CHAPTER 245

The Measurement of Bed Form Shapes in Hydraulic Models

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Abstract

Mobile bed hydraulic models have been used in the laboratory for a very long time. Attempts to predict the consequences of river engineering works, dams and barrages, flood protection schemes and dredging methods have led to wide ranging scientific research in material scaling. The design of breakwaters, beach protection systems and sea walls have long been studied in physical models. All of these require a method for measuring the effects of water movements and the resultant erosion, deposition and scouring of materials. This paper reviews some methods that have been used on laboratory models, and attempts to suggest ways forward in the future.

Introduction

Laboratory models of mobile bed properties require measurements of the topography resulting from water moving over the surfaces. This ranges from sedimentation effects in rivers to wave action on beaches. Measurements can be on the macro scale (ie, methods for producing 3D contours over the complete surface) or local 2D tracks of surface elevation (eg, scour around pile structures). It is a difficult measurement, as a wide range of materials and circumstances is encountered. Many experimental laboratories have developed specific techniques to suit particular projects, so it has always been difficult to design equipment and methods that are easily transportable between investigations.

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The durability of this style of investigation is confirmed by the fact that they still occur, and the long history (Hydraulic Models, 1942). In this reference, a description is given of a mechanical system for lowering a small probe onto the surface of the bed from a bridge over the model, and a scale to indicate its elevation. It is a source of surprise and regret that little real progress has been made in the last 50 years. This is partly due to the reluctance of civil engineering laboratories in all areas (government, private and university) to adequately invest in instrumentation development. Recent work by Jetté (1996) has shown what can be achieved by individual innovation, in this case to solve a specific field measurement problem.

This paper reviews some options, but concludes that a simple, adaptable, universal method has still only been possible using old technology, with the advantage of PC control. There must be better ways but time and resources have not permitted their development, underlining the comments above about lack of investment.

In recent years there has been a continuing interest at HR Wallingford in the effects of flowing water and waves over mobile beds. The range of work has included:

(a) Under-mining of sea walls
(b) Loss of sand from amenity beaches
(c) Prevention of siltation in navigation channels
(d) Research on the combined effects of waves and currents on bed load transport
(e) Embankment erosion and protection
(f) Scour around bed mounted structures

Most of this work requires the measurement of bed form disturbance to assess the effects of the existing regime and the consequences of engineering changes to the environment. Some researchers have used remote optical techniques (for example Oesch et.al., 1985) but most of these are time consuming to set-up, require sophisticated and expensive equipment, and cannot record what is happening underwater.

To overcome these objections a number of different mobile probe measurement methods have been developed by several laboratories.

Sensor Method	Use in Air	Use Under Water	Typical min. depth mm	Use in Air-Water Transition	Typical horizontal resolution at the bed mm	Typical vertical resolution mm
Conductivity	X	√	20	X	5	0.2
Optical retro-reflective	√	√	10	X	10	0.2
Ultrasonic	√	√	100	X	20	1
Laser distance sensor	√	√	60	X	2	<0.1
Touch Sensitive	√	√	Zero	√	2	0.1
Remote photographic	√	X	(Surface reflection)	X	?	?
Image analysis	√	?	?	?	?	?

TABLE 1 - COMPARISON OF METHODS

Table 1 shows some sensing methods that have been used and typical performance comparisons. There is only one universally applicable method, that of the touch sensitive, incremental technique. HR Wallingford has used optical servo probes for many years (HRS 1968), and the Delft conductivity probe has been popular (Delft 1985, and Villanueva, 1989). They are all subject to the limitations in the table. Models in flumes, for example, can be measured either by draining the water out or by flooding; it is always inconvenient, and a method which will traverse the (shallow) air-water boundary is better, even if the measurement process itself is slower. Early designs of touch probe were used by SOGREAH (Limnidyn, 1985) for a mobile bed river model, and by KENEK in Japan. The design requirements for an instrument include:

(a) Must operate in air, underwater, and through the air-water boundary in both directions.
(b) Must be suitable for sand, mud, coal dust, rocks, plastics, saw dust and in fresh or saline water.
(c) Vertical resolution to be better than 1mm, horizontal resolution to be better than 5mm in a working range of 10m. Horizonal range ideally unlimited.
(d) Options for use in flowing water to be available.
(e) Should be easy to move from one location to another, and be cheap to build.

(f) Expandable from 2D to 3D operation.
(g) Must be able to operate over steep rock faces.
(h) Automatic pc control and data logging.
(i) Good vertical range.
(j) Remote control options

There is an obvious choice of sensor operation, either

(a) Remote sensing probe with a large gap between the probe tip and the bed, or
(b) Servo operated probe following the bed surface with a small gap.

Option (a) is ideal for flowing water (to prevent scour around the probe tip) but has a poorly defined horizontal "footprint".

Option (b) provides good horizontal and vertical resolution but is unsuitable for use in flowing water or under waves.

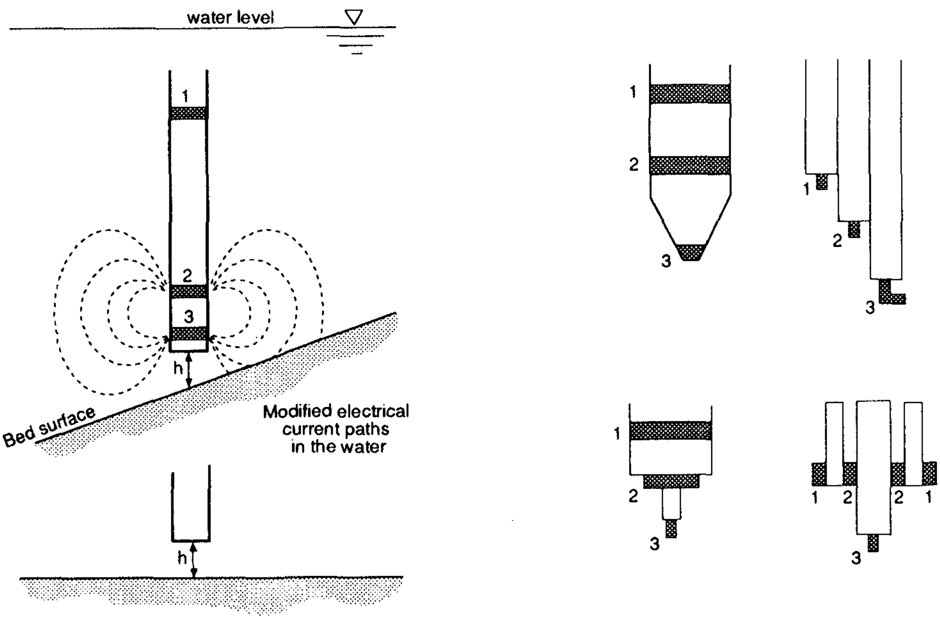
The well-equipped experimental hydraulic laboratory should have the capability to use any of the techniques described above, so that the varied demands of different experiments can be accommodated. Each method is described in more detail below.

Methods Available

Most of the techniques depend on a probe that is servo-driven so that its tip is near to the measured surface. The error between a reference value and the value of the measured variable is used to maintain a 'constant' following distance of the probe above the surface. Exceptions to this are the photographic, laser distance and image analysis methods.

Conductivity

This option has been available for a long time (Wilkie, 1954), and had been used even earlier using the water surface as a reference (Anon 1952). Essentially it consists of a probe that can measure the bulk conductivity of the water surrounding a probe tip, and variations that depend on the proximity of non-conducting surfaces. Figure 1 (a) shows the principle. Since the water properties affect the measured values, some method must be used to eliminate the problems caused by water conductivity variations.



(a) Operating principle **(b) Alternative probe design**

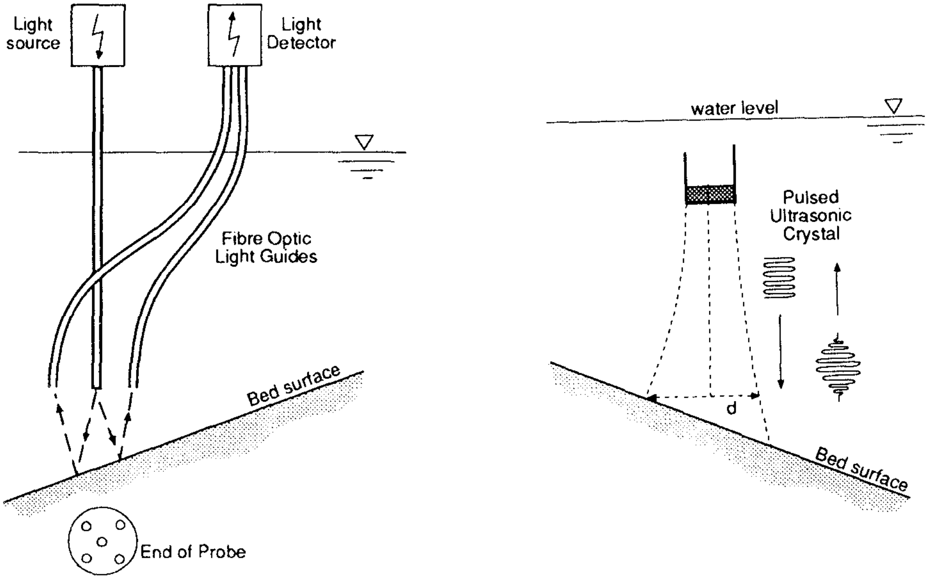
Figure 1 Conductivity Probes

The usual approach is to use an additional electrode (1) which is not affected by the surface proximity, and to use the bulk conductance measured between (1) and (2) as a form of compensation in a 'bridge'-type of arrangement.

At HR Wallingford we have experimented with a range of different probe tip designs, some of which are shown in figure 1(b). We have found that the following height H in 1(a) varies depending on the steepness of the surface. This would, of course, be expected, as the modification to the conductive path depends on the shape of the surface as well as the spacing. This is a very subjective problem, and care must be taken in the interpretation of results. The retro-reflective optical probe also has the same problem.

Optical retro-reflection

Again, this method has been used for a very long time (HRS 1968). It can be used in air (whereas the conductivity method cannot) but must be carefully optimised for the type of material over which it is working. It is also independent of water conductivity variations. The basic principle is to shine pulsed (infra-red) light on to the surface and detect the back scattered light. A convenient way to make a small diameter probe without active electronics in the water is to use fibre optic guides so that the source and detector are above water level, as in figure 2 (a).



(a) Optical Retro-Reflective (b) Ultrasonic

Figure 2 Optical and ultrasonic methods

The use of pulsed infra-red and synchronous detection helps to minimise the effects of ambient lighting. For effective operation, the surface must be a good homogeneous reflector such as sand or light plastics. It will not work satisfactorily over coal or gravel of mixed size and colour. Although it will operate in air or in water, the following height is different due to changes of refractive index. It can be adjusted to operate through the air-water boundary (with a step change of level at the boundary), but not the other way round. We have found that the probe collects water droplets at its tip as it emerges from the water, and this causes internal light reflections.

During some experiments, where the water has been drained away from a rippled sand bed, problems again occur even though the probe is always in air. This is because small pools of water are trapped between the ripples and cause surface reflection. The optical probe method has been used successfully over an eroded mud bed in a greenhouse to measure the effects of irrigation sprays.

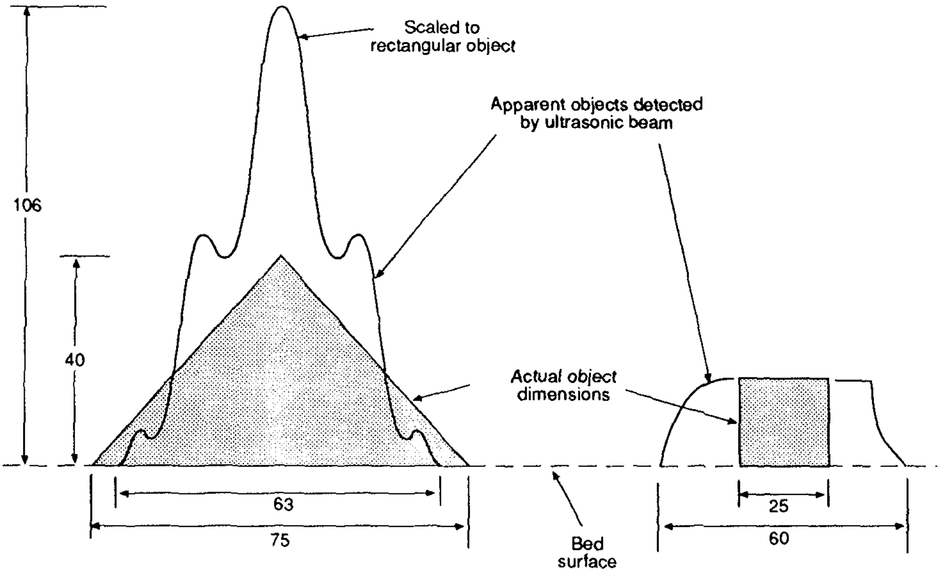
Both the conductivity probe and the optical probe can also be adjusted to detect the water surface location, which is useful for datum location. The HR optical probe has been mounted on a reversible carriage and used to traverse a rippled sand bed by ourselves for many projects, and also by others (Richards, 1986), using computer based logging.

Ultrasonic

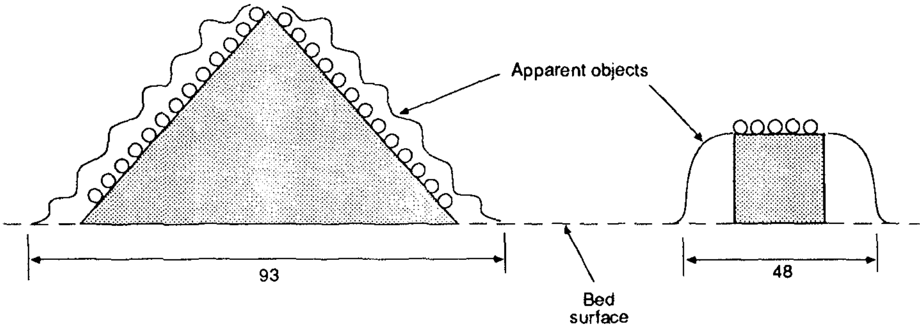
The use of ultrasonics for hydrographic survey work in the field has been developed to an extremely sophisticated level, and impressive imaging is achieved with side scan sonar. Sensors have also been used for sand ripple measurements (Jetté, 1996). Hydraulic modelling is not in the same price/performance environment, so the same intense development has not occurred.

Some laboratories have used ultrasonic probes, but there is a minimum water depth for satisfactory operation. This depends on the sensor frequency (hence the transmitted wavelength) and the accuracy of the time resolution of the returned pulse within the electronics. Figure 2 (b) shows the usual principle. It is clear that there must be enough time for the transmitted pulse to be detected back at the source before the next pulse is transmitted. Theoretically, bed slope could be measured by driving the probe at a constant horizontal speed, and then detecting the Doppler shift of the backscattered acoustic signal.

A potentially more important limitation is the transmitted beam width. The beam pattern of an acoustic source is complex, and the reader is referred to Stansfield for information. Simply, if the beam angle is 10°, then at a distance of 160mm above the bed, the horizontal projection 'd' will be about 28mm. A narrowed beam angle will improve this, but a larger spacing will degrade it. This sort of horizontal resolution is often inadequate for ripple measurements in models. A typical result is shown in figure 3. Steep ripples and edges of small stones are not measured accurately. This performance has been achieved with a 2.5 MHz probe mounted about 160mm above the bed. ideally, a vertically driven servo probe (as with the HR systems) would be used, but has not yet been tried. In addition, the vertical resolution is limited by the wave length (0.6mm at 2.5 MHz).



(a) Result from 'shiny' surfaces (mm)



(b) Objects as (a) covered with fine coal dust (mm)

Figure 3

Objects detected by a 10° ultrasonic beam with a source 160mm above the bed f = 2.5 MHz

Laser distance sensors

A wide range of solid state laser displacement sensors have become available in recent years. Some of these have been described by Shepherd (1994). At HR we have used the 'Keyence' type of sensor for bed measurements. The probe was packaged in a waterproof perspex housing and used on a fixed support underwater. A great advantage of this type of sensor is that it can be used with a good "stand off" (distance between the probe and the surface) so that flowing water does not cause scour of the bed. Used in this way, it is not necessary to operate the probe on a vertical servo drive unless the total range required is beyond the range of the sensor.

The method again relies on scattered reflected infra-red light, and will work well on sand but generally requires a good homogeneous light scattering surface. It is not satisfactory on shiny reflecting surfaces. The typical optical path is shown in figure 4, and the calibration is different in water than in air. The horizontal resolution is very good as the projected light spot has a diameter of less than 1mm. Calibration in air was linear but underwater it was non-linear.

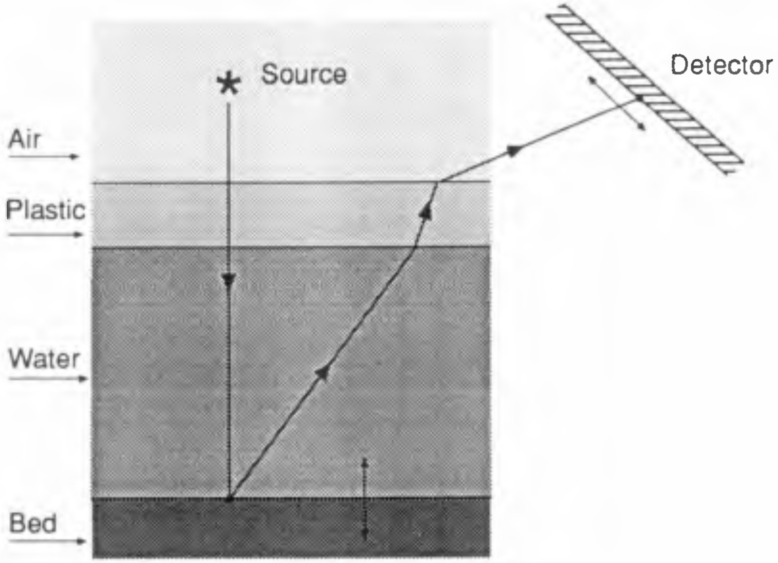


Figure 4 Laser Position Detector

There are other longer range optical 'time-of-flight' laser distance detectors and scanners that are potentially useful, but we have not yet investigated these. They are generally much more expensive than the short range distance detectors.

Touch sensitive detector

This is an extension of the retro-reflective probe described above, and as can be seen from Table 1, the only universal technique. This relies on the use of a 'diving bell' type of attachment as shown in figure 5, attached to the bottom of the optical probe. The very light weight (< 5g) piston has a good reflecting surface on its top, so that the intensity of the collected light is independent of the type of bed material.

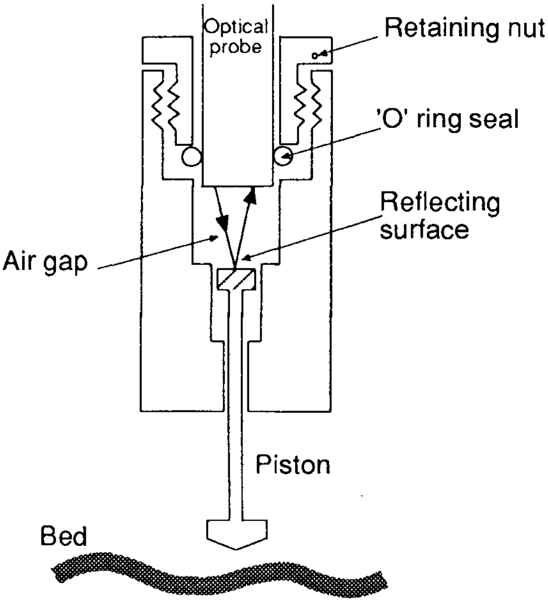


Figure 5 Universal Touch Probe

In operation, the probe is driven down to the bed, the piston tip contacts the bed and deflects by an amount which produces a repeatable level of light reflection at its top. The light level is compared with a fixed threshold which generates the error signal for the probe drive. The air gap is retained when the probe is underwater, so that the optical detection path is unchanged. Use through the air-water boundary has no effect on operation, and any type of bed material can be detected. The weight of the piston does not produce significant bed deformation.

Remote photography

An early example of remote measurements used Moiré fringe techniques (Oesch et al 1985), and a method used for height detection has potential for bed profiling (Nagle et al ca 1988). Early attempts to use digital image analysis on a rock beach at HR was not very successful due to the variations of surface reflection from wet and dry rock faces.

More recently Lowe and Steele at HR have been developing a method suitable for wide area beach contour measurement.

In principle, it consists of arranging suitable lighting to illuminate the edge of the water at the beach so that it produces adequate contrast to provide a good photographic image from an overhead camera. The water level is changed in known increments, and successive photographic images of the water edge produced, which can then be digitised as two coordinates. The values are then subject to numerical calibration based on the location of the data point and the measured projections of vertical calibration rods located at known positions on the model. Future plans include automatic image analysis of the photographic or video based images. Image processing has already been used for surface float tracking in hydraulic models, and it is probable that these techniques will be adopted for beach movement measurement.

Typical Equipment and Results

Application examples were presented at the Conference, together with results. Figure 6 shows a typical result of a a changing profile resulting from wave action. We have used profile measuring equipment for beach erosion studies, sea wall armour research, sediment transport, sand ripple propagation and mud erosion measurements. It is difficult to design universally applicable equipment, as detailed requirements vary with the type of experiment. However, it is possible to make available a range of methods that can be adopted for differing needs.

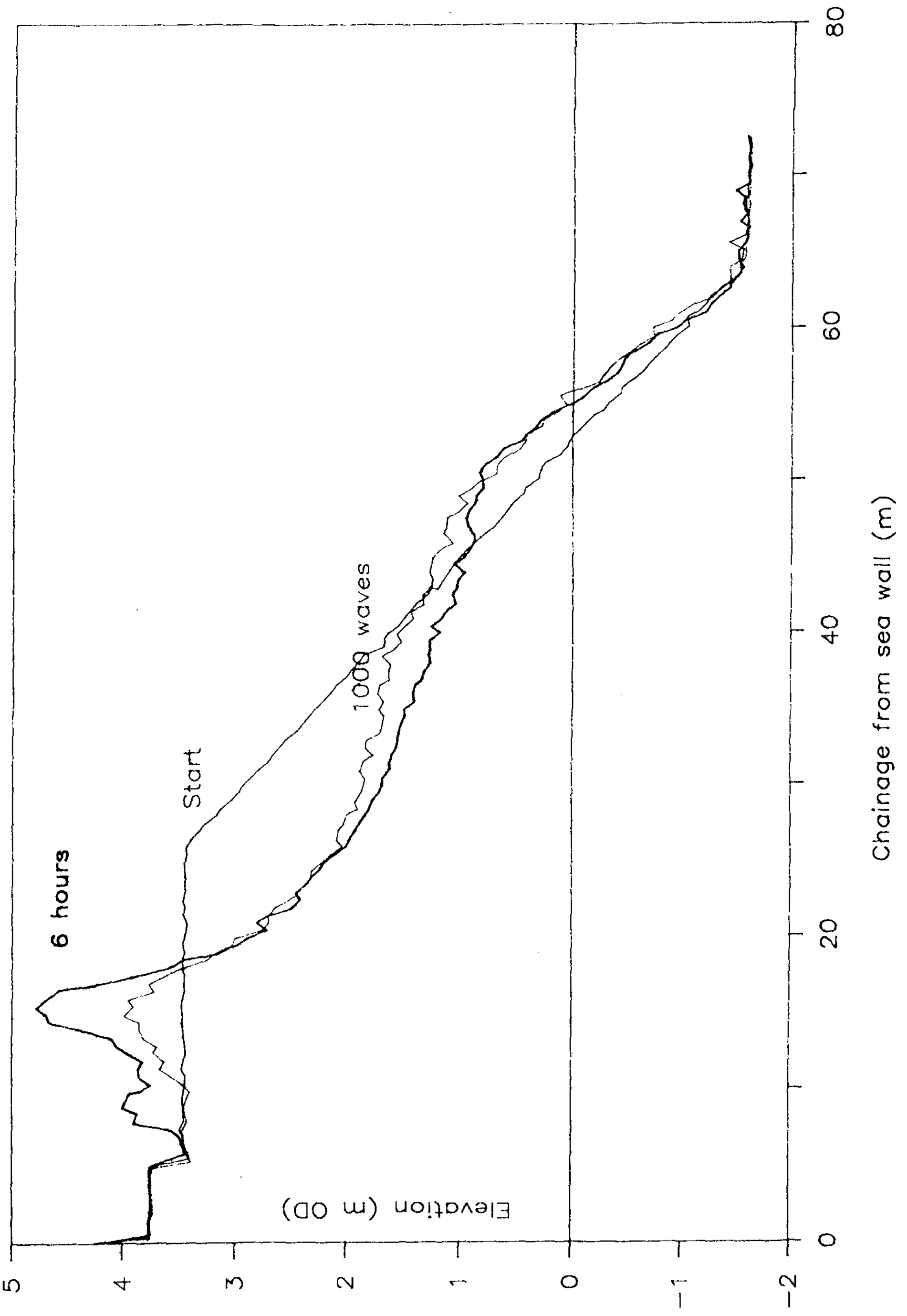


Figure 6 Profile Measurements on a Model Beach

Typical problems include the sag of instrument beam supports, either due to the weight of a moving carriage, or due to the weight of the beam itself. This can be remedied in several ways, for example:

(a) Use of a water surface datum location
(b) Software correction for measured values which are dependent on carriage position
(c) Overhead fixed datum reference compensation.

In most of our applications adequate support for traversing beams can be provided so that vertical errors due to sag effects are less than 1mm.

Conclusions

Measurements of bed profiles in hydraulic modelling have been very popular in recent years. Project specific studies and basic research both demand this type of measurement. The advances in numerical techniques also require experimental data to help prove computational models. Various methods have been used, but we have found that the touch sensitive technique is the only method completely independent of bed material, slope steepness and air-water boundaries. Photographic and image analysis methods are still in development, and solid state lasers will be important in the future.

Acknowledgements

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APPENDIX

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