Hydraulic Flow Demonstrator (Closed and Open Channel Flow)

Instruction Manual

S16

ISSUE 3

April 2011

Table of Contents

Disclaimer

This document and all the information contained within it is proprietary to Armfield Limited. This document must not be used for any purpose other than that for which it is supplied and its contents must not be reproduced, modified, adapted, published, translated or disclosed to any third party, in whole or in part, without the prior written permission of Armfield Limited.

Should you have any queries or comments, please contact the Armfield Customer Support helpdesk (Monday to Friday: 0800 – 1800 GMT). Contact details are as follows:

United Kingdom	International
(0) 1425 478781 (calls charged at local rate)	+44 (0) 1425 478781 (international rates apply)
Email: support@armfield.co.uk	
Fax: +44 (0) 1425 470916	

Copyright and Trademarks

General Overview

For use with:

S16-10 Hydraulic Flow Demonstrator (no flowmeter)

S16-11 Hydraulic Flow Demonstrator (with integral flowmeter)

Students generally find the fundamental hydraulics concept of energy and momentum difficult to grasp, particularly where free flow is concerned. While most students have an intuitive understanding of the elements of solid body behaviour, they find the response of fluids to force and energy changes much less comprehensible.

The Armfield S16 Hydraulic Flow Demonstrator has been developed to overcome this difficulty enabling the teacher of hydraulics to provide practical demonstrations of various flow phenomena at the same time as he explains the theory in the lecture room. The ease of use allows the student to set up different demonstrations relatively quickly and to observe the effect of changes in upstream water level, downstream water level etc.

The Armfield S16 Hydraulic Flow Demonstrator simply connects to a standard F1-10 Hydraulics Bench to permit the study of the following basic aspects of fluid flow:

Closed conduit flow

- Application of the Bernoulli and Continuity equations to converging and diverging flow
- Effect of gradual and sudden changes in cross section (energy losses)
- Using a contraction as a flow measuring device
- Using a Pitot tube to measure velocity / velocity profile
- Flow through a Culvert

Open channel flow

- Flow beneath a Sluice Gate (an undershot Weir)
- Flow over Sharp Crested, Broad Crested and Ogee Weirs

  Using hydraulic structures to measure flow in an open channel

  Effect of changes in upstream and downstream water level

  Characteristics of Clinging, Aerated, Depressed and Drowned Nappes

- Sub-critical, Critical and Super-critical flow / depth. Changes in Specific Energy and control imposed by the minimum energy condition
- Characteristics of Hydraulic Jumps

  Force and energy conditions in a Hydraulic Jump

  Flow patterns associated with Hydraulic Jumps, namely:

Impinging Jet, Breaking Wave, Surface Wave and Surface Jet

- Flow over Drop Structures / Energy Dissipation
- Changes in flow profile in relation to the Froude Number (predicting flow conditions in an open channel) E.g. Undular Jump (F = 1 to 1.7), Weak Jump (F = 1.7 to 2.5), Oscillating Jump (F = 2.5 to 4.5), Steady Jump (F = 4.5 to 9.0) and Strong Jump (F > 9.0)
- Observation of flow patterns associated with flow around hydraulic structures
- Velocity of gravity waves in shallow water / Formation of surface waves near critical depth
- Project work – Evaluation of user constructed hydraulic structures

The dimensions of the working section are large enough for the various hydraulic phenomena to be seen clearly by a group of students and measurements taken allow analysis of the conditions for later analysis.

Each exercise is introduced by an explanation of the underlying theory, so that the student has the relevant ideas, equations and diagrams before him when operating the Flow Demonstrator.

After completing the exercises suggested in this instruction manual the user will gain knowledge and a better understanding of the important phenomena associated with the flow of liquid through closed conduits and open channels.

When studying Hydraulics, the fundamental concepts of energy and momentum are sometimes difficult to grasp, particularly where free surface flow is concerned. The Armfield Multi-Purpose Teaching Flume has been developed to assist the student to overcome this difficulty. It provides a basic but nonetheless comprehensive facility for student experiments in open channel flow.

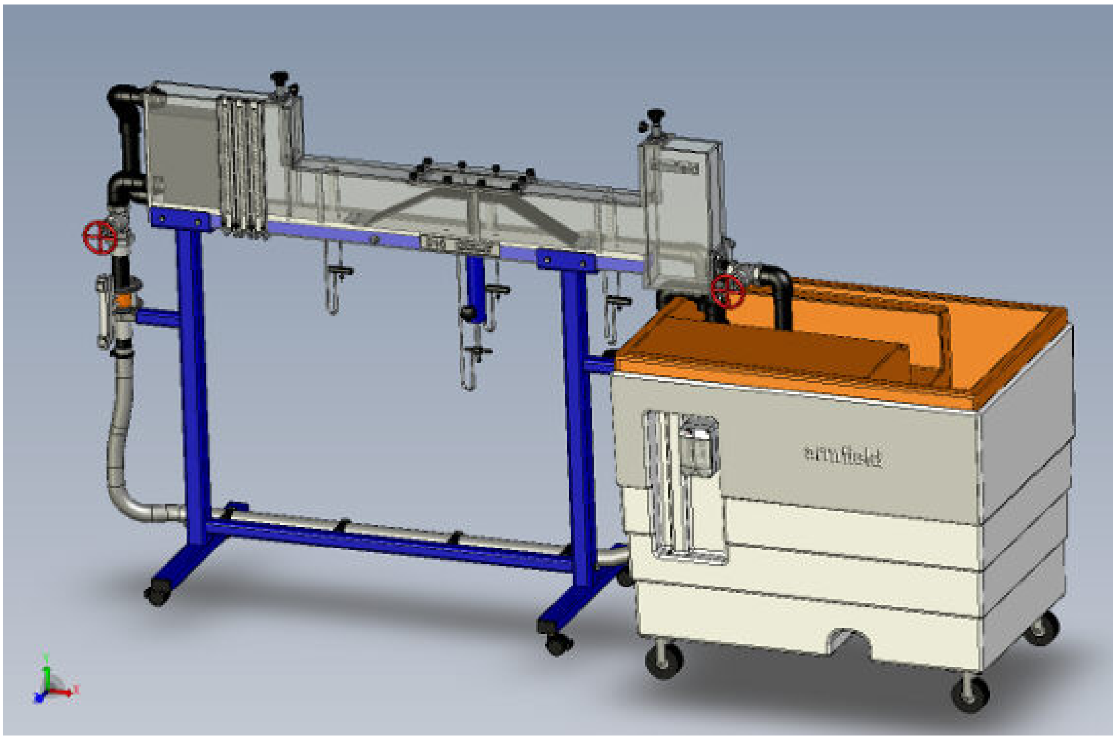
Although small in comparison with the majority of flow channels, the dimensions of the working section have been sized so that the various phenomena may be clearly seen and reasonably accurate results may be obtained from measurements taken.

The S16 Hydraulic Flow Demonstrator can be fitted with an optional direct reading flowmeter for convenience in operation. Version S16-10 does not include a flowmeter. Version S16-11 includes a direct reading flowmeter for convenience in operation. A set of basic models is included with both versions of the Hydraulic Flow Demonstrator.

The S16 Hydraulic Flow Demonstrator requires the use of a standard Armfield Hydraulics Bench F1-10 (ordered separately) which stores water for recirculation making the unit self contained, except for the provision of an electrical supply. The Flow Demonstrator can be quickly disconnected from the Hydraulics Bench if the bench is required for other applications or if it is necessary to move the Flow Demonstrator to a different location.

This instruction manual includes teaching exercises detailing the demonstrations and experiments which can be performed using the Flow Demonstrator and appropriate models. We wish to emphasise that these exercises do not exhaust the potential of the Flow Demonstrator or the models. There are many further investigations that an imaginative user can devise and the user can construct alternative models for installation in the Flow Demonstrator if required.

This instruction manual describes the use of both versions of the S16, namely S16-10 (no flowmeter supplied) and S16-11 (direct reading flowmeter included). References to the use of the direct reading flowmeter only apply to the S16-11. Measurement of flowrate when using the S16-10 is described in the operating section of this instruction manual.



S16 Hydraulic Flow Demonstrator shown with F1-10 Hydraulics Bench and optional flowmeter

Equipment Diagrams

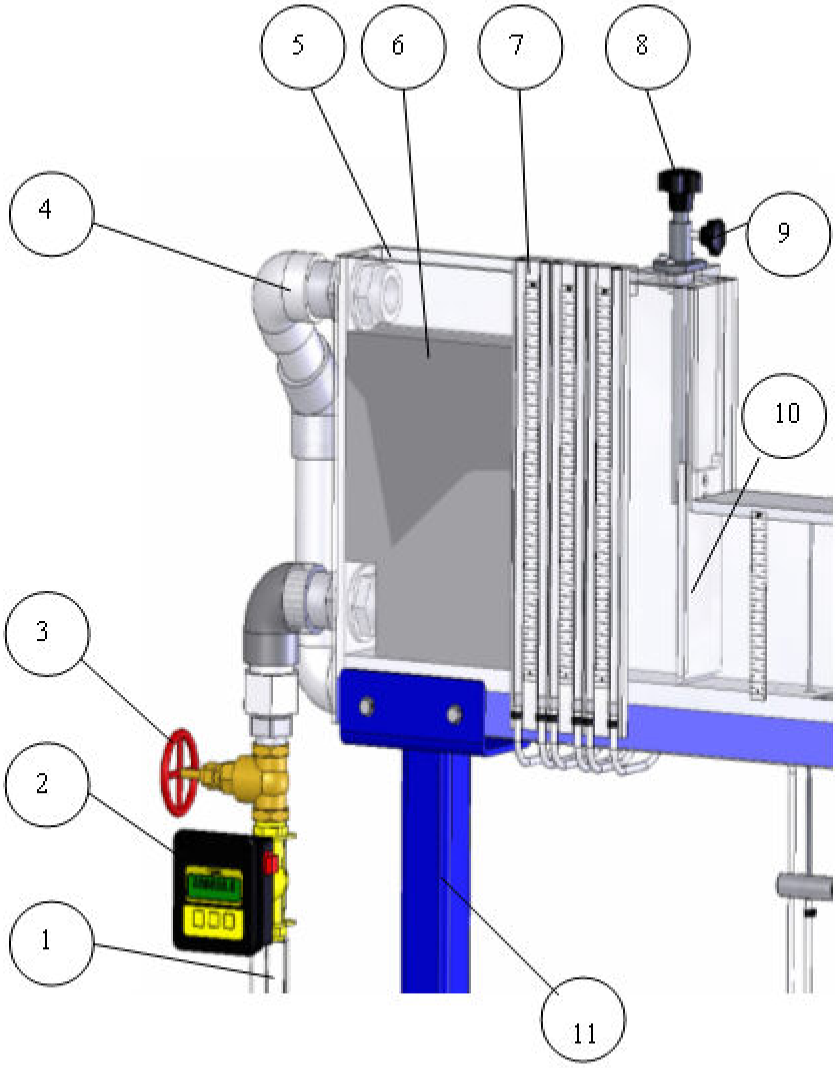


Figure 1: Inlet End of the Flow Channel

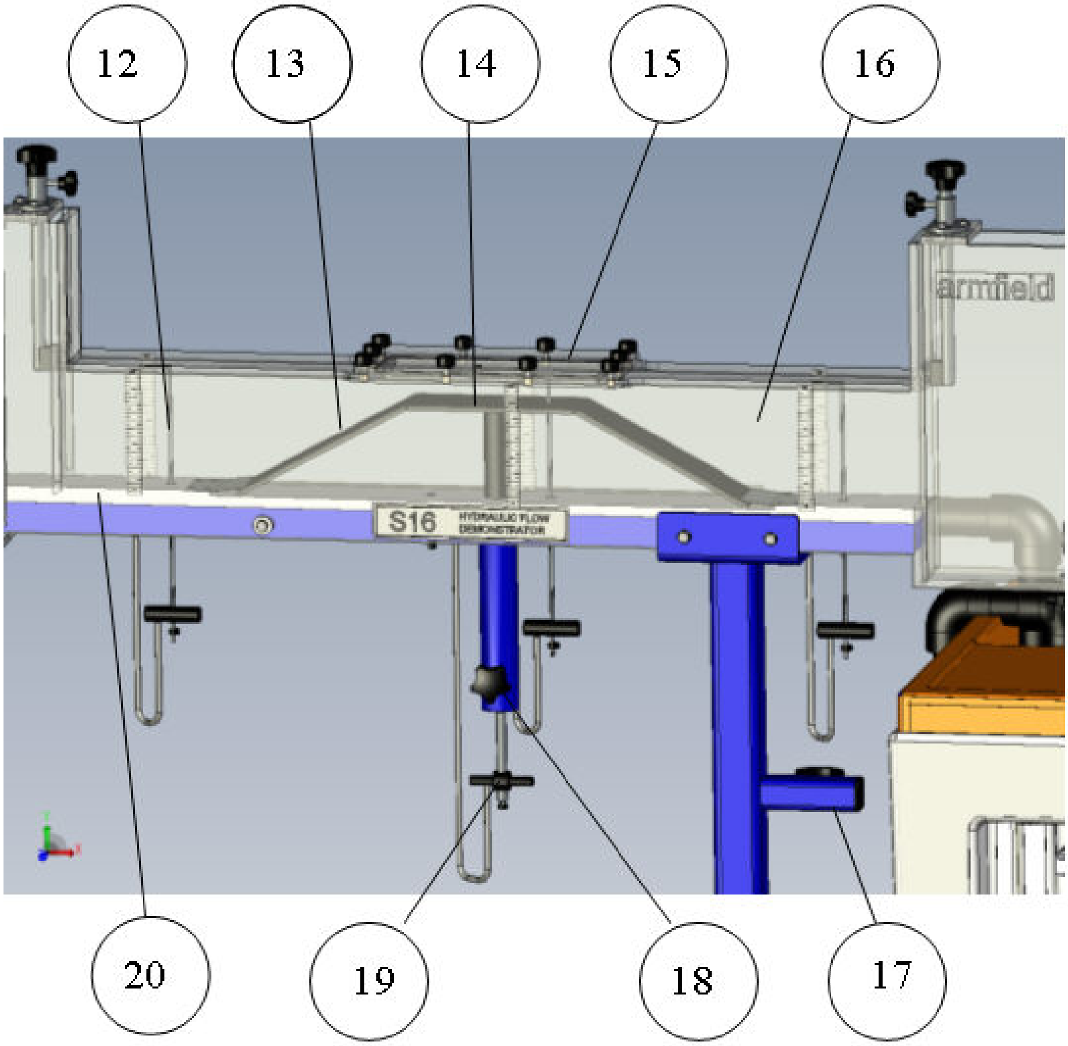


Figure 2: Working Section of the Flow Channel

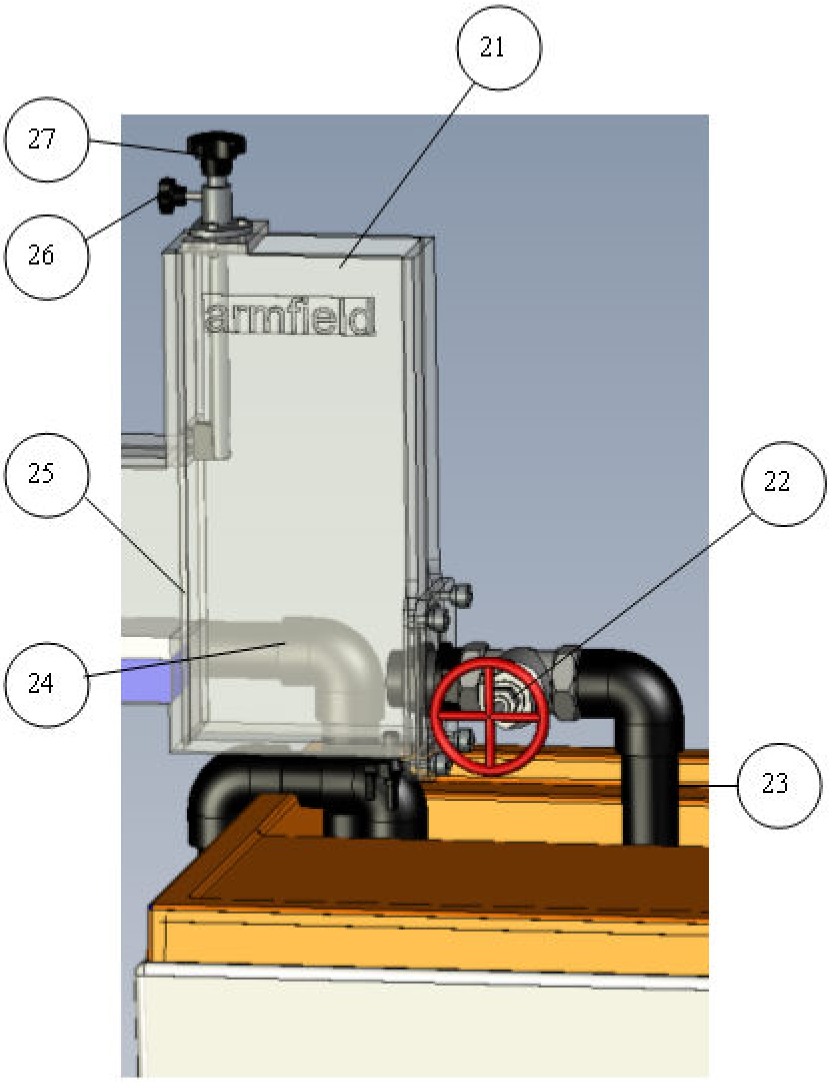


Figure 3: Discharge End of the Flow Channel

Important Safety Information

Introduction

All practical work areas and laboratories should be covered by local safety regulations **which must be followed at all times**.

It is the responsibility of the owner to ensure that all users are made aware of relevant local regulations, and that the apparatus is operated in accordance with those regulations. If requested then Armfield can supply a typical set of standard laboratory safety rules, but these are guidelines only and should be modified as required. Supervision of users should be provided whenever appropriate.

Your **S16 Hydraulic Flow Demonstrator** has been designed to be safe in use when installed, operated and maintained in accordance with the instructions in this manual. As with any piece of sophisticated equipment, dangers exist if the equipment is misused, mishandled or badly maintained.

Electrical Safety

The equipment described in this Instruction Manual operates using a service unit (the F1-10 Hydraulics Bench) that is powered by a mains voltage electrical supply.

- The Flow Demonstrator involves the use of water so any supply must be properly protected to minimise the possibility of electric shock.
- The F1-10 Hydraulics Bench must be operated as described in the F1-10 product manual, and must be tested regularly to ensure that the integral electrical protection is working correctly.

Wet Environment

The equipment requires a header tank containing water. During use it is possible that there will be some spillage and splashing.

- All users should be made aware that they may be splashed while operating the equipment, and should wear appropriate clothing and non-slip footwear.
- ‘Wet Floor’ warnings should be displayed where appropriate.
- Electrical devices in the vicinity of the equipment must be suitable for use in wet environments or be properly protected from wetting.

Moving or Rotating Components

The S16 Flow Demonstrator has moving components.

- Before operating the bed elevator ensure that no person or object can become trapped by the movement.
- Care must be taken when operating the sliding weirs incorporated in the inlet and discharge tanks.

Heavy Equipment

This apparatus is heavy.

- The apparatus should be placed in a location that is sufficiently strong to support its weight, as described in the Installation section of the manual.
- Where manual lifting is necessary, two or more people will be required for safety. All should be made aware of safe lifting techniques to avoid injury.
- Safety shoes and/or gloves should be worn when appropriate when moving the equipment.
- If the apparatus is to be repositioned after installation, the apparatus must be drained before it is moved.

Water Borne Hazards

The equipment described in this instruction manual involves the use of water, which under certain conditions can create a health hazard due to infection by harmful micro-organisms.

For example, the microscopic bacterium called Legionella pneumophila will feed on any scale, rust, algae or sludge in water and will breed rapidly if the temperature of water is between 20 and 45°C. Any water containing this bacterium which is sprayed or splashed creating air-borne droplets can produce a form of pneumonia called Legionnaires Disease which is potentially fatal.

Legionella is not the only harmful micro-organism which can infect water, but it serves as a useful example of the need for cleanliness.

Under the COSHH regulations, the following precautions must be observed:

- Any water contained within the product must not be allowed to stagnate, ie. the water must be changed regularly.
- Any rust, sludge, scale or algae on which micro-organisms can feed must be removed regularly, i.e. the equipment must be cleaned regularly.
- Where practicable the water should be maintained at a temperature below 20°C. If this is not practicable then the water should be disinfected if it is safe and appropriate to do so. Note that other hazards may exist in the handling of biocides used to disinfect the water.
- A scheme should be prepared for preventing or controlling the risk incorporating all of the actions listed above.

Further details on preventing infection are contained in the publication “The Control of Legionellosis including Legionnaires Disease” - Health and Safety Series booklet HS (G) 70.

Description

Where necessary, refer to the drawings in the Equipment Diagrams section.

Overview

The dimensions of the equipment allow the majority of the fundamental principles associated with closed conduit and open channel flow to be demonstrated and appropriate measurements taken to verify the underlying theory.

The Flow Channel is constructed in one continuous section using clear acrylic and is supported on two support pedestals (11 & 17). The Flow Channel consists of an inlet tank (see Figure 1) at the left hand end, a rectangular working section (see Figure 2) in the centre and a discharge tank (see Figure 3) at the right hand end.

The S16 Hydraulic Flow Demonstrator is designed to be used with an Armfield F1-10 Hydraulics Bench, which provides a re-circulating water supply and a volumetric measuring facility. The Flow Demonstrator can be used with an independent water supply of up to 1.6 litres/sec provided that water discharging from the channel can be intercepted.

The working section of the flow channel can be operated as an open channel or a closed conduit. Both end tanks are open to the atmosphere at the top.

Working Section

The parallel sided flow channel is constructed with clear acrylic sides that are sealed to a bed (20) fabricated from white acrylic. The clear sides allow full visualisation of the flow conditions inside the working section (16) and also the two end tanks.

The centre section of the bed (13) is variable in height and can be adjusted using an actuator (19) underneath the bed without stopping the flow of water through the working section. A clamp (18) on the actuator allows the bed to be locked at any height to suit the required demonstration. Hinged ramps upstream and downstream of the horizontal section are retained at the free ends by flexible carbon fibre flaps that minimise disturbance to the flow.

Pitot tubes (Total Head tubes) (12) and corresponding bed tappings (‘piezometric head’ tappings) are incorporated in the working section at three locations allowing the ‘total head’ and ‘piezometric head’ to be measured simultaneously at the upstream end, in the centre and at the downstream end of the working section. The Pitot tubes are fitted through the bed of the channel via glands that allow the tubes to be moved vertically up and down to permit measurement at different heights above the bed. Details about the Pitot tubes, bed tappings and the manometer tubes (7) used to measure the heads are given below in Pitot tubes, Bed tappings and Manometer tubes.

A removable rectangular panel (15) in the roof of the working section allows models of hydraulic structures to be installed in the working section and gives access to the working section for cleaning etc. The removable panel incorporates a watertight seal and is retained using thumb nuts. As the inlet tank and discharge tank are higher than the top of the working section, the removable panel should be replaced when operating the unit to prevent accidental spillage of water.

Models of three hydraulic structures are supplied with the S16, namely:

Sharp crested weir

Broad crested weir (with one rounded corner, one square corner).

Ogee weir

The models are retained by a single M4 cap headed screw into an insert (14) in the elevating part of the bed. The screw is retained in the model by a small ‘O’ ring over the threaded portion of the screw. The bed can be elevated when installing and removing models to improve access.

The user can introduce models of alternative structures with different shapes that have been constructed using suitable materials such as wood or plastic, making the equipment ideal for project work. Such models can also be secured to the insert in the bed of the channel using an M4 cap headed screw of appropriate length.

Transparent level scales are included at strategic positions on the walls of the working section. Level scales adjacent to the sluice gate (undershot weir) at the transition with the inlet tank and the plate weir at the transition with the discharge tank allow the height of each weir to be adjusted precisely to suit particular demonstrations. These scales are used to measure the depth of water at the entry to and exit from the working section. Level scales adjacent to each Pitot tube position (on the front and rear walls of the working section) are used to measure the height of each Pitot tube above the bed and the depth of the water upstream, downstream and mid way along the working section.

Inlet Tank

Water enters the parallel working section via an inlet tank (5) that is constructed from clear acrylic. The water entering the inlet tank flows through a section of open cell reticulated foam (6) to reduce any turbulence in the water and produce a smooth flow of water into the working section of the channel.

A sluice gate (undershot weir) (10) is incorporated at the exit from the inlet tank into the working section. The height of the gate is adjustable using a knob (8) at the top and a clamp (9) allows the gate to be clamped at any position between fully open and fully closed.

An overflow system (4 & 24) incorporated into the inlet tank conveys excess water to the channel in the F1-10 Hydraulics Bench if the level in the inlet tank is allowed to rise too far. This prevents water from spilling over the sides of the inlet tank if the level rises gradually, unnoticed by the operator. However, because the overflow relies on gravity it cannot dissipate the high flowrate that is possible from the F1-10 Hydraulics Bench if the sluice gate (undershot weir) in the inlet tank is too low or the outflow from the discharge tank is too restricted. Care must therefore be taken to adjust the flow into the equipment to suit the demonstration that has been configured.

Outlet Tank

Water exiting from the working section flows through the Outlet Tank (21) before discharging into the moulded channel on top of the F1-10 Hydraulics Bench where it returns by gravity to the sump tank via the volumetric measuring tank. Water exits the Outlet Tank via a flow control valve (22) that is removable and secured in position using thumb nuts. An integral seal minimises leakage where the valve is attached to the outlet tank and a vertical tube (23) minimises splashing as the water enters the channel of the F1-10.

Water height and flow conditions inside the working section are significantly affected by the height of the water in the Outlet Tank and two different techniques are used to vary the level in the working section to suit the type of demonstration.

Operating the working section as a Closed Conduit

When operating the Flow Demonstrator as a closed conduit the outlet flow control valve allows the outflow to be restricted so that the working section is allowed to flood. The valve can be finely adjusted, in conjunction with the inlet flow control valve (3) to give the required conditions inside the working section. The adjustable outlet weir (25) should be fully retracted into the floor of the Outlet Tank when using the channel as a closed conduit.

Operating the working section as an Open Channel

Opening the outlet flow control valve fully allows the working section to operate as an open channel with a free surface at all locations between the Inlet Tank and the Outlet Tank. For simple demonstrations the valve can be used to vary the height inside the working section provided that the water level does not reach the roof of the working section thereby eliminating the free surface. The adjustable outlet weir is normally retracted into the floor of the Outlet Tank when using the valve to control the outflow.

However, for traditional open channel demonstrations requiring downstream level control techniques, the valve should remain fully open. This allows the sliding weir to be used to vary the height of water at the downstream end of the working section (the tailwater level) that is important when demonstrating a Hydraulic Jump or drowning of a weir. The sliding weir can be adjusted in height using the knob at the top (27) and can be fixed in any position using the clamp (26). The sliding weir can be configured as an overshot weir for traditional flow demonstrations or, by raising the weir higher, it can be configured as an undershot weir (sluice gate) giving increased water velocity along the bed of the working section.

For Open Channel demonstrations where maximum flowrate is required the outlet flow control valve can be removed completely allowing the water to discharge directly into the channel on F1-10 with no additional restriction. When operating the equipment in this manner some splashing is inevitable and appropriate precautions should be taken.

Level Scales (Level Gauges)

As described above, transparent level scales are incorporated throughout the equipment to aid setting up and allow measurement of the water levels and weir heights associated with the hydraulic phenomena being demonstrated. All level scales are installed with the fixed bed of the channel as the measurement datum (0 mm). Scales in the working section are fitted to the front and rear walls to aid positioning of the Pitot tubes. Errors due to Parallax can be minimised by aligning the two scales visually to coincide with the tip of the Pitot tube. Moving the head up/down until the tip of the Pitot tube aligns with the same graduation on both scales will provide an accurate measurement of the height above the bed.

Pitot tubes, Bed tappings and Manometer tubes

Pitot tubes and bed tappings in the working section are connected to a bank of manometer tubes using flexible tubing. The manometer assembly attaches to the front wall of the inlet tank so that it is conveniently placed for viewing and is secured in position using a plastic screw on the top manifold. Each manometer tube indicates the piezometric head at the appropriate location. Comparison of the differences in levels between the manometer tubes allows the changes in ‘piezometric head’ and ‘total head’ to be observed and measured, allowing changes in ‘velocity’ to be determined.

The manometer should be primed when all three Pitot tubes are fully submerged below the surface of the water. Initial priming is effected by lifting the manometer assembly from the front of the inlet tank and tipping the top forward into a bucket or similar container. A drop of wetting agent in each tube will reduce the effect of surface tension and improve accuracy of the readings.

Air bubbles can be eliminated from the individual flexible tubes using the plastic syringe supplied with the equipment. The tip of the syringe is inserted into the top of the appropriate manometer tube and used to push water towards the tapping or Pitot tube in the working section or draw water into the manometer as required.

Each Pitot tube is located in a gland on the underside of the channel bed that incorporates a rubber ‘O’ ring seal to prevent water from leaking. Each gland should be tightened until the Pitot tube will move smoothly when pushed up or down but remain in position without leaking or turning. A tee handle at the bottom of each Pitot tube allows the tube to be moved to the required position.

Before taking measurements ensure that the Pitot tube is facing upstream and parallel with the flow of water.

Optional Flowmeter

An optional flowmeter (2) can be supplied with the S16 Hydraulic Flow Demonstrator to provide a direct reading of the volume flowrate of the water passing through the working section of the Flow Demonstrator. This provides a convenient means of setting up the various closed conduit or open channel demonstrations without the need for repeated timings using a stopwatch in conjunction with the volumetric tank of the F1-10 Hydraulics Bench. When supplied this flowmeter is mounted in the rigid pipework at the entrance to the inlet tank. The scale on the variable area flowmeter is calibrated to read the volumetric flowrate directly in litres/min.

Note that if operating the Hydraulic Flow Demonstrator with water flowing through the overflow in the inlet tank then the flow of water through the working section will not be the same as the reading on the flowmeter.

For information:

When supplied without the optional flowmeter, the Hydraulic Flow Demonstrator is coded S16-10.

When supplied with the optional flowmeter the Hydraulic Flow Demonstrator is coded S16-11.

When the flowmeter is not fitted (or at low flowrate below the measuring range of the instrument) the flowrate can be measured using the volumetric tank on the F1-10 Hydraulics Bench.

When supplied, the flowmeter is configured with the ‘Battery Save Mode’ set to ‘ON’. The instrument can be used at any time by pressing the ‘Enter’ button briefly to display the volumetric flowrate in units of litres per minute. To view the Total flow (not usually required for use with S16) press the ‘Enter’ button briefly again while the flowrate is displayed. The screen will remain on for a period of 30 seconds to allow a reading to be taken. To take another reading simply press the 'Enter' button briefly again. This mode of operation extends the battery life significantly. However, if continuous display of flowrate is required then the 'Battery Save Mode' can be set to 'OFF'. Refer to the Routine Maintenance section for instructions on how to change this mode or reconfigure the flowmeter.

Pedestals

The Acrylic channel is supported on a pair of pedestals that are connected by a horizontal member at the bottom. These pedestals incorporate castors with brakes that allow the unit to be easily moved when necessary then locked to prevent further movement.

Note: To minimise the size of the packing crate for shipping the feet on the pedestals are turned through 90 degrees. When removing the unit from the packing crate it will be necessary for two people to support the Flow channel while a third person rotates each foot and secures it using a suitable wrench or socket (Refer to the Installation section for further information).

The F1-10 Hydraulics Bench

The S16 is designed for use in conjunction with a standard F1-10 Hydraulics Bench. The F1-10 is not supplied as part of the S16.

Water is drawn from a sump tank in the base of the F1-10 by a centrifugal pump. The water is delivered to the inlet tank of the flow channel via a flexible tube (1) that is connected to the outlet in the moulded channel on the top of the F1-10. The flow of water through the working section is varied using the flow control valve at the entry to the inlet tank on the S16. The flow control valve on the F1-10 Hydraulic Bench can be adjusted to limit the flow of water so that the valve on S16 can be used for fine adjustments without flooding the equipment.

Having flowed along the working section of the flow channel and through the outlet tank, the water falls by gravity into the moulded channel on the top of the F1-10. The water then flows into a volumetric tank before returning to the sump tank under gravity. The volumetric tank provides a means (and demonstration) of measuring the flow of water through the flow channel when not using the optional direct reading flowmeter.

Flowrate up to approximately 1.2 litre/sec can be measured using the volumetric tank and a stopwatch (not supplied). In normal operation the dump valve in the base of the volumetric tank should be open to allow the water to re-circulate. When measuring the flowrate the dump valve is lowered into the aperture and the flow is measured by timed volume collection using the sight glass with level scale on the side of the F1-10 and a stopwatch.

At higher flowrate (above 1.2 litres/sec) it will be necessary to use the circular orifice plate supplied with the S16 to measure the flowrate as the base of the volumetric tank will remain flooded. To install the orifice plate lift the ball and weight from the aperture in the base of the volumetric tank then press the orifice plate into the aperture. At each flow setting allow the water level to stabilise in the volumetric tank (this may take several minutes after making a change in flowrate) then read the value from the upper scale on the F1-10 sight glass (level gauge). This reading in litres is used to find the actual flow rate by referring to the following table:

Scale Reading Litres	Flow Rate Litres/sec	Scale Reading Litres	Flow rate Litres/sec
0	1.41	12	1.78
1	1.44	13	1.81
2	1.48	14	1.84
3	1.51	15	1.86
4	1.54	16	1.89
5	1.57	17	1.92
6	1.60	18	1.94
7	1.63	19	1.97
8	1.66	20	2.00
9	1.69	21	2.02
10	1.72	22	2.05
11	1.75	23	2.07

Flow Rate Reference Table (Only used with S16 up to 1.6 l/s)

Note that when using the S16 Hydraulic Flow Demonstrator in conjunction with the F1-10 Hydraulics Bench the maximum flowrate available is approximately 1.6 litres/sec (approx 96 litres/min).

Additional information about the F1-10 Hydraulics Bench is provided in the separate product manual supplied with the F1-10. Refer to that manual for full information including installation and commissioning instructions.

Installation

Advisory

The F1-10 Hydraulics Bench should be commissioned before installation of the S16. Refer to the product manual supplied with the F1-10 for information on installation and commissioning the Hydraulics bench.

Before operating the S16, it must be unpacked, assembled and installed as described in this Installation Guide. Safe use of the equipment depends on following the correct installation procedure.

Installation Process

Where necessary, refer to the drawings in the Equipment Diagrams section.

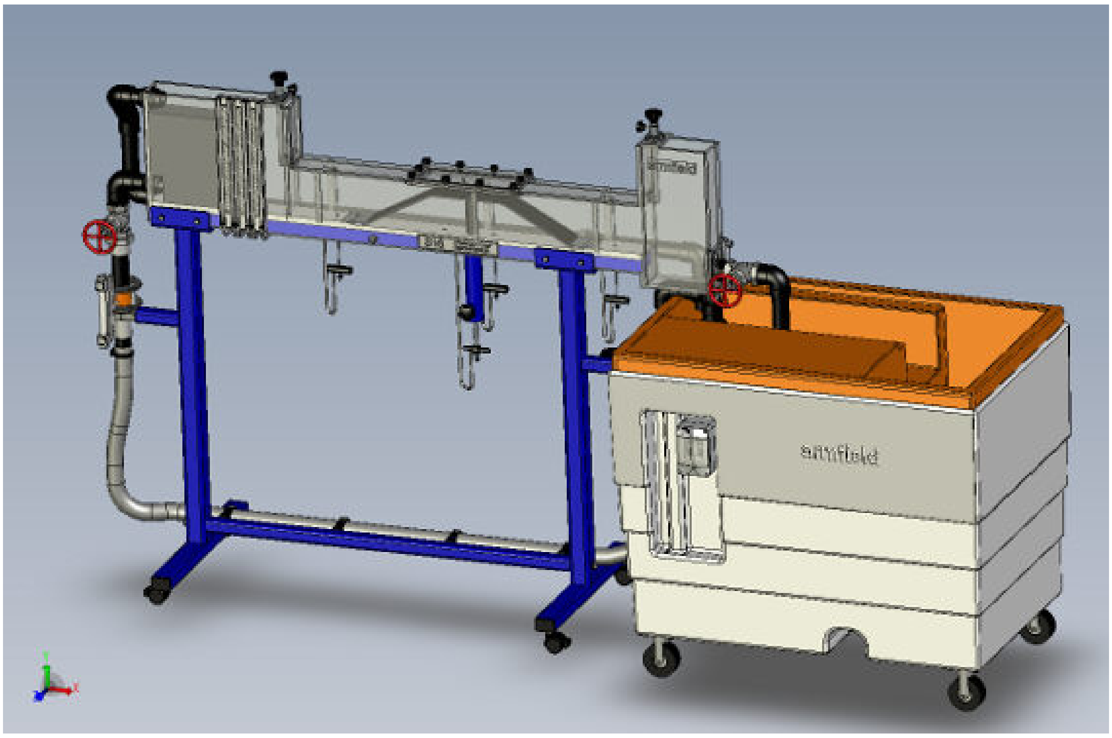
The Flow Channel is supplied complete, supported on two pedestals. The manometer, flexible inlet pipework and outlet flow control valve are removed for shipping.

Note: The feet on the pedestals are turned through 90 degrees to minimise the size of the packing crate for shipping. When removing the unit from the packing crate it will be necessary for two people to support the Flow channel while a third person rotates each foot and secures it using a suitable wrench or socket.

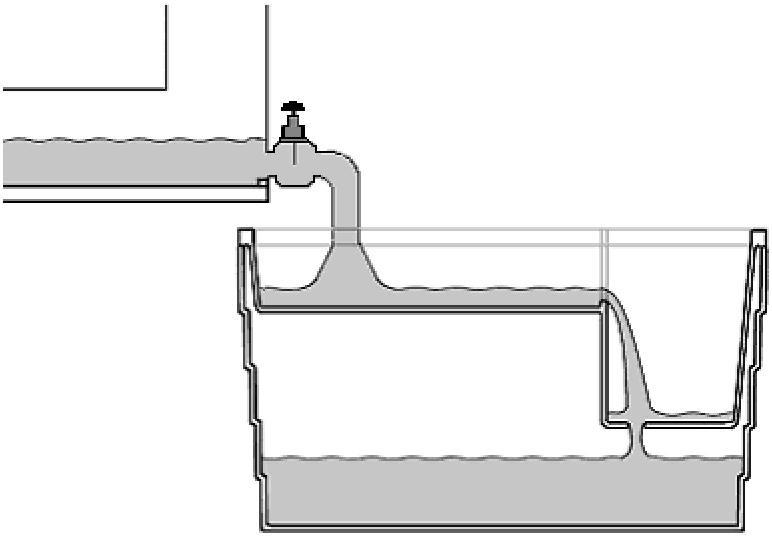
1. Carefully unpack the Flow Channel and other associated parts. The parts should be inspected for damage and checked against the advice note for any missing parts.

2. Support the Flow Channel to prevent it from falling over when removed from the crate. Partly unscrew the fixing on the underside of each foot, pull the foot away from the pedestal by approximately 15 mm then rotate the foot through 90 degrees and reengage the locating spigot. Tighten the fixing screw to secure the foot.

3. Locate the S16 in the required location. The floor should be firm and level (preferably concrete). The S16 will require an F1-10 Hydraulics Bench to operate. Disconnect any accessory that is already connected to the quick release connector on the F1-10 (connector located inside the top moulded channel on the F1-10). Remove the outlet flow control valve from the outlet tank on the S16 (if fitted) then position the F1-10 to the right hand end of the S16 as shown below:



4. Adjust the position the F1-10 at the downstream / right hand end of the S16 with the end of the outlet tank on S16 above the moulded channel on the top of the F1-10 as shown in the diagram below:



When roughly positioned attach the outlet flow control valve to the aperture at the end of the outlet tank using the thumb nuts supplied. The outlet valve on the channel should be aligned with the centre line of the moulded channel. Ensure that the outlet from the overflow is also located above the channel of the F1-10.

5. If not already connected, attach the flexible supply tube to the stub pipe below the inlet flow control valve (or optional flowmeter if fitted). Secure the tube with the tube clip provided.

6. Ensure that the F1-10 is switched off and the flow control valve on F1-10 is fully closed then unscrew the quick release connector from the bed of the channel. Screw the adaptor, supplied with S16, onto the threaded outlet in the bed of the channel ensuring that the flat rubber sealing washer is fitted. Connect the union at the end of the flexible tube on S16 to the union on top of the adaptor. The union incorporates a 'O' ring seal and only needs to be hand tight (do not use a tool to tighten the fitting).

7. Locate the multi tube manometer on the front of the inlet tank and tighten the plastic screw at the rear of the top manifold to secure it in position. The function of the screw is to prevent the manometer from being accidentally knocked off in use and the screw should not be over tightened.

8. Connect the Pitot tubes and bed tappings (located in the bed of the working section) to the manometer using the flexible tubing supplied. The upstream tappings should be connected to the left hand side of the manometer and the downstream tappings should be connected to the right hand side of the manometer so that the indicated heads correspond to the flow through the working section. Tighten the clips to secure the flexible tubes at both ends.

9. Ensure that the diffuser (open cell foam) is correctly positioned inside the inlet tank where it meets the bed of the channel. The action of the diffuser is to reduce any turbulence in the water entering the inlet tank and produce a smooth flow of water into the working section.

10. Place a spirit level on top of the channel and check that the channel is reasonably level. If the floor is not level it will be necessary to adjust the height of the individual castors as necessary using a suitable wrench.

11. Place the model hydraulic structures in a safe place where they will not be damaged.

12. Check that all packaging has been removed from the F1-10 Hydraulics Bench (if newly installed) and S16. Check that the clips on all flexible tubes are securely tightened.

13. Check that the drain valve on the underside of the F1-10 is closed. Check that the cock below each drain on the underside of the channel is closed. Check that the gland securing each Pitot tube is tightened sufficiently. Take care not to damage the rubber 'O' ring seals inside the glands. When correctly adjusted the Pitot tube will remain in the required position but slide smoothly up and down when adjusted from below.

14. Place a filling hose in the volumetric tank of the F1-10. Fill the sump tank with clean cold water by lifting the dump valve in the base of the volumetric measuring tank and allowing the water to drain from the volumetric tank into the sump tank. (When lifted, a twist of 90^o at the actuator will retain the dump valve in the open position.). Allow the sump tank to fill until the water level in the sump tank is just level with the circular outlet in the bottom of the volumetric tank (This can be viewed more easily by lifting the sealing ball and weight out of the hole temporarily).

15. If available, a few drops of wetting agent should be added to the water in the sump tank of the F1-10 to minimise the effects of surface tension.

Note: If too much wetting agent is added foaming will occur and it will be necessary to replace the water.

A few drops of wetting agent should also be introduced to the sight tube (level gauge), on the side of the F1-10, via the overflow tube at the top. This will reduce the meniscus, making readings clearer.

16. Ensure that the sloping stilling baffle is correctly positioned in the volumetric tank of the F1-10 such that the top edge is alongside the exit of the open channel in the moulded top. Lift the dump valve and twist the actuator through 90º to retain it in the open position.

17. Prepare the S16 for operation as follows:

If necessary, lower the elevating section of the bed to its lowest position using the actuator. Release the clamp then pull the actuator downwards until the bed is in its lowest position. Clamp the actuator to prevent further movement.

Ensure that the removable cover is fitted to the aperture in the top of the working section and secured using the thumb nuts.

Lower the three Pitot tubes so that the tips are approximately 20 mm above the bed of the working section.

Open the discharge flow control valve at the right hand end of S16 then close the inlet flow control valve fully.

18. Check that the flow control valve on the front of the F1-10 is fully closed then connect the mains lead from the F1-10 to the electrical supply.

19. Switch on the RCD on the front of the F1-10, then press the TEST button to check that the RCD is operating correctly. The RCD must trip. If the RCD does not trip or it trips before pressing the test button then it must be checked by a competent electrician before the equipment is used. Switch on the RCD again.

20. Operate the pump ON/OFF switch and confirm that the pump functions. Slowly open the flow control valve on F1-10 followed by the inlet flow control valve on S16 and check that water is delivered to the inlet end of the S16 channel.

Allow the water to flow along the working section of the flow channel and discharge into the F1-10. Allow circulation to occur for several minutes to remove air from the system. Adjust the position of the F1-10 if necessary to minimise splashing as the water discharges into the top of the F1-10.

21. Release the actuator of the dump valve to close the valve in the bottom of the volumetric tank. Fill the volumetric tank until water runs into the sump tank through the overflow. Now check that the sight tube (level gauge) is full and no air bubbles are present. Repeat this filling several times, ensuring that the sight tube is free from air bubbles.

22. If the F1-10 has not been commissioned previously close the flow control valve and allow water to drain from the volumetric tank until the surface is level with the step in the bottom of the tank. A few drops of wetting agent smeared onto the step will enable an accurate level to be achieved.

Slacken the securing screws at the top and bottom of the sight tube scale and position the scale so that the meniscus of the fluid in the tube is level with the black datum line engraved between the large and small scales. This will ensure that the scale is positioned accurately for volumetric measurements using either of the ranges.

Note: All volumetric readings should be taken with the stilling baffle installed, since calibration has been effected in this condition.

23. Gradually close the outlet flow control valve at the right hand end of S16 and allow the water level to rise in the working section. Partially close the flow control valve of F1-10 if the level rises too quickly. Allow the level to rise above the roof of the central working section so that the level is higher in the inlet tank and outlet tank then fully close the outlet valve and close the flow control valve on F1-10. Switch off the pump on F1-10.

It is suggested that the channel is left standing in this condition for at least one hour to allow any leaks to become visible. Check the channel and pipework for leaks and tighten the appropriate fittings as necessary.

The flexible tubing between the manometer and the Pitot tubes / bed tappings can be primed while the working section is filled as follows:

24. Add a drop of wetting agent or surfactant to the top of each tube on the manometer to minimise the effect of the meniscus.

Unscrew the plastic screw at the top of the manometer then lift the manometer assembly from the front of the Inlet Tank and tip the top into a bucket or similar container to allow water to flow through the flexible tubes to the manometer. Return the manometer to the front of the inlet tank and secure it by tightening the plastic screw.

Any air bubbles trapped in the individual flexible tubes can be expelled using the plastic syringe supplied with the equipment. The tip of the syringe (fitted with a short length of flexible tubing) is inserted into the top of the appropriate manometer tube and used to push water towards the tapping or Pitot tube in the working section or draw water towards the manometer as required.

It is essential that no air is present in the tappings, the Pitot tubes, the flexible tubing or the manometer tubes; otherwise readings obtained will not be accurate. With the water stationary in the working section the level in all six manometer tubes must be exactly the same. Any difference in height indicates that air is trapped somewhere between the working section and the manometer. Repeat the priming procedure until all readings are the same.

25. The equipment is now ready for use in conjunction with the exercises included in the S16 Instruction Manual.

26. If the equipment is not required for immediate use it should be drained. Ensure that the inlet flow control valve is closed and the F1-10 pump is switched off then open the discharge flow control valve and allow the channel to drain fully.

Note: After use always allow the water to drain down into the sump tank of the F1-10. The flow control valves on F1-10 and S16 can be opened to allow water to drain from the inlet tank and pipework to the sump via the pump.

The basic operation of the S16 has been confirmed. Refer to the Operational Procedures section in the S16 product manual for further information.

Electrical Supply

The F1-10 Hydraulics Bench requires a mains electricity supply. Refer to the F1-10 product manual (supplied with the Hydraulics Bench) for details.

Water Supply and Drain

Water for the S16 is provided by an F1-10 Hydraulics Bench. An initial fill of approximately 250 litres is required. Once the equipment has been installed and commissioned no permanent water supply or drain is required. A suitable drain and source of clean water will be required for draining and refilling the F1-10 after cleaning.

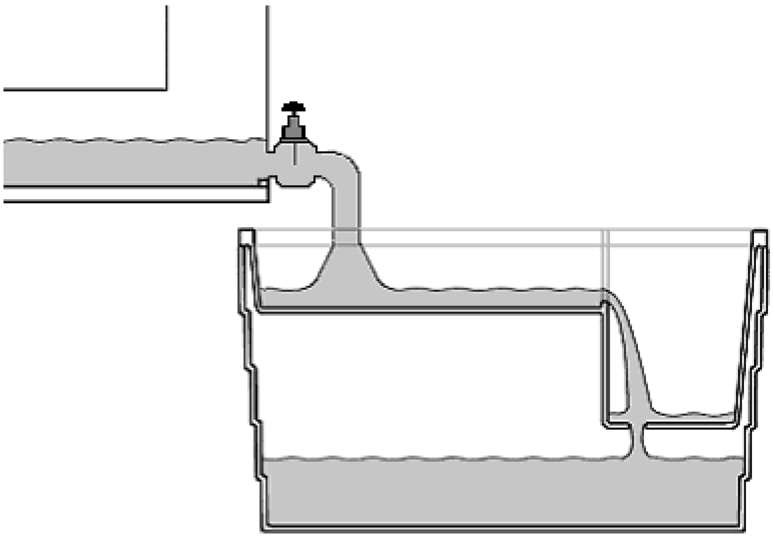
Operation

Where necessary, refer to the drawings in the Equipment Diagrams section.

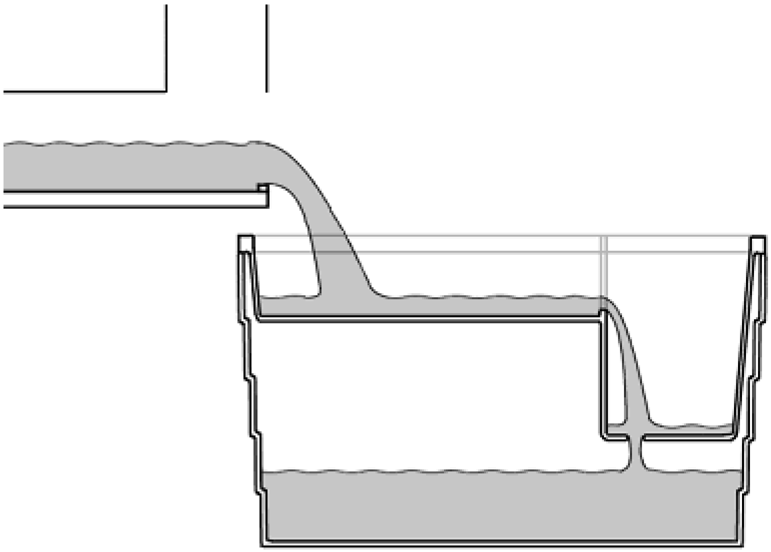
Operating the Equipment

Positioning the S16 relative to the F1-10 Hydraulics Bench

The S16 Hydraulic Flow Demonstrator is designed to be used with the F1-10 Hydraulics Bench and should be located to the left hand side of the F1-10. The F1-10 Hydraulics Bench and S16 are both mounted on casters for ease of repositioning. The outlet from the S16 discharges into the horizontal channel that is moulded into the top of the F1-10. The S16 must be positioned relative to the F1-10 to ensure that water discharging from the flow control valve and the overflow pipe will enter the top channel as shown below:



If operation is required with the flow control valve removed (to allow water to discharge freely at high flowrate) it may be necessary to move the F1-10 relative to the S16 to minimise splashing. Ensure that the outlet of the overflow is also located over the channel of the F1-10. Water should enter the left hand end of the channel as shown below:



To allow use with castors, the S16 is designed to be used on a flat floor with no significant changes in level. If the floor is not level it may be necessary to adjust the height of the individual castors to ensure that the working section remains horizontal. When moving the equipment it may be necessary to readjust the height of the castors.

Connecting the S16 to the F1-10 Hydraulics Bench

Disconnect any accessory that is already connected to the quick release connector on the F1-10 (connector located inside the top moulded channel on the F1-10). Ensure that the F1-10 is switched off and the F1-10 flow control valve is closed then unscrew the quick release connector from the bed of the channel. Screw the adaptor, supplied with S16, onto the threaded outlet in the bed of the channel ensuring that the flexible sealing washer is fitted. Connect the flexible tube from the S16 to the union on top of the adaptor. The union incorporates a 'O' ring seal and only needs to be hand tight (do not use a tool to tighten the fitting).

To restore the F1-10 to normal use; unscrew the union to disconnect the flexible tube then unscrew the adaptor from the threaded outlet in the bed of the channel on F1-10. Screw the quick release connector onto the threaded outlet to allow the F1-10 to be used with the appropriate accessories. It may be necessary to move the F1-10 slightly to the right to allow operation with some accessories but the castors on the F1-10 or S16 allow the units to be easily repositioned.

Filling the F1-10 Hydraulics Bench with water

Place a filling hose in the volumetric tank of the F1-10. Fill the sump tank with clean cold water by lifting the dump valve in the base of the volumetric measuring tank and allowing the water to drain from the volumetric at the actuator°tank into the sump tank. (When lifted, a twist of 90 will retain the dump valve in the open position.). When full ensure that the water level in the sump tank is just level with the outlet in the bottom of the volumetric tank.

A few drops of wetting agent or surfactant should be added to the water in the sump tank to reduce the effect of surface tension. Note that too much wetting agent will cause foaming in the water.

Preparing the Hydraulic Flow Demonstrator for use

Locate S16 at left hand side of F1-10 with outlet from channel and separate overflow pipe above channel in top of F1-10 as described above.

Fit the outlet control valve to the discharge end of channel and tighten all thumb nuts.

Fit the rectangular panel to the top of the working section and tighten all thumb nuts.

Open the outlet valve fully (discharge end of channel).

Close the inlet valve fully (above flowmeter if fitted).

Close the F1-10 flow control valve fully.

Raise the sluice gate (undershot weir) fully and clamp (inlet end of channel).

Lower the overshot outlet weir fully and clamp (discharge end of channel).

Lower the adjustable section of bed to its lowest position and clamp (0 mm on scale)

Lower all three Pitot tubes until flush with bed.

Add a few drops of wetting agent to the water in the F1-10 and one drop in each manometer tube to reduce surface tension and aid priming.

Start the F1-10 pump.

Open the F1-10 flow control valve fully.

Gradually open the inlet valve on S16 to give a steady flow along the bed of the working section (water will discharge into the moulded top on F1-10). Check the dump valve is open in the volumetric tank so that water returns to the sump tank.

Allow air bubbles to clear from the flexible tubing connecting S16 to F1-10.

Gradually close the outlet control valve until fully closed to flood the channel.

Gradually close the inlet control valve and fully close the valve when the water level reaches the overflow in inlet tank.

Raise and lower the elevating section of bed several times to displace any trapped air.

Allow the water level to stabilise in the end tanks then prime the bed tappings / Pitot tubes and manometer (tilt top of manometer into a bucket or similar container until all tubes run full of water).

When fully primed all levels in the tubes should coincide with the levels in the inlet tank and outlet tank (Any difference in levels means that air is trapped somewhere between the tapping and the manometer – use the plastic syringe at top of the affected manometer tube to force water through the tubing or suck water from the tapping until the tubing is clear of bubbles).

The equipment is ready for use. Refer to the Laboratory Teaching Exercises for further information.

Installing models of hydraulic structures

Drain the flow channel by opening the outlet flow control valve fully then remove the cover in the roof by removing the thumb nuts. The bed-mounted models are secured in place via a single screw into a threaded bush in the elevating part of the bed. The bed can be elevated if necessary to make installation easier.

To ease installation and minimise the risk of scratching, wet the seal on the model before attempting to install the model.

The broad-crested weir incorporates one square corner and one rounded corner at the crest and can be mounted either way round to demonstrate the difference on the flow patterns formed.

When installing the broad-crested weir for use as a culvert, the weir should be attached to the underside of the removable roof panel before refitting the panel.

Adjusting the height of the elevating section of bed

To change the height of the bed release the clamping screw on the front of the actuator below the bed then gradually slide the elevating section of bed to the required position using the grip at the bottom of the actuating rod. The height of the elevated bed above the upstream and downstream bed can be measured using the transparent scale on the front of the working section.

Any movement of the bed must be gradual so that water or air trapped under the bed can be displaced. After raising the height of the bed, water will gradually displace any air trapped below the bed.

For normal operation the bed should be retracted to its lowest position. When fitting or removing models etc the bed can be raised to improve access.

Adjusting the height of the sluice gate (undershot weir) at inlet

To change the height of the sluice gate release the clamp on the side of the actuating rod then slide the gate up or down to the required height using the knob at the top. Tighten the clamp when the gate is in the required position. The height of the gate above the bed can be measured using the transparent scale on the front of the inlet tank adjacent to the weir.

When the sluice gate is not required it should be raised to its highest position and clamped so that it does not affect the flow of water into the working section.

Adjusting the height of the outlet weir

To change the height of the outlet weir release the clamp on the side of the actuating rod then slide the weir up or down to the required height using the knob at the top. Tighten the clamp when the weir is in the required position. The height of the weir above the bed can be measured using the transparent scale on the front of the outlet tank adjacent to the weir.

In normal use the weir is raised as required to create an overshot weir. However, for some demonstrations the weir can be raised further to create a sluice gate (undershot weir) at the outlet.

When the outlet weir is not required it should be pushed down to its lowest position and clamped so that it does not affect the flow of water leaving the working section.

Varying the depth of water in the flow channel

The working section of the flow channel can be operated partially full (open channel) or completely full (closed conduit) depending on the demonstration required. The removable panel on top of the working section must be fitted and secured before operating the equipment as a closed channel.

The depth of water in the working section and the corresponding flowrate through it will depend on the configuration of the inlet tank and the discharge tank. The inlet flow control valve and sluice gate will affect flow into the working section. The discharge weir and the outlet flow control valve (when fitted) will affect the flow of water out of the working section (the tailwater level). These should be adjusted individually or in combination as required to give the required conditions in the working section.

Adjustment of the inlet flow control valve on the F1-10 Hydraulics Bench will affect the available flowrate through the S16 Hydraulic Flow Demonstrator. In normal use the flow control valve on the F1-10 should be adjusted to give adequate flow through the S16, to suit the required demonstrations, without allowing excess that could cause flooding of the equipment.

Before taking measurements of water depth, velocity, flowrate etc. the conditions inside the working section should be allowed to stabilise.

Installing the manometer

The manometer assembly supplied with S16 is used in conjunction with the three Pitot tubes and bed tappings in the working section to measure the ‘total head’ and ‘piezometric head’ at these locations. The local velocity of water flowing through the working section can be calculated from these measurements.

The manometer is simply hooked onto the top edge of the inlet tank on the S16 and secured with a plastic screw at the rear. The scales on the manometer are all referenced to the level of the bed in the working section upstream and downstream of the elevating section.

Priming the manometer and Pitot tubes

A drop of wetting agent or surfactant in each manometer tube will reduce the effect of surface tension and improve accuracy of the readings.

Partially fill the channel with water so that the tips of all three Pitot tubes are fully submerged below the surface of the water. This can be effected by raising the weir at the discharge end of the working section. The water in the channel should not be flowing during the priming operation.

Initial priming can be effected by lifting the manometer assembly from the front of the inlet tank and tipping the top into a bucket or similar container. Return the manometer to the front of the inlet tank and secure it by tightening the plastic screw.

Any air bubbles trapped in the individual flexible tubes can be expelled using the plastic syringe supplied with the equipment. The tip of the syringe (fitted with a short length of flexible tube) is inserted into the top of the appropriate manometer tube and used to push water towards the tapping in the working section or draw water towards the manometer as required dislodging any air bubbles that are trapped.

It is essential that no air is present in the tappings, flexible tubing or manometer tubes; otherwise readings obtained will not be accurate. With the water stationary in the working section the level in all six manometer tubes must be exactly the same. Any differences in height indicate that air is trapped inside one of the Pitot tubes / bed tappings or the flexible tubing connecting it to the manometer. Repeat the priming procedure until all readings are the same.

The differences in heads in some of the demonstrations are extremely small so complete priming is essential to avoid poor results. If a Pitot tube is raised above the water level, air will enter the head of the Pitot tube and it may be necessary to re-prime that tube before taking further readings. This can be carried out using the plastic syringe as outlined above.

The scales on the manometer give direct measurements of head of water in mm.

When operating the equipment care should be taken not to allow air to enter the Pitot tubes or bed tappings after the system has been primed. This can be avoided by ensuring that the Pitot tubes and elevated bed are not raised above the local water level. If air does enter a tapping it can be quickly removed using the plastic syringe as described above.

Taking measurements using the Pitot tubes, Bed tappings and Manometer bank

The Pitot tubes / bed tappings in the working section and bank of manometer tubes are used to determine the 'velocity head' h_v at different sections inside the working section.

Water velocity $u = \sqrt{2gh_v}$ or $u = \sqrt{19.62h_v}$ (m/s)

where h_v is the velocity head (the difference in the two manometer readings)

A complete analysis of the Pitot tube is included in Exercise C - Using a Pitot Tube to Measure Point Velocity.

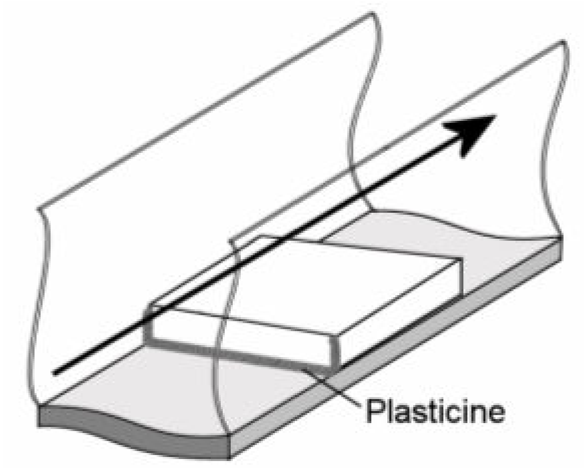
The velocity profile at each section in the channel can be obtained by moving the Pitot tube vertically, noting the readings on the manometer at each position and converting these readings to a velocity profiles.

Note: The scale on the manometer is referenced to the bed in the working section that is upstream and downstream of the adjustable section of bed. All readings on the manometer are therefore piezometric heads and must be corrected for elevation when determining the static head or total head at a point inside the working section. When using the manometers differentially, to determine the velocity head, the correction for elevation applies to both limbs of the manometer and can therefore be ignored.

Sealing models into the flow channel

The standard models supplied with the S16 incorporate flexible seals that are let into grooves in the side walls and should not require additional sealing in normal operation. When fitting a model into the working section, the seal should be lightly smeared with wetting agent (soapy water) to minimise friction and avoid scratching the sides of the working section.

Where additional models have been fabricated by the end user, or where high accuracy results are required, it may be necessary to prevent leakage around the model. Plasticine or similar flexible compound can be used at the upstream end of the model and should be placed between the side walls / bed of the channel and the sides of the model. This is to ensure that water flows over the model and not around or under it.



Equipment Specifications

Overall Dimensions

S16 only

Height	-	1.60 m
Length	-	2.20 m
Width	-	0.63 m
Weight (dry)	-	100 kg

S16 with F1-10

Height	-	1.60 m
Length	-	3.00 m
Width	-	0.90 m

Working Section Dimensions

Length of working section	-	1100 mm
Width of working section	-	77 mm
Height of working section	-	150 mm
Height of Inlet and Discharge Tank	-	340 mm (relative to bed)

Flow Rate

Operating flow range	-	0 – 1.6 litres/sec
Optional flowmeter range	-	20 – 200 litres/min +/- 1% FSD

(Supplied with S16-11 only)

Manometer

Number of tubes	6
Range of scale	300 mm
Measurement accuracy	+/- 0.5 mm

Models of Hydraulic Structures supplied with S16

The following hydraulic structures are supplied as standard with the S16 Hydraulic Flow Demonstrator:

Sharp crested weir

Broad-crested weir with square and rounded corners (also used inverted to create a Culvert)

Ogee weir

Adjustable height section of bed (permanently installed in bed of working section)

Adjustable sluice gate / undershot weir (permanently installed at inlet to working section)

Adjustable overshot / undershot weir (permanently installed at outlet from working section)

Environmental Conditions

This equipment has been designed for operation in the following environmental conditions. Operation outside of these conditions may result reduced performance, damage to the equipment or hazard to the operator.

a. Indoor use;

b. Altitude up to 2000 m;

c. Temperature 5 °C to 40 °C;

d. Maximum relative humidity 80 % for temperatures up to 31 °C, decreasing linearly to 50 % relative humidity at 40 °C;

e. Mains supply voltage fluctuations up to ±10 % of the nominal voltage;

f. Transient over-voltages typically present on the MAINS supply;

NOTE: The normal level of transient over-voltages is impulse withstand (over-voltage) category II of IEC 60364-4-443;

g. Pollution degree 2.

Normally only nonconductive pollution occurs.

Temporary conductivity caused by condensation is to be expected.

Typical of an office or laboratory environment

Routine Maintenance

Responsibility

To preserve the life and efficient operation of the equipment it is important that the equipment is properly maintained. Regular maintenance of the equipment is the responsibility of the end user and must be performed by qualified personnel who understand the operation of the equipment.

General

The F1-10 should be disconnected from the electrical supply when not in use.

Water should be drained from the S16 when not in use.

RCD test for F1-10 Hydraulics Bench

Test the RCD by pressing the TEST button at least once a month. If the RCD button does not trip when the Test button is pressed then the equipment must not be used and should be checked by a competent electrician.

Test condition of water in F1-10 Hydraulics Bench

Check that the water in the sump tank is clean and suitable for use. The water should be changed regularly to avoid stagnation (refer to Water Borne Hazards). The use of a corrosion inhibitor which includes a biocide/disinfectant will reduce the formation of algae or micro-organisms and allow water changes to be performed less frequently. The frequency of water changes will depend on usage, local conditions and whether or not a biocide is used. As most corrosion inhibitors for the treatment of water are used in closed systems, ensure that the inhibitor/biocide used is safe to handle and does not create a hazard to the health of operators handling models immersed in the treated water.

If it is necessary to change the water, drain all water from the channel then open the drain cock on the underside of the F1-10 Hydraulics Bench and allow the water to drain. A flexible tube connected to the cock will allow the water to be directed to a suitable drain.

Refill the sump tank as described in the Operation or Installation section, using clean water and add the correct amount of an appropriate corrosion inhibitor with biocide if required (must be suitable for use with aluminium alloy). The sump tank contains approximately 250 litres of water. Refer to the details supplied with the inhibitor used for information on dilution.

Open the outlet flow control valve on the S16. Close the inlet flow control valve on the S16. Close the flow control valve on the F1-10. Switch on the pump then gradually open the flow control valve on F1-10 followed by the inlet flow control valve on the S16 to circulate the water through the flow channel and the F1-10. Restrict the outlet flow control valve on the S16 to raise the water level to the overflow in the inlet tank to ensure that the inhibitor has dispersed thoroughly and coated all wetted surfaces with a protective film.

A few drops of wetting agent or surfactant should be added to the water in the sump tank to reduce the effect of surface tension. Note that too much wetting agent will cause foaming.

Check S16 for leaks

The S16 Hydraulic Flow Demonstrator, F1-10 Hydraulics Bench and interconnecting pipework should be checked visually for drips or staining associated with leaks. Any leaks identified should be attended to immediately to minimise deterioration of the equipment. Refer to the notes below on resealing for further information.

Full annual service

It is important to carry out a full service at regular intervals, at least annually or more frequently according to usage and local conditions. The full service must include the following:

Check for leaks

Ensure that the removable panel is fitted to the aperture in the roof of the working section.

Open the outlet flow control valve fully on S16. Close the inlet flow control valve on S16. Close the flow control valve on F1-10. Switch on the pump then gradually open the flow control valve on F1-10 followed by the inlet flow control valve on S16 to circulate water through the flow channel and the F1-10. Restrict the outlet flow control valve on S16 to raise the water level to the overflow in the inlet tank. Gradually close the Inlet and Outlet valves in combination to retain the water in the S16 then switch off the pump and allow the channel to stand for at least 24 hours. Check all joints, pipework etc. for leaks and mark any leaks for subsequent action.

Draining and Cleaning

Having inspected for any leakage all water should be drained from the channel and sump tank of F1-10.

The channel and F1-10 Hydraulics Bench should be cleaned using warm water with household detergent then rinsed and dried. Particular attention should be paid to the clear acrylic walls of the channel if deposits are obscuring the view, taking care not to scratch the soft plastic. In order to restore visual clarity to scuffed, discoloured or surface crazed acrylic, an abrasive metal polish may be used.

After cleaning with warm soapy water dry the equipment then check for any signs of damage.

While the F1-10 is drained the centrifugal pump can be checked. Refer to the leaflet supplied by the pump manufacturer for service details.

Note: Care must be taken not to use strong cleaning agents or strong solvents such as acetone, trichloroethylene or tetrachloride which will soften the material and cause crazing of the clear acrylic working section.

Check condition of the paintwork

Having checked the working section and pipework, any damage to paintwork on the supporting frame should be identified and touched up.

Any corrosion should be removed and the surface degreased. The cleaned surface should be primed before painting. A two pack etch primer/undercoat suitable for use with mild steel should be used to coat the mild steel support pedestals.

The colour specification of the original paint is Oxford Blue, BS105

Resealing

Any leaks, which were identified while the channel and pipework were filled, should be resealed using an appropriate sealant.

Weeping or dripping from fine cracks or joints in the plastic fabrication with gaps less than 1 mm may be made good using a penetrating sealant such as ‘Creeping Crack Cure’ that relies on capillary action but remains flexible when set.

'Silicone sealant' can be used where damage has occurred and larger gaps need to be filled. This sealant cures at room temperature but remains flexible.

All flexible hoses must be checked and replaced if perished.

Despite appearing leak-tight, all joints should be checked for integrity and re-seated if necessary.

Leaks from threaded joints should be sealed by wrapping PTFE tape around the thread before refitting the component.

Lubrication

All moving parts should be lubricated using a light grease or Vaseline taking care not to contaminate the inside of the working section. Special attention should be paid to the actuators for the elevating bed, the inlet weir and the discharge weir.

Where usage is unusually heavy or local conditions are extreme increase the frequency of lubrication to every 6 months.

Refilling

Refill the F1-10 Hydraulics Bench as described in the Operation section or Installation section.

Operate the S16 in combination with F1-10 and confirm that all leaks etc. have been resolved.

Cleaning the Models

Models used in the channel should be checked for damage and repaired if necessary. All models should be washed in warm water to which household detergent has been added.

The models supplied with S16 use clear acrylic in the construction and should not be cleaned using strong solvents such as acetone, trichloroethylene or tetrachloride which will soften the material and cause crazing of the clear acrylic.

In order to restore visual clarity to scuffed, discoloured or surface crazed acrylic, an abrasive metal polish may be used.

Reconfiguring the optional flowmeter

The optional flowmeter is supplied configured and ready to operate with the ‘Battery Save Mode’ set to ‘ON’. The instrument can be used at any time by pressing the ‘Enter’ button briefly to display the volumetric flowrate in units of litres per minute. To view the Total flow (not usually required for use with S16) press the ‘Enter’ button briefly again while the flowrate is displayed. The screen will remain on for a period of 30 seconds to allow a reading to be taken. To take another reading simply press the ‘Enter’ button briefly again. This mode of operation extends the battery life significantly. However, if continuous display of flowrate is required then the ‘Battery Saving Mode’ can be set to ‘OFF’.

To reconfigure the flowmeter

The setup of the flowmeter is split into six separate screens as follows:

RATE 1 Input flow ‘Rate Factor’ (Sr)

RATE 2 Input flow rate display ‘Decimal Point Factor’ (Dr)

RATE 3 Toggle ‘Battery Saving Mode’ (ON enabled or OFF disabled)

TOTAL 1 Input flow ‘Total Scale Factor’ (St)

TOTAL 2 Input flow total display ‘Decimal Point Factor’ (Dt)

TOTAL 3 Toggle front panel ‘Clear Total’ button (ON enabled or OFF disabled)

When used with S16 the recommended settings are as follows:

RATE 1 06.7077

RATE 2 0000.0

RATE 3 ON

TOTAL 1 00.1118

TOTAL 2 0000.0

TOTAL 3 ON

Press and hold the ‘Enter’ button for at least 1.25 seconds to enter the programming mode.

RATE 1 screen is displayed. To change the value press the ‘Clear setpoint’ button (►) until the required digit flashes then press the ‘Clear Total’ button (▲) repeatedly until the required value is displayed for that digit. Repeat until all digits are displayed correctly then press the ‘Enter’ button to move to the next screen.

RATE 2 screen is displayed. Press the ‘Clear Total’ button (▲) to see the decimal point appear then press the ‘Clear Total’ button (▲) repeatedly until the decimal point is located in the desired location. Press the ‘Enter’ button to move to the next screen.

RATE 3 screen is displayed. Press the ‘Clear Total’ button (▲) to toggle the ‘Battery Saving’ mode ‘ON’ or ‘OFF’ as required. ‘ON’ is recommended to extend the battery life significantly. However, continuous operation can be selected if required by setting ‘OFF’. Press the ‘Enter’ button to move to the next screen.

TOTAL 1 screen is displayed. Enter the required Total Scale Factor. To change the value press the ‘Clear setpoint’ button (►) until the required digit flashes then press the ‘Clear Total’ button (▲) repeatedly until the required value is displayed for that digit. Repeat until all digits are displayed correctly then press the ‘Enter’ button to move to the next screen.

TOTAL 2 screen is displayed. Press the ‘Clear Total’ button (▲) repeatedly until the decimal point is located in the desired location. Press the ‘Enter’ button to move to the next screen.

TOTAL 3 screen is displayed. Press the ‘Clear Total’ button (▲) to toggle the ‘Clear Total’ button mode ‘ON’ or ‘OFF’ as required. ‘ON’ is recommended to allow the indicated Total flow to be reset to zero. However, the button can be disabled if required by setting ‘OFF’. Press the ‘Enter’ button for at least 1.25 seconds to exit the programming mode.

Note: The flowmeter will revert to readout mode if no button is pressed for a period of 20 seconds.

Maintaining the optional flowmeter

The flowmeter requires very little maintenance except the following checks, periodically or if readings are suspect:

Unscrew the union nut and carefully remove the sensor from the pipe fitting without twisting the body.

Inspect the meter for signs of wear and obstructions or debris such as hairs wrapped around the paddle.

Inspect the ‘O’ rings for signs of damage. Replace the ‘O’ rings if swollen or cracked.

The four AA alkaline batteries can be replaced by removing the four screws and opening the front panel. Before replacing the cover ensure that the foam insert is in place.

Laboratory Teaching Exercises

Index to Exercises

A variety of Teaching Exercises are included in the following section that range from simple introductions to detailed studies of appropriate hydraulic phenomena.

Since different phenomena associated with hydraulic flow occur simultaneously it is difficult to isolate individual aspects. For example water flowing beneath a hydraulic structure such as a Sluice Gate (undershot weir) will create a Hydraulic Jump somewhere downstream of the weir in the working section under certain conditions so a basic understanding of the Hydraulic Jump is beneficial before performing a detailed analysis of the Sluice Gate. Similarly, limitations or controls imposed by upstream or downstream water level and changes in local velocity will affect the characteristics of flow over, around or under hydraulic structures in an open channel.

For this reason initial teaching exercises are included that configure the equipment correctly for a group of demonstrations and introduce the various hydraulic phenomena and their consequences on flow conditions before moving to more advanced exercises where individual characteristics are investigated and demonstrated in depth.

In some instances the initial exercises may be adequate to introduce the various phenomena. Where more detailed studies are required it is recommended that the initial exercises are completed first to ensure complete understanding of the complex phenomena and the consequences of their interactions.

The teaching exercises are grouped as follows:

Exercises A to G Flow in Closed Conduits

Exercises H to L Flow in Open Channels

Exercise L - Introduction to Flow Over Weirs

Exercises M to O Flow under a Sluice Gate and through a Culvert

Exercise M - Characteristics of Flow Beneath a Sluice Gate (an Undershot Weir)

Exercise N - Calculating the Force on a Sluice Gate (an Undershot Weir)

Exercise O - Characteristics of Flow Through a Culvert

Exercises P to R Critical Depth

Exercise P - Critical Depth – Derivation of the Specific Energy Equation

Exercise Q - Critical Depth – Control Imposed by the Minimum Energy Condition

Exercise R - Critical Depth – Velocity of Gravity Waves in Shallow Water

Exercises S to V Specific Energy & Forces in open streams

Exercise S - Response of Fast Flow to changes in Specific Energy

Exercise T - Response of Slow Flow to Changes in Specific Energy

Exercise U - Response of Slow and Fast Flow to Changes in the Force of a Stream

Exercise V - Investigating the Combined Effects of the Specific Energy and Force Equations

Exercise W Hydraulic Jumps

Exercise W - The Hydraulic Jump – Creating the Phenomena

Exercises X to Z Flow over different Weirs

Exercise X - Characteristics of flow over a Sharp Crested Weir

Exercise Y - Characteristics of flow over a Broad Crested Weir

Exercise Z - Characteristics of flow over an Ogee Weir

Note: S16 is extremely versatile and can be used for many other demonstrations including student project work involving the testing of alternative hydraulic structures.

Nomenclature

Name	Symbol	Unit	Definition
Cross sectional area	A	m^2	A = by
Velocity of gravity wave in still shallow water	c	ms^{-1}	$c = \sqrt{gy}$
Coefficient of contraction	C_c	-	Empirical
Coefficient of discharge	C_d	-	Empirical

Coefficient of velocity	C_v	-	$0.95<C_v<1.0$
Hydraulic mean depth	D_m	m	y
Specific energy head (total energy head measured relative to channel bed)	E	m	$E = y + U^2/2g$
Force of a stream	F	N	$F = \rho gby^2/2 + \rho Q^2/by$
'Piezometric head' reading on manometer	h_p	m	Measured (Bed tapping)
'Total head' reading on manometer	H	m	Measured (Pitot tube)
'Static head' (at height y+z above datum)	h_s	m	$h_s = h_p - (y + z)$
'Velocity head'	h_v	m	$h_v = H - h_p$
Total energy head or total head (height of energy line above datum)	H_x	m	$H_x = y + U^2/2g + z$ (If z = 0 then E = H)
Loss of total head between sections	ΔH	m	Calculated
'Total pressure'	p_t	Nm^{-2}	Measured
Volumetric flowrate	Q	$m^3\ s^{-1}$	Measured or Q = V/t using F1-10
Wetted perimeter (for rectangle)	P	m	P = b+2y
Hydraulic mean radius (for rectangle)	R_h	m	$R_h = by/(b+2y)$
Time	t	secs	Measured
Temperature of water	T	^oC	Measured
Local fluid velocity	u	$m\ s^{-1}$	Calculated
Mean fluid velocity	U	$m\ s^{-1}$	U = Q / by
Volume	V	m^3	Measured
Critical depth	y_c	m	Depth at which Specific energy is at a minimum

Depth of fluid flowing (at section x)	y_x	m	Measured
Density of water	ρ	kg m^{-3}	ρ = 0.998 at 20ºC
Height of weir crest above datum	z_w	m	Measured
Height of bed above datum (at section 2)	z_2	m	Measured

An appropriate nomenclature detailing the important parameters is included where relevant in the Theory section of each teaching exercise.

Common Theory

The solid boundary formed by the bed of the channel is referred to as the 'invert'. The fixed 'invert' upstream and downstream of the adjustable section is taken as the datum for all height measurements. The height of the adjustable section is also measured relative to this datum (z_2 is the height of the adjustable bed relative to the fixed sections at sections 1 and 3).

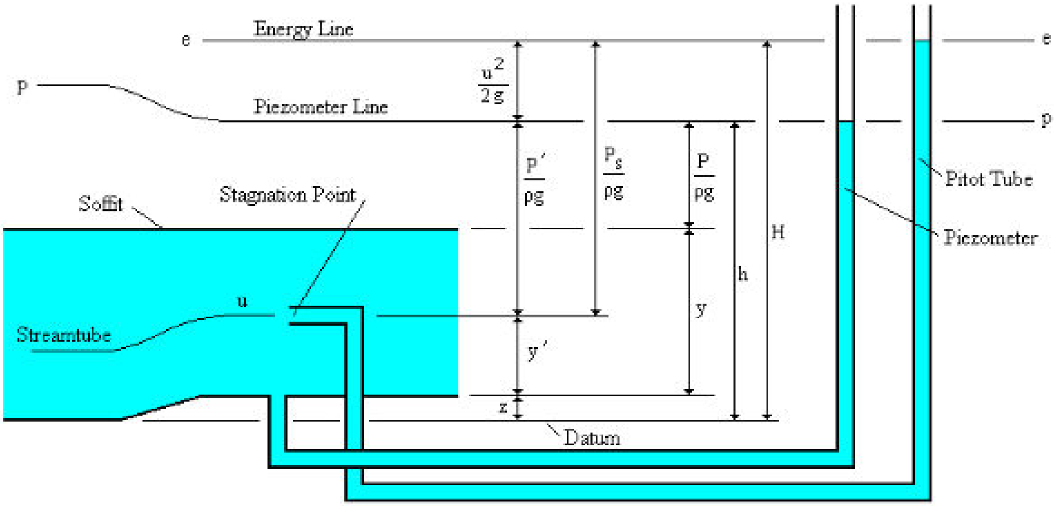
The solid boundary formed by the roof of the closed conduit is referred to as the 'soffit'.

Scales on the equipment measuring height are calibrated in mm for convenience in operation. When recording these measurements they should be converted to units of metres ready for use in the appropriate calculations. E.g. A water depth of 75 mm should be recorded as 0.075 m.

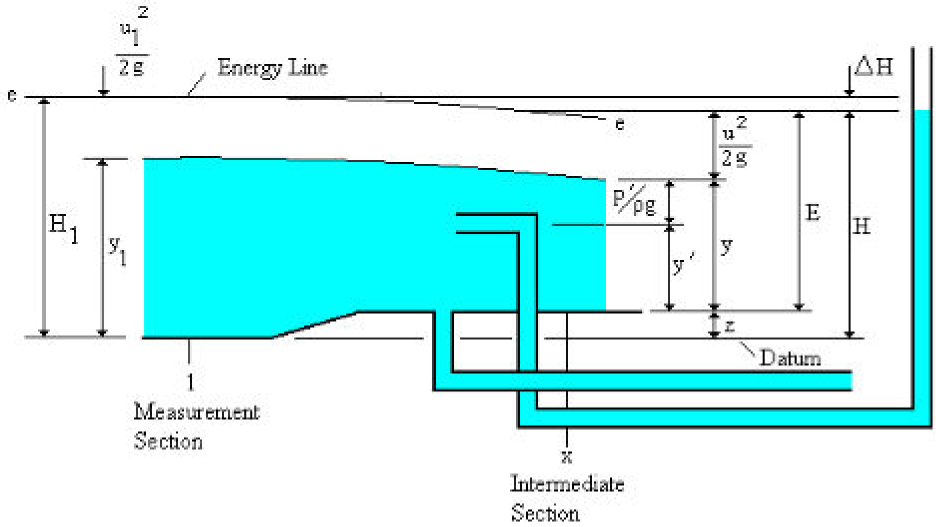
The density of water can be assumed to be 1000 kg/m^3 for most applications without significant error. However, the density of water changes slightly with temperature. For accurate results therefore, where calculations involve the density of water, the following values should be used:

Temperature (ºC)	Density kgm^{-3}
5	999.9
10	999.7
15	999.1
20	998.2
25	997.1
30	995.7
35	994.0
40	992.2

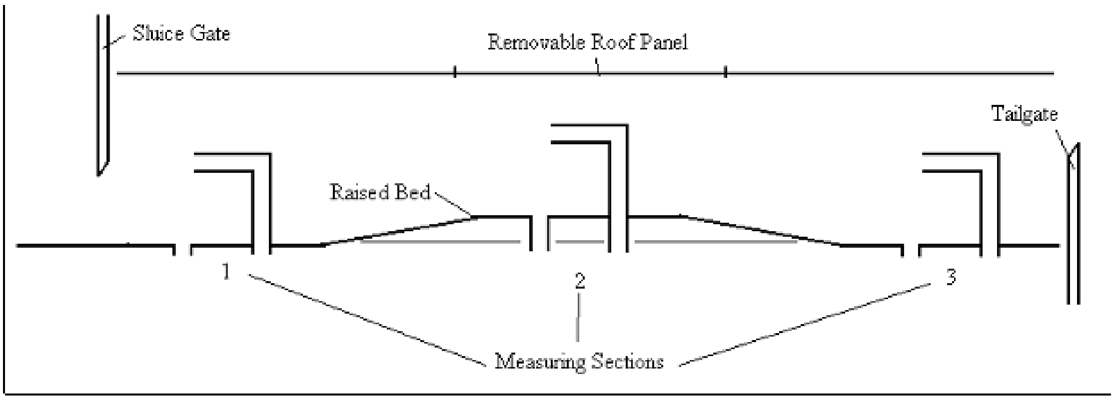
Note: Heads measured by the manometer are piezometric heads and always referenced to the upstream/downstream bed of the conduit. When it is required to obtain the true static head or true total head at a point in the fluid it is necessary to deduct the height of that point above the bed to obtain the true head.



Nomenclature appropriate to closed conduits



Nomenclature appropriate to open channels



Flow Boundaries and Measurement Sections

In the teaching exercises numerical subscripts are used to identify the location of the measurement sections as shown in the first diagram above. These are defined as:

1. Upstream of the sluice gate (depth in the inlet tank – left hand side of level scale adjacent to sluice gate)
2. Downstream of the sluice gate, before the rising section of bed (depth at entry to working section – level scale adjacent to left hand Pitot tube)
3. Above the elevated section of bed – scale adjacent to middle Pitot tube)
4. Downstream of the elevated section of bed (depth upstream of the tailgate – scale adjacent to right hand Pitot tube)

In addition to defining the sections, the following subscripts are also used:

g At the sluice gate opening

e Energy line

p Piezometric line (**Note:** Piezometric head is the sum of the pressure head and the potential head)

Exercise A - Preparing S16 to Demonstrate Flow Through Closed Conduits

Objective

To configure the S16 for teaching exercises involving water flowing through a closed conduit. The S16 should be configured in this manner before proceeding with Exercises B to G.

Method

Preparing the S16 for use as a closed conduit and priming the Pitot tubes, Bed tappings and manometer tubes ready for use.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Wetting agent or surfactant to reduce the effect of surface tension

Equipment Set Up

Locate S16 at left hand side of F1-10 with outlet from channel and separate overflow pipe both above channel in top of F1-10.

Fit outlet control valve to discharge end of channel and tighten all thumb nuts.

Fit removable cover to top of working section and tighten all thumb nuts.

Open outlet valve fully at discharge end of channel.

Close inlet valve fully (above optional flowmeter if fitted).

Close F1-10 flow control valve fully.

Raise sluice gate (undershot weir) fully at inlet end of channel.

Lower overshot outlet weir fully at discharge end of channel.

Lower adjustable section of bed to its lowest position (0 mm on scale).

Lower all three Pitot tubes until flush with the bed.

A few drops of wetting agent or surfactant in the F1-10 and one drop in each manometer tube will reduce surface tension and aid priming.

Start F1-10 pump.

Open F1-10 flow control valve fully.

Gradually open inlet valve on S16 to give steady flow along bed of working section (water will discharge into top of F1-10).

Allow air bubbles to clear from flexible connection to F1-10.

Gradually close outlet control valve until valve is fully closed to flood channel.

Gradually close inlet control valve so that water level does not rise too rapidly. Fully close inlet control valve when water level reaches overflow at top of inlet tank.

Close F1-10 flow control valve then switch off pump.

Raise middle Pitot tube to top of channel. Release clamping screw on bed actuator then slowly raise and lower elevating section of bed several times to displace any trapped air bubbles. Return bed to lowest position and clamp actuator.

Allow level to stabilise in end tanks then prime bed tappings, Pitot tubes, manometer tubes and flexible tubing as follows. Loosen plastic securing screw at top of manometer (located at rear). Lift manometer off side of inlet tank then tip top of manometer into a bucket or similar container until all tubes run full of water. Replace manometer on side of inlet tank and tighten plastic securing screw.

When fully primed level in all manometer tubes should coincide with levels in inlet tank and outlet tank (All water levels same height with no flow through the working section). Any difference in levels means that air is trapped somewhere between tapping and manometer. To remove air bubbles insert plastic syringe supplied into top of affected manometer tube to force water through tubing / suck water from tapping until clear of bubbles.

The equipment is ready to demonstrate flow in closed conduits.

When operating the equipment care should be taken not to allow air to enter the Pitot tubes or bed tappings after the system has been primed. This can be avoided by ensuring that the Pitot tubes and elevated bed are not raised above the local water level. If air does enter a tapping it can be quickly removed using the plastic syringe as described above.

Exercise B - Introduction to Flow Through Closed Conduits

Objective

To demonstrate visually the various phenomena and characteristics associated with water flowing through a closed conduit.

Note: This exercise is intended as a general introduction to the topic. Later exercises investigated this in more detail.

Method

By operating the working section flooded to create a closed conduit and varying the height of the adjustable bed to change the cross sectional area.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Equipment Set Up

As described in Exercise A with channel flooded, inlet valve and outlet control valves fully closed (no flow).

Ensure that sluice gate (undershot weir) at inlet is fully raised and overshot weir at outlet is fully lowered.

Procedure

Raise middle Pitot tube until tip is 130mm above the bed then raise elevating section of bed until 110mm above the bed (Conduit reduces from 150 mm to 40 mm then returns to 150 mm).

Locate upstream and downstream Pitot tubes 75mm above bed (mid height in each section). Ensure all three Pitot tubes point directly upstream.

Confirm that level in all manometer tubes is the same with water stationary (Re-prime if levels are not the same).

Switch on F1-10 and open F1-10 flow control valve fully.

Gradually open inlet flow control valve on S16 to fill end tanks and working section until working section is full. Gradually open outlet control valve and open inlet control valve together to maintain level inside end tanks while allowing flow through working section.

Increase flow until maximum is achieved without overflow operating (Outlet valve partially restricted to maintain working section full of water, inlet valve fully open).

Allow flow to stabilise in working section and allow manometer levels to settle.

Observe that static head at throat (contraction above elevating section of bed) is reduced below levels in inlet and outlet tanks. Also observe that total head at contraction is same as total head upstream (Bernoulli equation can be applied across a contraction).

Observe that there is a small loss in total head between throat and outlet of working section because of frictional losses in the expansion (Bernoulli equation cannot be applied across an expansion without accounting for losses).

Lower bed to mid height. Observe that static head at throat increases and frictional loss reduces because of reduced velocity.

Lower bed to lowest position (0 mm on scale). Observe that piezometric and total head is constant at three positions in working section (minimal loss because of very low velocity).

This simple demonstration illustrates how change in fluid velocity in a closed conduit affects the static and total head in the system. Frictional losses (especially significant where an expansion is involved) cause the static head and total head to reduce from inlet to outlet in the system (head is lost).

Later exercises evaluate these changes in more detail and demonstrate application of the Bernoulli equation.

Continue with Exercise C if time permits.

Conclusions

Changes in velocity and therefore velocity head cause the static head and the total head to change. Friction in the system (especially at an expansion) causes the total head and therefore the static head to fall slightly in the direction of flow due to losses in the system. Higher fluid velocity causes increased losses.

Exercise C - Using a Pitot Tube to Measure Point Velocity

Objective

To demonstrate how a Pitot tube (in conjunction with a manometer) is used to determine the Total head at a point in a fluid.

To demonstrate how local velocity can be calculated from measurement of the 'total head' and 'piezometric head' at a point.

Method

By changing the flow through the closed conduit and measuring the corresponding 'total head' and 'piezometric head' to determine the resulting fluid velocity at any point in the conduit.

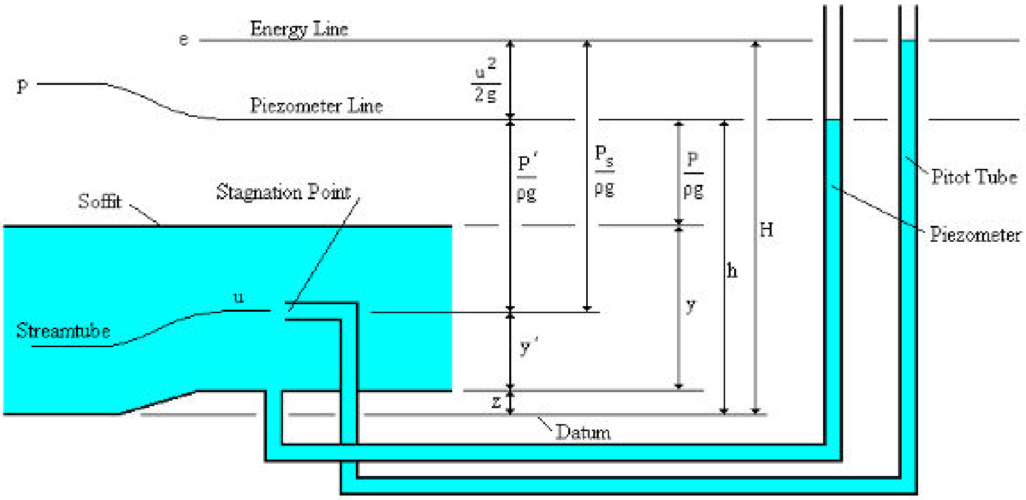
Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory



A small hole in the bed of the conduit allows the static head to be measured corresponding to the static pressure at that point in the conduit. Provided that the hole is clean and does not disturb the flow, a manometer tube connected to this tapping will indicate the static head where $h_s = p_s / \rho_f g$. However, when measured relative to the zero datum (the bed of the conduit) this is the static pressure measured at the bed and is called the piezometric head h_p. To obtain the static pressure at any other depth (e.g. at the height of the Pitot tube) it is necessary to deduct the height relative to the bed.

i.e. Measured piezometric head $h_p = p_s / \rho_f g + (y_1 + z)$ therefore static head at height y_1 (e.g. at the Pitot tube) $h_s = h_p - (y_1 + z)$

The Pitot tube is essentially a small bore tube that is parallel with the flow and is bent through 90º to allow convenient access through the bed of the conduit. At the tip of the Pitot tube the flow along the stream tube is momentarily arrested at what is called the stagnation point. The pressure at this point is called the stagnation pressure (the sum of the dynamic pressure and the static pressure). A manometer connected to the Pitot tube will indicate the total head corresponding to the stagnation pressure where from the Bernoulli equation:

$$H = p_s / \rho_f g + (y_1 + z) + \frac{u^2}{2g} \text{ or } H = h_s + (y_1 + z) + \frac{u^2}{2g}$$

But from above $h_s = h_p - (y_1 + z)$ when h_p is measured by the bed tapping so

$$H = h_p - (y_1 + z) + (y_1 + z) + \frac{u^2}{2g}$$

$$\frac{u^2}{2g} = H - h_p$$ therefore $$u = \sqrt{2g(H - h_p)}$$

Since $\frac{u^2}{2g}$ is the called the velocity head h_v, the difference in manometer readings can simply be referred to as h_v.

Therefore the velocity at the Pitot tube $u = \sqrt{2gh_v}$ m/s provided that h_v is measured in metres of water.

Note:

H is the total head

$p^1 / \rho g$ is known as the pressure head

$(y_1 + z)$ is known as the potential head

$u^2 / 2g$ is known as the velocity head

The sum of the pressure and potential heads is known as the piezometric head that is measured by the manometer tubes.

For a real flow the velocity and total head are not constant across a section of the conduit but the Pitot tube can still be used satisfactorily to measure the velocity where the pressure distribution is hydrostatic.

As with all hydraulic devices such as the orifice plate and the Venturi, an empirical flow coefficient or correction factor k is necessary to obtain accurate measurements from the Pitot tube. This is due to blockage of the flow, turbulence behind the device etc. However, provided that the Pitot tube is positioned parallel with the flow (pointing directly upstream and creating minimal blockage) the error will be small and the k factor can be assumed to be unity.

The velocity profile at each section in the channel can be obtained by moving the Pitot tube vertically, noting any changes in the total and piezometric heads on the manometer at each position and converting these readings to a series of velocity profiles. This is detailed in the next exercise.

u	= Local velocity of water	($m\ s^{-1}$)
k	= Pitot tube coefficient (can be assumed to be unity)	(Dimensionless)
H	= Total head (Total energy head)	(m)
p_t	= Total pressure = $\rho_f g H$	($N\ m^{-2}$)
h_s	= Static head	(m)
p_s	= Static pressure = $\rho_f g h_s$	($N\ m^{-2}$)
ρ_f	= Density of operating fluid (water)	($kg\ m^{-3}$)
ρ_m	= Density of manometer fluid (using water so $\rho_m = \rho_f$)	($kg\ m^{-3}$)
h_v	= Velocity head (Difference in levels in manometer $(= H - h_p)$	(m)
g	= Gravitational constant	($9.81 m\ s^{-2}$)

Equipment Set Up

As described in Exercise A.

Ensure that sluice gate (undershot weir) at inlet is fully raised and overshot weir at outlet is fully lowered.

Start with adjustable bed in lowest position (0 mm).

Procedure

With adjustable bed in lowest position (0 mm), three Pitot tubes at mid height in conduit and water flowing at maximum flowrate record total and piezometric head readings for all three positions.

Measure and record corresponding flowrate using flowmeter (if fitted) or time a measured volume using volumetric tank on F1-10.

Raise middle Pitot tube to 125mm. Raise adjustable bed to 100mm (50mm throat). Allow conditions to stabilise then record total and piezometric head readings for all three positions.

Measure and record corresponding flowrate using flowmeter (if fitted) or time a measured volume using volumetric tank on F1-10.

Raise middle Pitot tube to 140mm. Raise adjustable bed to 130mm (20mm throat). Allow conditions to stabilise then record total and piezometric head readings for all three positions.

Measure and record corresponding flowrate using flowmeter (if fitted) or time a measured volume using volumetric tank on F1-10.

Results

Calculate the local velocity at each position and each configuration from the differences in manometer levels. Compare each velocity with the average value obtained from flow measurement Q.

Note: Average velocity U = Average flowrate Q / Cross sectional area A.

Conclusions

The local velocity at a point in a fluid can be determined from a measurement of total head and static head at that point in the stream.

The total head can be determined using a Pitot tube. The static head can be determined using a tapping in the wall or bed of the conduit.

The velocity can be calculated from the difference between the manometer readings obtained from the Pitot tube and bed tapping.

Exercise D - Measuring Velocity Profiles using a Pitot Tube and Manometer

Objective

To measure the Velocity profile in the working section using a Pitot tube and manometer

Method

Using a Pitot tube and manometer to measure the changes in total head and consequently the changes in velocity profile created by different disturbances to the flow in the working section, typically the sluice gate (undershot weir) to create a velocity gradient / profile inside the working section then using the Pitot tubes to measure the profile by measuring the total head at different heights above the bed.

Equipment Required

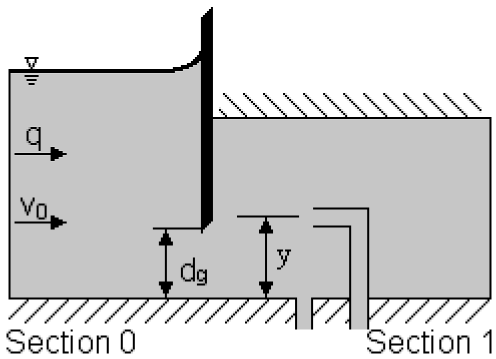
Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory

The theory of the Pitot tube was introduced in the previous exercise and demonstrated using relatively constant velocity inside the working section. In this exercise the Pitot tubes will be traversed vertically to measure the change in velocity with height resulting from an obstruction to the flow.



Velocity profile downstream of a sluice gate

Equipment Set Up

As described in Exercise A.

Procedure

Keep the conduit full of water (inlet and outlet valves fully closed).

Lower adjustable bed fully (0 mm).

Lower sluice gate (undershot weir) at inlet until the tip is 10 mm above the bed.

Raise overshot weir at outlet until tip is 50 mm above the bed.

Adjust inlet and outlet valves to give flow of water through conduit with depth of 200 mm upstream of sluice gate.

With upstream Pitot tube resting against the bed and the tip pointing directly upstream record total head and static head indicated on manometer.

Move Pitot tube vertically by 5mm then record corresponding total head indicated on manometer (static head will remain constant).

Continue to traverse Pitot tube vertically upwards in 5mm steps, recording the corresponding values of total head.

Repeat measurements using middle and downstream Pitot tubes for the same flow conditions.

Raise sluice gate by 10 mm then readjust flow to give depth of 200 mm upstream of sluice gate.

Repeat measurements using 3 Pitot tubes.

Raise sluice gate by 10 mm then readjust flow to give depth of 200 mm upstream of weir.

Repeat measurements using 3 Pitot tubes.

Results

For each measurement calculate velocity of the water.

Plot a graph of water velocity against height of Pitot tube to show the velocity profile at three different locations in the working section.

Conclusions

Changes in velocity with depth or position (the velocity profile) can be determined by traversing a Pitot tube across the area of interest. The velocity at each point can be determined from the difference in total head and static head and plotted against position of the Pitot tube show the velocity profile.

Explain the reasons for the differences in the velocity profiles obtained at different sections in the working section.

Exercise E - Application of the Continuity Equation

Objective

To demonstrate how the Conservation of Mass and the Continuity Equation can be applied to the flow of an incompressible fluid through a closed conduit.

Method

By using the Pitot tube to determine the change in velocity associated with a change in cross sectional area.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory

The continuity equation is simply a mathematical expression for the conservation of mass whereby all mass flow rates into a control volume are equal to all mass flow rates out of the control volume for a simple control volume with a single inlet and a single outlet.

i.e. $m_{inlet} = m_{outlet}$

However Mass flow rate $m = (\rho A v)$ where

ρ is the density of the fluid

A is the cross sectional area

v is the velocity of the fluid

Therefore $(\rho A_1 v_1) = (\rho A_2 v_2) = (\rho A_3 v_3)$

One of the simplest applications of this equation is determining the change in fluid velocity due to an expansion or a contraction in a closed conduit where the fluid density is constant. The same fluid must pass through all sections in the duct so the velocity must change in inverse proportion to the cross sectional area (if the cross sectional area doubles then the velocity will halve).

Equipment Set Up

As described in Exercise A. Ensure that sluice gate at inlet is fully raised and overshot weir at outlet is fully lowered.

Ensure that the elevated bed is in its lowest position (0 mm) and the Pitot tubes at stations 1, 2 and 3 are at mid height in the duct.

Procedure

With adjustable bed in lowest position (0 mm), three Pitot tubes at mid height in conduit and water flowing at maximum flowrate record total and static head for all three positions.

Measure and record corresponding flowrate using flowmeter (if fitted) or time a measured volume using volumetric tank on F1-10.

Raise middle Pitot tube to 125mm. Raise adjustable bed to 100mm (50mm throat). Allow conditions to stabilise then record total and static head readings for all three positions.

Measure and record corresponding flowrate using flowmeter (if fitted) or time a measured volume using volumetric tank on F1-10.

Raise middle Pitot tube to 140mm. Raise adjustable bed to 130mm (20mm throat). Allow conditions to stabilise then record Total and Static head readings for all three positions.

Measure and record corresponding flowrate using flowmeter (if fitted) or time a measured volume using volumetric tank on F1-10.

Results

Tabulate your measurements and calculations as follows:

For Station 1:

Static head	h_1 mm
Total head	H_1 mm
Velocity	v_1 m/s
Height of duct	y_1 m
Area of duct	A_1 m^2
Mass flowrate	m_1 m^3/s

For Station 2:

Static head	h_2 mm
Total head	H_2 mm
Velocity	v_2 m/s
Height of duct	y_2 m
Area of duct	A_2 m^2
Mass flowrate	m_2 m^3/s

For Station 3:

Static head	h_3 mm
Total head	H_3 mm
Velocity	v_3 m/s
Height of duct	y_3 m

Area of duct A_3 m^2

Mass flowrate m_3 m^3/s

Compare theoretical predictions with measurements.

Conclusion

Under steady flow conditions the mass flow of water at all locations inside the conduit is constant despite changes in the cross sectional area.

Comment on the effect of streamline curvature on the measurements where the flow passes over the elevated section of bed.

Exercise F - Head Loss Associated with Converging and Diverging Flow in a Closed Conduit

Objective

To measure the frictional losses associated with changes in cross section in a closed conduit.

Method

By measuring the change in static and total head before and after a change in cross section created by the elevated section of the bed.

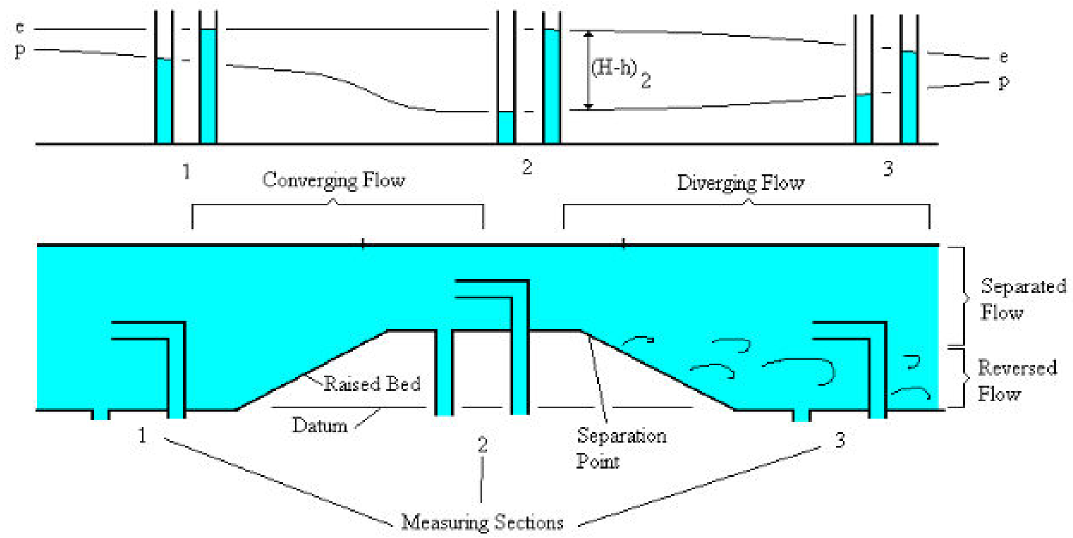
Equipment Required

Armfield S16 Hydraulic Flow Demonstrator

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flow rate when using the volumetric tank on F1-10

Theory



A contraction in the cross sectional area of the closed conduit shown above enforces a local acceleration of the steady flow and a convergence of its stream tubes according to the principle of continuity. The converging solid boundaries provide the necessary centripetal forces for turning the stream tubes but the net force on the flow between sections 1 and 2 is in the downstream direction. The static pressure difference between the two sections provides evidence of this force. Throughout this accelerating flow the total head is nearly constant, with the exception of a film of fluid adjacent to the solid boundaries which is retarded by shear forces.

In sharp contrast is the behaviour of flow through an abrupt expansion of the conduit. Here the solid boundaries cannot supply the centripetal forces required by the stream tubes to follow the sharp change in direction of the wall. At the separation point shown above the flow separates from the wall and only after a gradual process of divergence does it reattach itself farther downstream. Between the separated flow and the slow reverse flow in the lee of the separation point, is a layer of strongly sheared flow which breaks down into a series of eddies. The mixing action of these eddies is responsible for the deceleration and divergence of the main stream but at the expense of part of the total head which is dissipated by the eddies in the form of heat.

This loss of total head occasioned by a divergence violates the assumptions of the Bernoulli equation and invalidates its predictions.

Equipment Set Up

As described in Exercise A.

Procedure

Adjust the flow of water into the flume to obtain

The experiment can be repeated using a broad-crested weir installed inside the closed conduit to create a step change in cross section. It will be necessary to partially drain the channel and remove the top cover to install the weir (mounted with the square corner downstream to create a sudden change in cross section). Replace the top cover, refill the conduit then repeat the above exercise.

With care the broad-crested weir can be fitted without allowing air into any of the Pitot tubes; lower the Pitot tubes to be flush with the bed then lower the water level to approximately mid height before removing the top cover and fitting the broad crested weir.

Results

Tabulate your measurements and calculations as follows:

z2	Y2	Hp			H			u		
		1	2	3	1	2	3	1	2	3

Plot H verses Height of bed.

If the exercise has been repeated using a broad crested weir as an obstruction compare the results with those obtained when using the adjustable bed set to the same height of 75mm.

Conclusions

What can be concluded by looking at the graph?

In previous exercises it has been shown that the total head in a system remains constant unless losses occur. How much loss occurs? Why does this loss occur?

Exercise G - Using a Contraction as a Flow Measuring Device in a Closed Conduit

Objective

To demonstrate how flow in a closed conduit can be determined by measuring the head loss across a contraction (a change in cross section).

Method

Using the change in cross section created by the elevated bed to show how a Venturi tube or orifice plate can be used as a flow measuring device in a closed conduit.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory

The small losses of total head experienced by converging flows permit the use of contractions in conduits as flow measuring devices. Examples of these are Venturi tubes or orifice plates which predict the discharge in terms of measured static pressure difference and the geometry of the solid boundaries.

The boundaries shown in the diagram in Exercise D are similar in some resects to a Venturi tube. The discharge is predicted on the assumption that the flow experiences no loss of total head between sections 1 and 2.

$$h_1 + \left(\frac{u_1{}^2}{2g}\right) = h_2 + \left(\frac{u_2{}^2}{2g}\right)$$

For one dimensional, incompressible flow:

$u_1 = V_1$, $u_2 = V_2$ and $Q = V_1 y_1 b = V_2 y_2 b$

After a substitution in terms of Q for u1 and u2, the top equation becomes

$$h_1 = \left(\frac{Q^2}{2gy_1{}^2b^2}\right) = h_2 + \left(\frac{Q^2}{2gy_2{}^2b^2}\right)$$

After simplification

$$Q = \left(\frac{y_1 b \sqrt{2g(h_1 - h_2)}}{\sqrt{\left(\left(\frac{y_1{}^2}{y_2{}^2} \right) - 1 \right)}} \right)$$

The predicted value of discharge in this equation ignores the retardation of flow adjacent to the boundaries due to the effects of friction. The true discharge may be related to this predicted discharge by a coefficient C_v whose value must be determined from a calibration of the flow measuring device, i.e.

$$Q = \left(\frac{C_v y_1 b \sqrt{2g(h_1 - h_2)}}{\sqrt{\left(\left(\frac{y_1{}^2}{y_2{}^2} \right) - 1 \right)}} \right)$$

In practice the value of the coefficient falls within the range $0.90 < C_v < 0.99$ for a smooth contraction such as a Venturi. However, the value for C_v may fall as low as 0.6 for a sudden contraction such as an orifice plate.

Equipment Set Up

As described in Exercise A.

Procedure

Vary the flowrate by adjusting the inlet control valve (it may be necessary to close the discharge control valve partially at low flowrate to keep the conduit full.

After each adjustment allow the conditions to stabilise then record the following parameters at each setting:

H2

Hz

Q

Results

Calculate Cv for each set of readings then plot Cv versus velocity V_2 at the throat.

Conclusions

Comment on the use of a contraction as a flow measuring device.

Could an expansion be used in a similar way.

Exercise H - Preparing S16 to Demonstrate Flow Through an Open Channel

Objective

To correctly configure the S16 for demonstrations involving water flowing through an open channel. The S16 should be configured in this manner for Teaching Exercise's I to Z.

Method

Preparing the S16 for use as an open channel and priming the Pitot tubes, bed tappings and manometer ready for use.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11) with:

Sharp Crested Weir, Broad Crested Weir and Ogee Weir models

Armfield F1-10 Hydraulics Bench

Wetting agent or surfactant to reduce surface tension in the water

Equipment Set Up

Locate S16 at left hand side of F1-10 with outlet from channel and separate overflow above channel in top of F1-10.

Fit outlet control valve to discharge end of channel and tighten all thumb nuts.

Fit removable cover to top of working section and tighten all thumbnuts.

Open outlet valve fully (discharge end of channel).

Close inlet valve fully (above flowmeter).

Close F1-10 flow control valve fully.

Raise sluice gate (undershot weir) fully (inlet end of channel).

Lower overshot outlet weir fully (discharge end of channel).

Lower adjustable section of bed to its lowest position (0 mm on scale)

Lower all three Pitot tubes flush with bed.

A few drops of wetting agent or surfactant in the F1-10 and one drop in each manometer tube will reduce surface tension and aid priming.

Start F1-10 pump.

Open F1-10 flow control valve fully.

Gradually open inlet valve to give steady flow along the bed of the working section (water will discharge into top of F1-10).

Allow air bubbles to clear from flexible connection to F1-10.

Gradually close outlet control valve until fully closed to flood channel

Gradually close inlet control valve and fully close valve when water level reaches overflow on inlet tank.

Raise and lower elevating section of bed several times to displace any trapped air.

Allow level to stabilise in end tanks then prime bed tappings / Pitot tubes / Manometer (tip top of manometer into bucket etc until all tubes run full of water).

When fully primed all levels should coincide with levels in inlet tank and outlet tank (Any difference in levels means that air is trapped somewhere between the tapping and the manometer – use plastic syringe at top of affected manometer tube to force water through tubing / suck water from tapping until clear of bubbles).

Open discharge valve to lower water level below roof of working section. Close outlet valve to leave working section filled to approximately 100 mm depth.

Gradually open inlet valve to give a low steady flow and remove the discharge valve, ensuring that the Pitot tubes are kept submerged.

Note: Cover in roof of working section can be removed for clearer viewing / insertion of models etc. however, care must be exercised not to flood the working section as water will spill from the opening if the water level rises too far.

The equipment is ready to demonstrate flow in open channels.

Exercise I - Introduction to Open Channel Flow

Objective

To demonstrate visually the various phenomena associated with water flowing through an open channel.

Note: Each condition is investigated in depth in later teaching exercises.

Method

By using the S-16 and its various parts, this introduction will show the various phenomena and how they are induced for later experiments.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Equipment Set Up

As described in Exercise H. If S16 has been used for closed conduit demonstrations, lower the adjustable bed fully.

Procedure

Ensure that all three Pitot tubes are located just clear of the bed.

Confirm that level in all manometer tubes is the same with water stationary (Re-prime if levels are not the same).

Switch on the F1-10 and open F1-10 flow control valve fully.

Gradually open outlet control valve and inlet flow control valve alternately on S16 to maintain level inside depth of water in the working section.

Gradually open discharge valve until fully open.

Observe that water level falls until clear of roof of working section (when there is a continuous air space above the water between the inlet and discharge tanks the water is described as having a free surface / open channel flow). The difference in behaviour is dramatic and shown in the following demonstrations.

With water flowing along the channel observe that three Total heads are relatively high because of high velocity and static heads vary slightly with levels along length of working section.

Lower the sluice gate (undershot weir) to 15mm and observe the surface of the water and how the water level upstream of the weir rises.

Exercise J - Introduction to Flow Under a Sluice Gate and the Formation of a Hydraulic Jump

Objective

To observe the flow patterns associated with the flow of water under a sluice gate (undershot weir) and the conditions required downstream to form a Hydraulic Jump.

Method

By using the elevating section of bed installed in the S16 Hydraulic Flow Demonstrator, and inducing a hydraulic jump.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Equipment Set Up

As described in Exercise H.

Procedure

Ensure that outlet weir is fully lowered and outlet valve is fully open.

Gradually close inlet valve to give typically 0.8 l/s on flowmeter.

Gradually lower inlet weir (sluice gate) until tip is 10 mm above bed.

Gradually raise outlet weir in 5 mm steps causing the water level at the downstream end to rise. At each step allow conditions to stabilise in working section and observe changes in Total and Static heads.

At some point a hydraulic jump will form whereby the change from ‘fast’ flow to ‘slow’ flow necessitates a rapid dissipation of energy. Observe the differences in heads before and after the jump (High Total Head / Low Static head upstream because of the high velocity and Low Total Head / Higher Static head downstream because of the low velocity).

Continue to raise the outlet weir in 5 mm steps. At each step allow conditions to stabilise in working section and observe that location of Hydraulic jump moves towards the sluice gate. Also observe changes in ‘total head’ and ‘static head’ at each station.

At some point the hydraulic jump becomes suppressed and the sluice gate becomes flooded on the downstream side.

Use the upstream Pitot tube to observe the velocity profile behind the sluice gate (High velocity near the bed reducing quickly with depth).

Exercise K - Introduction to Flow Over a Hydraulic Structure

Objective

To observe the flow patterns associated with the flow of water over different bed profiles.

Method

By using the elevating section of bed installed in the S16 Hydraulic Flow Demonstrator, and the various models of weirs to demonstrate flow over these hydraulic structures.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Equipment Set Up

As described in Exercise H.

Procedure

Lower outlet weir fully and ensure outlet valve is fully open.

Ensure that adjustable section of bed is at its lowest position (0 mm on scale)

Ensure inlet weir is 10 mm above bed.

Adjust inlet valve to give typically 0.8 l/s on flowmeter / depth of 125 mm in inlet tank.

Ensure three Pitot tubes are just above the bed and fully submerged.

Raise adjustable bed 5 mm. Observe that water flows uphill over hump and down the other side. Observe Static and Total heads.

Continue to raise adjustable bed in steps of 5 mm. Observe that water continues to flow uphill because of its velocity and depth of water increases above elevated section of bed.

Continue to raise adjustable bed until velocity cannot maintain head above hump. Observe that a Hydraulic jump forms momentarily on upstream slope as the section between inlet weir and elevated bed becomes flooded.

Raise outlet weir until hydraulic jump forms at base of downstream slope.

Continue to raise adjustable bed and observe changes in flow patterns and Static and Total heads.

Set up the adjustable bed as level. Open the flow control valve and allow the water to enter the flow channel. By adjusting the valve, the depth of water can be varied in stages. At each stage the flow pattern of the water should be observed and noted.

The critical depth can be determined as a separate exercise if required.

Since the ramp is adjustable in height the above procedure can be repeated with the different profiles.

Exercise L - Introduction to Flow Over Weirs

Objective

To observe the flow patterns associated with the flow of water over different shapes of weir.

Method

By using the various models supplied with the S16 the flow of water over each of the weirs can be observed.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11) with

Sharp Crested Weir, Broad Crested Weir and Ogee Weir models

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flow rate when using the volumetric tank on F1-10

Equipment Set Up and Procedure

As described in Exercise H.

Procedure

Part 1 – Flow over a sharp crested weir

Raise inlet weir fully, lower outlet weir fully and close inlet valve.

Remove cover on top of working section.

Install Sharp Crested Weir at centre of elevating bed with chamfer downstream (highest point upstream). Use hexagon wrench to secure weir but do not over-tighten.

If elevated, lower the adjustable bed to its lowest position.

Partially open inlet valve and allow water level to reach top of weir. As water flows over weir observe that water clings to downstream face (clinging nappe).

Gradually increase flow to 0.7 l/s. Observe that nappe still clings to weir. Observe upstream water level.

Using plastic syringe or length of tube, inject air below surface of the water on downstream face of weir. Observe that water springs clear of weir (ventilated nappe) and assumes smooth profile similar in shape to Ogee weir. Observe small increase in upstream water level.

Gradually increase flow up to 1 l/s and observe flow patterns over weir and increase in upstream water level.

Gradually raise outlet weir and observe changes in flow over weir / changes in upstream water level when weir becomes drowned. Observe oscillations on surface of water downstream of weir as weir becomes submerged.

Note: A Sharp Crested Weir can be used to determine the flow of water by measuring the water level upstream. However, calibration is usually carried out in the ventilated condition. If the nappe clings to the weir or the weir becomes drowned then the flow measurement will not be accurate unless corrections are applied.

Repeat the above exercise but increase the flowrate without assisting the nappe to ventilate. Observe that at higher flowrate the nappe will ventilate naturally because of turbulence in the flow.

Part 2 – Flow over an Ogee weir

Observe that the shape of the Ogee weir follows the natural shape of the water flowing over a sharp crested weir when the nappe is fully ventilated.

If required replace Sharp Crested Weir with Ogee Weir and compare flow patterns over the weir. Observe that flow is smooth with little or no turbulence at the foot of the weir (No scour likely that would undermine the weir, even at low flowrate).

Part 3 – Flow over a broad-crested weir

Raise inlet weir fully, lower outlet weir fully and close inlet valve.

Remove cover on top of working section if fitted.

Install broad-crested weir at centre of elevating bed with radiused corner downstream. Use hexagon wrench to secure weir but do not over-tighten.

If elevated, lower the bed to its lowest position.

Partially open inlet valve and allow water level to reach top of weir. As water flows over weir observe that water clings to downstream face (clinging nappe).

Gradually increase flow to 0.7 l/s. Observe that nappe still clings to weir. Observe upstream water level.

Using plastic syringe or length of tube, inject air below surface of the water on downstream face of weir. Observe that nappe refuses to ventilate because of radius.

Gradually increase flow up to 1 l/s and observe flow patterns over weir and increase in upstream water level.

Gradually raise outlet weir and observe changes in flow over weir / changes in upstream water level when weir becomes drowned. Observe oscillations on surface of water downstream of weir as weir becomes submerged.

Note: A broad-crested weir can be used to determine the flow of water by measuring the water level upstream. However, if the weir becomes drowned then the flow measurement will not be accurate unless corrections are applied.

Repeat the above procedure with the broad-crested weir fitted the other way round (square corner downstream). Observe that the weir ventilates naturally without any assistance because of the turbulence created at the square corner.

Exercise M - Characteristics of Flow Beneath a Sluice Gate (an Undershot Weir)

Objective

To determine the characteristics of the flow beneath a sluice gate and the effect of upstream and downstream water levels on the flow rate.

To calculate the discharge coefficient and to observe the flow patterns obtained.

Method

By using the adjustable sluice gate installed at the entrance to the working section on the S16 Hydraulic Flow Demonstrator and operating the flow channel under a range of flow conditions.

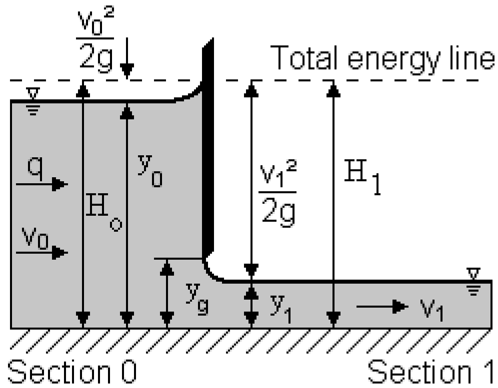
Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory



For flow beneath a sharp edged sluice gate (undershot weir) it can be shown that;

$$Q = C_d \, b \, y_g \sqrt{2 g y_o}$$ therefore: $$C_d = \frac{Q}{b \, y_g \sqrt{2 g y_o}}$$

where:

Q	= Volume flowrate	$(m^3.s^{-1})$
	= Volume/time (using volumetric tank)	
C_d	= Discharge coefficient	(Dimensionless)
b	= Breadth of weir	(m)

y_g	= Height of weir opening above bed	(m)
y_0	= Upstream depth of flow	(m)
g	= Gravitational constant	($9.81 m\ s^{-2}$)

$$H_0 = y_0 \frac{V_0^2}{2g} = y_0 + \frac{Q^2}{2g(y_0 b)^2}$$

$$H_1 = y_1 \frac{V_1^2}{2g} = y_1 + \frac{Q^2}{2g(y_1 b)^2}$$

where:

H_0	= Total head upstream of weir	(m)
H_1	= Total head downstream of weir	(m)
y_1	= Downstream depth of flow	(m)
V_0	= Mean velocity upstream of weir	($m\ s^{-1}$)
V_1	= Mean velocity downstream of weir	($m\ s^{-1}$)

Equipment Set Up

As described in Exercise H.

Ensure the flume is level, with the overshot weir fully retracted at the discharge end of the channel. Measure and record the actual breadth b (m) of the sluice gate.

The datum for all measurements will be the bed of the flume.

Record the datum readings.

Procedure

Adjust the knob on top of the weir to position the sharp edge of the weir 15 mm above the bed of the flume (y_g = 15 mm)

Gradually open the flow control valve and admit water until y_o = 0.100m measured using the upstream level scale. With y_o at this height, measure Q using the direct reading flowmeter or the volumetric tank with a stopwatch. Also measure y_1 using the downstream level scale. Raise the gate in increments of 0.001m maintaining y_o at the height of 0.100m by varying the flow of water. At each level of the gate record the values of Q and y_1. Stop once y_o can no longer be maintained at 0.100m.

Repeat the procedure with a constant flow Q allowing y_o to vary. Record the values of y_0 and y_1.

Results

Tabulate your readings and calculations as follows:

Breadth of gate, b = ……………..(m).

y_g	y_o	y_1	Q	C_d	H_0	H_1

Plot graphs of Q against y_g for constant y_0 and y_0 against y_g for constant Q to show the characteristics of flow beneath the gate.

Plot graphs of C_d against Q for constant y_0 and C_d against y_g for constant Q to show the changes in C_d of flow beneath the gate.

Conclusion

Comment on effects of y_o and Q on the discharge coefficient C_d for flow underneath the gate. Which factor has the greatest effect?

Comments on any discrepancies between actual and expected results.

Compare the values obtained for H_1 and H_0 and comment on any differences.

Exercise N - Calculating the Force on a Sluice Gate (an Undershot Weir)

Objective

To calculate the force exerted by water flowing beneath a sluice gate and the effect of upstream / downstream water levels and the degree of opening on the force.

Method

By varying the depth of water upstream / downstream and varying the height (opening) of the adjustable sluice gate (undershot weir) installed in the S16 Hydraulic Flow Demonstrator.

Although the force exerted on the gate cannot be measured directly for comparison with theory, calculation of the net force on the gate is a useful exercise and demonstrates the application of hydraulic theory.

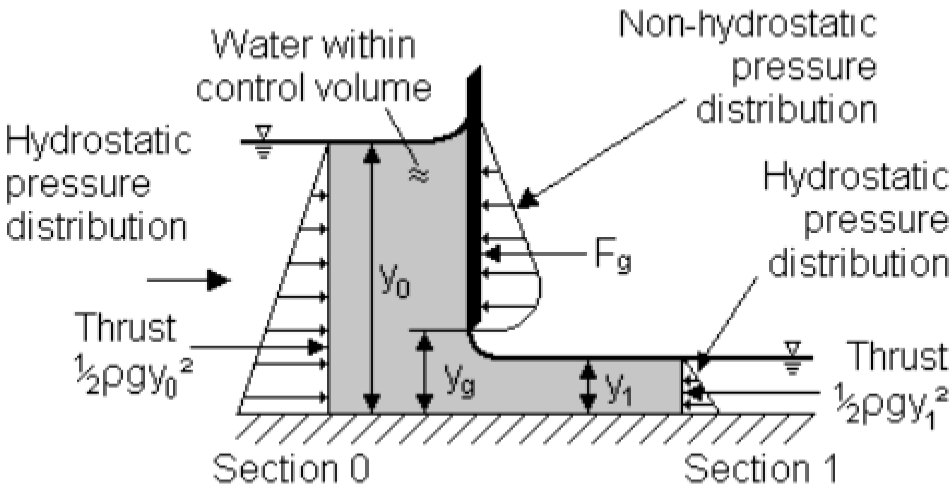
Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory



It can be shown that the resultant force on the gate is given by the equation:

$$F_g = \frac{1}{2}\rho g\, y_1^2\left[\frac{y_o^2}{y_1^2} - 1\right] - \frac{\rho Q}{b\, y_1}\left[1 - \frac{y_1}{y_o}\right]$$

The gate thrust for a hydrostatic pressure distribution is given by the equation:

$$F_H = \frac{1}{2}\rho g\left(y_o - y_g\right)^2$$

where:

F_g	= Resultant gate thrust	(N)
F_H	= Resultant hydrostatic thrust	(N)
Q	= Volume flowrate	($m^3\ s^{-1}$)
	= Volume/time (using volumetric tank)	
ρ	= Density of fluid	(kgm^{-3})
g	= Gravitational constant	($9.81m\ s^{-2}$)
b	= Breadth of gate	(m)
y_g	= Height of gate opening above bed	(m)
y_0	= Upstream depth of flow	(m)
y_1	= Downstream depth of flow	(m)

Equipment Set Up

Note: The measurements obtained in Exercise M can be used to perform the calculations in this exercise. If results are not available proceed as follows:

Set S16 up as in Exercise H. Ensure the flow channel is level, with the overshot weir fully retracted at the discharge end of the channel. Measure and record the actual breadth b (m) of the sluice gate.

Procedure

Adjust the knob on top of the weir to position the sharp edge of the weir 0.020m above the bed of the flow channel.

Gradually open the flow control valve and admit water until y_o = 0.200m measured using the upstream level scale. With y_o at this height, measure Q using the direct reading flowmeter or the volumetric tank with a stopwatch. Also measure y_1 using the downstream level scale. Raise the weir in increments of 0.010m maintaining y_o at the height of 0.200m by varying the flow of water. At each level of the weir record the values of Q and y_1.

Repeat the procedure with a constant flow Q allowing y_o to vary. Record the values of y_0 and y_1.

Results

Tabulate your readings and calculations as follows:

Breadth of Weir, b = ……………..(m).

yg	y0	y1	Q	Fg	FH	$\frac{F_g}{F_H}$	$\frac{y_g}{y_0}$

Plot a graph of the ratio $\frac{F_g}{F_H}$ against the ratio $\frac{y_g}{y_0}$.

Conclusion

Compare your calculated values for F_g and F_H and comment on any differences.

What is the effect of flow rate on the results obtained?

Comment on the graph obtained.

Exercise O - Characteristics of Flow Through a Culvert

Objective

To determine the characteristics and observe the flow patterns obtained for water flowing through a Culvert.

Method

By using the Broad crested weir model inverted to create a culvert and operating the channel at different heads upstream and downstream.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11) with

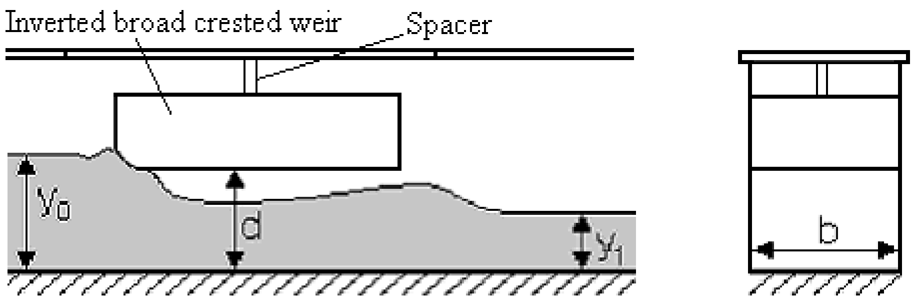
Broad Crested Weir model (Inverted to create the Culvert)

Spacer rod

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory



The culvert is a covered channel of comparatively short length which is typically installed to drain water through an embankment. The culvert acts as on open channel, as long as the section is partly full, and is normally used in this condition. However, under flood conditions the inlet or outlet may become submerged and a variety of flow patterns can exist. A culvert will run full, like a pipe, when the outlet is submerged or when the upstream level is sufficiently high.

The objective is to view the range of patterns which can exist, to determine the head/discharge characteristics and to determine the conditions necessary for the culvert to run full.

The performance of a culvert is defined by the ratio $\frac{y_0}{d}$ (typical values are in the range 1.2 to 1.5 depending on geometry and conditions).

where:

y_0	= Depth of flow upstream of the culvert at the point where the culvert runs full	(m)

d	= Height of the culvert	(m)

Equipment Set Up

As described in Exercise H.

Lower all three Pitot tubes to lowest position against bed.

Raise inlet weir fully, lower outlet weir fully and close inlet valve.

Remove cover on top of working section.

If elevated, lower the adjustable bed to its lowest position.

Install Broad Crested Weir on underside of removable cover with the radiused end upstream. Note: This is usually installed using the spacer to create a low culvert however, the spacer can be omitted to create a high culvert if required.

Measure and record the actual breadth b (m) of the culvert created.

Carefully install Weir / cover with radiused end of weir upstream. Tighten thumb nuts to secure cover.

Measure and record the height d (m) of the culvert created.

Gradually open inlet valve and allow water to flow through culvert. Increase flow to maximum then gradually close outlet valve until culvert runs full.

Adjust three Pitot tubes to mid height at each section and compare Static and Total heads.

Traverse Pitot tubes vertically and observe differences in velocity profile.

Raise elevating section of bed to reduce height of culvert (increase velocity in the Culvert). Record the new height d (m) of the culvert created then traverse Pitot tubes vertically and observe differences in velocity profile.

Procedure

Gradually open the flow control valve and admit the water into the flume. By altering the flow, gradually increase the depth of water upstream of the culvert until the culvert runs full. Observe and sketch the changing profile of the water flow as it passes through the culvert. When running full, measure and record the depth of flow y_0 upstream of the culvert, the flow depth y_1 downstream and the corresponding flowrate Q.

Raise the overshot weir by 5mm at the discharge end of the channel then repeat the above observations and record y_0, y_1 and Q when the culvert runs full.

Repeat the procedure raising the weir at the discharge end until the culvert remains full with no flow.

Repeat the procedure for increasing height of the channel bed.

If time permits repeat the above exercise for a different height of culvert (d) by adjusting the vertical position of the channel bed.

The change in flow profile when the radiused corner is positioned downstream could also be investigated.

Results

Tabulate your readings and calculations as follows:

Breadth of culvert, b =…………(m)

Height of culvert, d =…………..(m) Can be varied by elevating the bed.

y_0	y_1	Q	y_0/d

Conclusion

How many different profiles did you observe as flow through the culvert changes from partial to full flow?

What is your value for $\frac{y_0}{d}$ when the exit is not submerged?

How does this ratio change when the exit becomes submerged?

Are there any similarities between the culvert and the sluice gate (undershot weir) and if so under what conditions of flow do they occur?

Exercise P - Critical Depth – Derivation of the Specific Energy Equation

Objective

To derive the Specific Energy Equation and show that Critical Depth is a function of the flow per unit width.

To determine the relationship between the specific energy and upstream head for water flowing under a sluice gate (undershot weir).

Method

By using the adjustable sluice gate installed in the S16 Hydraulic Flow Demonstrator.

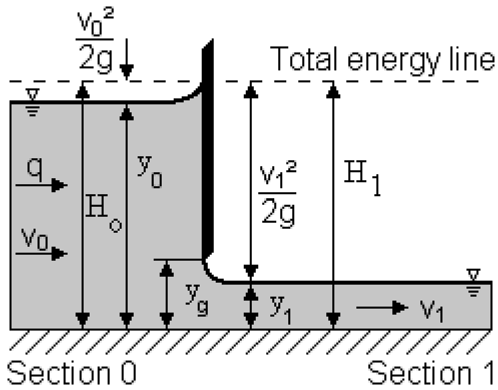
Equipment Required

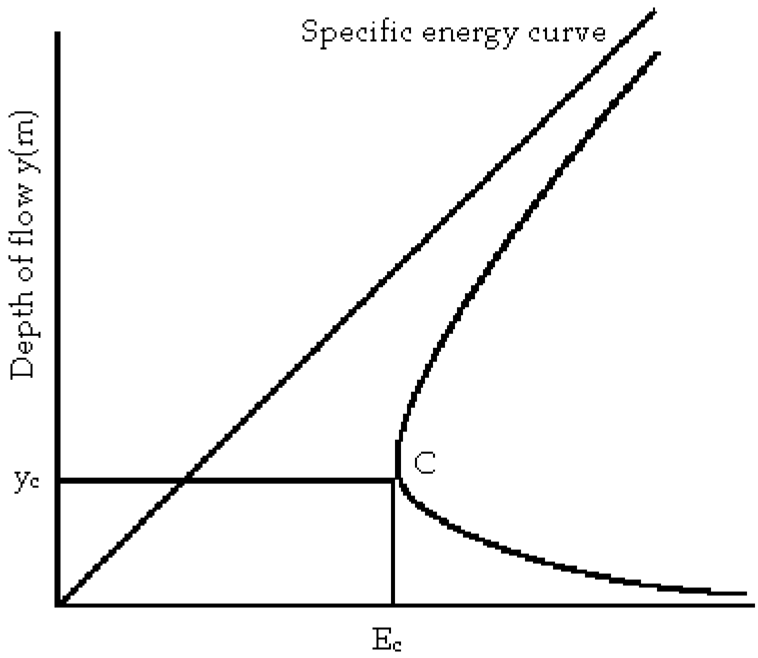
Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory





The depth and velocity of a given flow at any section of an open channel adapt themselves to the energy available at that section. For a constant discharge this energy reaches a minimum value at the 'critical' depth. This parameter is fundamental to a complete understanding of free flow behaviour because the response of a stream to energy (and force) depends on whether the actual depth is greater than or less than the critical depth.

In all calculations it is necessary to consider the width of the channel.

In an open channel it is convenient to use the bed as the datum and to compare the specific energy at different sections where the specific energy is defined as the sum of the potential energy (the depth of flow) and the kinetic energy (the velocity head):

$$E = y + \frac{v^2}{2g}$$

Considering unit width of channel the equation becomes:

$$E = y + \frac{Q^2}{2gy^2}$$

where:

E	= Specific energy	(m)
y	= Depth of flow	(m)
Q	= Volume flowrate	(m^3s^{-1})
	= Volume/time (using volumetric tank)	

g	= Gravitational constant	(ms^{-2})

Note: When the datum coincides with the bed E = H

A plot of specific energy against depth of flow gives a curve called the specific energy curve shown above. The shape of the curve shows that for a given specific energy there are two possible depths called the alternate depths. At point C on the curve the specific energy is at a minimum with only one corresponding depth called the critical depth y_c.

Flow at depths greater than critical is described as ‘slow’, ‘subcritical’ or ‘tranquil’.

Flow at depths less than critical is described as ‘fast’, ‘supercritical’ or ‘shooting’.

A family of such curves will exist for different flow rates through the channel.

When considering a rectangular channel of unit width, where the streamlines are parallel, it can be shown that:

$$y_c = 3\sqrt{\frac{Q^2}{g}} \quad \text{and} \quad E_c = E_{min} = \frac{3}{2} y_c$$

where:

E_c	= Minimum specific energy	(m)
y_c	= Critical depth	(m)

It should be noted that the surface of the water may appear wavy when the flow is near to the critical state because a small change in specific energy is accompanied by a large change in depth of flow – predicted by the shape of the specific energy curve.

Note: When the slope of a channel is just sufficient to maintain a given flowrate at a uniform and critical depth the slope is called the critical slope S_c. This can be demonstrated using the Armfield C4-MKII Flume or C6-MKII Flume that incorporate a bed with a constant variable slope. If these flumes are not available then a simple demonstration can be conducted using S16-10 by placing the left hand support (upstream end) on a suitable support. Scales etc. will not be vertical but a simple demonstration can be effected.

Equipment Set Up

As described in Exercise H.

Ensure the flow channel is level, with the outlet control valve fully open and the outlet weir in its lowest position.

The datum for all measurements will be the bed of the flow channel.

Procedure

Adjust the height of the inlet weir (sluice gate) so that the sharp edge of the weir is 10 mm above the bed of the flow channel (y_g.= 10 mm)

Gradually open the flow control valve and admit water until y_o = 220 mm measured using the upstream level scale. With y_o at this height, measure and record Q using the direct reading flowmeter or the volumetric tank with a stopwatch. Also measure and record y_1 using the downstream level scale.

Raise the weir in increments of 5 mm until y_g = 40 mm, allowing the upstream and downstream levels to stabilise, then measure and record the depths of flow y_0 and y_1.

Increase the flowrate Q slightly, lower the weir until y_0 = 200 mm. Measure and record Q then repeat the above measurements by gradually raising the weir.

If demonstration of critical slope is required raise the left hand support on packing so that the channel is tilted slightly, water flowing downhill, and gradually adjust the combination of flowrate and height of weir until critical depth exists along the length of the channel.

Results

Tabulate your readings and calculations as follows:

y_0	y_1	Q	E_0	E_1	E

Calculate E_0 and E_1 for each value of Q. Plot E_0 against y_0 and E_1 against y_1 to establish the shape of the curve on either side of the minimum energy point.

Plot your calculated values for E_c on the same axes.

On your graph draw a line through the critical point on each curve to show the critical state (tranquil flow above the line, shooting flow below the line).

Conclusion

How is the critical depth y_c affected by the flowrate Q?

How do your calculated values for E_c agree with the corresponding minimum energy points on your plotted curves?

If the channel was tilted, was it easy to find the combination to give critical depth in the sloping channel?

How did you know that critical depth had been achieved?

Exercise Q - Critical Depth – Control Imposed by the Minimum Energy Condition

Objective

To show the significance of the Minimum Energy Condition by the way that upstream water level is affected as the height of the bed is increased.

Method

By monitoring the depth of water upstream of the elevating bed and over the elevating bed as the height of the elevating bed is varied.

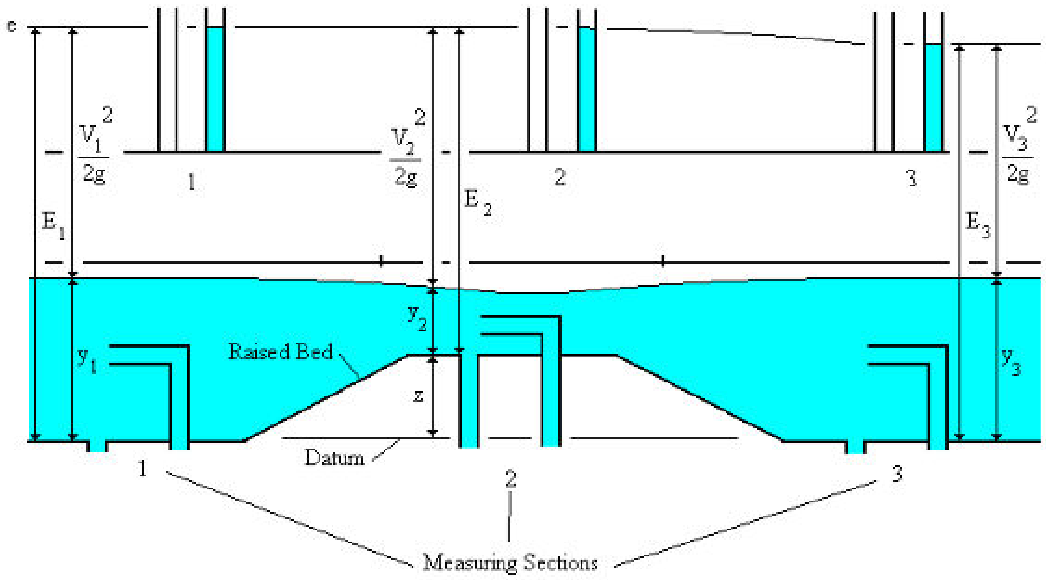
Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory



This exercise reveals the significance of the minimum energy condition at section 2 by the way in which upstream water levels are affected as z_2 (the height of the elevating bed) is increased.

Consider the flow in the channel to be in the 'slow' mode where all depths are greater than critical and controlled by the tailgate. For a constant discharge and a slowly increasing z_2 the control over y_1 rests with the tailgate until the diminishing specific energy over the raised portion of the bed reaches its minimum value for the chosen discharge. At this point the control over y_1 passes to the raised portion of the bed. As z_2 is further increased, E_2 remains constant at E_{min}, y_1 varies directly with z_2 and the raised bed acts as a weir. Thus, before the minimum energy condition, y_1 is independent of z_2 but thereafter it is independent of the tailwater condition.

In practice small losses of total head in the diverging flow downstream of section 2 will have a slight influence on upstream levels.

Equipment Set Up

As described in Exercise H.

Procedure

Lower the bed fully until z_2 = 0 mm.

Raise the tailgate to 75 mm.

Adjust the inlet flow control valve to give y_1 = 110 mm.

Measure Q.

Raise the bed in 5 mm increments maintaining Q at a constant flow. Allow the conditions to stabilise then measure y and E at sections 1, 2 and 3.

Results

Plot E_1 versus z_2 and E_2 versus z_2 and note the discontinuity in the slope of the line in each case. For the values of E and z corresponding to these discontinuities, compute (E_1 - z_2) and compare with E_2 and the computed value of E_{min} from the equations:

$$y_c = 3\sqrt{\frac{Q^2}{g}}$$ and $$E_{min} = \frac{3}{2} y_c$$

Note that the measured value of y_2 may not coincide exactly with y_c because of slight leakage past the raised bed and the curvature of the streamlines at all but the lowest flows.

Conclusion

When flow is 'slow' and above the minimum energy condition the upstream water level is independent of the height of the raised bed and controlled by the tailwater level. After the minimum energy condition is reached the upstream water level is independent of the tailwater condition and controlled by the height of the raised bed.

Exercise R - Critical Depth – Velocity of Gravity Waves in Shallow Water

Objective

To show the effect of Critical Velocity on Gravity Waves travelling through shallow water.

The velocity of solitary waves in still water

The effect of 'fast' flow on Gravity waves

The effect of 'slow' flow on Gravity waves

Method

By using a paddle and setting the S16 up in various different ways the effects of solitary and gravity waves can be observed on the flow of the water.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory

The application of elementary continuity and momentum principles to the motion of a solitary wave shows that its velocity, C, through still water, is given to a first approximation by:

$$c = \sqrt{gy}$$

For steady flow in the open channel at critical depth, the water velocity v_c and the wave velocity relative to the water, C_{crit}, are equal i.e.

$$V_c = Q / by_c = \sqrt{gy_c} = C_{crit}$$

The significance of this for 'slow' flow lies in the fact that, for a given discharge, the water velocity, V, is less than V_c (because $V \propto 1/y$), whereas the wave velocity C is greater that C_{crit} because $V \propto \sqrt{y}$.

Since $V_c = C_{crit}$ the water velocity must be less than the wave velocity.

For the case of 'fast' flow, similar reasoning shows that the water velocity is greater than the wave velocity.

Summarizing this argument in equation form:

For 'slow' flow: $y < y_c$ therefore $V < V_c = \sqrt{gy_c} < \sqrt{gy} = C$

For 'fast' flow: $y < y_c$ therefore $V > V_c = \sqrt{gy_c} > \sqrt{gy} = C$

In the former case, a wave will be propagated upstream with a velocity relative to the bed of (C - V) and downstream with a velocity of (C + V) but not upstream.

Consider the effect of an obstruction located at the downstream end of an open channel. If the flow is 'fast', the obstruction cannot propagate gravity waves upstream and it can impose no control on the upstream depths. In this case, control over the depths is exercised by the structure causing the 'fast' flow somewhere upstream.

If the flow is 'slow', however, gravity waves can travel upstream and the obstruction does impose its control over the upstream depths.

In general, 'fast' flow can be controlled only from upstream, while 'slow' flow in normally controlled from downstream.

Equipment Set Up

As described in Exercise H.

Procedure

Part 1

The velocity of solitary waves

Remove the cover from the roof of the working section.

Lower the adjustable bed to its lowest position.

Close the outlet flow control valve.

Fill the channel to a depth of 50 mm then close the inlet flow control valve.

Raise the tailgate to 80 mm to form a reflecting surface.

Lower the sluice gate (undershot weir) until it just touches the surface of the water.

Create a solitary wave by sweeping a paddle upstream of the gate.

Immediately lower the sluice gate to provide a second surface for the reflection.

From the first reflection of the wave at the tailgate, time its passage over one or more lengths of the working section, L.

Repeat the experiment for a range of water depths from 10 mm to 50 mm.

Part 2

The significance of gravity wave velocity for control ('Fast' flow)

Prepare the equipment as described in Exercise Q to produce 'fast' flow in the working section.

Using a paddle generate waves on the surface of the water upstream of the sluice gate inside the inlet tank (‘slow’ flow) then downstream of the sluice gate in the working section (‘fast’ flow).

Note the direction of propagation in each case and the characteristic ‘V shape of the wave on the ‘fast’ flow surface.

Confirm that the ‘fast’ flow depths are controlled by the sluice gate (undershot weir) and not by the tailgate.

Part 3

The significance of gravity wave velocity for control (‘Slow’ flow)

Raise the sluice gate fully.

Raise the bed until z_2 = 50 mm.

Adjust the inlet valve until y_1 = 75 mm initially.

Raise the tailgate to obtain y_1 = 90 mm so that ‘slow’ conditions prevail.

Generate waves on the water surface upstream and over the raised bed and note that they propagate in both upstream and downstream directions.

Lower the tailgate until critical conditions occur over the raised bed aand it acts as a weir.

Generate waves on the water surface upstream and over the raised bed and note the extent and direction of their propagation. Also note that a ‘herringbone’ wave pattern is generated by surface tension effects at the wall only when the depth is less than critical.

Re-establish ‘slow’ flow conditions over the raised bed and confirm that the tailgate controls ‘slow’ flow depths at section 1.

Prodiuce critical flow conditions over the raised bed and confirm that it, and not the tailgate, then controls levels at section 1.

Conclusion

The velocity of a gravity wave is related to the depth of the water.

Gravity waves can travel upstream when the flow is sub critical.

Gravity waves cannot travel upstream when the flow becomes critical.

Exercise V - Investigating the Combined Effects of the Specific Energy and Force Equations

Objective

To show how changes in the Specific Energy Equation and the Force of a stream can be predicted using the composite graph of Specific Energy and Flow Force for different flow conditions.

Method

By analysis of the combined curves produced in previous exercises.

Equipment Required

None

Theory

The experimental results obtained in previous exercises have confirmed the validity of the generalised specific energy and force curves and now these curves should be superimposed on the same graph. From this graph the changes in specific energy and force of a stream can be predicted for various cases as described below.

Procedure

Consider first the case of a hydraulic structure where negligible total head is lost as the flow changes from ‘slow’ to ‘fast’.

Draw a line at some constant value of the specific energy from the ‘slow’ to ‘fast’ limbs of the energy curve. At the two depths corresponding to this specific energy draw lines to intersect the force curve. Note that the force of the stream corresponding to the ‘slow’ flow depth is greater than the force corresponding to the ‘fast’ flow depth. This graphical construction, which is valid for any value of specific energy, shows that for a change from ‘slow’ to ‘fast’ at constant energy, there must be a reduction in the force of the stream. This occurs at a sluice gate as has been demonstrated in a pervious exercise.

Consider now the case where the force of a stream does not alter as the flow changes from ‘fast’ to ‘slow’.

Draw a line at some constant value of force from the ‘fast’ to ‘slow’ limbs of the force curve. At the two depths corresponding to this force draw lines to intersect the specific energy curve. Note that the energy of the stream corresponding to the ‘fast’ flow depth is greater than that corresponding to the ‘slow’ flow depth. This construction is valid for any value of the force term and shows that for a change from ‘fast’ to ‘slow’ flow with no external forces acting to alter the force of the stream, there must be a loss of energy. Such a case occurs at a ‘hydraulic jump’ which is demonstrated and analysed in the following demonstrations.

Thus these curves may be used to predict the energy and force changes occurring in open channel flow. In most cases there will be some change in both energy and the force of a stream but the curves can still be used together to establish the changes in one term consistent with changes in the other.

Exercise W - The Hydraulic Jump – Creating the Phenomena

Objective

To investigate the characteristics of a standing wave (the Hydraulic Jump) produced when 'fast' Flow upstream changes to 'slow' Flow downstream with a consequent degradation of energy.

To show how the type of jump varies with Froude Number.

Method

Using the adjustable sluice gate (undershot weir) upstream in combination with the overshot weir downstream to create standing waves in the working section.

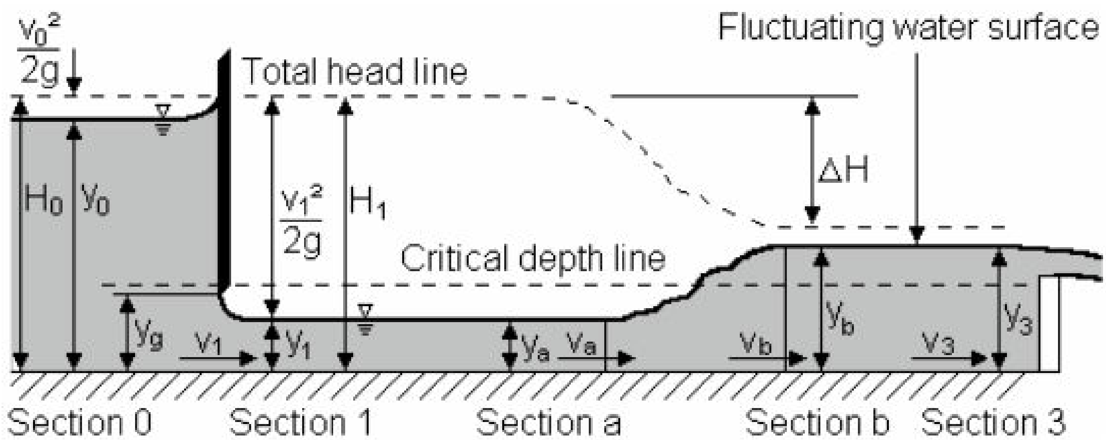
Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11)

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory



When water flowing rapidly changes to slower tranquil flow a **hydraulic jump** or **standing wave** is produced. This phenomenon can be seen where water shooting under a sluice gate mixes with deeper water downstream. It occurs when a depth less than critical changes to a depth which is greater than critical and must be accompanied by a loss of energy.

An **undular jump** occurs when the change in depth is small. The surface of the water undulates in a series of oscillations which gradually decay to a region of smooth tranquil flow.

A **direct jump** occurs when the change in depth is great. The large amount of energy loss results in a zone of extremely turbulent water before it settles to smooth tranquil flow.

By considering the forces acting within the fluid on either side of a hydrauli c jump of unit width it can be shown that:

$$\Delta H = y_a + \frac{V_a^2}{2g} - \left(y_b + \frac{V_b^2}{2g} \right)$$

where:

ΔH	= Total head loss across jump (energy dissipated)	(m)
V_a	= Mean velocity before hydraulic jump	(m s^{-1})
y_a	= Depth of flow before hydraulic jump	(m)
V_b	= Mean velocity after hydraulic jump	(m s^{-1})
y_b	= Depth of flow after hydraulic jump	(m)

Because the working section is short $y_a \approx y_1$ and $y_b \approx y_3$

Therefore simplifying the above equation:

$$\Delta H = \frac{(y_3 - y_1)^3}{4\, y_1\, y_3}$$

Equipment Set Up

As described in Exercise H.

Ensure the flow channel is level, with the overshot weir fully retracted at the discharge end of the channel. Measure and record the actual breadth b (m) of the sluice gate.

The datum for all measurements will be the bed of the flow channel.

Procedure

Adjust the knob on top of the weir to position the sharp edge of the weir 0.020m above the bed of the flow channel. Raise the overshot weir by 5mm the discharge end of the flow channel.

Gradually open the flow control valve and adjust the flow until an undular jump is created with small ripples decaying towards the discharge end of the flow channel. Observe and sketch the flow pattern.

Increase the height of water upstream of the weir by increasing the flowrate and increase the height of the overshot weir to create a hydraulic jump in the centre of the working section. Observe and sketch the flow pattern.

Measure and record the values of y_1, y_3, y_g and Q. Repeat this for other flowrates Q (upstream head) and heights of the gate y_g.

Results

Tabulate your readings and calculations as follows:

Breadth of gate, b =………..(m)

y_g	y_1	y_3	Q	H_b	ΔH

Calculate v_1 and plot $\frac{v_1^2}{gy_1}$ against $\frac{y_3}{y_1}$

Calculate $\frac{\Delta H}{y_1}$ and plot $\frac{\Delta H}{y_1}$ against $\frac{y_3}{y_1}$

Calculate y_c and verify $y_1 < y_c < y_3$.

Conclusion

Verify the force of the stream on either side of the jump is the same and that the specific energy curve predicts a loss equal to $\frac{\Delta H}{y_c}$.

Suggest an application where the loss of energy in a hydraulic jump would be desirable. How is the energy dissipated?

Exercise X - Characteristics of flow over a Sharp Crested Weir

Objective

To observe the flow patterns obtained with different flow conditions

To determine the relationship between upstream head and flowrate for water flowing over a Sharp Crested weir (Modular flow)

To determine the discharge coefficient and

To investigate the effect of drowning the weir (Non-Modular flow)

Method

By using the Sharp Crested weir installed in the S16 Hydraulic Flow Demonstrator and comparing the flow characteristics under a range of flow conditions.

To demonstrate the change in flow characteristics associated with the shape of the Nappe (profile of the water surface associated with a Springing, Depressed, Drowned or Clinging Nappe).

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11) with:

Sharp Crested Weir model

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory

The construction of the sharp crested weir is relatively simple and this type of weir lends itself to flow measurement in the laboratory. Its use in outdoor applications is limited because of the potential for damage to the sharp crest by debris in the water etc.

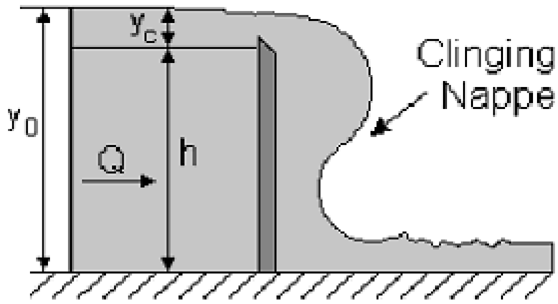
The flow separates from the solid boundary at the sharp crest and then falls under the action of gravity as a two-dimensional jet or nappe. Owing to the curvature of the flow, the pressure in the fluid over the crest is less than hydrostatic and thus the flow over a sharp crested weir exceeds that over a broad crested weir for the same value of Hw. The amount of curvature for the former depends on the value of hw/p

For convenience the flow over this weir is expressed in terms of the equation

$$Q = \frac{2}{3} C_d b \sqrt{2g} \, y_c^{\frac{3}{2}}$$

The lower boundary of the nappe entrains air from the cavity and the volume of and pressure within this cavity tends to decrease. Such behaviour alters the discharge characteristics of the weir and can lead to vibration of the nappe. These undesirable effects are avoided when the cavity is supplied with air through a connection with the atmosphere.

At low flowrate, the water flowing over the weir will cling to the rear face of the weir.



The profile assumed by water flowing over a weir or similar structure is called the nappe and this condition is described as a clinging nappe. It is also described as an unventilated nappe (the reason will become obvious).

The nappe can take four different forms:

- Springing
- Depressed
- Drowned
- Clinging

When a weir discharges freely at a reasonably high flow rate the nappe springs clear of the downstream face of the weir and the nappe is surrounded by air at atmospheric pressure. In a suppressed weir discharging between the walls of a discharge channel of the same width the nappe will remain in contact with the discharge channel walls. If no provision is made to ventilate the space under the nappe by supplying air then a partial vacuum will be produced. The discharge will then be increased due to the lower pressure under the nappe and the nappe will also be depressed or drawn towards the weir. In extreme cases the whole of the volume of air behind the nappe will be ejected and a turbulent recirculating volume of water will occupy the space under the nappe, this condition, which is known as a *drowned nappe* or *underwetted nappe.*

When water is flowing over a rectangular weir with no end contractions (i.e. in suppressed weirs), the nappe touches the side walls of the channel due to which air is trapped in the space between side walls, falling nappe, the weir and bottom of the channel as shown. This air is carried by the flowing water there by reducing the pressure below the nappe which may become negative or below atmospheric pressure. This causes more water to be drawn and hence increase the discharge through the weir.

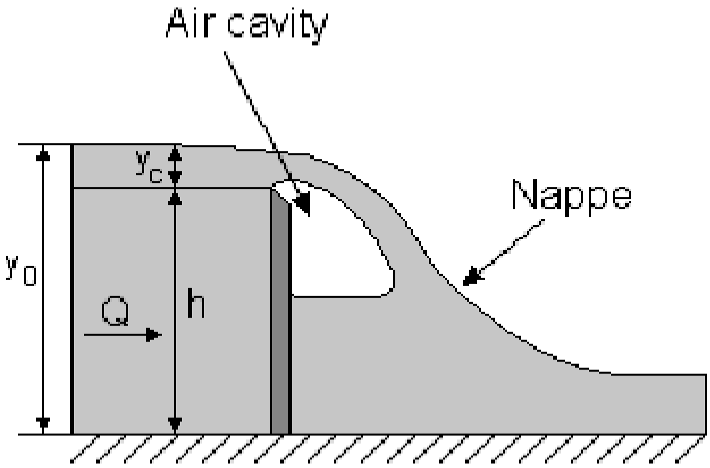
Such nappe is called depressed nappe where the discharge calculated from the formula will be of lower value. It has been observed that the discharge in depressed nappe will be 6 to 7 % more than that given by the formula.

Further withdrawal of air increases the vacuum pressure causing the lower nappe get attracted and adhered to the downstream of weir leaving no air space in between. This will cause further drawing of water and increase in discharge through the weir. The nappe in such condition is called Adhering or Clinging nappe. Discharge with such a nappe is found to be 25 to 30 % more than that obtained by the formula.

Hence, for the calculation of discharge through a suppressed weir, the pressure below the lower nappe should be equal to atmospheric pressure, so that there will be no extra withdrawal of water and discharge is obtained by using the formula. Such a nappe is called Free nappe. Thus, in order to apply the formula and obtain the discharge through suppressed weir, the atmospheric pressure has to be maintained below the lower nappe. For this, holes are made through the channel walls at the place just below the nappe and connected with a pipe open to atmosphere. This process is called Ventilation of Weir and the weir is called Ventilated Weir.

The top edge of the weir is called the Sill or Crest.

As the flow is increased the nappe will spring clear of the weir forming a smooth curve. This condition is referred to as a springing nappe or a ventilated nappe whereby the water is supported by a cavity of air at atmospheric pressure underneath the stream of water.



The air filled cavity will remain as the flow is decreased again until the flow is insufficient to maintain a full seal across the width of the weir and the nappe returns to the clinging condition.

For a rectangular sharp crested weir with ventilated nappe:

$$Q = \frac{2}{3} C_d b \sqrt{2g} y_c^{\frac{3}{2}}$$

therefore:

$$C_d = \frac{Q}{\frac{2}{3} b \sqrt{2g} y_c^{\frac{3}{2}}}$$

where:

Q	= Volume flowrate	($m^3.s^{-1}$)
V	= Volume (using volumetric tank)	
t	= Time (using volumetric tank)	
C_d	= Coefficient of discharge	(Dimensionless)
b	= Breadth of weir	(m)

y_c	= Upstream height above crest of weir	(m)
	= y_0 - h	
g	= Gravitational constant	(9.81ms^{-2})
h	= Height of weir crest above bed	(m)
y_0	= Upstream flow depth	(m)

When the rectangular weir extends across the whole width of the channel it is called a suppressed weir and the Rehbock formula can be applied to determine C_d as follows:

$$C_d = 0.602 + 0.083 \cdot \frac{y_c}{h}$$

Equipment Set Up

Set up as in Exercise H.

Ensure the flume is level.

Measure and record the actual breadth b (m) of the sharp-crested weir (overshot rectangular weir).

Measure and record the actual height h (m) of the sharp-crested weir.

The datum for all measurements will be the top edge of the weir plate (the crest).

Record the datum reading.

Open the flow control valve and admit water into the channel until it discharges over the weir then close the flow control valve to stop the flow of water. When water stops flowing over the weir record the datum reading.

Procedure

Adjust the flow of water into the flume to obtain flow depths y_0, increasing in about 0.010m steps. For each step measure the flowrate Q and the depth y_0. The flowrate Q can be determined using the direct reading flowmeter (if fitted) or the volumetric tank with a stopwatch. For accurate results the level scale must be far enough upstream to be clear of the draw-down adjacent to the weir.

If the nappe tends to cling to the back face of the weir then the ventilation tubes are filled with water. Ventilate the nappe by inserting the end of a piece of hollow tube into the space behind the weir. The nappe should spring away from the weir.

Sketch the flow pattern as the water flows over the weir when the nappe is ventilated properly. Reduce the flowrate slightly then block the ventilation tubes and sketch the flow pattern with the nappe clinging to the weir. Measure the flowrate Q and the head H while the nappe is clinging to the weir.

Results

Tabulate your measurements and calculations as follows:

Breadth of Weir b =………..(m)

Height of weir h =………..(m)

y_c	Q	$y_c^{3/2}$	log y_c	log Q	C_d

Plot Q against y_c, log Q against log y_c and C_d against y_c.

From the straight-line graph of log Q against log h find the intercept log k on the log Q axis and the gradient m.

The relationship between Q and h is then $Q = k\, y_c^m$.

Calculate C_d for the condition when the nappe is not properly ventilated.

Calculate the C_d predicted by the Rehbock formula.

Conclusions

The sharp crested weir is a simple device that allows the volume flowrate of water in an open channel to be determined from a single measurement of upstream water level.

The condition of the flow over the weir can seriously affect the upstream level so care must be taken to correct for conditions such as a clinging nappe or drowning.

Exercise Y - Characteristics of flow over a Broad Crested Weir

Objective

To determine the relationship between upstream head and flowrate for water flowing over a Broad Crested weir (Modular flow).

To calculate the discharge coefficient and to observe the flow patterns obtained.

To investigate the effect of drowning the weir (Non-Modular flow)

To investigate the effect of crest shape (Square or rounded corners).

Method

By using the Broad Crested weir installed in the S16 Hydraulic Flow Demonstrator and operating the channel under a range of flow conditions.

Equipment Required

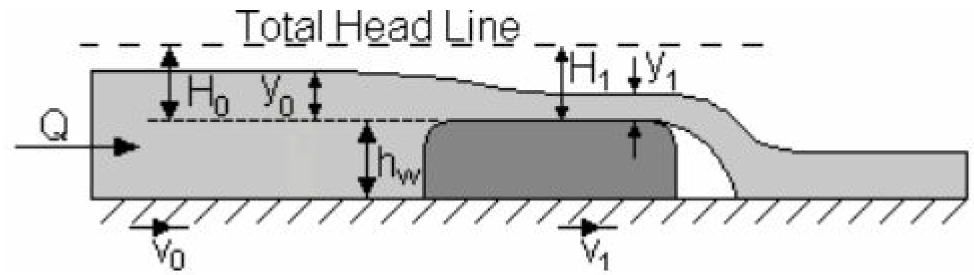
Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11) with

Broad Crested Weir model

Armfield F1-10 Hydraulics Bench

Stopwatch to measure flowrate when using the volumetric tank on F1-10

Theory



From conservation of energy and ignoring losses:

$$H_0 = H_1 = y_0 + \frac{v_0^{\,2}}{2g} = y_1 + \frac{v_1^{\,2}}{2g}$$

Therefore

$$v_1 = \sqrt{2g(H_0 - y_1)}$$

The flow rate Q is given by:

$Q = y_1 \, v_1 \, b_1$

$$= b\sqrt{2g\left(H_0 y_1^{\,2} - y_1^{\,3}\right)}$$

Provided that the weir is not submerged (downstream water level is low), the flow over a Broad Crested Weir may be assumed to be critical as it passes over the weir. Hence

$H_0 y_1^2 - y_1^3$ = maximum

At maximum

$$\frac{dq}{dh} = 0 \qquad = 2\,H_0 y_1 - 3y_1^2$$

Therefore

$$y_1 \qquad = \frac{2}{3} H_0$$

Therefore

$$Q_{max} \quad = b\sqrt{2g\left(\frac{4}{9}H_0^{\,3} - \frac{8}{27}H_0^{\,3}\right)}$$

$= 1.705\ bH_0^{3/2}$

The actual flow over a Broad Crested weir will be less than the theoretical flow so a coefficient is introduced into the equation:

$$Q_{actual} = 1.704\ C_d\ b\ H_0^{\frac{3}{2}}$$ where C_d is the coefficient of discharge.

i.e. $Q_{actual} = C_d \times Q_{theoretical}$

The Coefficient of Discharge may therefore be determined as

$$C_d = \frac{\text{Actual Flow Rate}}{\text{Theoretical Flow Rate}}$$

The above equations are valid provided that flow over the weir is Modular I.e. the level immediately downstream of the weir is lower than the crest of the weir. If the weir becomes drowned i.e. the level immediately downstream is above the crest of the weir then the weir can become non-Modular and the equations will not be valid without a correction for the downstream conditions.

Equipment Set Up

As described in Exercise H.

Ensure the flume is level, with the overshot weir fully retracted at the discharge end of the channel. Measure and record the actual breadth b (m) of the broad crested weir.

Rotate the middle Pitot tube to allow the Broad crested weir to be installed.

Install the weir in the flume with the rounded corner upstream. Ensure that the weir is secured to the tapping in the bed of the flume using the integral fixing screw but do not over tighten. Adjust the Pitot tube so that it is pointing upstream with the tip 5 mm above the crest of the weir.

The datum for all measurements will be the crest of the weir.

Record the height of the weir above the bed h_w(m).

Procedure

Adjust the flow of water into the flume to obtain heads y_0, increasing in about 5 mm steps. For each step measure the flowrate Q_{actual}, the upstream depth of flow above the weir y_0 and the depth of flow over the weir y_1 (where the flow becomes parallel to the weir). The flowrate Q_{actual} can be determined using the direct reading flowmeter or the volumetric tank with a stopwatch.

For accurate results the level measurement must be far enough upstream to be clear of the draw-down over the weir. The scale adjacent to the upstream Pitot tube should therefore be used for this measurement.

At each setting also observe and sketch the flow patterns over the weir.

Gradually increase the depth of the water downstream of the weir in small steps by raising the overshot weir at the discharge end of the channel. For each step measure the flowrate Q_{actual}, the upstream depth of flow y_0 and the depth of flow over the weir y_1. Observe and sketch the flow patterns over the weir.

Results

Tabulate your readings and calculations as follows:

Breadth of Weir b =…………(m)

Height of weir h_w =…………(m)

y_0	y_1	Q_{actual}	H_0	$Q_{theoretical}$	C_d

Plot graphs of Q_{actual} against H_0 and C_d against H_0.

Conclusions

Does the magnitude of the flowrate affect the discharge coefficient C_d? Does C_d increase or decrease with increasing flowrate?

What is the pattern of the water as it passes over the weir?

Does the height of the weir affect the discharge coefficient?

Would you expect the length of the weir crest to affect the discharge coefficient C_d?

What is the effect of drowning the weir (increasing the downstream depth)?

How does drowning affect the accuracy of the results based on the standard equation?

Exercise Z - Characteristics of flow over an Ogee Weir

Objective

To determine the relationship between upstream head and flowrate for water flowing over an Ogee Weir (Modular flow)

To determine the modular limit and to observe the flow patterns obtained.

To compare the shape of the weir with the ventilated Nappe created when using a sharp crested weir

Method

By using the Ogee weir installed in the S16 Flow Channel and operating the channel under a range of flow conditions.

Equipment Required

Armfield S16 Hydraulic Flow Demonstrator (S16-10 or S16-11) with

Ogee Weir model

Armfield F1-10 Hydraulics Bench

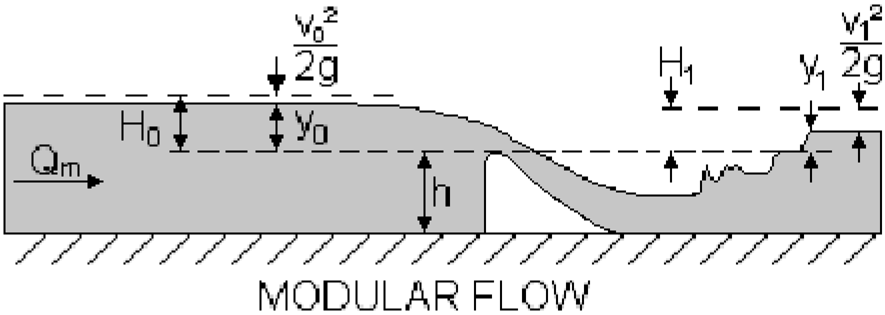
Stopwatch to measure flowrate when using the volumetric tank on F1-10

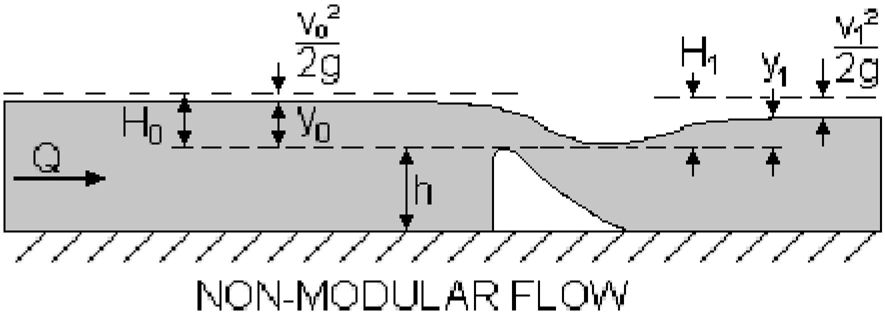
Theory

If, for a certain designed head, the cavity beneath the nappe of a sharp-crested weir were to be made solid, the new boundary would be similar to the ogee weir supplied with S16 where the weir is designed for an operating head h_d of 16mm. At this head the flow along the surface of the weir will be atmospheric. At lower heads the pressure will be positive along the surface and at higher heads the pressure will be negative. When the upstream head exceeds the design head by a factor of approximately 3x, separation occurs at the crest and there is a danger of cavitation occurring that could damage the surface of the weir.

The coefficient falls within the range $1.13 < C_w < 1.59$ when $0.4 < (h_w/h_d) < 3.0$.

At the design head $C_w = 1.31$.





For **Modular Flow** (the weir operates undrowned with low downstream water level)

$$Q_m = b\, C_d\, g^{\frac{1}{2}}\, H_0^{\frac{3}{2}}$$ therefore: $$C_d = \frac{Q_m}{b\, g^{\frac{1}{2}}\, H_0^{\frac{3}{2}}}$$

where:

Q_m	= Modular volume flowrate	$(m^3.s^{-1})$
	= Volume/time (using volumetric tank)	
b	= Breadth of weir	(m)
g	= Gravitational constant	$(9.81ms^{-2})$
H_0	= Total head upstream of weir crest	(m)
	$= y_0 + \frac{V_0^2}{2g} = y_0 + \frac{Q_0^2}{2g A_0^2} = y_0 + \frac{Q_0^2}{2g(y_0 b)^2}$	
y_0	= Upstream depth of flow above weir	(m^2)
Q_0	= Upstream flow rate = Q_m for modular flow	(m^3/s)
h	= vertical height to crest of weir	(m)
C_d	= Modular coefficient of discharge	(Dimensionless)

When the flow is modular the upstream head is not affected by changes in the downstream head. A single measurement of upstream head can therefore be taken to determine the volume flowrate over the weir.

For **Non-Modular Flow** (weir crest drowned, downstream water level high)

The weir ceases to act in modular fashion when:

$$\frac{H_1}{H_0} \geq 0.70$$

where:

H_1	= Total head downstream of weir crest	(m)
	$= y_1 + \frac{V_1^2}{2g} = y_1 + \frac{Q_1^2}{2gA_1^2} = y_1 + \frac{Q_1^2}{2g(y_1 b)^2}$	Q_1 = downstream flow rate
H_0	= Total head upstream of weir crest	(m)
	$= y_0 + \frac{V_0^2}{2g} = y_0 + \frac{Q_0^2}{2gA_0^2} = y_0 + \frac{Q_0^2}{2g(y_0 b)^2}$	Q_0 = upstream flow rate

When the flow is not modular the upstream head is affected by changes in the downstream head. A single measurement of upstream head is no longer adequate to determine the actual flowrate.

A reduction factor can be used to correct for non-modular flow where:

$$f = \frac{Q}{Q_m}$$

(Dimensionless)

where Q is measured using timed volume collection or flowmeter and Q_m calculated from:

$$Q_m = b\, C_d\, g^{\frac{1}{2}}\, H_0^{\frac{3}{2}}$$

using the upstream flow head and the value of C_d determined during modular flow.

Equipment Set Up

As described in Exercise H.

Ensure the flume is level, with the overshot weir fully retracted at the discharge end of the channel. Measure and record the actual breadth b (m) and the vertical height h_w (m) of the Crump weir.

For accuracy of measurement install the weir in the flume at least 0.4m downstream of the working section inlet (i.e. at a distance that is at least five times the maximum height of the weir), with the vertical face of the weir facing the inlet tank upstream. Ensure that the weir is secured to the tapped hole in the bed of the flume using the integral fixing screw.

The datum for all measurements will be the bed of the channel. Carefully record the datum readings.

Procedure

Open the flow control valve and allow the water to flow into the flume then adjust the valve to obtain a depth y_0 of 0.070m upstream of the weir. Maintain this level whilst measuring the downstream depth of flow y_1 and the flowrate Q.

Repeat this for 0.010m increments of y_0, recording the measurements of y_0, y_1 and Q and noting any variation in the flow patterns over the weir.

Raise the overshot weir at the discharge end of the flume. When the levels have stabilised record the measurements of y_0, y_1 and Q. Observe the changes in the flow patterns over the weir.

Results

Tabulate your readings and calculations as follows:

Breadth of Weir b =…………(m)

y_0	y_1	Q	H_0	H_1	Q_m	C_d	f

Determine the average coefficient of discharge for modular flow conditions.

Plot values of f against $\frac{H_1}{H_0}$ then determine the modular limit – the value of $\frac{H_1}{H_0}$ where f ceases to be unity.

Conclusions

How does your value for the modular limit compare with the recognised value of approximately 0.7?

How does the value of f change when the weir is drowned?

How are the flow patterns affected when flow over the weir changes from modular to non-modular flow?

Contact Details for Further Information

Main Office: **Armfield Limited**

Bridge House
West Street
Ringwood
Hampshire
England BH24 1DY

Tel: +44 (0)1425 478781
Fax: +44 (0)1425 470916
Email: sales@armfield.co.uk
support@armfield.co.uk
Web: http://www.armfield.co.uk

US Office: **Armfield Inc.**

436 West Commodore Blvd (#2)
Jackson, NJ 08527

Tel: (732) 928 3332
Fax: (732) 928 3542
Email: info@armfieldinc.com