HR Wallingford
Working with water

HRPP 463

Guidelines for physical modelling of mobile sediments

James Sutherland and Richard I Soulsby

Reproduced from a paper presented at:
Coastlab 2010 - Proceedings of the Third International Conference on the Application of Physical Modelling to Port and Coastal Protection
28 September to 01 October 2010
Barcelona

GUIDELINES FOR PHYSICAL MODELLING OF MOBILE SEDIMENTS

James Sutherland[1] and Richard I Soulsby[2]

[1] Principle Scientist, HR Wallingford, Howbery Park, Wallingford, OX10 8BA, UK.
E-mail j.sutherland@hrwallingford.co.uk
[2] Technical Director, Howbery Park, Wallingford, OX10 8BA, UK.
E-mail r.soulsby@hrwallingford.co.uk

Key Words
Physical modeling, mobile sediments, guidelines, HYDRALAB

Abstract
Physical model hydraulic experiments and model tests that use mobile sediments are performed in many laboratories across the world. This paper presents the main results from a set of guidelines on the physical modelling of sediment dynamics, which synthesised and documented procedure, practice and experience of partners in the EU collaborative project HYDRALAB-III. It does not attempt to cover all aspects of physical modelling, as these are already adequately covered by existing books, but draws together aspects in which the partners involved have a special expertise, particularly recent developments after most of the standard texts were published. Although many physical model mobile-bed tests are successfully completed, the need for improvements in data-basing is emphasised so that results are easier to re-use. The development and widespread adoption of appropriate standards for meta-data should be encouraged.

1 Introduction

Physical model hydraulic experiments and model tests that use mobile sediments are performed in many laboratories. As part of the EU collaborative project HYDRALAB-III www.hydralab.eu a set of guidelines was drawn up that synthesises and documents procedure, practice and experience of HYDRALAB-III partners concerning the laboratory physical modelling of sediment transport in rivers, estuaries and the sea (Sutherland and Soulsby 2010). These guidelines have subsequently been edited and included in an IAHR design guide (Sutherland and Soulsby, 2011). They do not attempt to cover all aspects of physical modelling, as these are already adequately covered by existing books; (Yalin, 1971, Dalrymple, 1985, Hughes, 1993 and van Rijn, 2007) rather, they draws together aspects in which the partners involved have a special expertise, and hence it complements the standard texts. The HYDRALAB guidelines have been developed to disseminate knowledge, methodologies, instrumentation and practices among the physical modelling community. This paper summarises the guidelines and outlines many of the main points.

2 Objectives and approach

The following general approach applies to consultancy applications involving physical modelling of sediment dynamics, and to some extent to research experiments as well. Steps 1 to 10 will normally be considered during the preparation of the proposal, and then refined once the work commences. The layout of this guideline broadly follows the steps of this approach.

1. The objectives of the study must be clearly identified, and a written statement agreed with the client. Misunderstandings at this stage are very difficult to correct later. For example, in a beach study is the plan shape, the cross-shore profile, or the longshore transport rate of primary concern? Establish whether the client wants only the model data, or an interpretation of what the data means. Establish what level of Quality Assurance the client requires.
2. The relevant physical processes must be identified and their approximate magnitudes estimated. The dominant processes must be reproduced in the model, and omission (or non-scaled reproduction) of lesser processes must be justified by consideration of the ratios of omitted to included processes.
3. Decide if the problem can justifiably be treated as having one horizontal dimension (1DH), or whether both horizontal dimensions (2DH) must be modelled. In the former case, a (narrow) current or wave flume will suffice. In the latter case, for rivers either a broad current flume or a full 2DH physical flow model is required, and for coastal and offshore problems a wave basin is required. Using a flume will reduce costs compared with 2DH facilities, and/or a larger number of tests could be performed, but at the expense of omitting cross-flume processes.
4. Consider the scaling issues and the scaling approach to be adopted. Decide whether natural density or low-density sediment will be used. Decide what the minimum scale is that will ensure that non-scaled phenomena have negligible effect. Decide whether a vertically distorted model should/can be used. Choose the geometric scale (and vertical exaggeration, for distorted models), and calculate the scale of other variables.
5. Decide what the requirements are for flow generation (where appropriate). How will the flows be circulated? What measures need to be taken to straighten the flows and ensure that entrance conditions are gradual and turbulence levels are natural?
6. Decide what the requirements are for wave generation (where appropriate). Should regular or irregular waves be used? Should long-crested or short-crested waves be generated? Does special attention need to be given to wave reflections (use of active or passive absorption), low frequency waves, wave velocity- or acceleration-skewness, re-circulation of water (e.g. from longshore currents)?
7. Decide how (and if) sediment will be re-circulated.
8. Choose the most appropriate model facility, bearing in mind all the above considerations. Decide whether the scaling benefits of using a large facility (e.g. near-full-scale wave flume, oscillating water tunnel) outweigh the considerable added costs, time and staff resource needed.
9. Decide what needs to be measured, what instruments to use, whether their accuracy is adequate, their calibration requirements and data logging requirements and data storage.
10. Plan a test series. Leave adequate time for calibrations and preliminary tests. Allow sufficient time for turn-around between tests.
11. Estimate the costs in conjunction with planning the test series. This is best done as a fixed sum for commissioning (and de-commissioning) the facility including preliminary tests and

calibrations, plus a unit cost per test. Also estimate the time necessary to complete the test series, allowing 10-20% contingency time for breakdowns etc. Consult with the client to ensure that cost and time are in line with his expectations.

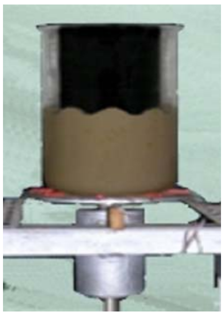
12. Design the model, including moulding of the bed, construction of structures, placement of rock armour or scour protection.
13. Perform the calibrations of the instruments and the current and/or wave generation facilities. Perform preliminary tests to establish the best routine for the main test series.
14. Perform the test series. Examine the first few tests particularly carefully, analysing the data as far as possible, and noting the time taken per test. Adapt the procedures and test series if necessary. Log the data in an organised manner.
15. Keep detailed notes in a dedicated log-book (one book for the whole study, not separate ones kept by different individuals). Ensure that everything is recorded, including sketches where useful. Remember to record water temperature, especially if suspended sediments are involved. Don't trust to memory, or assume that something is too obvious to require a note.
16. Analyse the data, preferably as the test series proceeds.
17. Interpret the data, including conversion of model results to prototype scale.
18. Establish the sources and magnitudes of errors, and quote these together with the interpreted results.
19. Write a report on the study.
20. Archive the data and paperwork in a way that will be retrievable over the number of years required by the client or by Quality Assurance requirements.

3 Choice of Facility

The range of model facility types can be divided into "standard" facilities which are widely distributed (though of various sizes), and "special" facilities which are only found in a few laboratories in Europe. However, it should be appreciated that some facilities which come under the heading of "standard" are in fact rare or unusual because either they are exceptionally large (overcoming scaling difficulties), or they have additional special features.

Standard facilities

- Current flumes
- Wave flumes
- Wave basins (with or without currents)
- River physical models
- Tidal physical models



Special facilities

- Oscillating water tunnels and U-tubes
- Oscillating trays, including in current flumes
- Total Environment Simulator
- Rotating facilities e.g. race-track flumes, annular cells (shown right), Coriolis facilities

The HYDRALAB "Inventory of experimental facilities and instruments in Europe", (see www.hydralab.eu/N_facilities.asp) provides an overview of such facilities, their sizes and characteristics.

4 Principles of scaling

A physical model is in principle an analogue computer, where a physical parameter measured in the model represents the same parameter at the corresponding location in the prototype. In the case of scale models the quantity measured in the model has to be transformed by a scaling or model law to obtain the estimated magnitude of the actual prototype parameter.

A vital first step in the planning of laboratory experiments and physical modelling is consideration of the scaling laws that apply. This is essential for deciding the correct way to scale up model results to interpret them quantitatively at prototype scale (e.g. sediment transport rates). However, it is also important for cases where only qualitative results are required (e.g. patterns of erosion and deposition of sediment) as it is still necessary to reproduce the relative strengths of the forcing factors correctly. Neglect of scaling considerations could render model results either meaningless or misleading.

The basic philosophy for movable-bed models can be formulated as ensuring that the relative magnitudes of all dominant processes are the same in model and prototype. Preferably, the scale model should be validated using field (prototype) data, but often this is not feasible and large-scale model results are used as prototype data. The scaling must be considered for both the hydrodynamics and the sediment dynamics, and correct scaling of the former does not necessarily lead to correct scaling of the latter.

Two “tricks of the trade” are sometimes used to assist with obtaining scale-similarity:

- Use of a distorted-scale model, in which the vertical scale-factor is smaller than the horizontal scale-factor (i.e.vertical exaggeration)
- Use of low-density model sediment, which gives an extra variable that can be utilised to obtain scale-similarity of more than one parameter.

Despite their apparent advantages, both of these techniques introduce extra uncertainty into the interpretation of model results at prototype scale, so they should be avoided if possible, or used with a full understanding of the consequences if they are adopted. Further discussion of these techniques is given later in this section. However, we will start by considering an undistorted model, and natural-density sediment.

The model scale factor, N_X, of a physical parameter X is defined as the ratio of the prototype value of X to the model value of X. Thus the geometric model scale factor in an undistorted model is N_l , where l is any characteristic length (e.g. defining the bathymetry, or the size of a structure). In a distorted-scale model N_l is the geometric scale factor in the horizontal direction, and N_h is the geometric model scale factor in the vertical direction (including water depth h). In undistorted models, $N_h = N_l$, while in distorted models the vertical exaggeration is N_l / N_h . Similarly, model scale factors can be defined for any other physical variables; for example, N_t, N_{ws}, N_{qb} are the scale factors for time t, settling velocity w_s, and bedload transport rate q_b.

Hydrodynamics: Froude scaling

The most widely used, and generally applicable, scaling law used for the hydrodynamics of free-surface flows in physical models is Froude scaling. If the geometric scale (i.e. the ratio of lengths l in the prototype to those in the model) of an undistorted model is N_l, then with Froude scaling all times are scaled by N_t , where $N_t = (N_l)^{1/2}$. This scaling law was developed in the 19th century by William Froude on the basis of his pioneering model tests of ship dynamics in towing tanks. Furthermore, it can be shown from consideration of the momentum equations that Froude scaling is applicable in general to free-surface flows where the dominant controlling force is gravity. This scaling follows from the need to maintain constant ratios between the various terms in the equations of motion in order to have dynamic similarity between model and prototype. The relationship $N_t = (N_l)^{1/2}$ is required because the gravitational acceleration, g (units [LT^{-2}]), is normally the same in model and prototype (with the exception of centrifuges for modelling of soil mechanics). This scaling is equivalent to the requirement that the Froude number $U/(gh)^{1/2}$ is the same at model and prototype scales, where U is (current or wave-orbital) velocity, and h is water depth. For open channel flow the Froude number is a very important parameter describing the character of the flow: tranquil or shooting flow, whether disturbances can propagate upstream or not and the magnitude of variations in the surface level when the flow is disturbed. For surface gravity waves no similar important dimensionless Froude number can be defined – even though surface gravity waves are some of the hydrodynamic phenomena best reproduced in a scale model based on Froude's model laws.

Many hydrodynamic quantities are correctly scaled by Froude scaling:

- Current speeds scale as $N_U = (N_l)^{1/2}$
- Wave heights and wavelengths scale as N_l
- Wave periods scale as $N_T = (N_l)^{1/2}$
- Wave orbital velocities scale as $N_U = (N_l)^{1/2}$
- Wave orbital excursion amplitudes scale as N_l
- Keulegan-Carpenter numbers applicable to sediments or rock-protection ($KC = Uw\ T/d$) and structures ($KC = Uw\ T/D$) are identical in model and prototype provided that the bed material is geometrically scaled, because they depend only on the ratio of bed material (or structure) size to wave orbital excursion. Here d is grain or rock diameter, D is structure diameter, Uw and T are wave orbital velocity amplitude and period.
- Current drag coefficients in rough turbulent flow are identical in model and prototype provided that the bed material is geometrically scaled, because they depend only on the ratio of bed roughness to water depth
- Wave friction factors in rough turbulent flow are identical in model and prototype provided that bed material is geometrically scaled, because they depend only on the ratio of bed roughness to wave orbital excursion
- Bed shear-stresses τ in rough turbulent flow scale as velocity-squared provided that the bed material is geometrically scaled and water densities are identical, and hence $N_\tau = N_U^2 = N_l$

However, in a scale model only a single force can be correctly reproduced at a time. For example it is not possible to reproduce the forces of gravity and viscosity in the same model when water is the fluid in the model as well as in the prototype. In a scaled-down physical model a Froude model law gives reduced flow velocities compared to the prototype, while a correct scaling of the viscous forces (maintaining the same value of the Reynolds number in model and prototype) would require an increase of the flow velocities in the model compared to the prototype. The Reynolds number is consequently reduced in the Froude model by a factor of $Nl^{3/2}$, and the viscous effects will be more pronounced in the model than in the prototype. This makes it more likely that the model flow is smooth turbulent or transitional ($Re^* < 70$), in which case the last four bullet points above would not hold.

In general wave phenomena like shoaling, refraction and diffraction follow the Froude model law, and the wave field over a given bathymetry can be quite accurately reproduced in a model. The onset of wave breaking, the breaker type and the wave decay due to breaking can be reproduced, but depends on the magnitude of the model waves. Even though small waves may be reproduced satisfactory outside the surf zone, the viscous and surface tension effects can be of significance for the characteristics of wave and flow phenomena inside the surf zone. This must be addressed specifically when planning a model test involving breaking waves. The distribution of the flow field over a bathymetry, for example the distribution of the specific discharge (discharge per metre width) and the mean flow velocity over a river cross section will normally be satisfactory reproduced, still provided that the Reynolds number is sufficiently high to ensure turbulent flow in model.

Furthermore, some sediment dynamic quantities are correctly scaled by Froude scaling, provided that the bed material is geometrically scaled and has the same density (relative to the water) as the prototype:

- Shields parameters of sediments and rock-protection in rough turbulent flow are identical in model and prototype, because they depend on the ratio of bed shear-stress to grain size, if the density-ratio *s* and *g* are the same in model and prototype
- The threshold Shields parameter of rock-protection is (almost) identical in model and prototype provided that the model rock is sufficiently large that viscous effects can be ignored. However, this only holds true (to within 10%) for non-dimensional grainsize $D^* > 120$, which for quartz in fresh water at 20ºC corresponds to $d > 5$mm. For smaller model rocks, and for sandy sediments, the threshold Shields parameter varies with D^* and will generally not correspond between model and prototype.

Quantities which depend on more than one dimensional physical variable are not easy to scale down from prototype to model, as they do not scale correctly with Froude scaling. These include cases in which a significant role is played (at model and/or prototype scale) by any of the following processes:

- **Viscous forces.** In cases where the viscous forces are dominant at prototype scale, the Reynolds number rather than the Froude number should be made equal in model and prototype. Examples include:
  - laminar wave boundary layers (weak waves)
  - permeability effects on percolation through sediment beds in beach dynamics and offshore foundations
  - settling velocities of fine sediments in suspension. These are very dependent on the Reynolds number, but the settling is due to the action of gravity and it can therefore not be reproduced accurately in a scale model unless the sediment density is changed.
  - wave friction factors in smooth and transitional turbulent flow
  - current drag coefficients in smooth and transitional turbulent flow

  Hot water is sometimes used to reduce the kinematic viscosity of water at model scale (but has a limited applicability), and air is sometimes used as a substitute for water in models at very small scale.
- **Surface tension forces.** If waves are modelled at a very small scale, capillary waves (dominated by surface tension) might be of similar wavelength to gravity waves, which will disturb the wave dynamics. The level of the water table within a beach depends on surface tension, and percolation in the swash zone on a shingle beach will normally not be reproduced correctly. Droplet formation depends on surface tension, although this is not usually important for sediment dynamics.
- **Coriolis accelerations.** The effect of the Earth's rotation is important only at prototype scales larger than a few kilometres and time scales larger than a few hours, e.g. in the tidal dynamics of coastal seas, large estuaries and inlets. These effects can be modelled using rotating (Coriolis) turntables, although it is unusual for these to be used for sediment dynamics.
- **Electro-chemical forces between sediment grains.** If medium sand in the prototype is attempted to be reproduced in, say a 1:50 scale model, the grain size in the model will be of the order 10 micron. In this range the inter-granular forces begin to be of significance, for example as a stabilising force for a resting grain. In addition to the effects of viscosity this imposes an effective limit to the grain size of prototype material which can be reproduced directly in a scaled down model to produce quantitative results.

Scaling of sediment transport

The scaling of sediment transport rate does not usually follow directly from Froude scaling. In general, the scaling of sediment transport requires knowledge (or more usually an assumption) of the form of a sediment transport formula that is appropriate to the scenario being modelled. If the sediment transport formula is written in terms of a product of powers of the input parameters, then the scaling law can be derived as the same product of the scale-factors for the input parameters. Multiplicative coefficients drop out of the scale relationship, so it is not necessary to know these. However, some sediment transport formulae cannot be written in terms of power laws, in which case the ratio of the full expression at prototype and model scales must be taken. Again, leading multiplicative coefficients drop out, but some internal coefficients do not, in which case a sensitivity analysis to the coefficients is necessary to give a range of results at prototype scale. In addition, a sensitivity analysis to the use of other possible sediment transport formulae should be made.

An exceptional case in which Froude scaling can be applied directly is that of bedload transport of shingle (gravel or cobbles) in which the model shingle is larger than 5mm and has the same density ratio s as the prototype. In this case, the Shields parameters of incident currents and waves are identical in model and prototype, and so is the threshold Shields parameter. Since the non-dimensional bedload transport is often expressed as a function of only the incident and threshold Shields parameters, the Froude scaling holds good. The sediment transport at a point has (volumetric) units of [$m^2.s^{-1}$], and hence the scale factor for the bedload transport rate q_b is $N_{qb} = N_l^2.N_t^{-1} = N_l^{3/2}$. The long-shore bedload sediment transport rate integrated across the beach profile Q_b has (volumetric) units of [$m^3.s^{-1}$], and hence the scale factor for the bedload transport rate is $N_{Qb} = N_l^{\ 3}.N_t^{-1} = N_l^{5/2}$. In both cases the results can be converted to mass units by multiplying by the sediment density. The shape and angularity of the prototype shingle should also be reproduced at model scale as far as possible. Further details of the modelling of shingle is given in the full guidelines (Sutherland and Soulsby, 2010, 2011).

Scaling of morphological evolution

Provided that the sediment transport rates and directions are faithfully reproduced in the model, the modelled morphological evolution should faithfully represent the prototype situation. This is because the morphological evolution is governed by the divergence of the sediment transport rate, which applies equally at model and prototype scale. For suspended transport it is important that lag effects are reproduced correctly in the model. This can be achieved by scaling such that Z = ws/u* is the same in model and prototype – however, it is not in general possible to scale by the Froude number and by Z simultaneously, so a compromise scaling is often necessary. An alternative is to use low-density sediment to achieve this, but the caveats in the full guidelines should be referred to.

The rate of evolution of the bed is governed by the morphological time-scale T_M. For the "ideal case" of Froude scaling for bedload transport defined above, the morphological timescale scales as $N_{TM} = (Nl)^{1/2}$. If this ideal scaling cannot be obtained, the time scale for morphological evolution will deviate from the Froude scaling law. In some cases, for example scour tests, the geometry of the morphological evolution will be similar in the model and the prototype, and an estimate of the time scale may be made from the sediment transport rate estimated for the two cases. However, there are severe limitations to this technique, for example if the ratios between bed- and suspended load are not the same or if the geometries of the morphological evolution are not similar.

Examples of model scaling for river sediment models, coastal sediment models, beach and dune erosion models, scour pit development and rock scour protection are given in the full guidelines (Sutherland and Soulsby, 2010, 2011).

5 Model Scale

Large-scale models (i.e. small geometrical scale factor) have advantages over small-scale models (large scale factor) in terms of:

- more certainty of scaling the results up to full-scale, due to smaller scale-factors being used
- smaller scaling errors due to extraneous processes, especially due to their relatively small unscaled effects of viscosity.

These benefits must be set against:

- the additional expense, labour and time involved in needing larger quantities of water and sediment
- reduced accessibility (more difficult to get close to features of interest)
- longer setting-up times (water filling and draining; filling, moulding and removing sediment)
- longer run times (resulting from the smaller geometrical, and hence time, scale factor).

The relative merits must therefore be considered of having more reliable results, but for a small number of test cases of limited (prototype) duration, versus a larger number of test cases and longer (prototype) test duration but with greater uncertainty in scaling-up the results obtained.

6 Model sediment

The following factors should be considered when choosing the model sediment:

- If the scaled-down sediment has a diameter d_{50} less than about 60 - 100μm, electrochemical cohesive forces become important and would spuriously influence the sediment dynamics
- The presence of even very small quantities of clay (5 – 10%) could cause cohesion of larger grains at model scale, even though they would not at prototype scale. This can also apply to biological cohesion.
- The scaled-down sediment should be in the same hydrodynamic roughness regime as the prototype – in many cases a sand bed that would be hydrodynamically rough at prototype scale will become hydrodynamically smooth at model scale (spurious effect of viscosity)
- Low density sediments can be considered if they (a) help to preserve scale similarity, (b) allow sediment to move under modelled flows, or (c) provide a larger permeability in cases where this is important
- However, low density sediments may also have disadvantages (see full guidelines for details) such as (a) having different shaped grains, (b) floating on the water surface due to surface tension, and (c) making the scaling laws less transparent
- The source of model sediment. Choose between (a) natural beach/river sediment, which might reproduce the range of grain-sizes realistically, but might also contain mud, shell fragments, biological debris, etc, and (b) industrial sands (used in metal casting) which have very well-controlled grain-size distributions, can be obtained with various colourings, and can be delivered in small or large quantities, but are expensive and come in a limited number of sizes.

7 Boundary conditions on sediment

In tests where sediment transport is expected to be significant, the mobile sediment bed may lower significantly during the test, unless sediment is fed into the system at the upstream end. Most simply, this can be achieved with a sediment feeder system, in which sediment is introduced continuously at the upstream end, but not re-circulated. Simple feeder systems will not require manual intervention. Differences between input and output cause a change of bed slope, after which it disappears. For long-running experiments it is advantageous to re-circulate the sediment. There are two types of sediment recirculation systems:

- online recirculation systems, where sediment captured at the downstream end is fed back continuously to the upstream end, and
- offline recirculation systems, where sediment is collected at the downstream end of the flume and a similar volume is input at the upstream end.

An online system operates all the time, and recirculates what comes out of the downdrift end, so the method can be used for long tests and does not depend on modelling to determine the volume of sediment to be transported. However, an online system does not allow the transport rate to be measured accurately, except by periodic sampling or by a sediment flux measurement in the recirculation pipe. Moreover, some water will be recirculated with the sediment, which will adjust the discharge of the flume. An offline system can be easy to operate and can have a good temporal resolution. However, offline systems require more manual intervention, may not input the same volume of sediment that is being output and may require short test durations, if the sediment traps fill up quickly. Further details are given in Sutherland and Soulsby (2010, 2011).

8 Measurement techniques for sediment transport

The HYDRALAB sediment guidelines do not attempt to reproduce the coverage of measurement techniques that can be found in textbooks, such as that of van Rijn (2007). Rather it describes recent advances that the HYDRALAB participants use in the following areas:

- bedload sediment transport– Section 9;
- suspended sediment concentrations – Section 10;
- bathymetry or morphology – Section 11.

9 Measurement techniques for bedload sediment transport

Figure 1 Conductivity concentration metre

Methods for measuring bedload transport include the use of luminescent tracers and bedload samplers but also include more recent, developmental techniques, including those described below.

The Conductivity Concentration Metre system is an instrument for the concentration measurements of sand-water mixtures with varying conductivity of liquid. The principle is based on the conductivity change of a sand-water mixture due to the variation of the quantity of non-conductive sand present in the measured area. It is used to measure suspended sand transport in the sheet-flow layer in wave conditions in large wave flume.

The Ultra High Concentration Meter (UHCM) determines particle concentration by measuring the attenuation of sound between a transmitter and receiver placed 11mm apart. The instrument is specifically applicable in flows with high sediment concentrations of up to 1200g/l for China clay and up to 400 g/l for 0.2mm sand. Each sensor has a diameter of 9 mm and width of 6 mm. The output signal of the probe is linearly proportional to the concentration.

10 Measurement techniques for suspended sediment transport

The concept of using acoustic diagnostics in the underwater environment is attractive and straightforward. A pulse of high frequency sound, typically in the range 0.5-5 MHz in frequency, and millimetric/centimetric in length, is transmitted from a directional sound, source usually mounted within about a metre above the bed, and the backscattered signal gated into range bins and digitised. As the pulse propagates down towards the bed, sediment in suspension backscatters a proportion of the sound and the bed generally returns a strong echo. The backscattered signal amplitude and rate of change of phase respectively provide profiles of suspended sediment particle size and concentration, and the three orthogonal components of flow, while the bed echo provides the time history of the bed location. The objective of using acoustics has been to obtain profile measurements of the suspended sediment and flow with sufficient spatial and temporal resolution to allow turbulence and intra-wave processes to be probed, which coupled with the bedform morphology observations, provide sedimentologists and coastal engineers with new measuring capabilities to advance our understanding of sediment entrainment and transport. Recent applications are given in Thorne, Davies and Bell (2009) and Hurther and Lemmin (2008) and include acoustic backscatter systems, coherent acoustic Doppler profilers and ripple profilers.

An optical backscatter sensor (OBS) measures turbidity and suspended solids concentrations by detecting infra-red light scattered from suspended matter (van Rijn, 2007). The response of an OBS sensor strongly depends on the size, composition and shape of the suspended particles. Battisto et al. (1999) show that the OBS response to clay of 0.002 mm is 50 times greater than to sand of 0.1 mm of the same concentration. Hence, each sensor has to be calibrated using sediment from the site of interest. The measurement range for sand particles (in water free of silt and mud) is about 1 to 100 kg/m^3. The sampling frequency generally is 2 Hz.

Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) are optical methods that involve using a camera to capture more than one image of particles in the water and determines their velocity from distance moved and time between photographs. The particles can be mobile sediment particles or tracer particles (often small and/or low density) that should follow the fluid motion. Recently efforts have been made to measure the flow speed of the fluid (represented by the movement of micron-sized seeding particles) and of sediment in suspension from the same image. PIV measures the average velocity of the particles within a small area, while PTV tracks individual particles between images.

Bottle and trap samplers collect a water sample from the experiment to determine the local sediment concentration. The fluid velocity at the intake would ideally be the same as that of the surrounding fluid. Some samplers simply fill a bottle (van Rijn 2007) while others use a pump system and may have a number of bottles for sampling at different times. For example, the Aberdeen Oscillatory Flow Tunnel has four multi-bottle pump sampling systems that rotate in phase with the regular oscillatory flows generated. This allows sediment concentration to be determined at different locations (such as different elevations above the bed) and at regular phases through a flow cycle. Details of the sampler can be found in O'Donoghue and Wright (2004).

11 Instruments for measuring bathymetry

Measurements of bathymetry can be made in the dry, by lowering the water level before measurement is made and raising it after, or in the wet by measuring the seabed through the water column. The advantages and disadvantages of each approach are discussed in the full guidelines.

Examples of methods that can only be used in the dry include:

- Terrestrial laser scanners;
- Some forms of acoustic and optical sensors that can be included in a bed profiling system, can scan transects of the bed profile or can measure continuously at a point.
- Touch-sensitive bed profiler which is good for capturing the profile of rocks (whether in a rubble mound breakwater or a cobble beach) where a dragged wheel may stick or smooth out the profile too much.
- The movement of armour stones or units can be determined by taking photographs of a section of the armour both before and after a test, from precisely the same position. A comparison of the photographs reveals the stones or units that have been moved.

Draining a big flume is too long a job, so profiles must be taken with it full. The traditional approach to doing this is to deploy a bed level measuring device on a carriage that moves along a set of rails and scans the elevation in a straight line. An additional requirement is that the bed level measuring device can operate from the dry part of the beach to the wet part. Other methods are also used.

One recent advance in the development of bathymetric measurement devices has been the use of commercial laser scanners, which can be used to collect point-clouds of (x,y,z) bathymetric data. Typically thousands of points can be sampled in each second, with an accuracy that depends on the setting, range and number of times that each point is sampled. One commercially-available system can sample 5,000 points per second with an rms accuracy of 1.4mm at a range of 10m, based on sampling each point 4 times. Increasing the number of times each point is sampled reduces the rms error, but increases the length of time it takes to scan an area. For example, this system can be used to survey an area of 10m by 5m at an average spatial resolution of 10mm by 10mm in 1000 seconds, sampling each point 10 times for a rms error of 0.9mm. The points sampled in the scanner's coordinate system can be transformed into the coordinates of the physical model by scanning in targets (normally spheres) that are in known locations (determined by traditional survey techniques). A 3D elevation model produced using a laser scanner is shown in Figure 2.

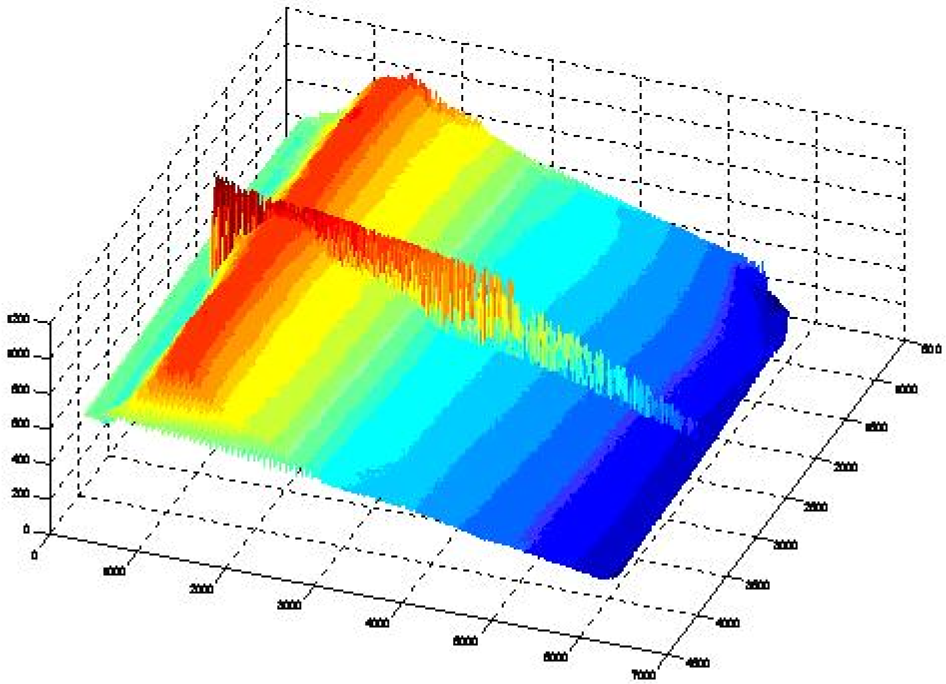


Figure 2 Physical model bathymetry measured using a laser scanner (courtesy of HR Wallingford)

12 Procedure for undertaking tests

Calibration is an essential preliminary to the main test series. It includes:

- Calibration of individual instruments (current metres, depth gauges, wave gauges, sediment transport instrumentation, etc.)
- Calibration of the flow and/or wave generation (settings to produce a given set of currents or wave heights and periods).

A provisional table of planned tests should be drawn up at the outset. However, flexibility is required, as it might be necessary to alter it as the test series proceeds, due to tests taking longer than anticipated, or in response to results from the first few tests.

Usually in sediment-related modelling there are many variables that could be altered (water depth, current speed, wave height/period/direction, sediment size/grading, initial bathymetries, etc.) It is often impractical to cover all combinations of a series of values of each variable. For example, all combinations of three each of depth, current speed, wave height, wave period and sediment grainsize would yield 243 tests. Instead, a sub-set is usually chosen, for example, a baseline set of the most representative value of each variable is chosen, and one variable at a time is varied. In the example given above, this would yield 11 tests – a much more manageable number.

13 Data acquisition, storage and retrieval

Modern data handling and storage technology can cope with large volumes of data, ensuring that all raw data can be kept and subsequently re-processed if necessary. In order to do this the data format must be well documented so that data can be retrieved even when the original hardware and/or software used to collect the data has become obsolete. Increasingly it also means that meta-data (information about the data) is stored electronically with the raw data. Alternatively the meta-data on the experiment may be recorded in a report, which should be stored with the data in a commonly readable format (such as pdf). At least one backup copy of all data should be kept in a separate building from the master copy.

Different laboratories have their own systems for acquiring data. The development of enabling technologies (Wells et al., 2009) offers the potential to use the experience of the wider scientific community by adopting common standards and developing them for the needs of hydraulic laboratories. Steps in this direction are to be encouraged.

Documentation must be available at different levels:

- the infrastructure,
- an experimental project (for instance a Transnational Access project),
- an experiment, and
- a record from a particular device in an experiment.

The infrastructure should be described, both in terms of the physical facility (description, photographs, dimensions, purpose, track record) but also the organisation that hosts it, with an emphasis on chain of responsibility for the facility and its databases. Available instrumentation should be described as should the standard coordinate system.

Details of an experiment may include funding organisations, key staff (particularly principle investigators and visiting researchers), purpose of the experiments, dates and duration of experimental programme, budget (likely to be confidential) and a listing of all publications including laboratory notebooks, data reports, the database of results and subsequent publications (if known about) such as conference proceedings, journal papers and theses.

Details of an experiment will include the location and type of instruments, parameters measured (with their units), sampling rates and duration, directory and file names of raw data and the target conditions run. This level will also contain free remarks on the experiment (e.g. quality appreciation, observations on particular events, calibration procedures).

Records from a particular device in an experiment should include

- the time of all measurements in the record relative to the time origin of the experiment,
- the absolute time origin, with date-time (e.g. 2006-05-30 14:02:12),
- names of the recorded physical quantities,
- calibration parameters needed to translate the recorded data into the physical quantities,
- complementary information needed to control and reproduce the experimental procedure (such as sensor name, gains, motor speed, options depending on the instrument used).

Storing information from all these different levels together and in a systematic way should allow a dataset to be used by scientists or engineers who were not involved in the data collection or storage.

In these days of austerity it is important that the value of data from physical models can be demonstrated through its re-use by other experimenters and modellers. Good data sets are difficult, time-consuming and expensive to collect. However it is often difficult to re-use datasets due to poor documentation. This leaves the potential user unsure what information is being presented or whether to trust the data given. This situation will be improved only when experimenters adopt much more thorough standards for data management and pay a lot more attention to the development of suitable meta-data for their experiments. The development of meta-data standards should be promoted within the physical modelling community. Some work on this will be conducted during the EC-funded project HYDRALAB-IV (2010-2014).

Interpretation of the results from the physical modelling of sediment dynamics should be conducted by, or under the supervision of, a senior researcher or consultant. Any interpretation should be illustrated using examples from the dataset and should refer to the limitations of the model, as well as its strengths.

14 Summary

Physical model hydraulic experiments and model tests that use mobile sediments are performed in many laboratories across the world. This paper presents the main results from a set of guidelines (Sutherland and Soulsby, 2010, 2011) on the physical modelling of sediment dynamics, which synthesised and documented procedure, practice and experience of partners in the EU collaborative project HYDRALAB-III (http://www.hydralab.eu). The guidelines do not attempt to cover all aspects of physical modelling, as these are already adequately covered by existing books, such as those by Yalin (1971) Dalrymple (1985) Hughes (1993) and van Rijn (2007). Instead, the guidelines draw together aspects in which the partners involved have a special expertise and hence they complement the standard texts, particularly with regard to developments that have occurred after most of the standard texts were published.

Moreover, this paper does not cover all aspects of the guidelines, but picks out a number of sections that are of particular relevance. Most section of this paper only provide a subset of the contents of the full guidelines (Sutherland and Soulsby, 2010, 2011).

Although many physical model mobile-bed tests are successfully completed, indicating the maturity of the science, the need for improvements in data-basing is emphasised so that results are easier to re-use. The development and widespread adoption of appropriate standards for meta-data should be encouraged, as this would allow data to be more widely shared and re-used.

Acknowledgments

The work described in this publication was supported by the European Community's Sixth Framework Programme through the grant to the budget of the Integrated Infrastructure Initiative HYDRALAB-III, Contract No. 022441 (RII3). The authors would also like to thank all the other contributors to the guidelines: R.Bettess, L. van Rijn, J. Kirkegaard, R. Deigaard, M. Sumer, H. Oumeraci, J. Grüne, J. Sommeria, P. Thorne, E. Foti, R. Musemaci, S. McLelland, A. Sanchez-Arcilla, I. Cácares, J. Ribberink, M. Kleinhans, L. Rákóczi, G. Szepessy & L. Hamm.

References

Battisto, G.M., Friedrichs, C.T., Miller, H.C. and Resio, D.T., 1999. 'Response of OBS to mixed grain size suspensions during Sandy Duck'97'. Coastal Sediment Conference 99, ASCE, New York. pp. 297-312

Dalrymple, R.A., 1985. 'Physical Modelling in Coastal Engineering'. Balkema, Rotterdam.

Hughes, S.A., 1993 'Physical models and laboratory techniques in coastal engineering', World Scientific Publications, 568pp.

Hurther, D., and Lemmin U., 2008. 'Improved turbulence profiling with field adapted acoustic. Doppler velocimeters using a bi-frequency Doppler noise suppression method.' J. Atmos. Oceanic Technol., 25 (2), 452-463.

O'Donoghue, T. and Wright, S., 2004, 'Flow tunnel measurements of velocities and sand flux in oscillatory sheet flow for well-sorted and graded sands,' Coastal Engineering, 51, 1163-1184.

Sutherland, J. and Soulsby, R.L. (Eds), 2010. 'Guidelines for the physical modelling of sediment dynamics.' Available from http://www.hydralab.eu/guidelines.asp. [Accessed 19/02/10.]

Sutherland, J. and Soulsby, R.L. (Eds), 2011. 'Guidelines for the physical modelling of sediment dynamics'. Chapter 6 of A Users Guide to Hydraulic Modelling and Experimentation, IAHR.

Thorne, P. D., A. G. Davies, and P. S. Bell, 2009, 'Observations and analysis of sediment diffusivity profiles over sandy rippled beds under waves,' Journal of Geophysical. Research., 114, C02023, doi:10.1029/2008JC004944.

Van Rijn, L.C., 2007. 'Manual Sediment Transport Measurements in Rivers, Estuaries and Coastal Seas'. Aqua Publications, Amsterdam.

Wells, S., Sutherland, J. and Millard, K., 2009. 'Data management tools for HYDRALAB – a review'. HYDRALAB Report NA3-09-02, available from http://www.hydralab.eu/hydralabIII/publications.asp (page accessed 20/12/10).

Yalin, M.S., 1971. 'Theory of Hydraulic Models'. Macmillan.

Fluid thinking...smart solutions

HR Wallingford provides world-leading analysis, advice and support in engineering and environmental hydraulics, and in the management of water and the water environment. Created as the Hydraulics Research Station of the UK Government in 1947, the Company became a private entity in 1982, and has since operated as a independent, non profit distributing firm committed to building knowledge and solving problems, expertly and appropriately.

Today, HR Wallingford has a 50 year track record of achievement in applied research and consultancy, and a unique mix of know-how, assets and facilities, including state of the art physical modelling laboratories, a full range of computational modelling tools, and above all, expert staff with world-renowned skills and experience.

The Company has a pedigree of excellence and a tradition of innovation, which it sustains by re-investing profits from operations into programmes of strategic research and development designed to keep it – and its clients and partners – at the leading edge.

Headquartered in the UK, HR Wallingford reaches clients and partners globally through a network of offices, agents and alliances around the world.

HR Wallingford
Working with water

HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA
UK

tel +44 (0)1491 835381
fax +44 (0)1491 832233
email info@hrwallingford.co.uk

www.hrwallingford.co.uk