Estuarine Morphodynamics

Development of SedErode - Instrument for In-Situ Mud Erosion Measurements

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Summary

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This report outlines the development of SedErode, which is an instrument for measuring the critical erosion shear stress of cohesive sediments in the intertidal environment.

SedErode is based on a previous instrument, ISIS, (Williamson and Ockenden 1996) which has been radically redesigned to improve its portability and speed of deployment, whilst still keeping the main elements of the successful ISIS concept.

The design of the SedErode instrument included the detailed analysis of the components of the instrument, and specifications for an improved device and its subsequent manufacture. Investigations into the method of operation and the hydrodynamic regime generated by SedErode to a sediment surface were undertaken, and are described in detail in this report.

SedErode has been tested and calibrated against data from hot film shear stress probes and a new calibration equation relating the applied shear stress to the gap under the bell head discharge has been derived.

The instrument has been fully tested at a number of different muddy sites, and used as part of a large intertidal mudflat survey in the Dollard Estuary, Netherlands. SedErode has proved portable and easy to use on intertidal mudflat sediments and can now be used for routine measurements on cohesive sediments.

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1 Introduction

ISIS (Instrument for Shear stress In-Situ) is an instrument which measures the critical shear stress for erosion (τ_{cr}) of cohesive sediments (Williamson and Ockenden, 1996). This parameter is a major input into morphodynamic models of coastal and estuarine areas. These models are used to predict the distribution of the flow-induced shear stress which is then compared to the local τ_{cr} to predict the onset of erosion and the rate of erosion once this value has been exceeded. It is therefore important that field measurements of τ_{cr} are obtained in estuarine and coastal study areas so that erosion is correctly predicted.

An ISIS prototype has already been developed at HR Wallingford Ltd. and has been used successfully to measure τ_{cr} at 9 different muddy sites in the UK and Europe, resulting in over 130 measurements of τ_{cr}. These measurements have already highlighted the spatial variability of τ_{cr} and a relationship between τ_{cr} and dry density and sand content for some of the sites (for example Blue Anchor Bay, Severn Estuary, Williamson, 1994).

However, the existing version of ISIS is heavy and cumbersome to use, and further development was required to make a portable, rugged instrument which can be applied to a wider range of locations in the coastal region. To achieve this the ISIS instrument required a radical redesign, in the light of the experience gained in the field, whilst still retaining the successful design element of the radial flow bell head. The essential requirements for a redeveloped instrument are that it is both easier to deploy and quicker to use.

This report describes the development and testing of the new version of ISIS which has been renamed SedErode (Sediment Erosion Device), to distinguish it from its predecessor.

2 Objectives

The objective of the development project was to improve the existing prototype of ISIS. The main effort has been directed at making a version of ISIS (Figure 1) which is lighter, more portable, and easier and quicker to use. Efforts have also been made to reduce the amount of user interpretation required when deploying the new instrument, to make it less of a research tool and more applicable to routine measurements.

The key features of the new design for a developed ISIS (SedErode) are that it is:

- lighter to carry
- easier to deploy
- quicker to use - taking one measurement in 15 minutes rather than 1 hour
- able to produce more objective results without significant loss of accuracy

A number of issues fundamental to improving the instrument were highlighted prior to establishing the specifications and design details of the new instrument.

Subsequent investigations included:

- how to reduce the size and weight of the system
- how to increase the speed at which measurements can be made
- improved understanding of the physics of the flow under the bell head
- dye-release tests for flow visualisation under the bell head
- analysis of the ISIS calibration data and function for applied shear stress
- development of a physically-based calibration formula
- deployment methodology

Figure 2 shows the shape of the bell head and the principle flow characteristics under the bell head.

3 Design

3.1 Design considerations

i) Gap

The gap under the bell head (Figure 2) is an important variable as it controls the applied shear stress. In the previous version of ISIS the gap was measured using two ultrasonic gauges to determine the head to bed distance. The drawbacks of using the ultrasonic probes are that they increase the deployment time, add significant weight (display console) and complexity to the ISIS system, and are a sensitive and expensive method of measurement. The advantage of the gap measurements is that the gap is established at every site, the degree of positioning accuracy can be assessed, and measurements of the gap can also indicate the onset of erosion.

It was decided on the grounds of simplicity and portability to operate SedErode at one fixed gap setting which is predetermined by positioning the bell head within a fixed geometry supporting section above the sediment surface. The existing ultrasonic devices can be dispensed with, thereby reducing the amount of operator interpretation required.

ii) Bell head shape

The ISIS bell head shape contains a flat section, for the ultrasonic gap sensors, and this shape was optimised using a 3D flow modelling package to produce the most even shear stress distribution across the bed. It was decided not to change the bell head shape as re-modelling the flow patterns under the bell head to reestablish an optimised radial shear stress profile would involve considerable effort and would not significantly improve either the portability nor speed of measurement.

iii) Head section design

It was decided to make the head section shorter than in ISIS and therefore less cumbersome to use and more portable. The main elements of the SedErode head section are shown in Figure 3.

iv) Measurements

The ISIS system utilises an ultrasonic flowmeter to monitor the flow discharge (Figure 1). This is a heavy item. It was decided to omit this from the new system and to calibrate the pump speed directly with the discharge.

The onset of erosion is determined from the continuous output of an infra-red light extinction meter (nephelometer) detecting the concentration of sediment recirculating through ISIS. This instrument will be retained but will be installed directly in the head section to complement the more compact design (Figure 3). This will also greatly speed up the response time to detect an increase in turbidity. The nephelometer will be satisfactory for most applications.

v) Pump and power supply

The pump used in the ISIS system was over-specified for the operating range typically required for intertidal and coastal sediments. Also it is heavy and operates with one-inch tubing which is difficult to handle. The advantages of the pump are that it is capable of generating high discharges (thus applying high shear stresses), and is of mono-pump design which is non-pulsing, resistant to wear by sediment-laden water and provides a reliable constant discharge level.

Tests with a smaller impeller-type pump with half-inch tubing indicated that a lighter pump can be used to generate the range of flow discharges required, with the added flexibility afforded by the smaller diameter tubing.

It was decided to continue to use the 2 x 12 volt D.C. power source but to improve the type of batteries to gel type, which have a higher energy to weight ratio. The shorter time taken to recirculate the water in the SedErode system (which holds about 1 litre as opposed to about 7 litres in ISIS) will also reduce the total energy requirements.

vi) Control box

The new control box will contain the following: the pump controller (with known calibration for discharge); the turbidity readout from the nephelometer, low power supply indicator, and; logging ports for pump setting and nephelometer.

3.2 Specifications

The bell head section is the major component of the new instrument, and this is connected to the rest of the system which generates the discharge and monitors the turbidity. An essential requirement for the new instrument is that the instrument is light, self-contained, compact and rugged. This was important so that the instrument was more portable (than ISIS) in the mudflat environment and would allow shorter deployment time and access to softer sediments. The principle requirements for the new design were to make SedErode:-

- lighter and more compact
- easier to deploy
- quicker to use
- simpler to operate and to interpret the results
- less expensive to build

The SedErode instrument was treated as two sections; the **head unit** which interfaces with the sediment surface, and the **pumping and control system**. For the purposes of design it was sensible to consider the specifications for each major part of the instrument separately.

3.2.1 Head unit

The head unit must be lightweight and easily portable in a muddy intertidal environment. It must be manufactured so that it is durable, compact and self-supporting once positioned on a sediment surface. The unit must be easy to clean (perhaps by the use of detachable clip-together sections).

The head section will comprise the following:

- Bell Head (bottom)
- Diffuser (middle)
- Mixing chamber (top)
- Supporting column and flange (surround)

It is envisaged that the components of the head unit are combined together so that they support each other, and form a continuous, sturdy unit. The overall height of the head unit shall not exceed 0.4m and the total weight shall be less than 10kg.

i) Bell head shape

This is the lowest part of the head section and will have a cross-section defined by specific radial coordinates (supplied by HR Wallingford). This section must be accurately machined to a high tolerance (±0.05mm) to produce the required shape. The head section must fit centrally inside a supporting column of internal diameter 90mm. The central outlet bore must widen to 1/2" BSP internal bore diameter smoothly over the length of the head unit ending in a quick release connection at the top of the head unit. The central outlet bore will need to pass through the diffuser and mixing chamber, and be sealed from both. The design chosen was for the bell head to be made of PVC or similar material, and 50mm deep to allow the incoming water (from the diffuser) around the annular space to stabilise. It must be attached rigidly to the diffuser section.

ii) Diffuser section

The purpose of the diffuser is to allow recirculating water to return under the SedErode head, but to impart no additional flow circulations under the bell head. Therefore it must break up any flow patterns before they pass under the head and be capable of conveying the same discharges that are removed through the bell head section. The diffuser acts as a last point of removal of air bubbles before entering the volume under the SedErode bell head.

The input into the diffuser will go through the mixing chamber above and be sealed from it. The pipework connection to the diffuser must allow easy filling of the SedErode head section and a quickfit connection to 1/2" BSP flexible pipe. Bleed valves must be incorporated to allow air to be bled for the system after filling. The diffuser will be firmly positioned between the bell head and the turbidity chamber. The previous diffuser designs have employed holes or mesh to disperse the incoming flow. The outlet tube from the bell head will pass through the centre of the diffuser and be sealed from it. The design chosen was for a diffuser of diameter 84mm (the same as the bell head), and 50mm deep in order to keep the head unit compact and easy to use. A mesh (of hole size about 2mm diameter) was used to form the walls surrounding the diffuser chamber.

iii) Mixing Chamber

The mixing chamber provides space in the system in which to mix the water which has passed over the sediment surface and measure the turbidity. The mixing chamber will be an enlargement to the outlet tube above the bell head in which to install the nephelometer (an optical backscatter turbidity probe), via a watertight seal. The nephelometer is a stainless steel backscatter probe with a 8mm diameter and needs to be positioned in the centre of the mixing chamber. The mixing chamber should be dark to optimise the optical conditions at the probe tip. It is desirable to mount the nephelometer sideways into the mixing chamber so that any air bubbles will pass by and not adhere to the probe surface, disrupting the measurement. The water in this chamber at any time should represent the water just removed from the sediment surface, so that if any sediment is eroded and brought into suspension it is readily detected by the nephelometer. It is also hoped that this chamber between the bell head and the suction side of the pump will remove any pulsing created by the pump from reaching the bell head.

The mixing chamber should be firmly attached to the support column and the underlying diffuser and bell head sections. The 1/2" BSP connections to and from the pump (from the bell head and to the diffuser) will be located in the top of this section, and it is important that these connections are strong and easily connected and disconnected to the pumping system (with cold and muddy hands!). The connection for the diffuser (incoming water) should be open when disconnected so that water can be introduced into the head section prior to connecting up the pumping system and starting a measurement run. The mixing chamber must be compact (say 50mm deep) and the diffuser inlet will pass through it (but be sealed from it).

iv) Supporting column and flange

The function of the supporting column is to position the SedErode head securely above the sediment surface, and to provide an isolated water volume for the SedErode bell head. The supporting column and flange should provide a sturdy base for the SedErode head section. The supporting column and flange should be designed so that when the flange is securely resting on the sediment surface with the lower column cutting into the bed then the SedErode bell head is a set distance above the bed surface. A supporting column sinking depth of 50mm into the bed is recommended for most intertidal sediments. The bell head must be positioned with a tolerance better than ±0.5mm at a vertical distance 6mm from a smooth underlying sediment surface. This positioning will be achieved and held by the supporting column and flange. This gives a range of applied shear stress from about $0.1\mathrm{Nm}^{-2}$ to $3\mathrm{Nm}^{-2}$ over the water discharge range $0.05\mathrm{ls}^{-1}$ to $0.5\mathrm{ls}^{-1}$.

A water-tight port of 8mm diameter which passes into the mixing chamber is required near the top of the SedErode head section to position the nephelometer prior to each measurement run.

The SedErode head section should be securely held within the supporting column, which should have an internal diameter of 90mm. The entire head section should be easy to carry by one person in a mudflat environment, and it is suggested that the total diameter of the flange is not more than 400mm. For a typical intertidal mud dry density of $600\mathrm{kgm}^{-3}$ (bulk density about $1350\mathrm{kgm}^{-3}$) the present support frame does not sink when the 5.5kg ISIS head section and 11.5kg weights are used over a support area of $0.15\mathrm{m}^2$. This indicates an approximate bearing strength of greater than $1100\mathrm{Nm}^{-2}$ for typical estuarine muds. Using this fact, and noting the HSE safe carrying weight of 10kg for the SedErode head section, the supporting flange should have a minimum area of $0.1m^2$.

As the column is pushed into the bed a bleed valve should be opened to prevent any excess pressure build up in the column which might affect the pore pressures in the bed.

3.2.2 Pumping and control system

The head unit is attached to the pumping system after it has been positioned on the sediment surface and filled with clear water. The SedErode system then comprises a recirculating loop with water pumped from the SedErode bell head (thereby generating flow over the bed surface) via the outlet connection, through pipework to the pump, and back into the head section via the diffuser through the inlet connection. The pumping system should be able to be filled with water and bled of air prior to attaching the connections to the SedErode head section. This means that there should be some way of opening and shutting the ends of the pipework, as well as the quick-release connectors for easy deployment.

The pumping and control system comprises of:

- pipework
- pump and motor
- control unit

i) Pipework

The pipework should be comprised of durable, non-kinking flexible tubing which is capable of withstanding field conditions of summer and winter temperatures as well as fresh and saltwater conditions without significant change in the material properties. In particular the pipework must not flatten at bends, which reduces the discharge. The pipework should also be easy to clean e.g. dilute acid and soapy cleaners.

ii) Pump and Motor

The pump and motor should be rugged enough to operate in the marine environment, on either tidal mudflats or on ship. The power requirements should thus be kept to a minimum, to reduce the consumption from batteries (if used) and the size and weight of the pump. The pump motor should be operated from a dial (or similar) on the control box and be capable of producing a range of discharges in the range 0 to at least $0.5ls^{-1}$. Pulsing flow must be avoided.

iii) Control Unit

The control unit will contain the essential control and recording facilities for use with the SedErode system. This will include a readout panel (or similar) to display the on-line value of turbidity in the recirculating system and a dial to control the discharge through the system. This dial will be calibrated against known discharges through the system by HR Wallingford. Logging ports must be available so that the discharge (pump voltage or current) and turbidities (0-1 volts) can be logged if desired.

The control unit must be lightweight, compact and simple and rugged to use in the marine mudflat environment. The complete system must be both splash and rainproof.

3.3 Manufacture

It was decided to sub-contract the detailed component design and manufacture out to an experienced designer who had substantial experience in producing oceanographic equipment, and energy-saving electronics. Mr V. A. Lawford of L. M. Services Ltd., was subcontracted to design and build the SedErode system from the detailed specifications provided by HR Wallingford. The instrument was built, tested and modified to produce the final version of SedErode which was delivered to HR Wallingford in Summer 1996. (Figure 4 shows the general arrangement of the SedErode design). Plate 1 shows a close up of the SedErode head section during testing.

SedErode has the following key features:

i) The bell head shape is the same as for ISIS but with a single gap of 5.8mm achieved by the use of a flange which rests on the mud surface. There is no longer a mechanism for moving the head vertically with respect to the sediment surface.

   The gap accuracy has been estimated at a tolerance of ±1mm (about the preset gap of 5.8mm) over the 0.045m radius sample area. This assumes a horizontal positioning accuracy of ±0.5mm and a vertical variation in the sediment surface topography of ±0.5mm.

ii) The discharge range is 0 to 0.4ls^{-1} produced by a small 12 volt bilge pump positioned on the flange. This corresponds to an applied shear stress range for typical operating conditions from 0 to about 2Nm^{-2}.

iii) The SedErode system is now fully portable and comprises a head module and a control box.

   The head unit contains the bell head, mixing chamber, nephelometer, diffuser and recirculating pipework. The control box contains a fully rechargeable power supply, applied shear stress control and logging ports. The system is fully portable in the estuarine mudflat environment, with the head section weight at 7.8kg, and the control box at 13.7kg.

4 *Investigations*

A number of investigations were carried out to establish the possibilities for improvements in the operation speed and the flow regime and hydrodynamics.

4.1 Speed of operation

The volume of the recirculating system was reduced and compacted into one unit reducing the number of pipe connections that have to be made under field conditions.

The large system volume of the previous ISIS meant that the time for the recirculating water to become fully mixed (and thus reach a stable turbidity reading) was a minimum of 4 minutes at the lowest discharge setting (about 0.05ls^{-1}). It was decided to keep the volume of the recirculating water in SedErode to a minimum to reduce both the weight of the system and the mixing time. The time calculated to fully mix the water in the SedErode system is now estimated at 1 minute at the lowest discharge setting (about 0.05ls^{-1}).

4.2 Flow regime and hydrodynamics

4.2.1 Dye release tests

Dye release tests were undertaken early in the development programme in order to achieve a better understanding of the hydrodynamic conditions under the bell head.

These tests were conducted in the laboratory with the previous version of ISIS, using perspex plates with dye injection points at different radii from the centre of the bell head. The dye injection height was flush with the plate so that the flow regime at the bed surface could be visualised. Figure 5 shows the set up which was used for these tests.

The dye-release tests investigated the flow patterns under a range of different conditions including radial position, gaps of 4, 5 and 6mm and discharges between 0 and 0.7ls^{-1}.

The observations indicated that the flow at the outer radial position of the bell head was turbulent (as the flow stream turned the 'corner' under the outer edge of the bell head). Between 45 to 30mm from the centre of the bell head the flow became progressively less turbulent, and was laminar at discharges less than about 0.1ls^{-1}. This was considered attributable to the radial streamlining of the flow as it proceeded towards the centre of the bell head (ie. channelling the flow streamlines into the centre of the bell head). It was not clear from the observations whether the flow was laminar or smooth turbulent in the region between 0 and 30mm from the bell head centre. A common feature of the flow pattern was that of a non-dispersing stream of dye towards the centre, which developed a 'wiggle' at higher discharges. Figure 6 shows a diagram of the flow patterns observed under the bell head in the flow range 0.1 to 0.3ls^{-1}.

Two other tests were carried out at a gap of 5mm and discharges between 0.05 and 0.3ls^{-1} (see Figure 5):

> - An outer 'deflector' was added around the edge of the baseplate to try and make the flow less turbulent at the outer edge. The deflector ring had cross-sectional dimensions of 5mm x 5mm, with a smoothly rounded edge in the corner region under the bell head. The presence of the deflector increased the size of the outer region where the flow was turbulent due to the flow stream turning the outer corner under the bell head, and did not decrease the turbulent region as expected.
>
> - A wire (diameter about 1mm) was attached to the baseplate under the head at a radius of 30mm to examine the effect of an irregular topographic feature. This configuration resulted in no noticeable change in the flow conditions observed under the bell head.

It is assumed that these results generally apply to the SedErode head.

4.2.2 Theoretical considerations

Initial theoretical investigations into the shear stresses generated by the bell head compared well with previously obtained calibration data (direct measurements of shear stress applied to the bed with ISIS). These results indicated that the flow regime under the head was generally smooth turbulent, but with a transition from laminar to smooth turbulent at low discharges.

Two different approaches were applied to formulate the physical parameters which control the applied shear stress generated by the bell head. These investigations were aimed at producing a physics-based calibration equation which related the controlling parameters (flow discharge, gap height under the head, and water viscosity) to the bed shear stress being applied. The two approaches used to estimate the flow regime under the bell head were:

- flow between parallel flat plates
- flared-pipe flow

Appendix 1 describes the two different theoretical approaches to the flow regime under the bell head, and the formulations for laminar and smooth turbulent conditions for each approach.

Essentially all the approaches indicated that the pumping discharge Q was related to the shear stress $\tau(=\rho u_*^2)$ applied to the bed through dimensionless quantities.

$$\frac{Q}{D\,\nu} = f\left(\frac{u_* G}{\nu}\right) \qquad (1)$$

Where $\left(\frac{u_* G}{\nu}\right)$ is the gap Reynolds number

u_* = friction velocity (ms^{-1})
G = gap under bell head (m)
ν = kinematic viscosity (m^2s^{-1})
Q = discharge (m^3s^{-1})
D = diameter of bell head (m).

5 Calibration

The new bell head and SedErode recirculating system needed to be evaluated prior to use so that the applied shear stresses at different pump (discharge) settings was known, and the accuracy and errors associated with the erosion shear stress measurements could be estimated.

The purpose of the SedErode calibration was to assess the following parameters:

i) Calibration of a applied shear stress against bell-head to bed gap and discharge

The basic requirement was to make measurements of the applied shear stresses generated under a range of typical operating conditions, covering the full discharge range, 4 radial positions under the bell head and allowances for variations in bed topography and positioning error. These measurements should produce a data set of shear stress for different values of Q, G and radius to allow the theoretical function (equation 1) to be assessed.

ii) Repeatability of SedErode applied shear stress

The accuracy and repeatability of the applied shear stress generated by the SedErode system could be assessed by making 3 repeat calibration runs involving measurement of the shear stresses at 4 different radii for a gap of 6mm over the discharge range 0.05 to 0.5ls^{-1}. The gap was reestablished independently for each run.

iii) Estimation of Error in applied shear stress

Errors associated with positioning tolerances of ±1mm about the 6mm gap were obtained by measuring the shear stresses for gaps of 7mm and 5mm. Calibration runs measured shear stresses over the discharge range 0.05 to 0.5ls^{-1} and at 4 different radii. This allowed the range of accuracy to be determined for a positioning tolerance of ±0.5mm and a surface topography variation of ±0.5mm thus giving a combined tolerance of ±1mm.

5.1 Calibration rig

Hot film shear stress probes were used to calibrate the SedErode instrument at PEP Research and Consultancy Limited, Plymouth (University of Plymouth). The hot film shear stress probes consisted of 2 pairs of gold film strips flush-mounted onto circular, perspex disk mountings. The hot film probes are made by Dantec Ltd. and the PEP calibration rig and application of the hot film probes for shear stress measurement is described by Graham et al. (1992).

The calibration of the SedErode head was achieved by measuring with the hot film probes the applied shear stresses generated with different discharges and gaps. The hot film probe pairs mounted on perspex circular calibration disks were inserted at different radial positions under the SedErode bell head. The size of the perspex disks containing a pair of hot film shear stress probes was 25mm diameter x 10mm thickness.

As the SedErode system has a fixed bell head position within the support column, spacer washers were added or removed to pillars in the head section to generate different gap settings. The gap was measured with an electronic vernier rule at a number of different positions under the bell head for each gap setting.

Gaps of 4.6mm, 6.5mm and 7.4mm were used for the SedErode calibration. There were 2 calibration plates each containing 2 mounting holes for the PEP Dantec hot film probe mountings. Shear stresses could thus be measured at 4 different radial locations under the SedErode bell head.

The hot film shear stress probes were precalibrated at PEP so that the conversion from voltage output to applied shear stress was known for each pair of probes before insertion into the SedErode calibration rig. Some post calibrations were also undertaken.

The water used to calibrate SedErode was deaerated tap water with a small addition of Decon wetting agent. The SedErode pump generated heat during the calibration runs, and the temperature of the recirculating water was measured at the start of each discharge step so that a correction for the applied shear stress (via viscosity) could be made.

5.1.1 SedErode discharge calibration

The discharge through the SedErode system was calibrated at HR Wallingford against the control box settings (pump voltage, battery voltage and pump current). It was found that the discharge was only dependent on the pump voltage.

The discharges were measured using an electromagnetic flowmeter inserted into the SedErode pipework. A correction factor was evaluated to allow for the loss in pumping discharge efficiency due to the additional pipework and flow meter (see Appendix 2 for details).

Figure 7 shows the SedErode discharge calibration against pump voltage after corrections for loss of head via the flowmeter and additional pipework.

5.1.2 Calibration of the hot film shear stress probes

The calibration of the hot film shear stress probe pairs was carried out by PEP 4 weeks prior to the visit by HR Wallingford. The calibration method is explained by Graham et al (1992). The voltage-squared output of the hot film shear stress probes is related to the cube-root of the applied shear stress. Figure 8 shows the pre calibration data for the probe pairs 37 and 38.

The shear stress data obtained from the hot film shear stress probes was corrected for changes in water viscosity due to temperature changes.

5.2 Measurements

5.2.1 Settings

3 different gaps were tested which covered the expected operational gap range under the SedErode head. The mid-gap was 5.6mm with an overall expected tolerance of ±1mm. The gaps settings for the calibration runs suggested were set out in Table 1.

Each calibration run involved the measurement of applied shear stresses under the bell head over the SedErode operational discharge (and thus shear stress) range (0 to 0.4ls^{-1}, corresponding to 0 - 2Nm^{-2}).

5.2.2 Method

For each radius, gap and flow setting 5 readings of the hot film shear stress voltage were taken at 10 second intervals. The measurements were taken when the flow under the bell head was stable and any bubbles under the head had been removed. Each calibration run consisted of a series of flow steps of about 1 minute duration each and took approximately 15 minutes.

5.3 Results

There were some initial problems with SedErode due to restrictions in the pipework and bubbles under the head, which were resolved by strengthening the pipework and adding a wetting agent to the water. Operational difficulties with the hot film probes resulted in only 25 reliable data points being obtained during the 3 days available for testing (Run 1). The pre-calibration data set (Figure 8) was used to calibrate the measured voltages into applied shear stress values, for Run 1 before observations indicated that the probe pair had lost its original response characteristics.

It was decided, on the basis of the small amount of calibration data to combine the new SedErode calibration data set (25 data points) with the previous ISIS data set (over 200 data points of shear stress for a range of different gap, discharge and radial settings). Both instruments had the same bell head shape and configuration, and differed only in the size and volume of the recirculation system and pump type. It was considered that the applied shear stresses under similar conditions should be the same for both instruments. Comparisons of the

SedErode small data set against the previous ISIS data set showed that these assumptions were justified.

Table 2 summarises the calibration data used to fit the SedErode hydrodynamic function for applied shear stress. The data covers 4 radial positions: 12, 18, 25 and 31mm from the bell head centre, discharges in the range 0.05 to $0.6 ls^{-1}$, and gaps from 4mm to 10mm, based on a bell head shape designed for a gap of 6mm.

5.4 Analysis

The SedErode measured shear stress data was corrected for the temperature and salinity of the water used during the calibration conditions (salinity = 0 ppt). The 4 theoretical functions for laminar and smooth turbulent conditions for flat plate theory and flared pipe theory respectively were tested against the measured data (see Appendix 1). The data was plotted with the following parameters:

$$x = \frac{u_* G}{\nu} = \text{gap Reynolds number} \tag{2}$$

and

$$y = \frac{Q}{D\,\nu} \tag{3}$$

where for SedErode the following values apply:

Q = discharge = 0 - 0.4l/s ($0.4 \times 10^{-3}\ m^3s^{-1}$)
D = internal diameter of bell head (0.09m)
G = gap = 5.8mm (5.8×10^{-3}m)
ν = viscosity (m^2s^{-1}; function of water temperature and salinity)
u_*= friction velocity (ms^{-1})

It was found that the applied shear stress for the discharge range of 0 - 0.4l/s in SedErode fitted the flat plate approach the best and was always laminar at these discharges. Figure 9 shows the flat plate laminar function and the calibration data at different radial positions for the SedErode operational range. A transition from laminar to smooth turbulent conditions occurred at about $2Nm^{-2}$, which corresponded to a gap Reynolds number (x) = 210.

The function for flat plate laminar conditions which best fitted the data set was found to be:

$$\frac{Q}{D\,\nu} = 0.1\left(\frac{u_* G}{\nu}\right)^2 \tag{4}$$

Rearrangement of this formula, and substituting equation for shear stress in terms of friction velocity ($\tau_o = \rho\, u_*^2$) yields the following formula for applied shear stresses generated by the SedErode head:

$$\tau_o = \frac{10\rho\nu.Q}{D\,G^2} = A\,Q \tag{5}$$

where:

A = coefficient of discharge (SI units $kgm^{-4}s^{-1}$)

For a fixed gap as in the SedErode system, it is found that the applied shear stress is simply a linear dependence on the discharge, Q, with the coefficient A, typically between 3 and 5 units, depending on the temperature and salinity of the water, which determine the density and viscosity (Soulsby, 1994). Table 3 provides a look up table for the value of the coefficient A to convert SedErode discharges into applied shear stresses, for a range of typical estuarine temperature and salinities, when the discharge is in litres per second (A units are in $kgm^{-1}l^{-1}s^{-1}$).

Calculation of the variation in the applied shear stress for topographic changes of ±1mm (in the gap) at a maximum discharge of about $0.4ls^{-1}$ produced an approximate error of ±20% in the mean gap shear stress (based on a gap of 5.8mm for SedErode).

Figure 10 shows the measured values of the applied shear stress from the hot film shear stress probes against the calculated shear stresses derived using equation 5. Error bands of ±20% have also been added to indicate the uncertainty in τ due to positioning error which might be expected under typical mudflat topographical conditions.

The laminar flat plate function (equation 5) has been adopted as the calibration equation for subsequent deployments of SedErode and ISIS in the region Q = 0 - 0.4l/s. This supersedes the empirical calibration equation used previously for ISIS calibration (ETSU, 1992).

6 Testing and Deployment method

6.1 Testing

The SedErode instrument was tested both in the laboratory and field to ensure that it was fit for purpose. Some fine tuning of both the design and the choice of components was made after testing on the mudflats close to Mersea boat hard. This included changing the pump to a higher specification version to ensure discharges up to about $0.4ls^{-1}$, minor modifications to the positioning and configuration of the recirculating pipework, joints and logging ports and recharging circuitry.

Laboratory tests included checking that the discharge output was stable, easy to control and gave the correct discharge range and power consumption. The final instrument was capable of producing up to $0.4ls^{-1}$ via a dial control. The control box contains 2 x 12v gel batteries which provide enough power for around 6 hours under typical SedErode operating conditions in the field (ie. increasing discharge steps). Continuous use of SedErode at maximum discharge would drain the batteries in about 1 hour or so. Recharging takes about 7 hours so a backup battery pack is also available. The SedErode instrument was found to be portable and self-contained and highly suitable for measurements at the low water period on most intertidal sediments.

Field testing included site visits and trials at 3 different muddy sediment locations; a typical estuarine mudflat at low water (King's Hard, West Mersea), estuarine saltmarsh close to Mersea Island causeway, and the edge of a freshwater reservoir. SedErode proved easy to deploy at all of these locations, and a typical measurement time including positioning for the deployment, data collection and removal took around 20 minutes. Plate 2 shows SedErode being tested close to King's Hard.

SedErode was fully tested in the Dollard Estuary, Holland, in May 1996 where it was used to measure erodibility as part of a collaborative mudflat study (EC funded INTRMUD project). A total of 16 measurements of critical erosion shear stress were made over three low water exposure periods (Mitchener and Feates, 1996), with the typical SedErode deployment time lasting approximately 15 minutes. Once again the instrument was found to be highly suitable for use under typical intertidal mudflat conditions.

6.2 Deployment method

A suitable operational procedure for SedErode under typical intertidal mudflat conditions is as follows:

- Position SedErode onto a flat, representative section of bed sediment, by pushing the locating tube into the sediment until the instrument is supported by the flange. Take auxiliary measurements, photographs, or surface samples if required.

- slowly fill the system with local, deaerated clear water and bleed the system of air.

- establish any logging connections and zero the nephelometer.

- run for 2 minutes at the lowest pump setting (1.5 on the dial produces about $0.05 ls^{-1}$) to establish a turbidity baseline prior to applying higher shear stresses

- increment the discharges (thus applied shear stresses) by 0.5 increments on the dial setting on the control box, allowing 1 minute at each setting

- run each applied shear stress step for 1 minute (monitoring the turbidity at the start and end of each step)

- establish the point of erosion by analysis of the turbidity time series, when a large jump in turbidity occurs, and confirm that bulk erosion has occurred by ensuring that more erosion occurs at the next highest discharge setting.

- slowly reduce the discharge, turn off the control box, and remove SedErode from the mud surface. Clean SedErode head section if required before positioning on the next site.

7 Analysis of results

The output from the SedErode measurements can be logged to produce a time series of applied shear stress and turbidity in the system. The turbidity can be directly calibrated against the concentration of the mud under test, and this record gives the sediment response to the applied shear stress steps. Figure 11 shows an example of the typical results.

Analysis of the time series data yields the value of shear stress for the onset of surface erosion, and the erosion rate as material is removed from the surface. The interpretation as to the definition of erosion depends on the application of the results, but for most engineering purposes it is practical to consider that erosion occurs when there is "bulk erosion" which continues when a higher shear stress is applied (Amos et al, 1992). Another definition of cohesive sediment erosion is "benign erosion", when loose surface deposits are removed and resulting in small discontinuous turbidity increases. The use of the SedErode instrument and results can be chosen by the user and the interpretation varied to investigate specific erosion characteristics of cohesive sediments.

8 Applications

SedErode can be used on any cohesive-based sediment to measure the surface erosion shear stress, a fundamental parameter for input into predictive models of coastal and estuarine cohesive sediments. Measurements have enabled the relationship between erosion shear stress and simpler measures of sediment properties, such as density and sand content, to be investigated. Examples of sites at which SedErode can be deployed to provide useful data are:

- intertidal mudflats
- river banks
- coastal areas
- sewer and drainage systems
- saltmarshes
- reservoirs

To date SedErode (and its predecessor ISIS) have been used to measure in excess of 130 measurements of surface critical erosion shear stress at intertidal sites covering the Dollard Estuary (Netherlands), 3 sites in Severn Estuary (UK), Humber Estuary (UK), Tollesbury Creek, Essex (UK), and Mersea Island, Essex (UK).

ISIS has also been used successfully on a MAFF ship cruise to measure the erosion shear stress of underwater sediment surface cores from the Sellafield mud patch. A small modification to the ISIS positioning frame was made so that the ISIS head section could be deployed on NIOZ core samples. A total of 19 measurements of critical erosion shear stress were made over a period of 3 days. The details of these measurements are given by Feates and Mitchener (1996).

Future developments of SedErode, using experience and knowledge gained during this project may include an underwater version of SedErode, either diver-positioned or within a 'lander frame' which could be deployed from a small ship.

9 Conclusions

The ISIS instrument for measuring the critical erosion shear stress of cohesive sediment has been successfully improved and tested and a superior version, SedErode, has been manufactured. SedErode operates on exactly the same principles as ISIS, but differs from ISIS owing to the following improvements:

- increased portability, weighing only 21kg in total

- control box and head unit, carryable by one person in typical field conditions
- fixed bell head to sediment gap - less user interaction required
- shear stress range 0 - 2Nm^{-2} - applicable for typical coastal and estuarine sediment
- easier to use and faster deployment time of about 15 minutes

The new instrument SedErode has been found to be reliable in the field and easy to carry and position. As a direct result of the total measurement time having been reduced to about 15 minutes, more measurements of the critical erosion shear stress over typical intertidal mudflats during low water exposure periods can be made. To date over 130 measurements of erosion shear stress have been made with SedErode and its predecessor ISIS.

SedErode can still be used on seabed core samples and the laboratory, with the use of purpose-built flanges for positioning.

It is now expected that the SedErode instrument will be used for routine measurements of erosion shear stress in the UK and abroad, so that the factors controlling the erodibility of cohesive sediments can be better understood and predicted.

10 Acknowledgements

Thanks are due to Mr J S Damgaard for his input into the theoretical considerations, and Mrs E C Stevenson and Mr R W Adams for their assistance with processing the calibration data. The hot film shear stress probes used for calibration were provided by PEP, Plymouth Ltd.

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(* Please note that H J Mitchener was H J Williamson prior to 6.8.96)

Tables

Table 1 SedErode calibration test plan

RADII 12 and 31mm (Calibration plate A)

Run 1	gap 6.5mm (mid-gap)
Run 2	gap 4.6mm (error estimation at high shear stress)
Run 3	gap 6.5mm (repeat 1 of mid-gap)
Run 4	gap 7.4mm (error estimation at low shear stress)
Run 5	gap 6.5mm (repeat 2 of mid-gap)

RADII 18 and 25mm (Calibration plate B)

Run 6	gap 6.5mm (mid-gap)
Run 7	gap 4.6mm (error estimation at high shear stress)
Run 8	gap 6.5mm (repeat 1 of mid-gap)
Run 9	gap 7.4mm (error estimation at low shear stress)
Run 10	gap 6.5mm (repeat 2 of mid-gap)

SedErode Setting	Approximate Discharge (ls^{-1})
2	0.05
3	0.10
4	0.15
5	0.20
6	0.25
7	0.30
8	0.35
9	0.40
10	0.45

Table 2 Summary of the calibration data used to fit the applied shear stress function

Instrument	Gap (mm)	Radius (cm)
SedErode	7.4	12
ISIS	4	12,18,25,31
ISIS	5	12,18,25,31
ISIS	6	12,18,25,31
ISIS	7	12,18,25,
ISIS	8	25
ISIS	9	25
ISIS	10	25

Table 3 Look up table for the coefficient A to convert SedErode discharges (l/s) to applied stress for different water temperature and salinity

		Look-up table for coefficient A ($kgm^{-1}l^{-1}s^{-1}$)																				
		Temperature (°C)																				
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Salinity (ppt)	0	5.92	5.72	5.53	5.35	5.18	5.02	4.86	4.72	4.58	4.45	4.32	4.20	4.08	3.97	3.87	3.76	3.67	3.58	3.49	3.40	3.32
	1	5.91	5.75	5.59	5.43	5.27	5.11	4.96	4.80	4.64	4.48	4.32	4.22	4.12	4.02	3.92	3.82	3.72	3.62	3.52	3.42	3.32
	2	5.92	5.76	5.60	5.44	5.28	5.12	4.96	4.80	4.65	4.49	4.33	4.23	4.13	4.03	3.93	3.82	3.72	3.62	3.52	3.42	3.32
	3	5.93	5.77	5.61	5.45	5.29	5.13	4.97	4.81	4.65	4.49	4.34	4.23	4.13	4.03	3.93	3.83	3.73	3.63	3.53	3.43	3.33
	4	5.93	5.78	5.62	5.46	5.30	5.14	4.98	4.82	4.66	4.50	4.34	4.24	4.14	4.04	3.94	3.84	3.74	3.64	3.54	3.44	3.34
	5	5.94	5.78	5.62	5.47	5.31	5.15	4.99	4.83	4.67	4.51	4.35	4.25	4.15	4.05	3.95	3.85	3.75	3.64	3.54	3.44	3.34
	6	5.95	5.79	5.63	5.47	5.31	5.15	5.00	4.84	4.68	4.52	4.36	4.26	4.16	4.06	3.95	3.85	3.75	3.65	3.55	3.45	3.35
	7	5.96	5.80	5.64	5.48	5.32	5.16	5.00	4.84	4.68	4.53	4.37	4.26	4.16	4.06	3.96	3.86	3.76	3.66	3.56	3.46	3.36
	8	5.97	5.81	5.65	5.49	5.33	5.17	5.01	4.85	4.69	4.53	4.37	4.27	4.17	4.07	3.97	3.87	3.77	3.67	3.56	3.46	3.36
	9	5.98	5.82	5.66	5.50	5.34	5.18	5.02	4.86	4.70	4.54	4.38	4.28	4.18	4.08	3.98	3.87	3.77	3.67	3.57	3.47	3.37
	10	5.98	5.83	5.67	5.51	5.35	5.19	5.03	4.87	4.71	4.55	4.39	4.29	4.19	4.08	3.98	3.88	3.78	3.68	3.58	3.48	3.38
	11	5.99	5.83	5.67	5.51	5.35	5.19	5.04	4.88	4.72	4.56	4.40	4.30	4.19	4.09	3.99	3.89	3.79	3.69	3.59	3.48	3.38
	12	6.00	5.84	5.68	5.52	5.36	5.20	5.04	4.88	4.72	4.56	4.40	4.30	4.20	4.10	4.00	3.90	3.80	3.69	3.59	3.49	3.39
	13	6.01	5.85	5.69	5.53	5.37	5.21	5.05	4.89	4.73	4.57	4.41	4.31	4.21	4.11	4.01	3.90	3.80	3.70	3.60	3.50	3.40
	14	6.02	5.86	5.70	5.54	5.38	5.22	5.06	4.90	4.74	4.58	4.42	4.32	4.22	4.11	4.01	3.91	3.81	3.71	3.61	3.50	3.40
	15	6.03	5.87	5.71	5.55	5.39	5.23	5.07	4.91	4.75	4.59	4.43	4.33	4.22	4.12	4.02	3.92	3.82	3.71	3.61	3.51	3.41
	16	6.04	5.88	5.72	5.56	5.40	5.24	5.08	4.92	4.76	4.60	4.44	4.33	4.23	4.13	4.03	3.93	3.82	3.72	3.62	3.52	3.42
	17	6.04	5.88	5.72	5.56	5.40	5.24	5.08	4.92	4.76	4.60	4.44	4.34	4.24	4.14	4.03	3.93	3.83	3.73	3.63	3.52	3.42
	18	6.05	5.89	5.73	5.57	5.41	5.25	5.09	4.93	4.77	4.61	4.45	4.35	4.25	4.14	4.04	3.94	3.84	3.74	3.63	3.53	3.43
	19	6.06	5.90	5.74	5.58	5.42	5.26	5.10	4.94	4.78	4.62	4.46	4.36	4.25	4.15	4.05	3.95	3.84	3.74	3.64	3.54	3.44
	20	6.07	5.91	5.75	5.59	5.43	5.27	5.11	4.95	4.79	4.63	4.47	4.36	4.26	4.16	4.06	3.95	3.85	3.75	3.65	3.55	3.44

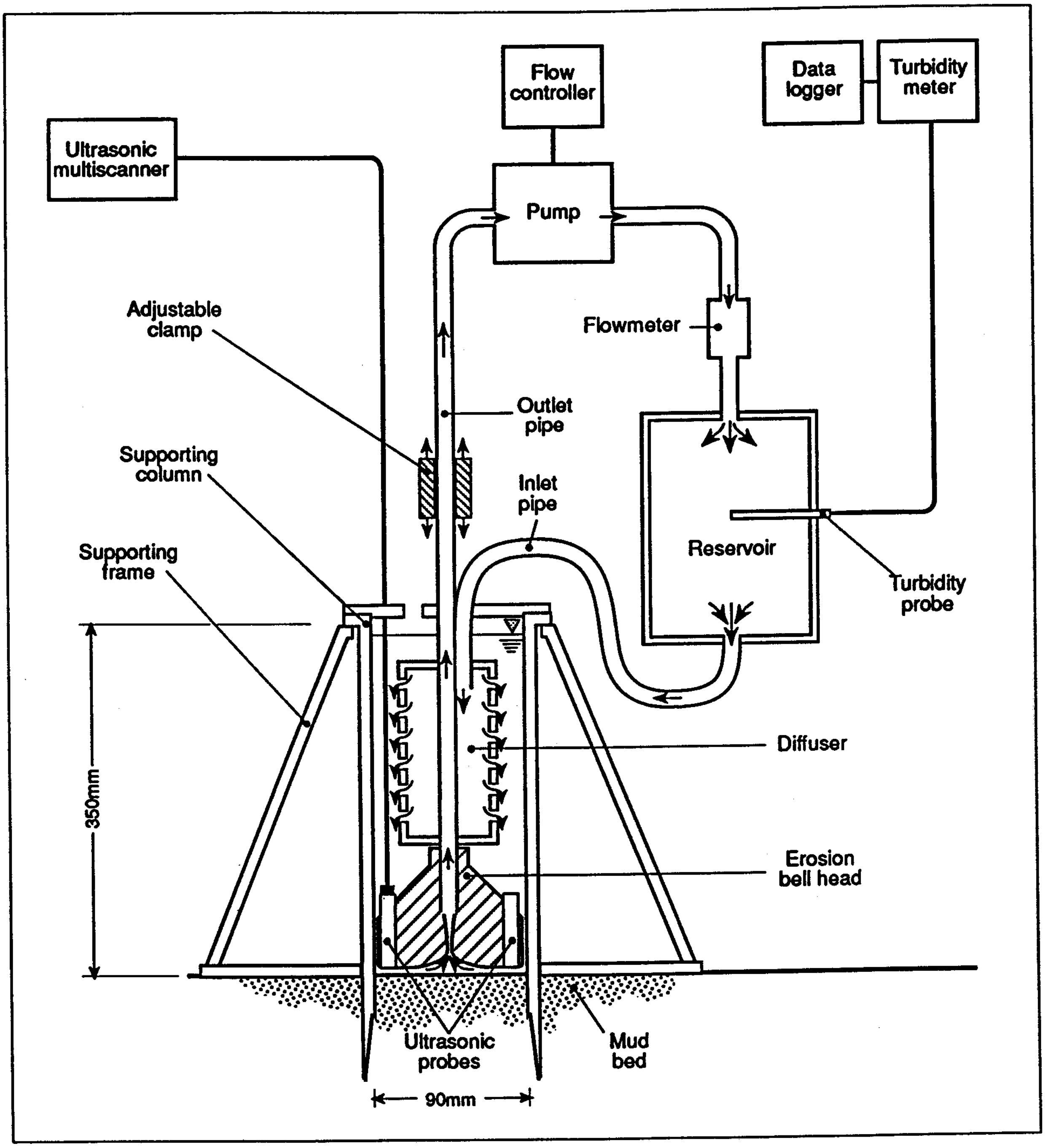
for $\tau = AQ$

τ = applied shear stress (Nm^{-2})

Q = discharge (ls^{-1})

A = coefficient of discharge in ls^{-1} (units $kgm^{-1}\,l^{-1}s^{-1}$)

Figures



ISIS - Instrument for Shear strength In-Situ

Figure 1 Previous ISIS system diagram

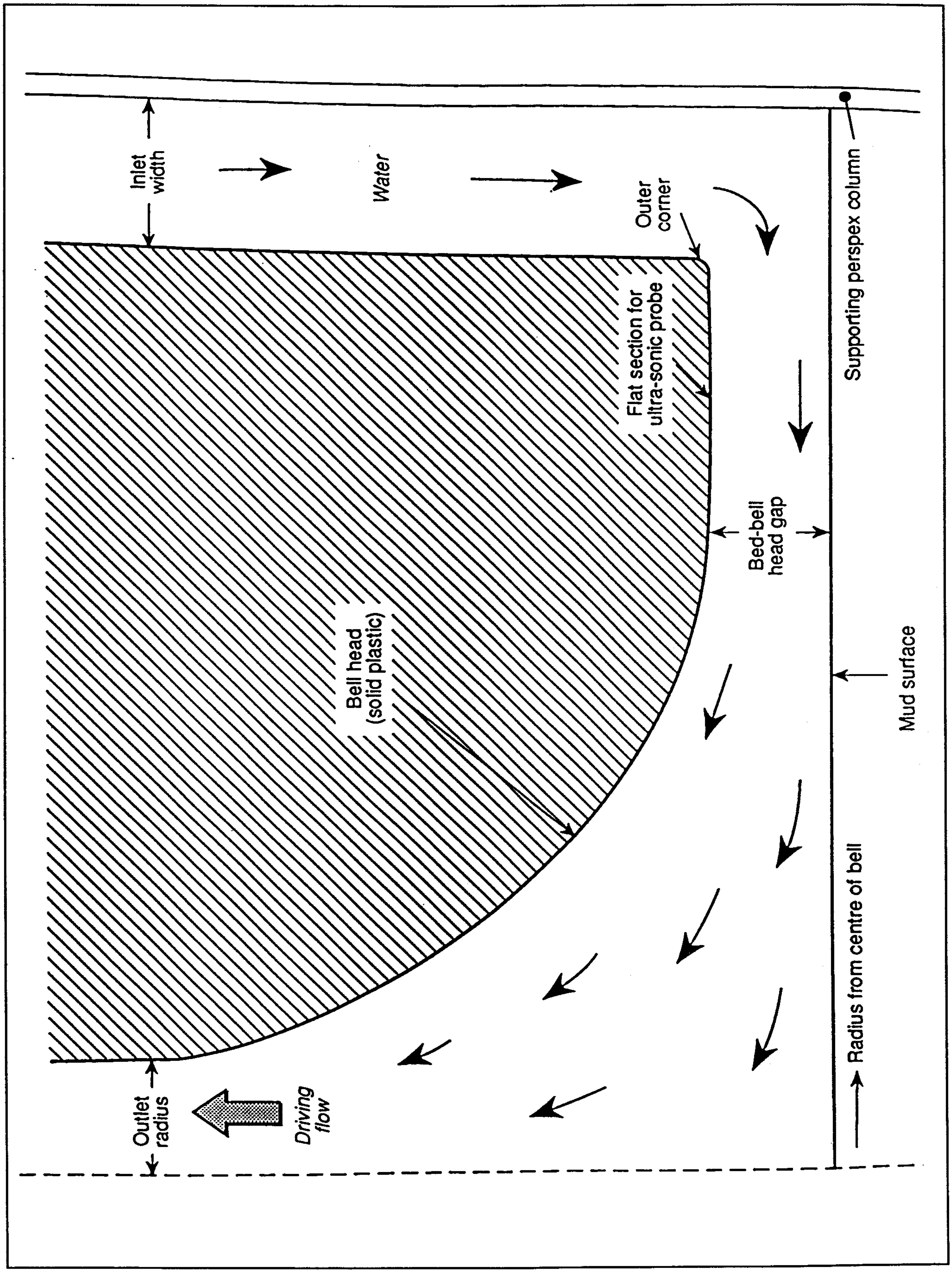


Figure 2   Shape and flow characteristics under the bell head

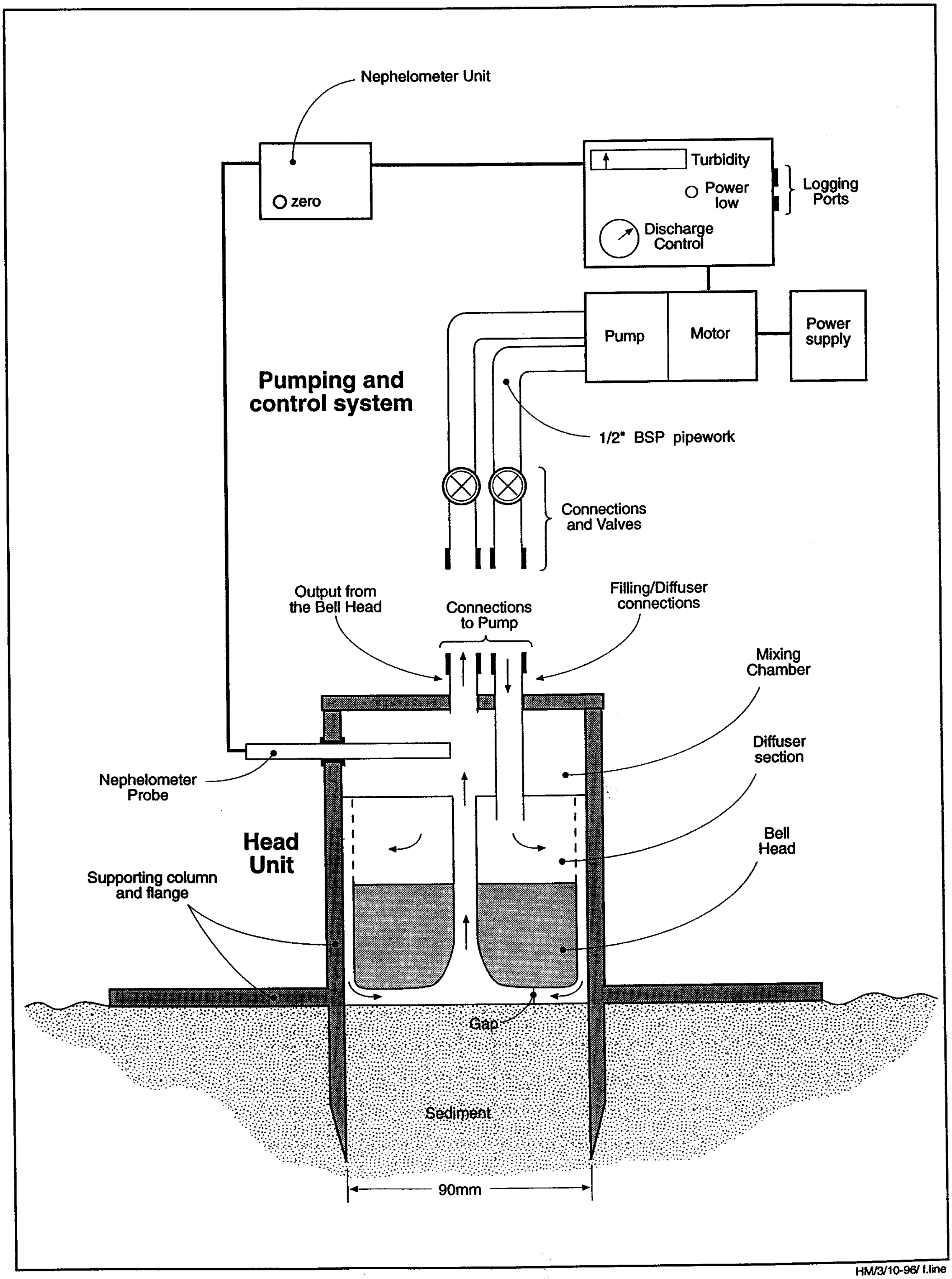


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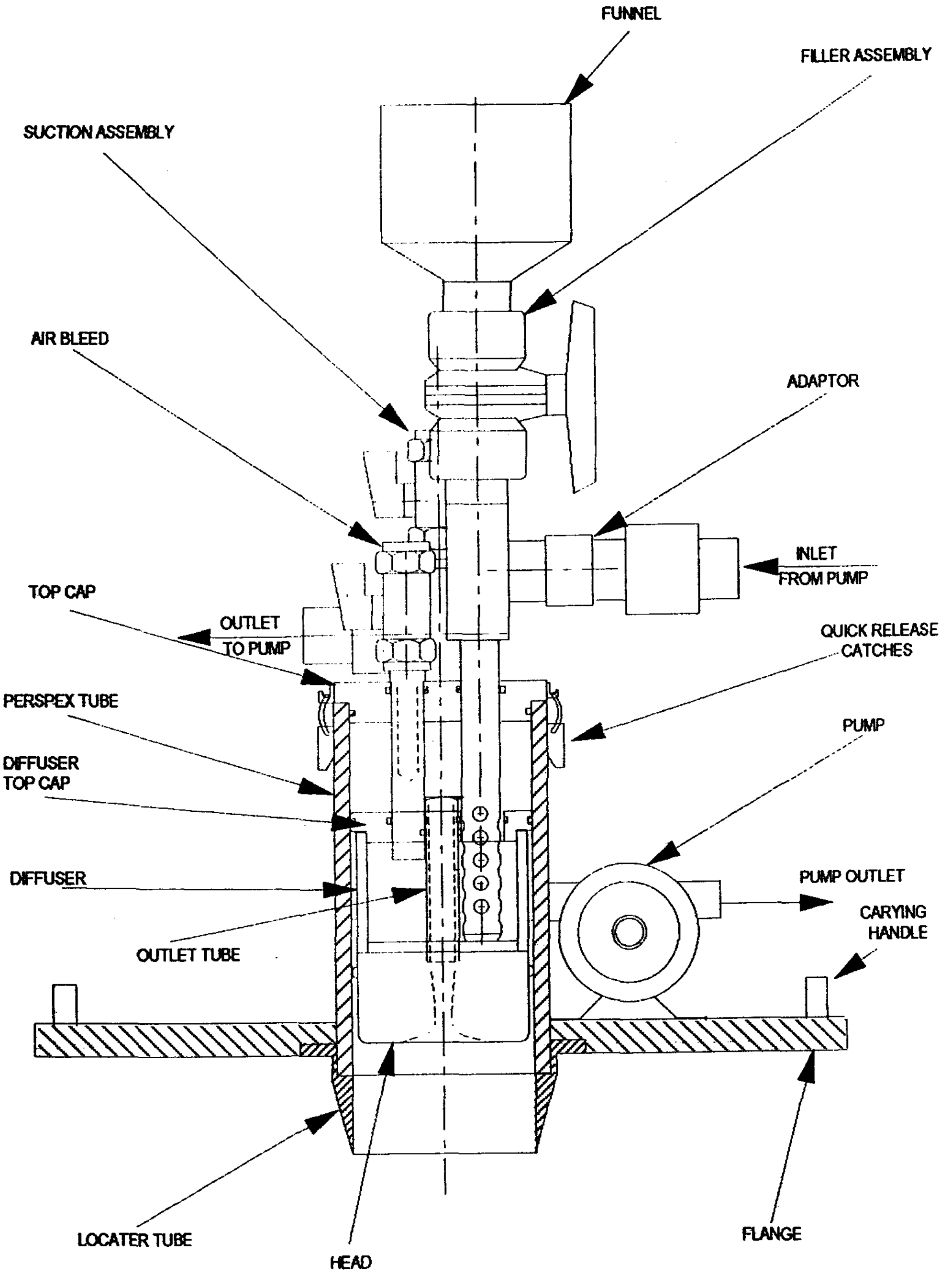
Figure 3 Main conceptual elements of the SedErode design



HEIGHT	400 mm
DIAMETER	400 mm
WATER VOLUME	1 litre (approx)
WEIGHT	9 Kg

Figure 4 The general arrangement of the SedErode design

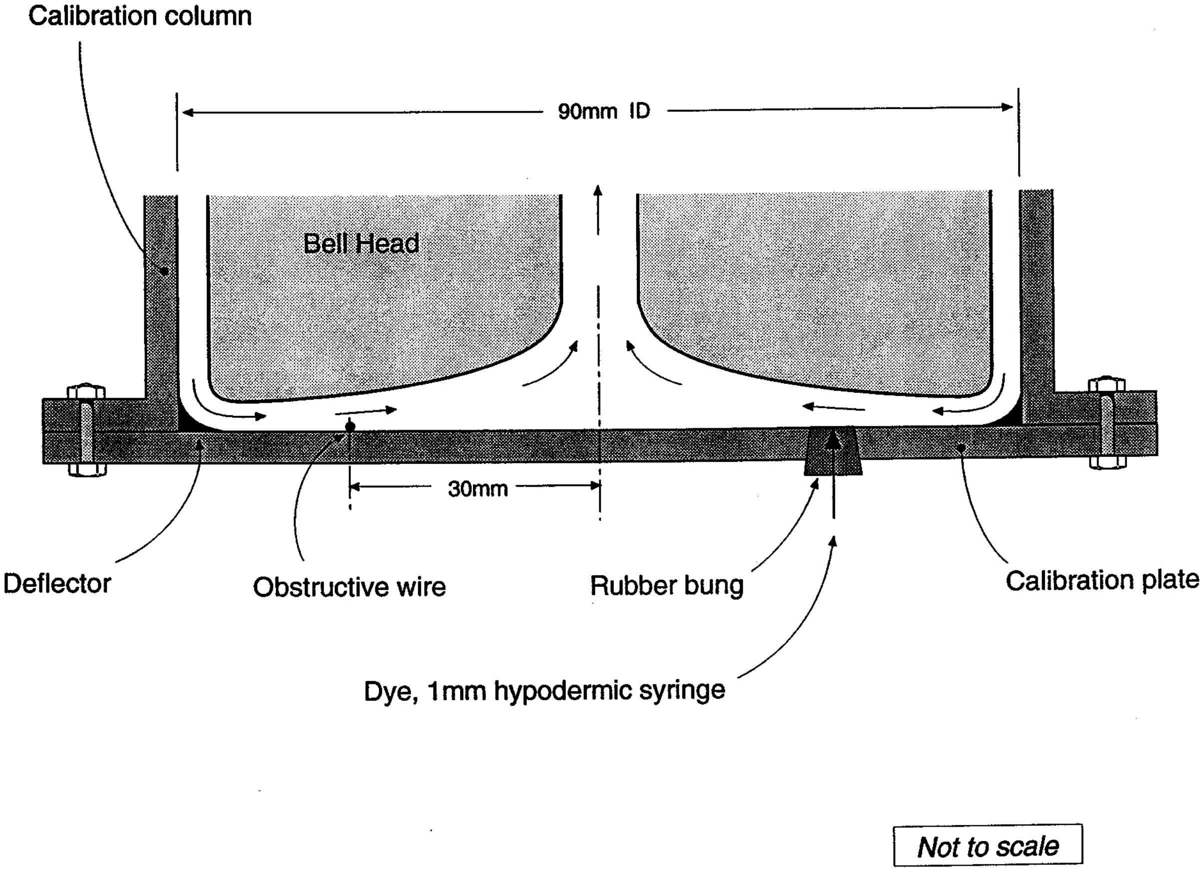


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Figure 5 Set up for dye-release tests

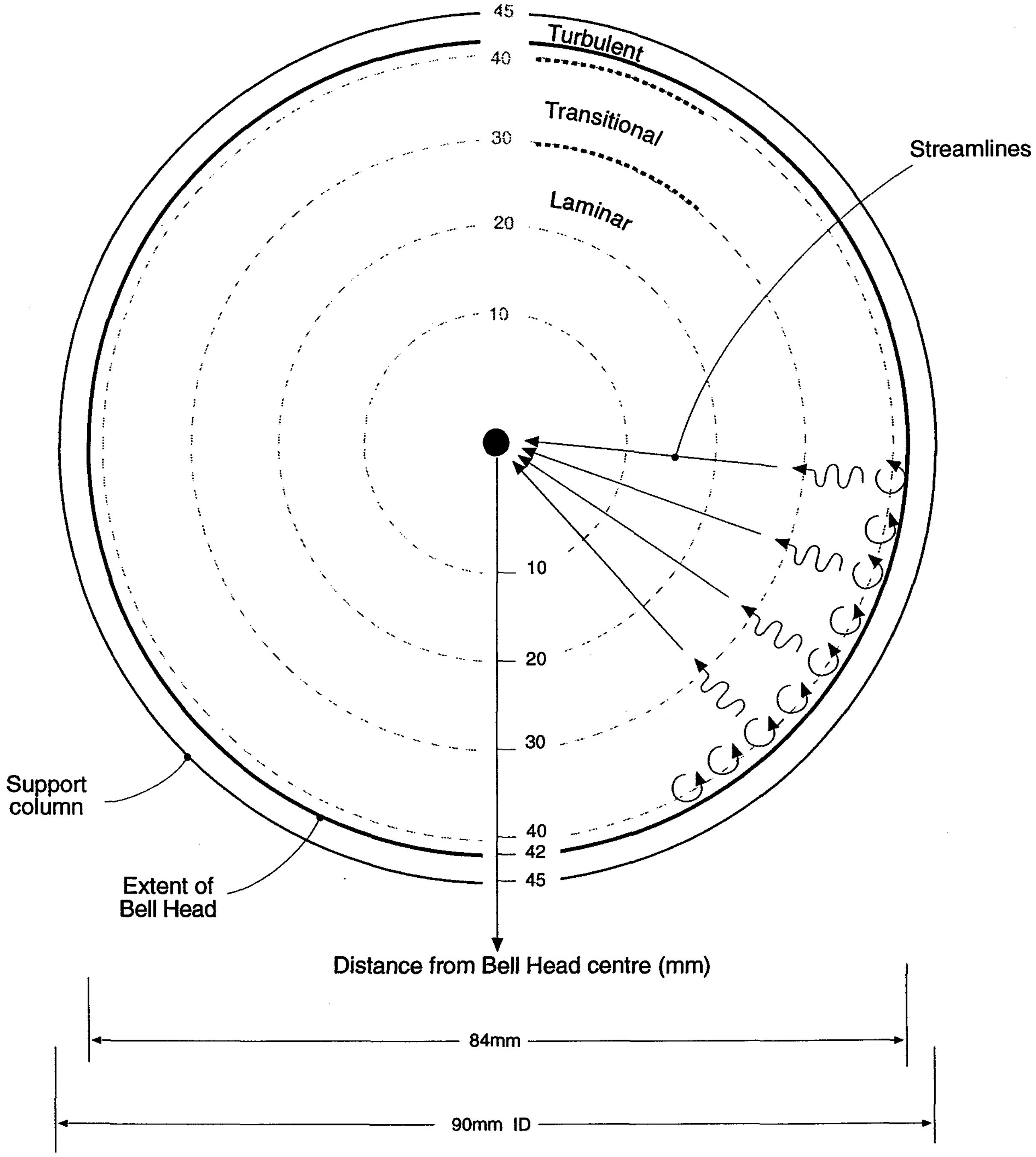

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Figure 6 Diagram of typical flow conditions observed during dye-release tests

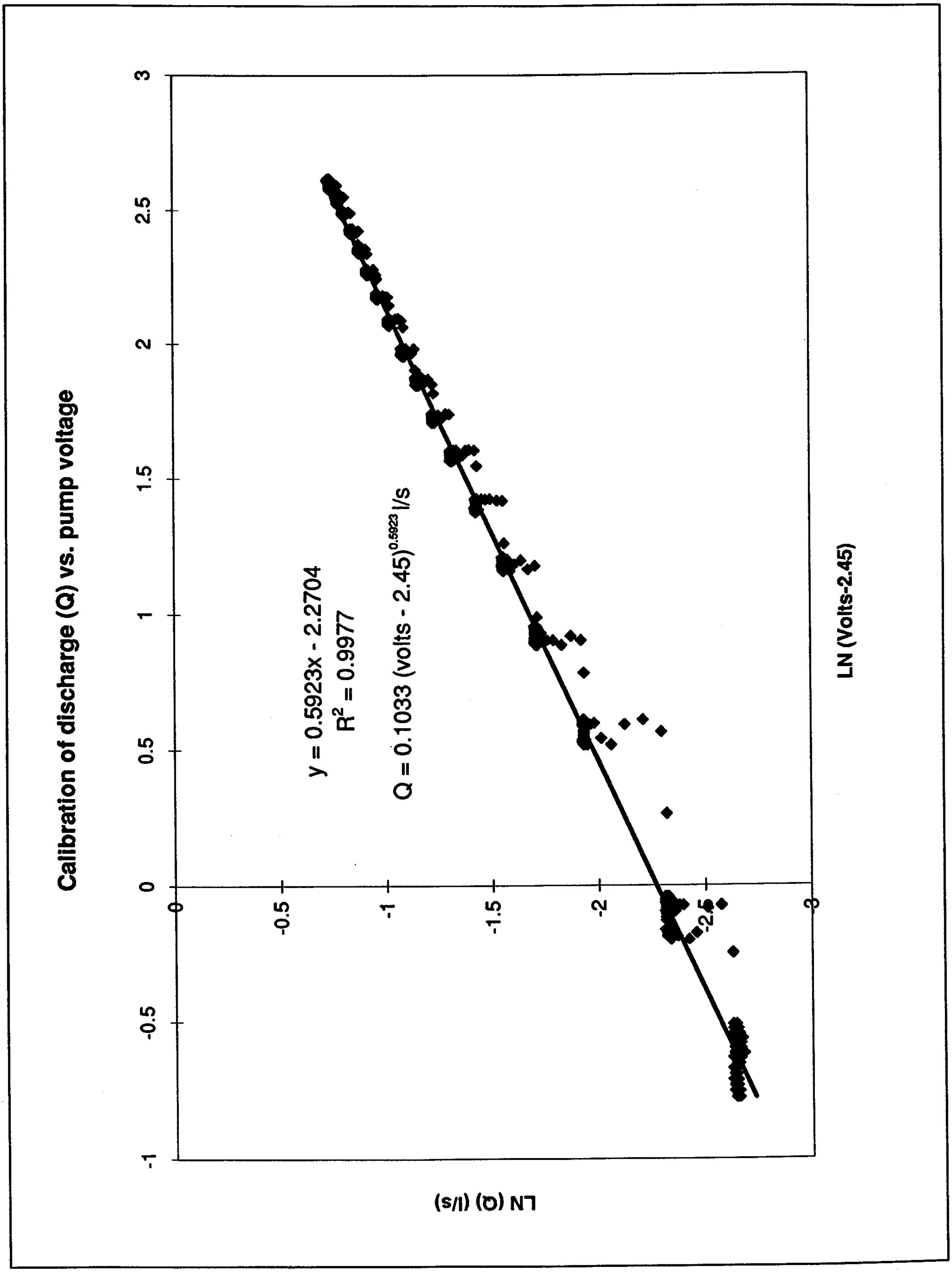


Figure 7   SedErode discharge calibration against pump voltage

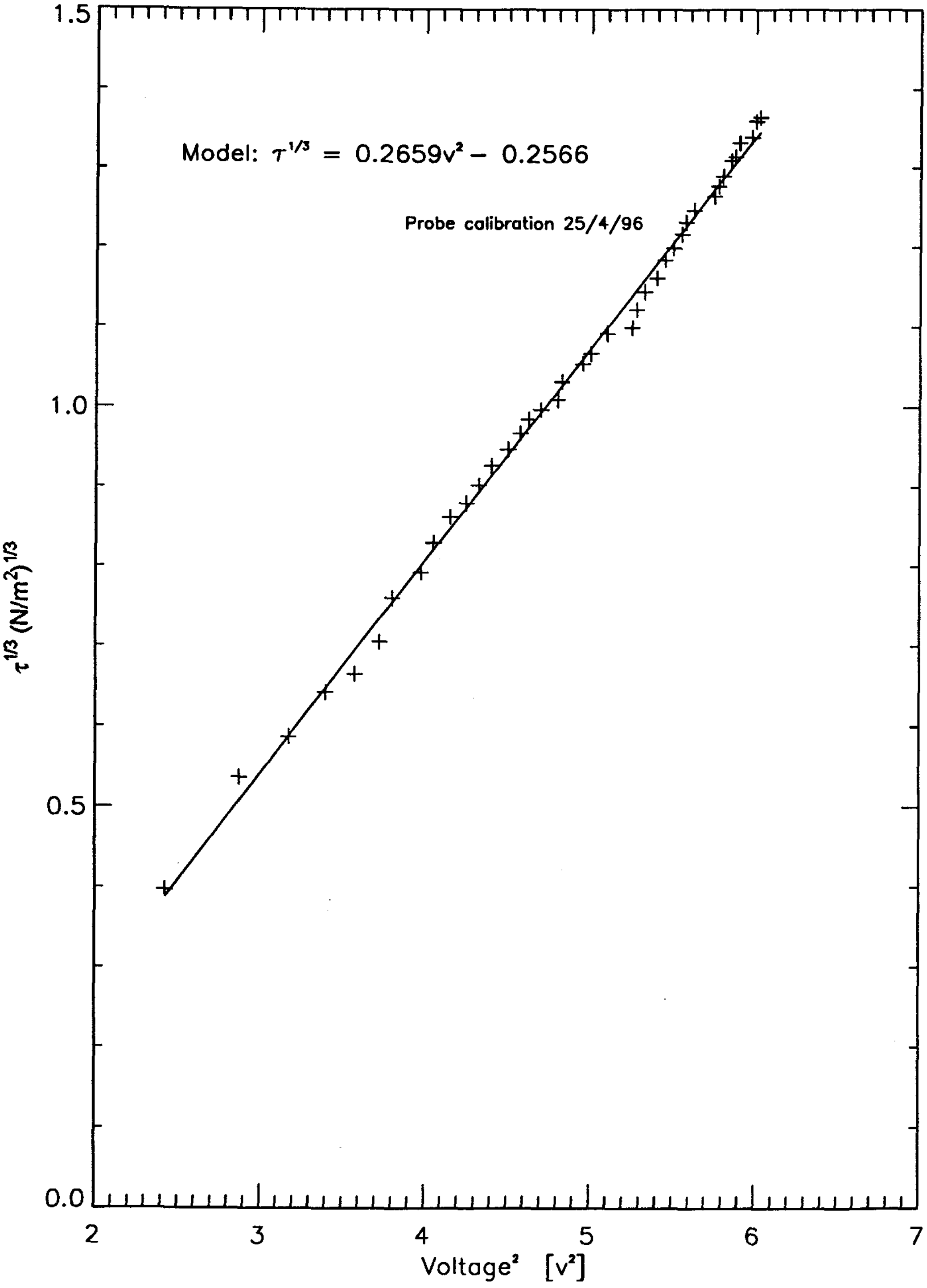


Figure 8 Calibration curve for the hot film shear stress probe pair 37 an 38

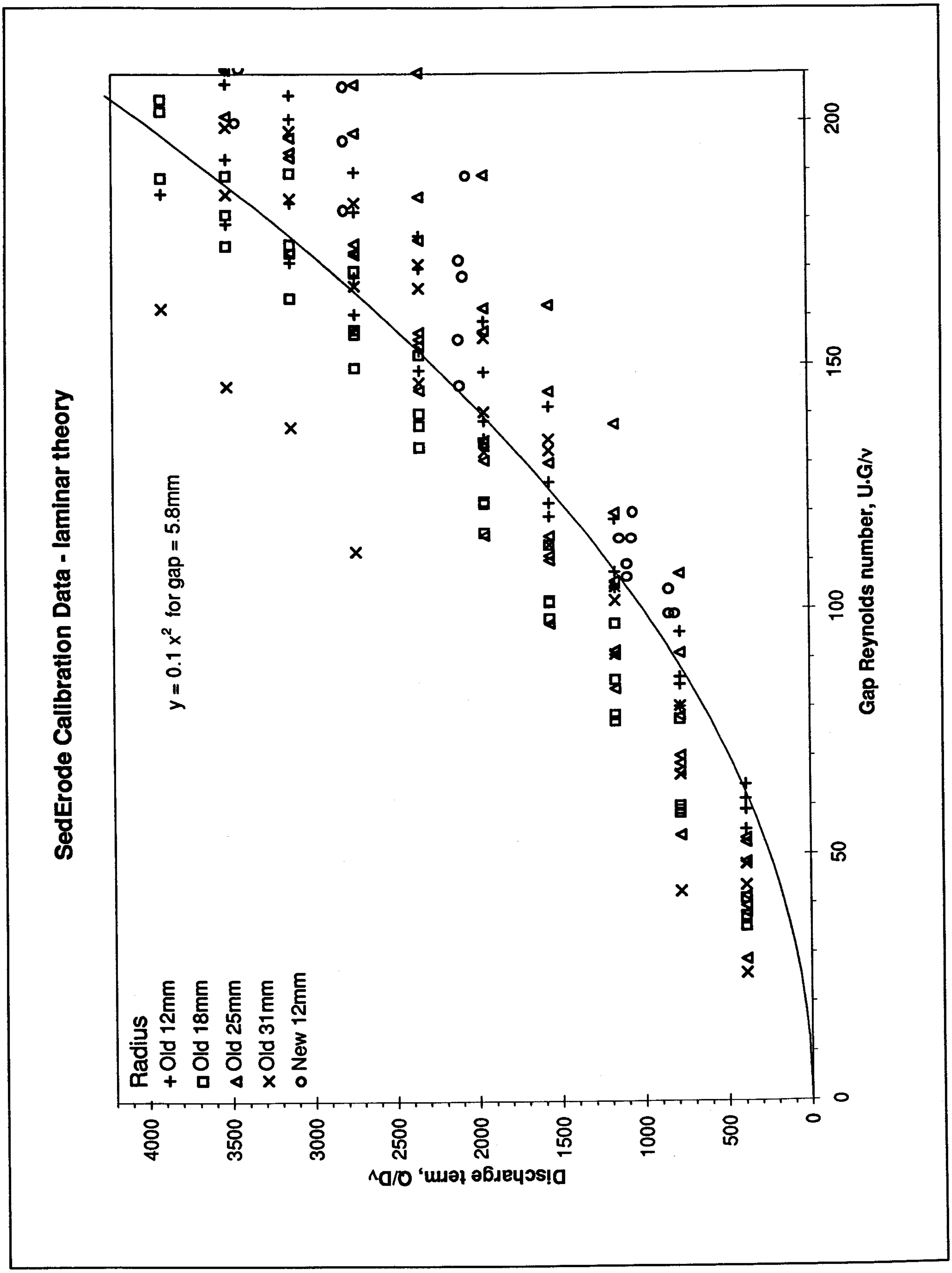


Figure 9 Calibration data and fitted laminar function for applied shear stress

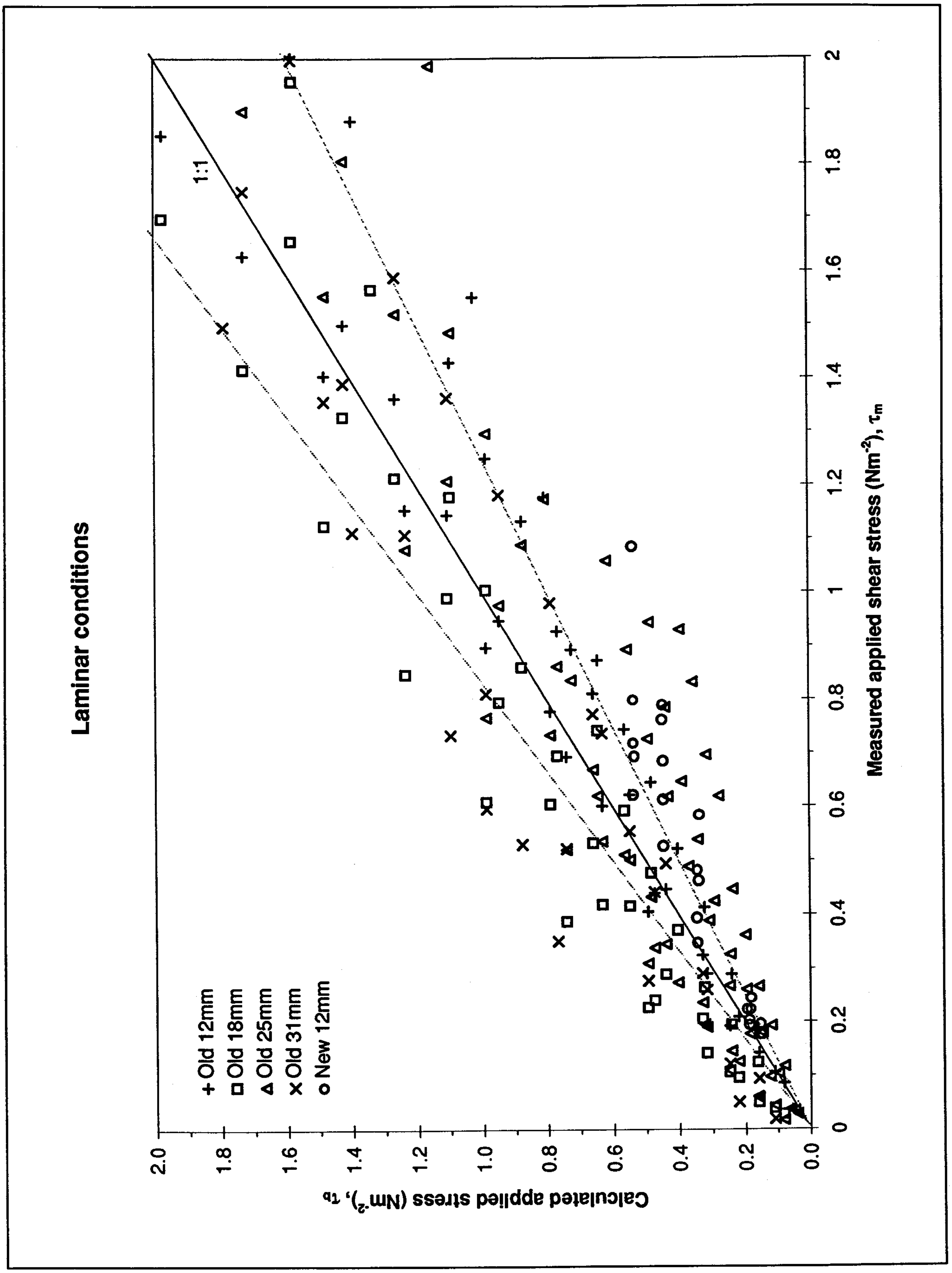
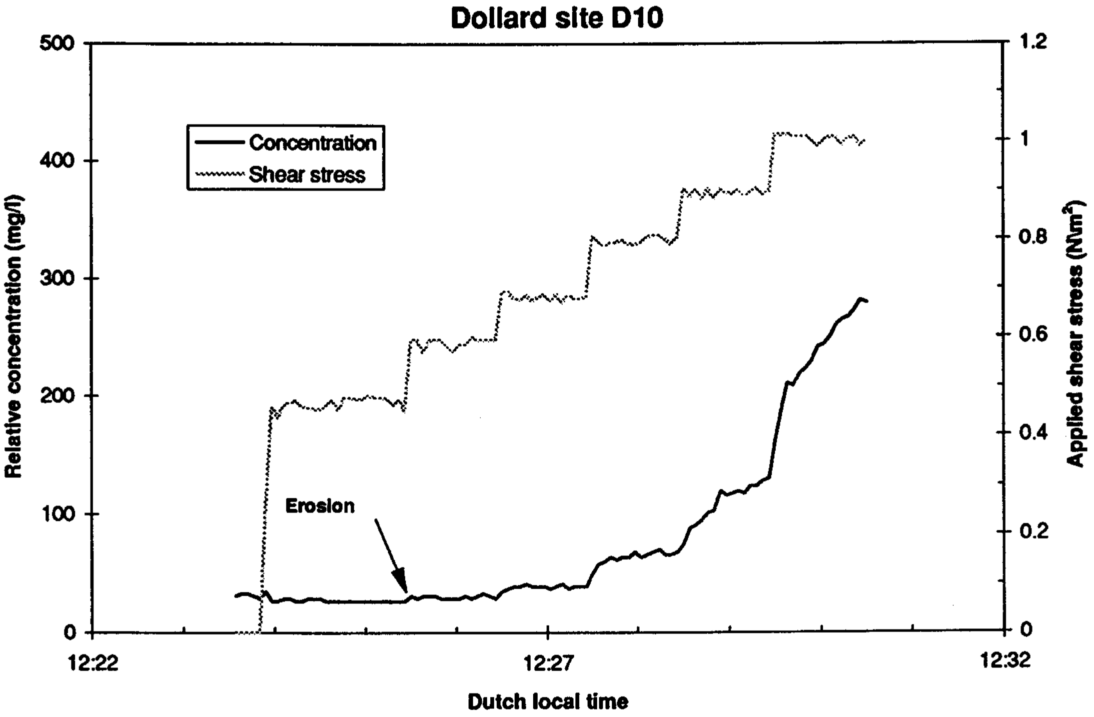


Figure 10 Predicted vs measured applied shear stress for the SedErode calibration



Site: **Dollard Estuary, Netherlands**
Time: 12:18
Date: 22/05/96
Operator: H.J.Mitchener

Data file: (downloaded from Squirrel data logger)
Path: ..\sediments\helen\intrmud\dollard\d10.l01

Site description:
texture: medium / hard
colour: medium
covering: algal film
topography: pitted / smooth
biologically activity: ~
composition: mud / sand
other features: ~

Surface sample: (from top 5mm) - D10
Bulk density: 1800kg/m^3
Sand content: 83.66%
Mud content: 16.34%
Organic carbon (by ignition): 3.79%

Shear vane: 33mm vane
Observer: N.Feates
Measurements (kPa): 3.3
3.6
3.9
3.3
4.0
Average: 3.6

Photographs: Film 2
Time: 12:18 Number: 29
Time: 12:18 Number: 30
Time: ~ Number: 31

Critical erosion shear stress: 0.60N/m^2

Figure 11 Example of typical results obtained using SedErode

Plates

Plate 1 Close-up of the SedErode head section

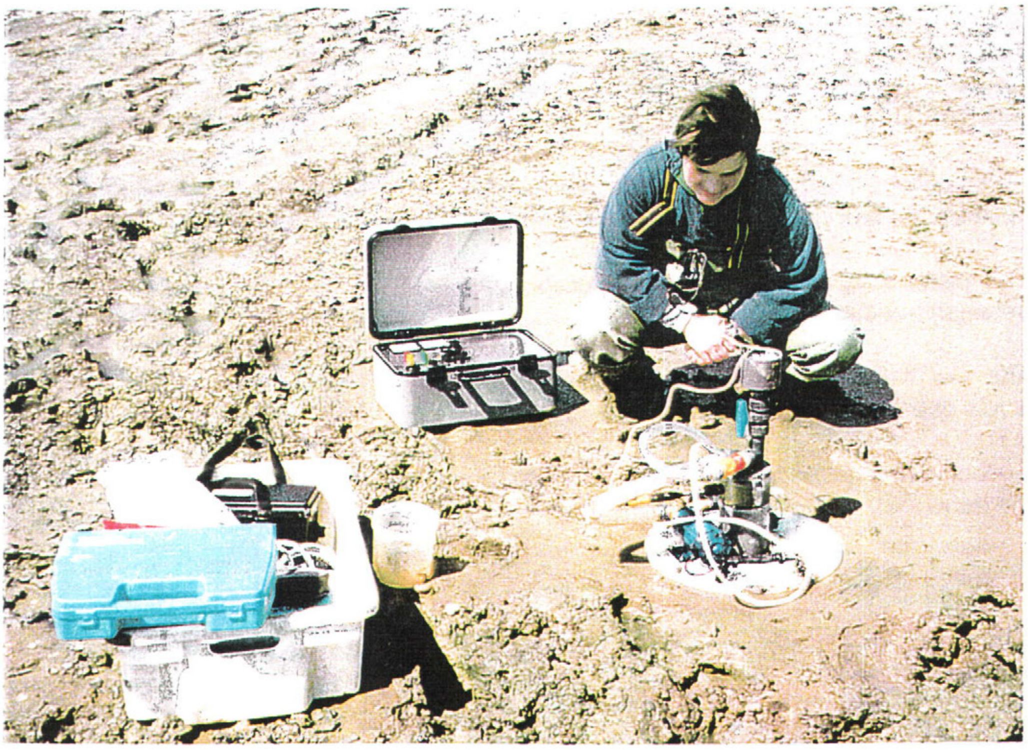


Plate 2 SedErode in action at West Mersea during testing

Appendices

Appendix 1 Theoretical Approaches to the Flow Regime under the bell head

i) Approach 1 (Flat plates)

The first approach was to assume that the hydrodynamic regime under the bell head could be likened to radial flow between two parallel plates whose separation increases gradually towards the origin (see Figure A1.1). The parameters are:

r = radius from the centre of the bell head (m)
a = radius of outlet tube opening (m)
h = distance from bell head to sediment surface (m)
D = diameter of bell head (0.09m)
G = gap under flat section (m)
Q = discharge (m^3s^{-1})
h(r) = function describing the shape of the bell head
z_{om} = roughness of underlying mud surface (m)
z_{ot} = roughness of bell head surface (m)
z = height above sediment surface (m)
τ_b = applied bed shear stress (Nm^{-2})
u_* = friction velocity (ms^{-1})
ν = kinematic viscosity (m^2s^{-1})
ρ = water density (kgm^{-3})

The following assumptions and conditions were then applied:

- The equations of continuity and r-momentum were applied in axi-symmetric polar coordinates
- Advective and normal stress terms were neglected
- Pressure dropped off linearly between the outer radius and the outlet tube
- Volume conservation by ensuring that the discharge through any annulus of diameter 2r and height h is constant (ie. constant Q).

The following quantities were investigated:

- variation of bed shear stress with radius
- function for τ_b
- function h(r) (bell head shape) where τ_b is constant
- τ_b dependence on D, G and Q for:

a) Laminar conditions (constant viscosity):

The equation relating shear stress to bell head parameters under laminar conditions is given by:

$$\tau_0 = \frac{6\rho\nu Q}{\pi\ D\ G^2} \tag{1}$$

This expression indicates that under laminar conditions the applied shear stress (τ_b) is:

- proportional to discharge (Q)
- inversely proportional to gap squared (G^2)
- proportional to viscosity (thus dependent on salinity and temperature)

The function for constant radial shear stress under laminar conditions is given by:

$$h(r) = \frac{G\,D^{1/2}}{(2r)^{1/2}} \tag{2}$$

This expression indicates that the shape of the bell head under laminar conditions is only dependent on the gap (G) and the diameter (D).

b) Turbulent conditions (eddy viscosity varying parabolically between z=0 and z=h)

The equation relating the applied shear stress to bell head parameters under turbulent conditions is given by:

$$\tau_b = \rho\left(\frac{\kappa Q}{\pi[\ln(G/z_{om}) - 1 - (\ln(G/z_{om})/\ln(G/z_{ot}))]DG}\right)^2 \tag{3}$$

Now if the bell head and mud surface is hydrodynamically smooth (as deduced from the dye release tests) then:

$$z_{om} = z_{ot} = \frac{\nu}{9u_*} \tag{4}$$

Substitutions for z_{om} and z_{ot} yields the following function for the smooth turbulent definition of the applied shear stress:

$$\tau_b = \rho\left(\frac{\kappa Q}{\pi[\ln(9u_*/\nu) - 2]DG}\right)^2 \tag{5}$$

But

$$\tau_b = \rho u_*^2 \tag{6}$$

which means that u_* is on both sides of the equation and τ_b has to be iteratively solved for the bell head parameters.

ii) Approach 2 (Pipe Flow)

The second approach was to assume that the flow regime under the bell head could be likened to a flared pipe (Figure A1.2). Using the streamflow approach the friction velocity is given by (Rouse, 1949):

$$u_*^2 = IgR \tag{7}$$

Where
I = energy slope (non-dimensional)
g = acceleration due to gravity ($9.81\,ms^{-2}$)
R = hydraulic radius (G/2) (m)

The Reynold's number for the flow is given by Schlichting (1955):

$$R_e = \frac{4Rv}{\nu} \tag{8}$$

where

v = Q/A, cross-sectional average velocity (ms^{-1})

For a maximum discharge in the SedErode system of $0.4 ls^{-1}$ ($4 \times 10^{-4}\ m^3s^{-1}$) and a kinematic viscosity of $1.2 \times 10^{-6}\ m^2s^{-1}$, the value of Reynold's number is about 1300. Therefore it is likely that the flow regime under the bell head is laminar at low SedErode operating discharges and smooth turbulent at higher discharges, with the critical value for laminar pipeflow occurring at about $R_e = 580$.

a) Laminar conditions (constant viscosity):

For laminar flow:

$$\lambda = \frac{64}{R_e} \tag{9}$$

where

$$\lambda = 8\left(\frac{u_*}{v}\right)^2 \tag{10}$$

v = cross-sectional average discharge under the SedErode head ($m^3s^{-1}m^{-2}$)
= Q/A where $A = 2\pi(D/2)G$ (m^2)

Using equation (6) this approach gives the following expression for the applied shear stress:

$$\tau_b = \frac{4\rho\nu Q}{\pi D G^2} \tag{11}$$

This expression implies that the applied shear stress is dependent on the gap, discharge and water conditions (density and viscosity) and is the same form as the flat plate approach, with τ_b proportional to G^{-2} as found in equation 1.

b) Turbulent conditions

For conditions of smooth turbulent flow (Blasius pipe flow):

$$\lambda = \frac{0.316}{R_e^{1/4}} \tag{12}$$

This yields the following expression for the applied shear stress under smooth turbulent conditions:

$$\tau_b = \frac{\rho\nu^{1/4}}{8}\,\frac{0.316}{(2Q/\pi D)^{1/4}}\left(\frac{Q}{\pi D G}\right)^2 \tag{13}$$

This is a fairly complex equation, but defines applied shear stress in terms of the G^{-2} and $Q^{1.75}$, which is similar to the expression found for the flat plate approach (equation 5).

It is important to note that all of equations (1), (5), (11) and (13) can be cast in the dimensionless form:

$$\frac{Q}{D\nu} = f\left(\frac{U_* G}{\nu}\right) \tag{14}$$

Hence, irrespective of which of the theories is most generally correct, it should be possible to derive a calibration curve from the calibration data by plotting ($Q/D\nu$) against ($u_* G/\nu$). The value of u_* can the be read off for a particular set of values of Q, D, G, and ν.

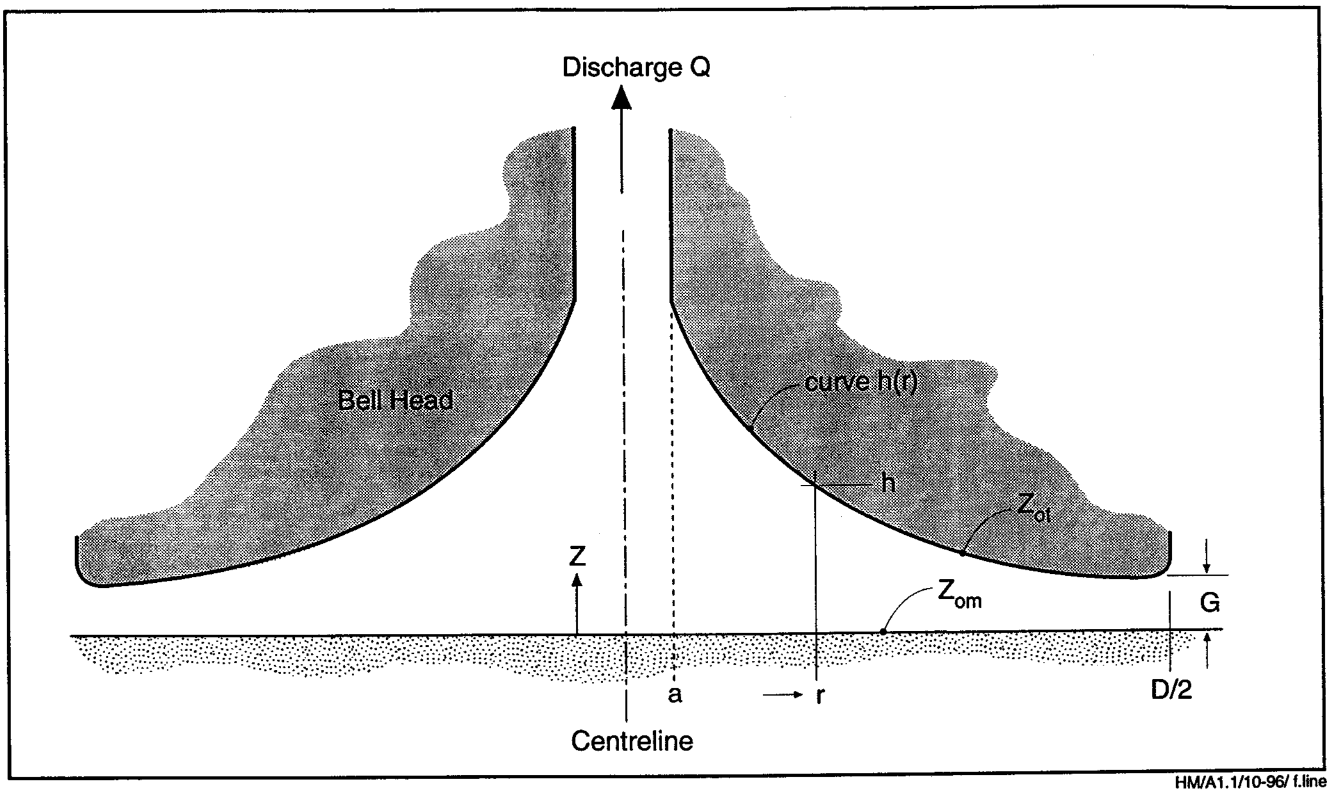


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Figure A1.1 Diagram of the hydrodynamic approach of 2 parallel plates

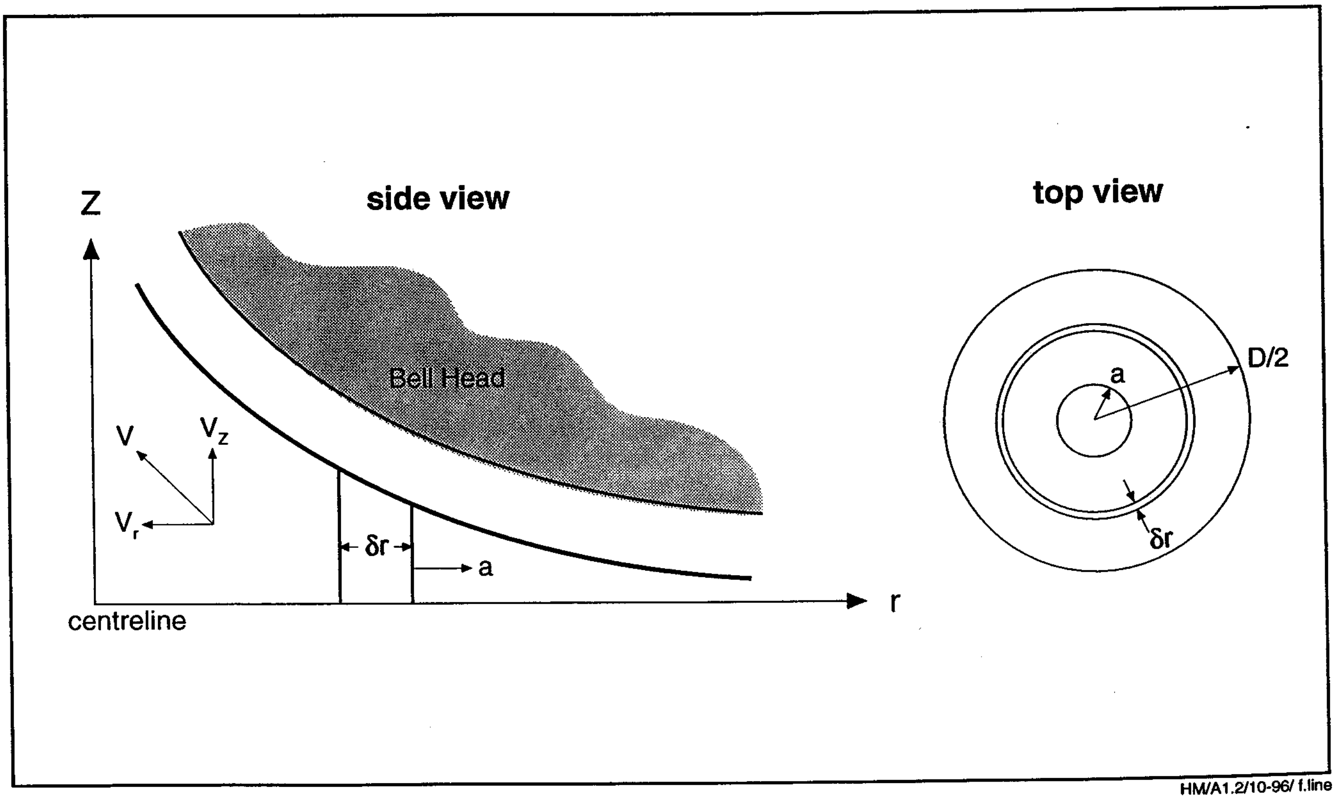

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Figure A1.2 Diagram of the hydrodynamic approach of flared pipe flow

Appendix 2

SedErode discharge calibration

Appendix 2 SedErode discharge calibration

An electromagnetic (Khrone) flowmeter was connected into the SedErode pipework so that discharges could be measured without significant change in the pipework configuration. Even so, the addition of an extra length of tubing with the flowmeter attached, resulted in a pressure loss in the system. Thus before the SedErode calibration tests, an assessment of the pressure loss was undertaken.

A tank was positioned at a height 3.05m above the floor, with a known length of SedErode tubing (1" BSP on the suction side of the pump). The discharge expected for such a system can be calculated by:

$$Q = mA(2gh)^{1/2} \qquad (1)$$

where
Q = discharge (m^3s^{-1})
m = dimensionless coefficient- a function of system geometry
A = cross-sectional area of tubing (m^2)
g = gravity constant (ms^{-2})
h = head difference between the upper water level and tubing opening at the bottom (m)

Experiments were carried out using the same initial head and pipework with and without the additional tubing and flowmeter. Results showed that the coefficient m was 0.2100 without the restriction and reduced to 0.1824 with the restriction. This equated to a factor of 0.869 (0.2100 ÷ 0.1824) efficiency for the SedErode discharge output with the additional flowmeter and tubing added.

Tests were then carried out to measure the SedErode pump voltage, measured discharge for the full range of SedErode discharges from dial setting 0.5 to 11, in 0.5 unit increments. The discharges measured at each setting were then corrected for the losses due to the extra restriction (x 1.1513 = 1/0.869) and a calibration data set of pump voltage against discharge output was obtained.