbed by vegetation for photosynthesis. These sensors do not require calibration and can detect light irradiance in a limited solid angle which depends on the model characteristics. A number of instruments can be used to measure concentration of nutrients in a water sample collected from a facility. Total organic carbon analysers can measure the concentration of organic carbon available for vegetation photosynthesis. Ion-chromatographs and automated analysers can measure the concentration of a variety of ions important for vegetation metabolic activity. Examples of studies that have involved measurements of these kinds include Koch (1994), Thomas et al. (2000) and Weitzman et al. (2013).

Figure 5: HYDRALAB+ experiments in the Total Environment Simulator, University of Hull: vegetated braided stream during and after flood event

3.3 EXPERIMENTS WITH BIOFILMS

Biofilms growing on river bed or coastal sediments may affect sediment stability considerably, but these biostabilisation effects are currently not well understood due to their complex interactions with the surrounding environment (Gerbersdorf and Wieprecht, 2015; Grabowski et al., 2011). This lack of knowledge hinders understanding of the effects of climate change and the development of adaptive strategies, even though an impact of climate change on biofilms is evident (Romaní et al., 2014; Villanueva et al., 2011; Butterwick et al., 2004).

3.3.1 Previous experimental studies on biofilms

i) Experiments with natural biofilms

Most current knowledge on the potential of natural biofilms to impact sediment mobility comes either from field studies (e.g. Amos et al., 2004, Widdows et al., 2000), straight flume experiments under unidirectional flow (Thom et al. 2015a; Vignaga et al., 2013; Graba et al., 2010) or mesocosm experiments (Chen et al. 2017; Tolhurst et al. 2002, Thomsen & Gust, 2000).

Straight flumes are amongst the most widely used flumes for biofilm cultivation. Some flumes have been purposely constructed for investigations on biostabilisation (e.g. Thom et al., 2015a; Vignaga, 2012: “Ervine flume”; Singer et al., 2006). Other studies have modified existing flumes for that purpose (e.g. Vignaga, 2012: “Yalin flume”; Graba et al., 2010). Physical experiments on biostabilisation in wave-dominated environments are rare (Droppo et al., 2007).

Other studies have used samples from the field and transported them to the laboratory. Larned et al. (2004) immersed acrylic plates in a river, which were later placed in large aerated tanks prior to measurements. One of the biggest challenges investigating the impact of biofilms is that they quickly adapt and interact in complex ways to their environmental conditions. To study natural biofilm behaviour in a flume setting with a certain degree of similarity to natural “field” biofilms, requires environmental flumes in which external impacts such as light intensity and duration, water temperature and nutrient supply can be controlled (Rice et al. 2010; Jonsson et al., 2006). Only a few experimental facilities in hydraulic engineering are currently equipped with such controls. An example is the Total Environment Simulator, University of Hull, which has been (and is) used for experiments on biostabilisation. Against this background, mesocosm experiments are a valuable

alternative to straight flumes due to their comparably small dimensions. Round-shaped mesocosms (sometimes called microcosms) such as the Gust chamber (Thomsen and Gust, 2000) are benthic chambers with rotating paddles or a rotating disc (Chen et al., 2017) and may be equipped with additional instrumentation (e.g. turbidity meter for quantification of eroded sediment).

ii) Experiments with surrogate biofilms

Using surrogates to study natural biostabilisation effects is currently on the agenda of HYDRALAB+. Surrogates may have some advantages over natural biofilms: they do not require time to grow, which means experiments can be speeded up and long term effects could (hypothetically at least) be modelled; and their mechanical properties can potentially be designed for different research needs.

A number of studies in the early 2000s used surrogates (e.g. Tolhurst et al., 2002; Black et al., 2001). The studies have mainly used Xanthan gum, which is a rheology modifier produced by the bacteria *Xanthomonas campestris*. Tolhurst et al. (2002) investigated the stability (erosion threshold and erosion rate) of Xanthan gum at different concentrations using a Cohesive Strength Meter (CSM). They found that stability increased with Xanthan gum concentration, a result supported by Black et al. (2001). Additionally, Tolhurst et al. (2002) compared their results to in-situ measurements on biofilms that contained an equivalent quantity of EPS (extracellular polymeric substance) and found that the artificial Xanthan gum-sediment mixture was approximately half as stable as their natural counterparts. They hypothesised that the reasons for this difference are related to a) the quality (proteins and lipids) of the Xanthan and b) the different characteristics of natural EPS as secreted by organisms.

Bedform development under cohesive effects (Malarkey et al. 2015; Schindler et al., 2015; Parsons et al., 2016) has been studied in the TES. For that purpose, different types of substrata were prepared representing physically cohesive and combined physically and biologically cohesive sediments. The substrata were placed in the flume and subjected to high flow velocities. The bed topography was monitored to determine morphological changes. Large-scale morphodynamics have also been studied by mixing surrogate EPS in analogue-reach scale models, and were shown to be successful in demonstrating the effects of biological cohesion (Hoyal and Sheets 2009; Kleinhans et al., 2014). For example, Kleinhans et al. (2014) summarizes the effects of adding PHPA (a synthetic polymer) to study delta morphology.

Figure 6: Side-view photograph of biofilm grown on glass beads, University of Stuttgart; maximum thickness of EPS layer is ~5mm

3.3.2 HYDRALAB+ experiments on biofilms

The following experiments on biofilms have been conducted as part of HYDRALAB+, aimed at gaining new insights into the behaviour of biofilm-induced stabilisation and providing valuable experience on dealing with practical issues associated with working with biofilms.

i) Erosion threshold of natural bio-sediment: University of Hull (Total Environment Simulator)

The TES was divided into nine channels of length 9.0 m and width 0.48 m. Each channel contained a sediment bed with thickness 0.1 m. Different sediments were used (0.11 mm, 1.0 mm, 50/50 mix). Brackish water (~30 grams of salt per litre) was recirculated at flow velocities in the range 0.1 – 0.5m/s and appropriate illumination was set with the help of grow lamps (12/12 day/night cycle). As an inoculum, waste water from the local aquarium was added and additionally rocks (with biofilm) sampled from the Humber estuary were placed in the flumes. The biofilm was allowed to grow for seven weeks. After a consolidation phase of two weeks samples were taken for biological analysis (EPS content) and CSM measurements were made to determine the stability of the biofilm-sediment matrix (van de Lageweg et al., 2017).

ii) Erosion threshold of surrogate bio-sediment: University of Hull

The sediment entrainment threshold and erosion behaviour of four different types of synthetic EPS were tested: a control test without EPS and four tests with increasing EPS content (1.25 g, 2.5 g, 5 g and 10 g per kg of sediment (0.1mm). The sand-EPS mixture was poured into plastic Petri dishes (5 cm diameter, thickness of the mix = 1cm). Two mixing procedures (referred to as “wet” and “dry mixing”) were applied and, additionally, the effect of different conditions commonly found in hydraulic laboratories was examined by varying water temperature, pH and salinity. Finally, CSM measurements were conducted to quantify the biostabilisation effects and assess the sensitivity of the biostabilisation effects to a) the preparation procedure, b) the time after application and c) environmental factors (Lageweg et al., 2017).

iii) Adhesion of surrogate bio-sediment EPS: LUH

A novel technique (MagPI-IP, see Thom et al., 2015b) is used to determine the stickiness (adhesion) of the surrogate EPS, with the aim of comparing it with the stickiness of natural biofilm from previous experiments. Determination of stickiness is useful for more detailed studies on biostabilisation. Four different mixtures were produced with varying ratios of EPS powder to water.

iv) Erosion of surrogate bio-sediment: erosion flume, LUH

Erosion experiments with surrogate EPS/sand mixtures were conducted in a small tilting flume. Different adhesive surrogates (Xanthan gum) were added at different EPS/sediment ratios to sand (~0.6 mm). The slope of the tilting flume was increased incrementally and the erosion threshold and mechanism of failure were monitored. Comparisons have been made between the failure mechanisms of surrogate EPS and natural biofilms.

Figure 7: Biofilm sampling in the field

3.3.3 Key issues to be considered for experiments with biofilms

Depending on the purpose and scope of the study, experiments with biofilms need to address some or all of the following practical issues:

(i) Temperature
(ii) Light regime
(iii) Salinity
(iv) Inoculation and nutrients
(v) Sediment selection
(vi) Preparation of surrogate EPS
(vii) Measuring erosion threshold

More complex biological analysis (Chl a, EPS compounds, diversity, determination of microbial community composition etc.) should ideally be part of biostabilisation experiments, especially when natural conditions are need to be replicated (Gerbersdorf and Wieprecht, 2015, and references therein). However, such analysis is not within the scope of the guidelines presented here. In addition, the guidelines do not cover determination of biofilm material properties (adhesion, cohesion, viscosity). The reader is referred to Böl et al. (2013), Grabowski et al. (2011), Guelon et al. (2011), Thom et al. (2015), Vignaga et al. (2012) and Boulêtreau et al. (2011) for details relating to material properties.

3.3.4 Practical guidance

The following guidelines for conducting physical experiments with biofilms are based on a literature review and experience from experiments conducted during the course of the HYDRALAB+ project. The guidelines are intended for those who want to study biostabilisation in the laboratory, either to replicate natural biofilm behaviour or for fundamental investigations on biostabilisation.

As environmental conditions strongly influence the growth and stabilisation potential of biofilms, and these conditions can be significantly different depending on the investigated site, the season, water chemistry, biotic interactions and many more, it is impossible to recommend specific values of e.g. temperature, light intensity to be set for biofilm cultivation. Instead the current guidelines point at the most important aspects to be considered when conducting experiments with biofilms and their practical implementation in physical experiments. References and typical values of environmental parameters are given to help the reader design their own experimental setup.

(i) Temperature

Controlling water temperature is vital for biofilm cultivation. Heating of water circulated in flumes is likely, due to the performance demands of the pumps over several weeks. Heat exchangers supplied with cold water can be used to control the water temperature (see e.g. Thom et al., 2015a). Another possibility to control the temperature is to place the flumes in an air-conditioned room (Singer et al., 2006) or to partly replace the water directly from a nearby river (Graba et al., 2010). Temperature should ideally correspond to values measured in the field.

(ii) Light regime

Flumes can be equipped with fluorescent tubes (e.g. OSRAM Biolux®: Thom et al., 2015a), hot-wire spot lights and LEDs (Vignaga, 2012) or neon tubes (Graba et al., 2010). To modify light intensities in an easy way, the illumination source should be adjustable in height. It should be ensured that the light intensities on the biofilm surface are homogeneous; heterogeneities could result in spots of extreme or absent growth (Vignaga, 2012). Light intensities should be set within a range of approximately 0 – 100 µmold/m²s, depending on the environmental regimes to be investigated (e.g. very turbid systems, shallow waters, etc.). Light intensity in the PAR range (400 – 700 nm) can be measured underwater on the sediment surface using a radiometer (e.g. LICOR LI-192 Underwater Quantum Sensor). Typical values for the duration of the day/night cycle are 8/16 and 12/12.

(iii) Salinity

Most knowledge on biostabilisation comes from the marine environment, where biostabilisation effects are believed to be more important than in freshwater environments. The abundance of cations in saltwater may be responsible for the seemingly higher potential for biostabilisation of sediments (Gerbersdorf and Wieprecht, 2015). However, recent physical experiments on biofilms cultivated in riverine freshwater systems indicate an equivalently high biostabilisation effect (Thom et al., 2015a; Gerbersdorf et al., 2009). To ensure relevant results, the salinity of the system should correspond to the salinity in the field. For example, Parsons et al. (2016) set the salinity similar to estuarine conditions by adding sodium chloride (16 psu).

(iv) Inoculation and nutrients

Often natural river water is used as an inoculum (e.g. Thom et al., 2015a; Graba et al., 2013). Normally this water contains enough cells for the initial formation of biofilms and may even contain enough nutrients (depending on the volume of circulated water and the duration of the experiments). To obtain nearly constant nutrient conditions, Graba et al. (2013) replaced their water directly from the Garonne River every four hours. A similar approach was used by Singer et al. (2006). However, this procedure may require filtering to avoid contamination with larger organisms (e.g. insect larvae) and suspended matter. To ensure sufficient nutrient supply, some studies have added nutrient solutions to the recirculated water. For example, Vignaga et al. (2012) mixed in a commercially-available solution (BG11). Sediment samples from a natural stream can serve as an inoculum (Mendoza-Lera et al., 2015), as they contain enough cells for a biofilm to start growing.

(v) Sediment selection

The selection of the sediment substrate for biofilm cultivation is critical for the erosion threshold of a biofilm-sediment matrix. Natural substrate (e.g. from a river or estuary) typically has a high

content of organic matter, nutrients and associated microbes, which are favourable for biofilm growth. However, the disadvantage is that these constituents need to be analysed to determine their impact on the biofilm growth. To relate these additional parameters to biostabilisation effects is especially difficult if experimental conditions need to be reproduced in a later experiment (e.g. to study the influence of seasonality). A useful approach to circumvent this is to use artificial, inert sediment such as glass beads.

The size of the sediment is crucial for erosion studies. With either too large or too small sediment, the biostabilisation effect might not be relevant. Lick et al. (2004) analysed the initiation of movement of different size quartz particles with added bentonite (to mimic cohesion/adhesion effects) and reported that the major increase of critical bed shear stress occurred for particles in the size range 0.1-0.4 mm. In a further study, Fang et al. (2014) found that for sizes between 0.01 mm and 0.2 mm, adhesive and cohesive forces dominate over weight and electrostatic forces. However, HYDRALAB+ experiments have demonstrated significant effect of biofilm on sediment stability for grain sizes up to 0.71 mm.

(vi) Preparation of surrogate EPS

The HYDRALAB+ studies on surrogate EPS demonstrated a good similarity between the mimics and natural biofilms in terms of biostabilisation effect and erosion behaviour, and may therefore be used in future research on, for example, predicting the impact of climate change on biostabilised sediments and morphology. Four different surrogate materials, which are commercially available and relatively inexpensive, have been tested. These studies showed that some surrogates are more suitable than others and care has to be taken in surrogate preparation and setup, because of the impact of water chemistry (pH, salinity), temperature and experiment duration (due to winnowing of the EPS, see van de Lageweg et al., 2017). Generally, Xanthan gum has proved to be a good candidate as a surrogate for biostabilisation experiments as its induced stability behaves in a linear and predictable fashion. Furthermore, if mixed correctly, values of critical erosion threshold and adhesion are in the range of values reported in the literature. Still, care has to be taken as Xanthan gum provided by different suppliers might have different material properties.

The surrogate is prepared as follows. Depending on the desired stability and erosion behaviour, Xanthan gum powder is mixed with water (e.g. 0.15 – 2.0 weight-%) at room temperature using a stirring blender or magnetic stirrer. The duration of mixing should be long enough to produce a homogeneous mix and destroy larger aggregates that are formed (2-3 minutes). The surrogate EPS and dry sediment are then filled into a container (at desired ratio) and carefully mixed again until the surface of the sediment-grains is homogeneously wet. When using this mixture in erosion tests, the surface must be flat to avoid irregularities in surface roughness. To achieve a certain degree of similarity to natural biofilms, it is recommended to produce two layers of sediment, a top layer with a thickness ≤ 5mm (Chen et al., 2017) using the EPS-sediment mix and a bottom layer without EPS.

(vii) Measuring erosion threshold (CSM)

For determination of the critical erosion threshold, a number of standard methods exist (straight and annular erosion flumes, wave flumes, mesocosms), which are all well known in the community and are therefore not described here. Instead, we describe the CSM device, which has been applied multiple times in biostabilisation research and has also been successfully used for HYDRALB+ experiments. The CSM is a portable erosion device (https://partrac-csm.com/) used for

quantification of entrainment thresholds and erosion rates (Paterson, 1989; Tolhurst et al., 1999; Tolhurst et al., 2002). It uses a vertical jet of water that impinges on the sediment surface, generating a normal and tangential stress at the interface. These stresses can be converted to a critical shear stress (τ_c) via calibration (see van de Lageweg et al., 2017). The CSM allows a number of different test routines, allowing variation in jet pulse duration, pressure increments and maximum applied pressure. Van de Lageweg et al. (2017) applied test routine S7, which covers a large erosional range and which has also been used by Tolhurst et al. (2002) to enable direct comparison between the data.

3.4 EXPERIMENTS WITH ICE

The primary issue for experiments involving ice is to correctly model the ice mechanical properties. Sea ice forming in nature is exposed to variable conditions. These conditions affect the structure of the ice, which in turn affects the properties and mechanical behaviour that influence ice loads on structures. To model wave-ice interaction correctly, the elasticity of the ice cover needs to be scaled correctly. Recent studies (von Bock und Polach and Ehlers, 2015) have pointed out that model-scale ice behaves elastic-plastically, even under low stress, which affects the strain modulus (i.e. the effective Young's modulus) and Cauchy similitude might not therefore be maintained. Ice flexural strength and thickness are generally the most important parameters for loading on inclined structures such as ships. Ice compressive and crushing strength and fracture toughness are especially important in the context of vertical structures.

Figure 8: Preparation of model scale ice through seeding in HSVA; the process results in model ice with a columnar structure, similar to the structure of ice in the nature.

3.4.1 Previous experimental studies on the mechanical properties of ice

The strength of sea ice and parameters affecting the strength have been studied for decades. Tests have shown ice to be a complex material, with properties that depend on several physical and chemical factors (Timco and Weeks, 2010). When it comes to ship performance, flexural strength is the most important property of the ice, as ships are usually designed to break the ice by bending it downwards. Thus, flexural strength is commonly correctly scaled in experiments, while other mechanical properties are subject to scale effects.

i) Flexural strength

The flexural strength of ice depends on many parameters, including temperature, loading direction, ice grain structure, grain size, test type (cantilever or simple beam), loading rate, beam size and, for sea ice, ice salinity and brine volume (Timco and Weeks, 2010). Timco and O'Brien (1994) combined several databases and showed that the flexural strength can be determined based on the square root of the brine volume, which depends on temperature and salinity. Values above 1.5 MPa have been measured, but the flexural strength of first-year sea ice typically reaches up to 1 MPa and decreases with brine volume, being of order 100 to 150 kPa for warm sea ice (Timco and Weeks, 2010). Estimates of the flexural strength of old ice are of order 0.8 to 1.1 MPa in winter and 0.4 to 0.6 MPa in summer (Timco and Weeks, 2010). In the Baltic Sea, four-point bending tests have yielded a flexural strength of 0.58 MPa on average (Kujala et al., 1990) and values of 0.42 to 0.55 MPa when determined from cantilever beam tests (Enkvist, 1972; Määttänen, 1976). Thus, ice flexural strength is commonly considered to be 0.5 MPa or higher for design purposes; as an example, the design flexural strength was 0.69 MPa in the case of USCGS Healy (Jones et al., 2001).

The development of model scale ice has resulted in increased interest in the use of chemicals to affect ice strength. The general conclusion is that dopants added to the water weaken the ice in terms of flexural strength (e.g. Borland, 1988). Timco (1981) conducted the most extensive flexural strength tests with different chemicals. The chemicals included various mass fractions of acetates, amides, inorganic salts and sucrose. The higher mass fractions led to lower flexural strength. Different model basins use different chemicals, including urea, a mixture of aliphatic detergent, ethylene glycol and sugar (EG/AD/S), ethanol and salt (e.g. Borland, 1988; Hirayama, 1983; Lehmus, 1988; Nortala-Hoikkanen, 1990; Lau et al., 2007; Riska et al., 1994). Two different methods to produce model scale ice are used: spraying (e.g. Riska et al., 1994) and seeding (e.g. Evers and Jochmann, 1993). As noted by Lau et al. (2007), the scale ratio ranges from 12 to 60, but the typical range is 10 to 40. Thus, the flexural strength of the model scale ice should range from 15 to 60 kPa. Measurements in model scale basins have shown that model scale ice produced from different solutions cover this range (Spencer and Timco, 1990; Timco, 1986; Narita et al., 1988; Nortala-Hoikkanen, 1990; Riska et al., 1994; Evers and Jochmann, 1993; Hirayama, 1983).

ii) Compressive strength

Compressive strength is particularly important in the context of ice interaction with vertical structures. Sanderson (1988) was the first to combine several measurements to produce the famous pressure-area curve (increase in area decreases nominal pressure). The curve has been revised by other authors (e.g. Masterson et al., 2007) and has been published for ships by combining several full-scale measurements (e.g. Taylor et al., 2010). The compressive behaviour of sea ice is highly complex as the material may respond elastically, visco-elastically and visco-plastically (Sinha, 1982;

Timco and Weeks, 2010). It has been found that several factors influence the measured value of compressive strength (Timco & Weeks, 2010): intrinsic factors (temperature, salinity, density, ice type, crystal size and orientation) or test condition factors (rate of loading, confinement conditions, loading direction, sample size, stiffness of the test machine, and sample preparation techniques). The range of reported values of compressive strength is therefore very wide. Lau et al. (2007) calculated that the ratio between compressive and flexural strength should be between 1.8 and 5. Measurements have shown that for fine-grained saline and ethanol model ice the ratio is between 1 and 2 (Nortala-Hoikkanen, 1990; Riska et al., 1994), between 2 and 3 for CD-EG/AD/S and EG/AD/S (Lau et al., 2007; Timco, 1986), and between 1.5 and 5 for urea-doped ice (Timco, 1986).

iii) Strain modulus

Elastic modulus can be determined by either measuring the propagation of elastic waves in the ice sheet or by measuring the ultrasonic velocity in a small ice sample (Timco and Weeks, 2010). Any mechanical measurement of the modulus (either by small beam tests or in-situ cantilever beam) is not truly elastic since ice behaves as a viscoelastic material. Thus, Young's modulus determined from mechanical measurement is the strain modulus. Measurements have shown that the values of elastic modulus vary between 1.7 to 5.7 GPa, when determined from flexural waves, and from 1.7 to 9.1 GPa when determined from the body-wave velocities (Weeks and Assur, 1967, 1968). Strain modulus measurements show large scatter, with values between 1 and 5 GPa on average (Timco and Weeks, 2010). Modulus (strain and Young's) decreases with brine volume (Timco and Weeks, 2010). Thus, the minimum value of the ratio of strain modulus to flexural strength is 2000 and the upper value is 8000 (e.g. Timco, 1980; Riska et al., 1994). The measurements have shown that the ratio for Urea-doped model ice is less than 2000 and, thus, cannot fulfil the minimum requirement for the ratio (Hirayama, 1983; Narita et al., 1988) and EG/AD/S-doped ice can in some occasions reach the minimum value for the ratio (Timco, 1986). However, the ratio has been shown to be at the correct range with the density-corrected (CD-)EG/AD/S model ice (Lau et al., 2007). Similarly, the fine-grained saline ice can reach the whole ratio scale from 2000 to 8000 when the concentration of sprayed water-salt solution is controlled (Nortala-Hoikkanen, 1990). The fine-grained ethanol ice (Riska et al., 1994) and columnar saline ice (when treated with micro-air-bubbles, Evers & Jochmann, 1993) also cover the major part of the ratio range between 2000 and 8000.

iv) Crushing strength

Like compressive strength, crushing strength is important in the context of vertical structures (Sodhi, 2001). By crushing strength is meant the ductile deformation or brittle failure of an ice feature against a structure. Whether the ice fails in a ductile or brittle manner is highly dictated by the speed of the indentor with respect to the ice (Sodhi, 2001). Probably the best known and most analysed full-scale measurements on offshore structures have been the measurement campaigns on Molikpaq platform (e.g. Hardy et al., 1988; Wright et al., 1986; Wright and Timco, 1994). The measurements showed that while crushing occurred only 1 % of the time, the highest loads occurred at these times (Sodhi, 2001).

In model-scale tests, the focus is usually on the global loads. A structure is pulled through a model-scale ice sheet and the global forces are measured (ITTC, 2014); alternatively, the model ice sheet is pushed past a structure that is mounted to the basin. The use of a tactile sensor sheet has enabled study of the local loads and pressure pattern on the model structure during the ice-crushing events

(Ziemer and Deutsch, 2015). Another approach to measure crushing strength is the indenter test, where a cylindrical specimen is pushed through the ice, with cylinder diameter and speed of push being dependent on the ice thickness. The crushing strength of sea ice was found to be in the range of 3 to 7 MPa while indenter tests in columnar model ice have shown values between 50 and 200 kPa. The ratio between the model and full-scale crushing strength therefore matches typical scale ratios for offshore model tests.

v) Fracture toughness

Fracture toughness depends on loading rate and ice type, with less dependence on temperature and grain size (Timco and Weeks, 2010). The fracture toughness of sea ice and model-scale ice were extensively measured in the past, but only relatively recently has it been shown that the setup used was lacking, with the result that fracture toughness was not properly measured (Dempsey, 1991; Mulmule and Dempsey, 2000). Several field campaigns conducted since by Dempsey and co-workers have shown that, for thick first-year sea ice, fracture toughness is of the order 250 $kPam^{0.5}$. Totman et al. (2007) developed a method to measure the correct $K1_c$ of small samples in the laboratory and found fracture toughness to be approximately 115 $kPam^{0.5}$. However, Schulson and Duval (2009) criticised these experiments, suggesting that the loading rate had been low enough to cause creep behaviour, which affects the results.

Lau et al. (2007) reviewed fracture toughness tests conducted with various model-scale ice and showed that the fracture toughness of model scale ice is higher than the toughness of sea ice. However, as the compiled tests with model scale ice were conducted before a proper testing method for fracture toughness had been established, the results are questionable.

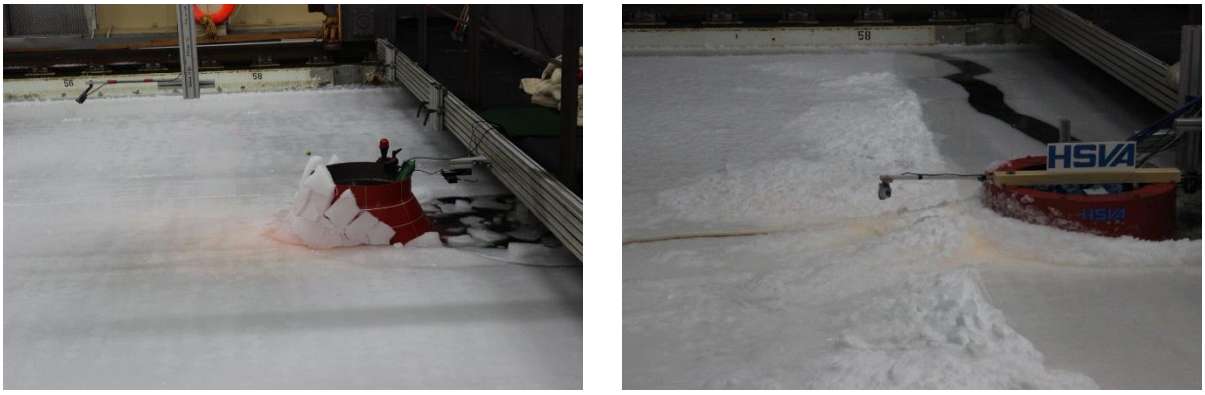

Figure 9: Left: Inclined structure breaking ice sheet by bending upwards. Right: Vertical structure breaking ice by crushing.

3.4.2 HYDRALAB+ experiments on mechanical properties of ice

i) Flexural and compressive strength tests: Aalto and HSVA

In model-scale tests, it is usual to set the flexural strength of the model-scale ice and subsequently check the compressive strength and other properties to ensure they are within an acceptable range. The acceptable range is taken as variation in the ratio between the flexural strength and the other observed mechanical property. The dependence of compressive strength (and other properties) on flexural strength for ice used in different ice tanks is largely unknown. This also applies to specimen geometry and property gradients (von Bock und Polach and Ehlers, 2015; von Bock und Polach, 2015). Accordingly, a set of complementary HYDRALAB+ experiments are to be conducted at HSVA

and Aalto, in which compressive strength is measured for a range of ice-sheet geometries and flexural strengths. The ice sheet thickness (h) will be between 25 and 45 mm (exact value to be decided); the compressive strength will be tested for three geometries: length x width = h x h, 4h x 2h and ah x bh (where the values of a>4 and b>2 are to be decided). Each sheet will be tested for 3 – 4 values of flexural strength, where the flexural strength is varied by adding heat and is measured.

3.4.3 Key issues to be considered in measuring ice mechanical properties

As noted above, several parameters affect the mechanical properties of ice. Depending on the purpose and scope of the study, experiments concerned with the mechanical properties of ice need to address some or all the following practical issues:

(i) Dimensions (width and length) of the sample (relates to scale effects and applied beam theory)
(ii) Test type (e.g. cantilever or simple beam)
(iii) Loading / strain rate (affects failure mode)
(iv) In-situ or ex-situ (in-situ refers to tests on the ice basin and ex-situ outside the ice basin)

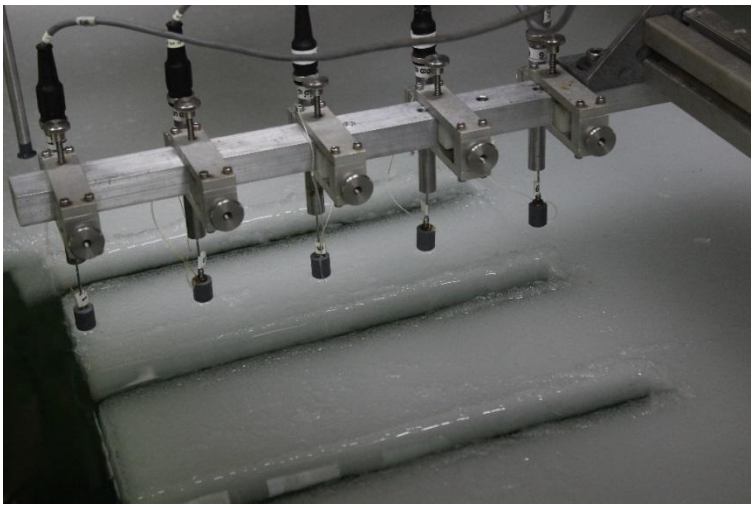

Figure 10: Cantilever beam test: beam is loaded from free-end and displacements measured along beam

3.4.4 Practical guidance

The following guidance is based on the ITTC guidelines (2014).

(i) <u>Flexural strength</u>

It should be noted that the determination of flexural strength is based on Bernoulli beam theory, even though the material properties of ice do not satisfy the assumptions inherent in that theory. Thus, values obtained are indicative of the flexural strength rather than being the actual flexural strength.

Cantilever beam

The in-situ cantilever beam test is the most common method to determine the flexural strength of ice in a laboratory. A floating cantilever beam having length l and width w is cut to the ice sheet in-situ (bedded on water) in a manner that the root of the beam remains attached to the ice sheet. The

tip of the beam is loaded downwards or upwards at a constant speed until the beam fails. The recommended beam dimensions are l=(5-7)*h, w=(2-3)*h, where h is ice thickness. A standard pattern/jig should be used for cutting. The failure should occur with the same mode (brittle or ductile) as in the model test with the ship / structure. In a case of tests with model ships, the relatively high speed of the model often causes a brittle bending failure. Thus, the flexural strength tests should be conducted at sufficient speed to ensure a similar failure mode. However, a too fast loading speed should be avoided to prevent hydrodynamic effects influencing the test results. The flexural strength is calculated following the Bernoulli-beam theory from the measured load, load length from the root, width and thickness of ice. It should be noted that the results are notch sensitive. Thus, the root corners of the beam should be rounded.

Three-point bending

Three-point bending tests can be conducted in-situ or ex-situ. In ex-situ testing, the beam must be carefully extracted from the ice sheet to avoid damaging the sample. The beam dimensions should be similar to those of the cantilever beam test. The test apparatus should consist of round supports to avoid stress concentrations at the edges. The diameter should be small enough to be line-like, but large enough to avoid stress concentrations. The flexural strength is determined from Bernoulli beam theory when the load, length, breadth and the thickness are known. It should be noted that in ex-situ measurements, the water might drain out from the sample, which might affect the results.

(ii) Uniaxial Compression test

The uniaxial compressive strength of ice can be determined in-situ or ex-situ. It is recommended to be conducted in-situ, in order to avoid water drainage from the sample. The in-situ specimen is prepared in the same manner as for the cantilever beam test. The beam is loaded by pushing / compressing it from the free end. In ex-situ tests, the sample is placed between two steel plates to compress it. Compressible material is placed between the sample and the loading plates to compensate for unevenness and to avoid sliding. The recommended dimensions are l=4*h, w=2*h, or l=w=h. The loading rate should be high enough to cause brittle failure. The compressive strength can be determined from the failing load and the cross-sectional area of the sample. It should be noted that compressive strength is size-dependent: the larger the sample, the smaller the measured compressive strength. However, larger samples are easier to handle.

(iii) Strain modulus

Infinite plate on elastic foundation – plate bending method

The model ice sheet is loaded uniformly over a circular area by placing dead weights in discrete increments. The deflection at the centre of the load is measured with high accuracy as the displacements are small. In addition, the loads should be small and duration short to avoid plastic deformation and creep. The loading should be applied at least 4 characteristic lengths away from the wall and the surface of the ice should be vibration free due to sensitive displacement measurements. The strain modulus can then be determined from the measured force (dead weight), displacement, density of water, thickness of ice, and Poisson ratio.

If the displacement is measured away from the loading, the strain modulus can be determined with Bessel functions. Furthermore, the modulus can be determined also if a large loading radius is

applied, or from beam bending tests by measuring the displacements from several locations. The details of these methods are described in ITTC Guidelines (2014).

(iv) Crushing strength

Indenter test

The crushing strength is determined with an indenter test. The test is conducted in-situ. The test area should be confined by the surrounding ice sheet to enforce failure by crushing. In the test, a cylinder with a force sensor is pushed through the ice sheet at constant speed in the brittle range (relative rate of strain $\dot{\varepsilon} = \frac{v}{4D}$ larger than 0.01). To determine speed-independent results, the tests should be repeated with different speeds. The diameter of the cylinder, D, depends on the ice thickness, with D/h > 1. The crushing strength based on the indenter method is determined following Korzhavin (1962), which requires knowledge of the measured force, the shape factor of the structure, a contact factor, ice thickness, diameter of the indenter, and the value of D/h.

The proper testing methods and requirements for the fracture toughness tests have been set-up only recently. Thus, the procedure is not covered by ITTC Guidelines. However, a typical size for the sample is h x 10*h x 20*h. HSVA adopt the following approach. A recess is prepared at one side. In the middle of the recess a thin cut is made into the flow. Distance meters are then set onto the ice sample going across the thin cut. The recess is then pushed to the sides at defined speed and the force is measured by load cells (Lu et al., 2015; Morley & Dempsey, 2015).

(v) Fracture toughness

Aspects to consider when planning fracture toughness tests include (i) notch acuity; (ii) notch sensitivity; (iii) crack growth stability; (iv) crack path stability; (v) specimen size; (vi) positive geometry; (vii) keyhole (KH) tension test; (viii) doubly-edge-notched-doubly-slotted (DENDS) tension test; (ix) stable fracture and the stress-separation-law; (x) loading rate.

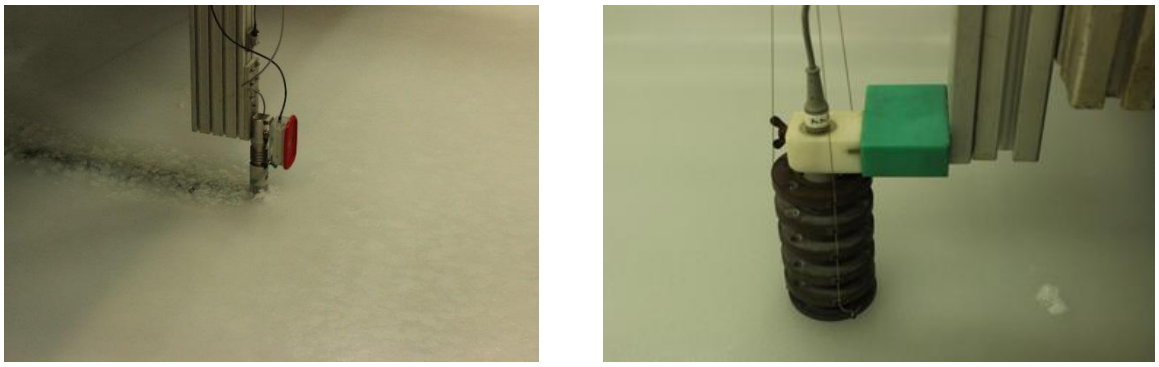

Figure 11: Left: Cylindrical indenter pushed through ice sheet. Right: Strain modulus measured using dead weights over ice sheet and measuring displacement from the middle.

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