



Drainage and Seepage Tank

Instruction Manual

S1

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General Overview

The class of problems involving flow of water through permeable media has a wide range and is of considerable importance to engineers and scientists. The Armfield Drainage and Seepage Tank, Model S1, facilitates a detailed study of the movement of water through permeable media.

The engineer is probably the one who faces such problems most frequently and whose success or failure will often depend on his knowledge and understanding of phenomena related to the movement of the water in soils. This is one of the most important aspects in the design of almost all hydraulic structures. Consider an earth or rock fill dam, for instance. Water flows directly through the engineering structure itself. Obviously, it is important to know how much water we can expect to lose from the reservoir by seepage through the dam. We also need to know whether a certain kind of soil can be used to construct the dam without running the risk that the reservoir will run dry after filling. The safety and the very existence of the dam depends on the flow pattern of the penetrating water and on the balance of the hydraulic and static forces. Many earth dams have collapsed because of improper design with respect to the movement of water through their bodies. In fact, the conditions of seepage are vital, not only for earth dams, but for any dams having permeable materials in the foundations. A dam can collapse or be badly damaged as a result of seepage underneath its bottom, or because of hydrostatic forces exerted by the penetrating waters. These forces cannot be determined without prior determination of the flow pattern underneath the structure. Once known, they can be altered using drains, cut-offs, sheet pile walls and other means to change the flow pattern.

Similar problems arise in other engineering structures built from, or on, soil. As examples, we can mention levees, road and railway embankments, canals, navigation locks, foundations of buildings, bridges, harbour walls and similar structures.

Another engineering field where good understanding of water movement in soil is essential is water supply and drainage. In both we are concerned with extracting water from saturated strata by using wells, horizontal galleries, tile lines, or trenches. In this type of problem, we usually deal only with the flow pattern and quantity of the water traversing the strata. The forces exerted by seepage remain of secondary importance.

Mining is an area where both seepage and ground water flow is fundamentally important. The design of an effective drainage system for a mine must be based on profound knowledge of permeability, of the degree of water saturation of the various geological layers, of seepage rates and of the effect of pumping or draining the water on the balance of forces.

Ground water hydrology and hydrogeology are the main non-engineering fields dealing with flow of water through permeable media and require the study of problems such as salt water intrusion into fresh water basins, underground movement of water towards inner channels, discharge of ground water into surface run-offs, recharge of water from rivers to underground storage, artificial recharge of ground water.

Generally speaking, the movement of water through soil under natural conditions is very complex and cannot be reproduced in full in the laboratory. This complexity is caused by the non-uniformity of natural soils over large areas, the stratified and the tectonic structures of geological layers, and by the fact that water movement in

nature is generally three-dimensional. Such movement is not easy to handle mathematically.

In the laboratory, we have the advantage of being able to use homogeneous materials of known properties. This simplifies the problem and makes it possible to reduce the number of components involved. By this means significant relationships between the physical properties of the medium and characteristics of flow are found. To further simplify the problem, we usually restrict ourselves to a two-dimensional flow, investigating conditions in a vertical cross section* along the horizontal direction of the moving water mass. The Armfield Drainage and Seepage Tank, Model S1, is specifically designed to permit the simulation in the laboratory of such vertical cross sections.

* For obvious practical reasons the cross sections are not planar across sections. But their thicknesses are small in relation to the height.

Equipment Diagrams

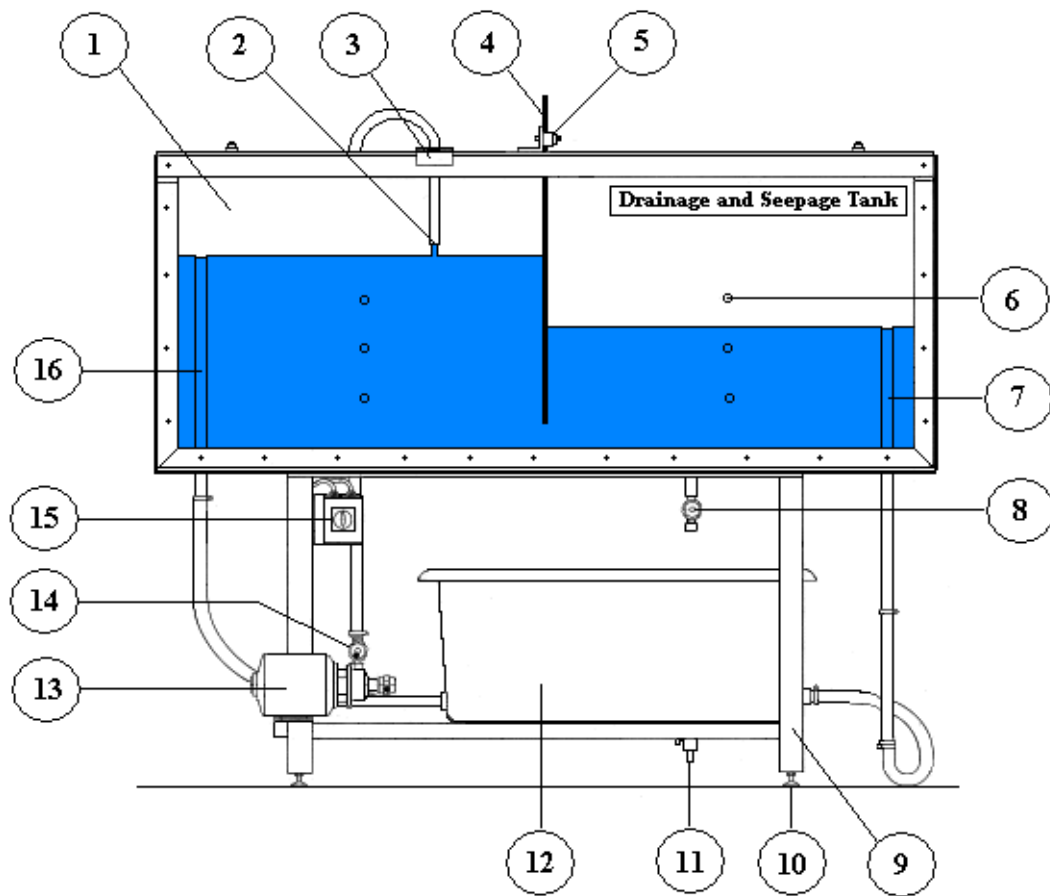


Figure 1: Front View of S1 Drainage and Seepage Tank (Shown with impermeable baffle fitted but not filled with sand)

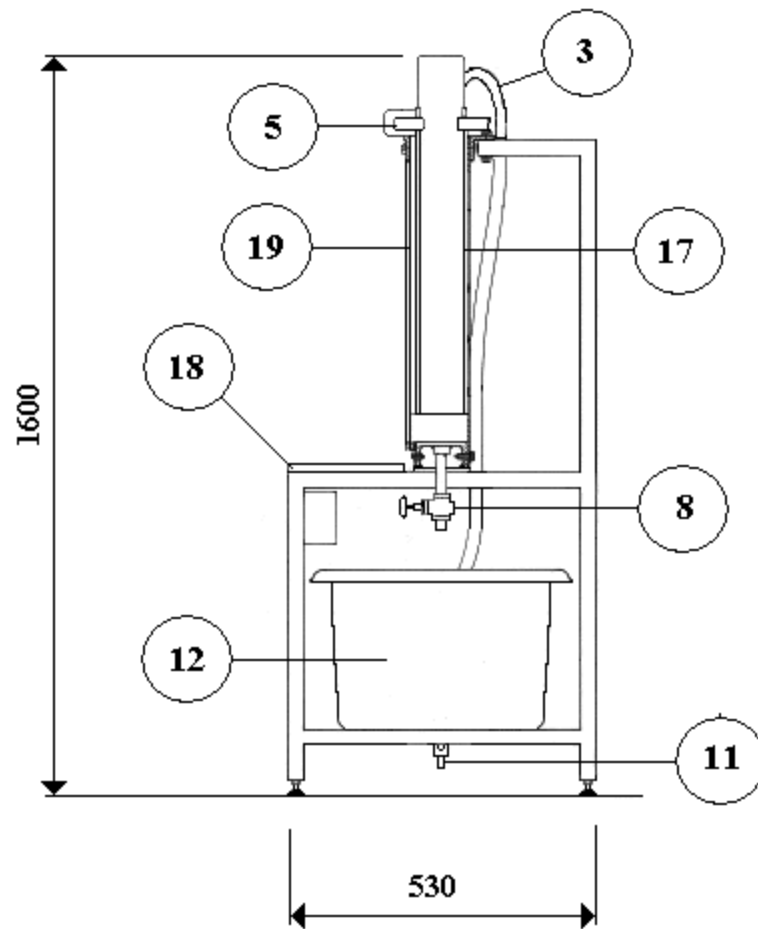


Figure 2: Side View of S1 Drainage and Seepage Tank

Important Safety Information

Introduction

All practical work areas and laboratories should be covered by local safety regulations which must be followed at all times. If required Armfield can supply a typical set of standard laboratory safety rules.

Your **S1 Drainage and Seepage Tank** 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 may exist if the equipment is misused, mishandled or badly maintained. If the equipment is used in a manner not specified by Armfield then the protection provided by the equipment may be impaired.

The S1 is a heavy piece of equipment, and should be lifted fork lift if possible. Ensure that the arms of the fork lift do not foul the sump moulding in the base of the unit. Do not attempt to lift the unit when it is full of sand or water.

Electrical Safety

The equipment described in this Instruction Manual operates from a mains voltage electrical supply. It must be connected to a supply of the same frequency and voltage as marked on the equipment or the mains lead. If in doubt, consult a qualified electrician or contact Armfield.

The equipment must only be connected to a mains supply with a reliable earth connection so that the equipment is adequately earthed.

The equipment must only be operated using a fused electricity supply. Details of required fuse ratings can be found on page 10.

The equipment must not be operated with any of the panels removed.

To give increased operator protection, the unit incorporates a Residual Current Device (RCD), alternatively called an Earth Leakage Circuit Breaker, as an integral part of this equipment. If through misuse or accident the equipment becomes electrically dangerous, the RCD will switch off the electrical supply and reduce the severity of any electric shock received by an operator to a level which, under normal circumstances, will not cause injury to that person.

At least once each month, check that the RCD is operating correctly by pressing the TEST button. The circuit breaker **MUST** trip when the button is pressed. Failure to trip means that the operator is not protected and the equipment must be checked and repaired by a competent electrician before it is used.

Accidents can be avoided provided that equipment is **regularly maintained** and **staff** and **students** are made aware of potential hazards. A list of general safety rules is included in this manual, to assist **staff** and **students** in this regard. The list is not intended to be fully comprehensive but for guidance only.

Please refer to the following notes regarding the Control of Substances Hazardous to Health Regulations.

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

After filling the sand tank with appropriate sand (not supplied) and filling the sump tank with water the equipment provides a self contained facility for the study of flow through permeable media. The sand tank has a toughened glass front and the aluminium back permits the insertion of pressure tapplings, tile drains etc.

Drainage and Seepage Tank

A metal frame supports the sand tank (1) above a sump tank (12) and centrifugal pump (13). The frame has adjustable feet (10) to allow the glass fronted sand tank to be levelled in both planes. The frame also includes a shelf (18) located in front of and just below the bottom of the sand tank.

The sand tank is fabricated with an aluminium back panel (17) incorporating six tapping points (6) and a front panel of toughened glass (19). The tapplings in the rear panel are fitted with sealing plugs that can be removed to incorporate a tile drain (described in detail later) or used as tapping points, if required.

Two independently adjustable overflows (7 & 16) fitted through the floor, at each end of the sand tank; allow different water levels to be maintained at each end of the sand tank to suit different demonstrations. Water is returned to the sump tank by the overflows. Each overflow incorporates a plug of open cell foam material to prevent particles of sand from washing into the sump tank.

Two aluminium rails along the top edges of the sand tank provide location for an adjustable clamp (5) for an impermeable baffle plate (4) or lateral pressure plate (described later) when required. The rails also allow the position of the clamp (3) for the water inlet (2) to the sand tank to be varied to suit different demonstrations.

A drain valve (8) in the floor of the sand tank allows water to be drained from the sand tank after use. Care should be taken to ensure that no sand particles fall into the sump tank when filling the glass fronted sand tank or making changes during experiments.

The sump tank can be emptied using the sump tank drain (11).

An electrical switch (15) controls the operation of the pump and hence the supply of water to the surface of the sand in the sand tank. The flow of water to the sand tank can be varied using a flow control valve (14) at the pump outlet.

Permeable Medium (Sand)

The equipment supplied does not include the permeable medium (sand) required for experimental studies. For the Teaching Exercises suggested it is advisable to use a washed, narrow range sand (coarse sand) with no significant fraction finer than 0.5mm. Alternative sand can be used if required to suit specific requirements.

Accessories supplied

The following accessories are supplied for use with S1:

Foundation Pressure Plate

Straight Permeable Membrane (x2)

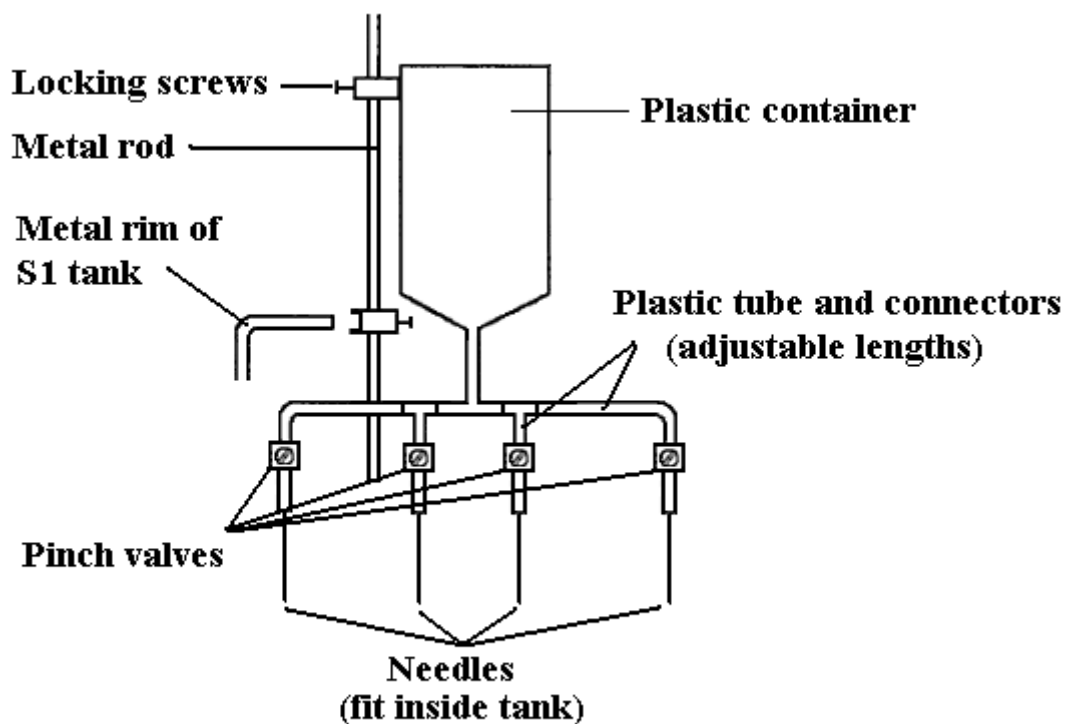
Curved Permeable Membrane

Lateral Pressure Plate

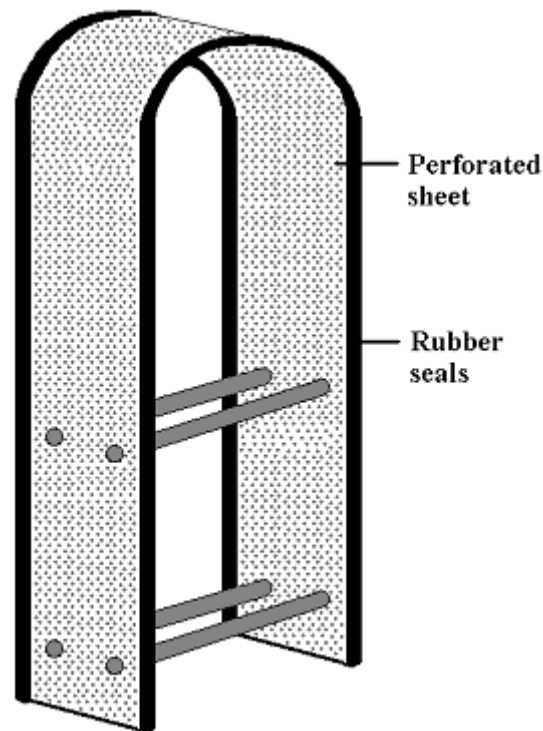
Tile Drain (x2)

Dye Injection Unit

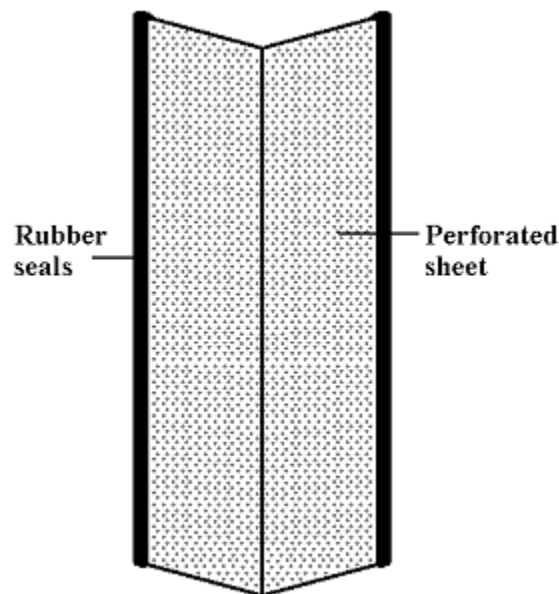
This consists of a dye reservoir that is mounted on a metal rod clamped to the top rail of the sand tank as shown below. 6mm internal diameter flexible tubing and 'T' pieces are used to form four outlets from the dye reservoir, each outlet incorporating a pinch valve to vary the flow of dye and a hypodermic needle at the end to inject the dye into the sand. The length of each flexible tube can be varied to locate the injectors at different positions and different heights in the sand tank to suit particular demonstrations.



Permeable Membranes



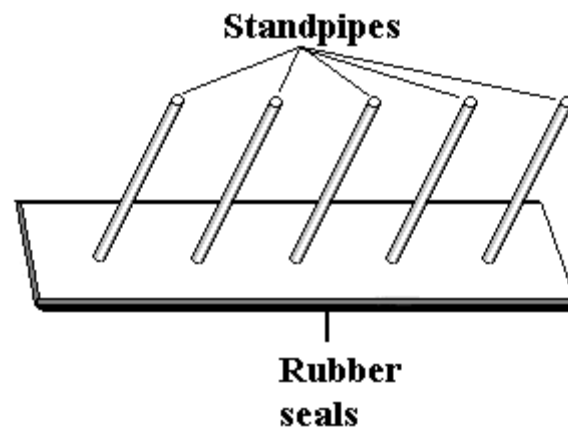
Curved Permeable Membrane



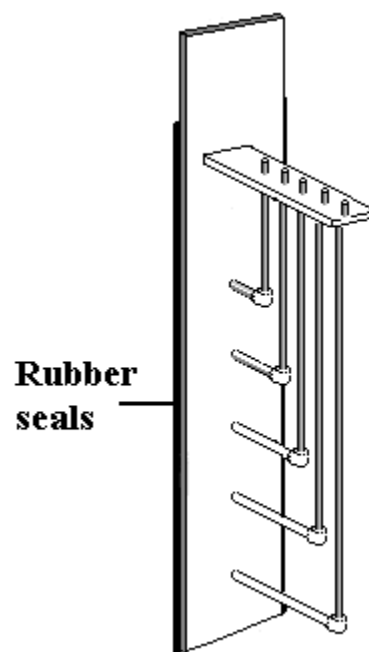
Straight Permeable Membrane

Two straight and one curved membrane are supplied with S1. Both membranes are formed from perforated sheet metal that is covered with fine woven material with perforations small enough to prevent the passage of sand particles. Rubber strips on the sides seal the membranes to the vertical front and rear walls of the sand tank. The 'V' shaped straight membrane can be located adjacent to the outlets inside the sand tank to allow variation of the water depth without the sand affecting the height adjustment.

Impermeable Membranes for Pressure Measurement



Foundation Pressure Plate



Lateral Pressure Plate

Both plates are made of 6mm thick PVC sheet and have rubber sealing strips along the edges. The foundation pressure plate is 610mm long with 5 Perspex tubes 210mm long normal to the surface, as standpipes. The lateral pressure plate is 720mm long, with longitudinal reinforcement and five standpipes cranked through 90°. Each impermeable plate incorporates filters over the connections to the standpipes on the inlet face to prevent sand from entering the tubes.

Tile Drain

Two tile drain assemblies are supplied for demonstration of dewatering using the tile drain technique. The tile drains can be used independently or in combination as required.



Tile Drain

Each drain consists of an 8mm internal diameter copper tube, with one end closed and having a pattern of eighteen holes drilled along its 150mm length. The open end is connected to a clean PVC tube 500mm long. Fine woven material is fastened around the copper tube to act as a filter.

These tile drains can be screwed into any of the six tappings in the aluminium plate at the rear of the tank, having removed the appropriate sealing plug. Each tapping incorporates a screwed plug to seal the tapping when no tile drain is fitted.

Installation

Advisory

Before operating the equipment, it must be unpacked, assembled and installed as described in the steps that follow. Safe use of the equipment depends on following the correct installation procedure.

Electrical Supply

Electrical Supply for Version S1-A

The equipment requires connection to a single phase, fused electrical supply. The standard electrical supply for this equipment is 230 V, 50 Hz. Check that the voltage and frequency of the electrical supply agree with the label attached to the supply cable on the equipment. Connection should be made to the supply cable as follows:

- GREEN/YELLOW - EARTH
- BROWN - LIVE (HOT)
- BLUE - NEUTRAL
- Fuse Rating - 1 AMP

Electrical Supply for Version S1-B

The equipment requires connection to a single phase, fused electrical supply. The standard electrical supply for this equipment is 120 V, 50 Hz. Check that the voltage and frequency of the electrical supply agree with the label attached to the supply cable on the equipment. Connection should be made to the supply cable as follows:

- GREEN/YELLOW - EARTH
- BROWN - LIVE (HOT)
- BLUE - NEUTRAL
- Fuse Rating - 2 AMP

Electrical Supply for Version S1-G

The equipment requires connection to a single phase, fused electrical supply. The standard electrical supply for this equipment is 220 V, 60 Hz. Check that the voltage and frequency of the electrical supply agree with the label attached to the supply cable on the equipment. Connection should be made to the supply cable as follows:

- GREEN/YELLOW - EARTH
- BROWN - LIVE (HOT)
- BLUE - NEUTRAL
- Fuse Rating - 1 AMP

Installing the Equipment

This item is supplied as one major assembly, together with all accessories listed above.

After careful removal from the packing case it should be positioned on a suitable floor with adequate access space on all sides.

Commissioning

1. Position the equipment as required ensure that the floor is adequate to support the weight of the equipment when filled with sand and water.
2. Level in the sand tank in both planes by means of the four adjustable feet (10) on the underside of the frame.
3. Check that the sides of the sand tank are parallel with each other. (It is helpful for the fitting of the models if the dimensions between the channel sides at the top slightly exceed that at the base of the channel).
4. Ensure that the tank inlet pipe is located in the clamp (3) at the top of the sand tank.
5. Check that sump tank drain (11) and sand tank drain (8) are both closed.
6. Fill the sump tank with water.
7. Connect the electrical supply cable to the appropriate mains supply.

Switch on the RCD then press the test button on the RCD. The RCD must trip. Switch on the RCD again.

8. Close the flow control valve (14) then check the operation of the centrifugal pump by operating the mains switch. Gradually open the flow control valve and confirm that water is supplied to the sand tank.
9. Raise both overflow pipes (7 & 16) to maximum height and fill the sand tank with water to check for any leaks. Tighten the clamp strip fixing screws if necessary.
10. Lower both overflow pipes and drain the water from the sand tank.
11. Check the fit of all models supplied and ensure that all rubber side seals function correctly (a smear of wetting agent on the seals will aid fitting and removal).
12. Assemble the dye injection system as shown in Dye Injection Unit in the Description section. Check the operation of the pinch valve on the flexible tube connected to each injector needle and water-test the reservoir for leaks.

Having established that all the listed checks are satisfactory, the equipment can now be fitted with the selected porous medium in preparation for experimental work.

Choice of Sand

It is advisable to use washed, narrow range sand (coarse sand) with no significant fraction finer than 0.5mm. The sand should be placed in the tank after the tank has been filled with water to ensure better spreading and mixing.

Operation

Operating the Equipment

See the Laboratory Teaching Exercises for details on operating the equipment.

Equipment Specifications

Overall Dimensions

Length - 1.60m

Width - 0.60m

Height - 1.45m

Sand Tank Dimensions

Length - 1.50m

Width - 0.10m

Height - 0.60m

Circulating Pump

Duty at 50 Hz: 35 l/min maximum flow

2.2m maximum head

Duty at 60 Hz: 33 l/min maximum flow

3.3m maximum head

Drive: Magnetic coupling

Motor rating: 18 Watts output

Equipment Location

The equipment is designed to stand on level ground capable of carrying the loadings involved. Access is required all round the assembly.

The equipment requires connection to a 0.1kW single phase, fused electrical supply. Four metres of supply cable are included with the equipment.

The equipment is a self-contained unit and needs only a temporary supply of cold water for the initial filling of the sump tank and for cleaning/flushing purposes.

Electromagnetic Compatibility

This apparatus is classified as Education and Training Equipment under the Electromagnetic Compatibility (Amendment) Regulations 1994. Use of the apparatus outside the classroom, laboratory or similar such place invalidates conformity with the protection requirements of the Electromagnetic Compatibility Directive (89/336/EEC) and could lead to prosecution.

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 2000m;

- 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 $\pm 10\%$ 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

In addition to regular maintenance the following notes should be observed:

1. When not in use, the equipment should be disconnected from the electrical supply and water should be drained from the sand tank and sump tank.
2. The equipment should be kept clean. Any build up of sand in the sump tank should be removed to avoid damage to the circulating pump.
3. After use the tile drains and permeable membranes should be washed thoroughly to remove any particles that may be blocking the filter material.
4. After prolonged use scale may build up on the inside of the glass panel preventing a clear view of the water levels inside the sand tank. To clean the glass it will be necessary to remove the sand then clean the glass using a proprietary descaler.
5. At regular intervals remove the plug of open cell foam from the top of both overflow pipes and wash them thoroughly to remove any particles that may be trapped in the foam. When refitting the foam only partially insert it into the overflow so that it can be removed again easily at a later date.

Laboratory Teaching Exercises

Index to Exercises

[Exercise A - Seepage Underneath a Sheet Pile Wall](#)

[Exercise B - Seepage Through an Earth Dam](#)

[Exercise C - Draining Effect of a Tile Line](#)

[Exercise D - Draining Effect of an Open Trench](#)

[Exercise E - Uplift Pressure on Foundation of Structures](#)

[Exercise F - Changing Uplift Pressure by Changing Length of Flow Lines](#)

[Exercise G - Reduction of Uplift Pressure by Draining](#)

[Exercise H - Reduction of Lateral Thrust on a Retaining Wall by Draining](#)

[Exercise J - Quicksand](#)

[Exercise K - Stability of an Earth Dam](#)

[Exercise L - Well Draining](#)

General Comments

The following set of experiments has been designed to demonstrate the most typical situations that arise in dealing with water as it moves through a permeable medium. The situations described are mostly "engineering" situations. In addition to the water and the medium through which it moves, they usually involve some artificial, or "engineering" element like a wall, a dam, a tile line etc. There are fourteen basic experiments and two variants described. However, any number of other practical investigations can be made which will add to general knowledge and enrich the experience of the experimenter.

Several basic rules should be followed in order to obtain good results. First of all, great care is needed in sealing the areas of contact between the membranes and the tank walls. To achieve a well-sealed contact requires clean, sand-free tank walls and membrane edges. Since the membrane will move downstream under the water pressure, when a sealer is used it should be applied along the downstream side of the contact area. The second important rule is to pour water into the tank slowly, starting with the downstream pool. And finally, it should be remembered that it is seldom successful to alter the experimental set-up after the contact areas have been sealed and the tank filled with sand and water. Each change of location of a membrane inside the tank usually requires the same amount of work and care as the set-up of a new experiment.

A detailed step-by-step description of each operation is given in the set-up of Exercise A. In the following teaching exercises detailed descriptions of the recurring basic operations (dye injection, membrane sealing, etc) are not repeated.

Basic Theory

a. Darcy's Law

The flow of water through porous media is governed by what is known as Darcy's Law: "The flow rate through porous media is proportional to head loss and inversely proportional to the length of the flow path".

Darcy's Law can be expressed mathematically as:

$$Q = AK \frac{\Delta h}{\Delta L} \quad \dots (1)$$

where

Q = flow rate

A = cross-sectional area of flow

K = a proportionality constant, called the "coefficient of permeability"

Δh = head loss

ΔL = length of the flow path.

A more usual statement of Darcy's Law, however, in terms of velocity of flow.

Since velocity is given as $v = \frac{Q}{A} \quad \dots (2)$

division of equation (1) by A leads to the familiar statement of Darcy's Law:

$$v = K \frac{\Delta h}{\Delta L} \quad \dots (3)$$

Since the ratio $\frac{\Delta h}{\Delta L}$, which is called "hydraulic gradient: and is analogous to slope, is dimensionless, the coefficient of permeability K must have the dimensions of velocity for equation (3) to be valid. The coefficient K is different for different materials and is determined in the laboratory by using equation (1) in the form:

$$v = \frac{Q}{A} \frac{\Delta L}{\Delta h}$$

Note that all the right-hand side terms can be directly measured. A method of doing so is shown in Figure i below.

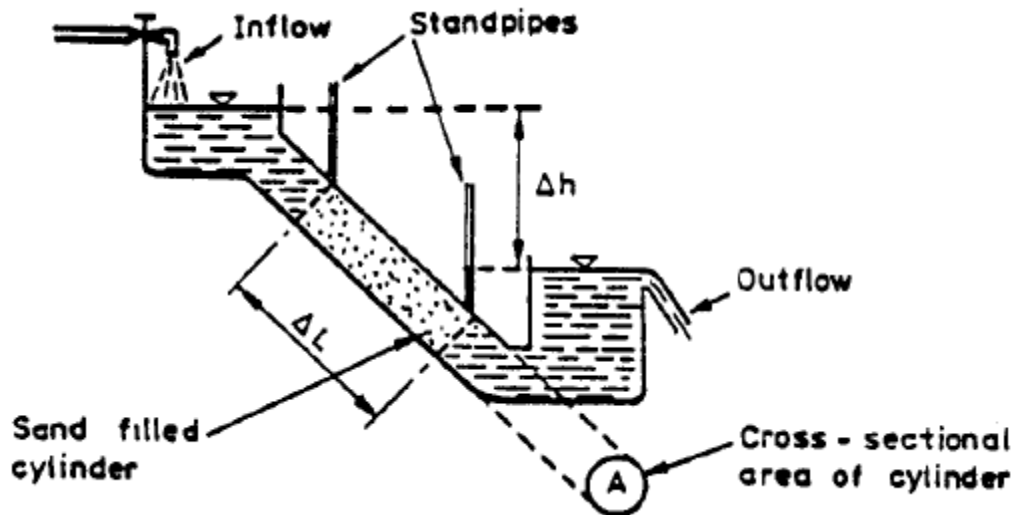


Figure i

For the purpose of classifying various types of soil with respect to permeability it has been found convenient to make use of a so-called, "laboratory (ie. 'standard') coefficient of permeability" designated as K . K is defined as the flow of water at 60 deg F in gallons per day through a one-square-foot cross sectional area of the soil in question under an hydraulic gradient of one foot per foot.

Classification of soils with respect to K

Class of soil	Clean gravel	Clean sands, mixtures of clean sands and gravels	Very fine sand	Unweathered clays
K_s (gal/day/ft ²)	$10^6, 10^5$	$10^4, 10^3, 10^2$	$10, 1, 10^{-1}, 10^{-2}$	$10^{-3}, 10^{-4}, 10^{-5}$

b. Flow Nets

Flow Lines and Equipotential Lines

A flow net is a graphical representation of flow through soil (or any other porous medium). From the flow net, information may be obtained on such features as the amount of seepage or leakage below a dam or through an earth dam, the uplift pressure caused by the water on the base of a concrete dam (or, say a harbour wall); and the danger of a "quick" or liquefaction condition at points where seepage water comes to the ground surface.

The path which a particle of water follows in its course of seepage through a saturated soil mass is called a flow line. In isotropic soil, flow follows paths of greatest hydraulic gradient, much as bodies rolling or sliding downhill tend to pick paths having the steepest slope.

It follows from Darcy's Law, and from common sense that water can flow through soil only if some head difference h exists between the places between which the flow might occur. This head difference (which may be made up of several components, see Figure iii) represents a certain amount of potential energy which is transformed into the kinetic energy of the moving

water. The soil through which the water is pushed by the pressure head resists its movement in much the same manner, as a rough surface resists, or brakes, the movement of a sliding body.

The soil resistance to moving water is called viscous friction since it causes a gradual dissipation of the kinetic energy in the moving water. Within limitations it can be treated as a negative head.

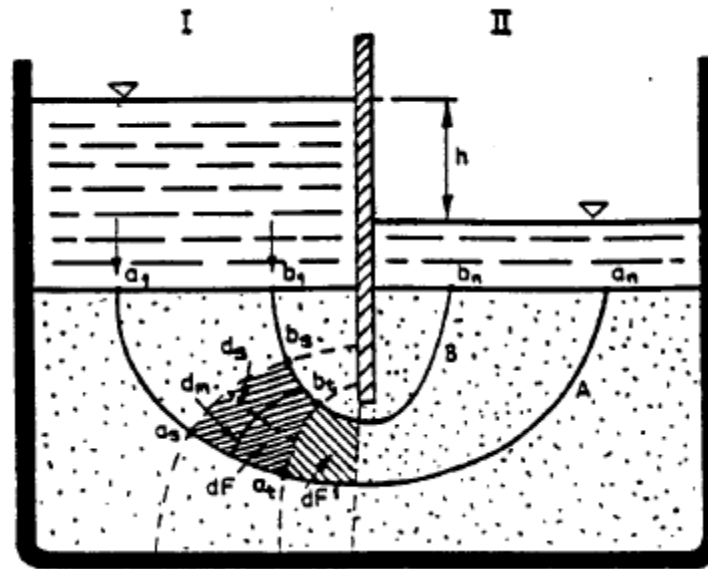


Figure ii

Let us imagine a situation where water penetrates under a sheet pile wall from basin I to basin II as shown above and let the pressure head between the two basins be h . Water will enter the soil along the whole bottom of basin I, and according to the location of its point of entry, each elemental volume will follow a different path on its way to basin II. However, all the elemental volumes, whatever paths they follow, will have the same potential at the points of entry and, similarly, they will have the same potential when eventually reaching the bottom of basin II. This follows from the fact that the water tables in both basins I and II are horizontal as well as their bottoms. So the pressure is constant along the whole bottom of each basin.

Now we pick two of the unlimited number of possible flow lines and denote them by A and B as shown in Figure ii above.

The lines connecting points with equal potentials on different flow lines are called equipotential lines. Thus we see that the contours of the two bottoms represent two equipotential lines since they connect, respectively, points a_1 and b_1 having equal potentials, and points a_n and b_n also having equal potentials.

Naturally, pairs of points having equal potentials must also exist between the two pairs located at the beginning and the end of the flow lines. Examples of such pairs are represented by points a_s , b_s and a_t , b_t . The connecting lines $a_s b_s$ and $a_t b_t$ represent the equipotential lines between the pairs.

Such a system of flow lines and equipotential lines is what is called the flow net. In each flow net, the flow lines and the equipotential lines intersect at right angles.

This important feature of a flow net can be explained as follows. Just as water flowing downhill naturally follows the steepest path, so does water flowing between equipotential lines follow the path of maximum gradient. By definition, gradient is the difference in potential between two equipotential lines divided by the distance between the lines. If the lines are parallel the maximum gradient will occur where the distance between the lines is least, ie. along any line which is perpendicular to the equipotential lines. This is true even if the equipotential lines are infinitely close to one another.

Now imagine two adjacent equipotential lines which are infinitely close to one another but not parallel. The shortest distance between the two lines at any point along one of them can be established as follows. Using the intersection of the two equipotential lines as a centre, describe an imaginary arc that passes through the point in question and also intersects the second equipotential line. The chord of that arc which is contained between the two equipotential lines can be shown to be the shortest distance between the two lines at the point in question. Hence, the gradient will be maximum along that chord. However, by definition, the two lines are infinitely close together at that point.

So the difference in length between the arc and the chord is infinitely small. Hence, at that point, the gradient along the arc is equal to the gradient along the chord. By construction, the arc is perpendicular to each equipotential line at its intersection with that line. It follows, then, that all lines representing the paths of maximum gradient intersect all lines of equipotential at right angles.

Since flow follows the path of maximum gradient, it, too is perpendicular to all equipotential lines.

c. Rate of Seepage

Now consider that same portion of the water that seeps out of basin I and into basin II (see diagram above) in a given time will pass through an area dF bounded by the two flow lines ($a_s a_t$ and $b_s b_t$) shown. This seepage, Q , will be measured in gallons per unit of time per running foot (ie. per foot normal to the plane of the section). If we designate that portion of the seepage passing through dF as dq we get from Darcy's Law:

$$dq = K \, dm \, \frac{dh}{ds} \quad \dots (4)$$

where dh is the potential drop between the two equipotential lines, the only unknown in equation (4).

If we choose equipotential lines such that the area dF resembles a square, then the distance dm is approximately equal to ds , and equation (4) reduces to:

$$dq = kdh \quad \dots (5)$$

For the subsequent "square" area dF' the discharge is

$$dq' = K dh' \quad \dots (6)$$

However, we can get only as much water into dF' as has passed through dF . There is simply no other place from which the water could come. Nor is there any other place where the water from dF could go. Therefore we have:

$$dq = dq' \quad \dots (7)$$

which, from equations (5) and (6) gives:

$$dh = dh' \quad \dots (8)$$

This is a very important result. It implies that the potential drop between two adjacent pairs of equipotential lines is the same if they share the same pair of adjacent flow lines and enclose an area similar to a square.

If a pair of flow lines is given, there is only one way to divide the strip between them into a sequence of "squares" (ie. tetragonals) whose four corners form right angles and whose mean distances between opposite faces are alike. Therefore, if we succeed in dividing the strip between the two flow lines into a sequence of such "squares", we can use their number n for calculating the potential drop dh between two successive equipotential lines. Since all the values of dh must be the same according to equation (8) we have:

$$dh = \frac{h}{n} \quad \dots (9)$$

Knowing dh we can finally determine from equation (5) the discharge (per unit length) through the area between two flow lines.

Although it is advantageous to have a "square" flow net, it is also possible to determine dh from a rectangular net if all the rectangles between two flow

lines have the same ratio $\frac{dm}{ds}$. Denoting this ratio by c , equations (5) and (6) become respectively.

$$dq = K c dh \quad \dots (10)$$

$$dq' = K c dh \quad \dots (11)$$

which again means that equation (8) holds and we can obtain dh from equation (9) where n is the number of rectangles between the two flow lines. Discharge dq is then obtained from equation (10).

If, for some reason, we do not have a flow net consisting of squares or geometrically similar rectangles, we would have to measure the actual heads at all equipotential lines in order to obtain the potential drops between each.

d. Boundary Conditions

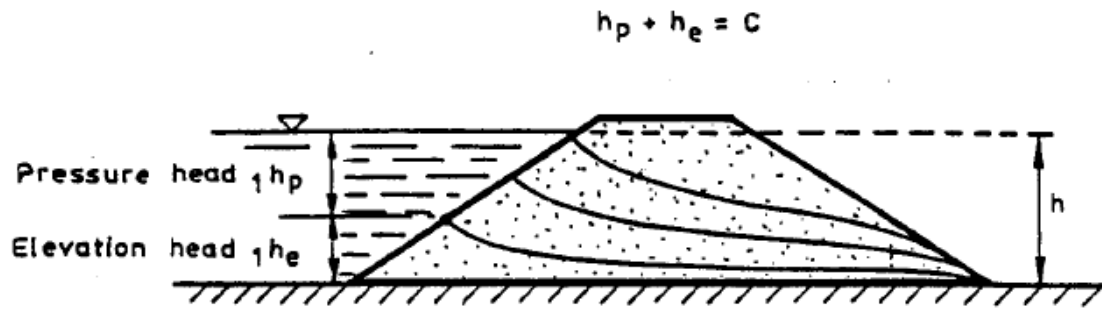


Figure iii

If the conditions at all points of the boundary of the cross section of a soil mass are fixed and clearly defined, the flow net is uniquely determined. An example of such a case is represented by the situation shown in Figure ii. Here the bottoms of basin I and II represent two equipotential lines, the perimeter of the soil mass along the two walls and the bottom of the tank represents one flow line, and the perimeter of the part of the impermeable screen immersed in the soil represents another line.

These two flow lines and two equipotential lines fully determine the shape of the flow net since there is only one shape of the net of which the above two pairs of lines can be a part. Under such clearly specified conditions the flow net is completely determined by its geometrical properties. It can be obtained directly by a graphical, trial-and-error-sketching method.

Its determination does not require any additional mathematical solutions (although such solutions exist for some types of boundary conditions). Nor is it necessary to seek the correct flow line pattern experimentally.

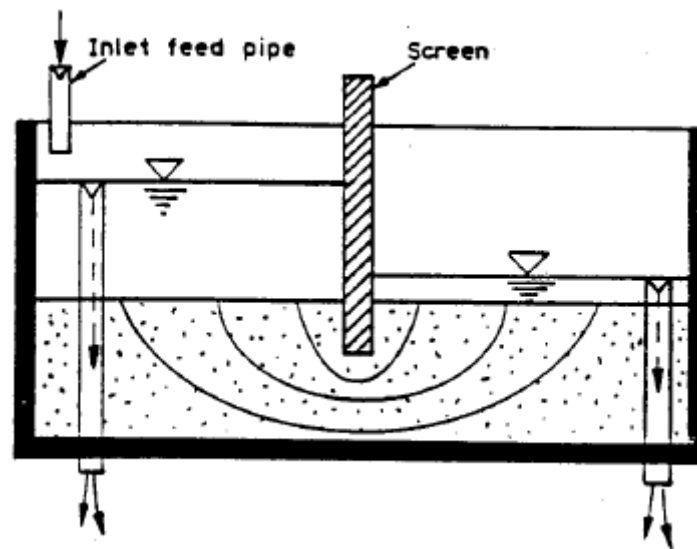
There are, however, many cases of seepage where boundary conditions are not so clearly defined, as in part b. Flow Nets above. A typical such case is seepage through an earth dam shown above. Here the upstream slope of the dam represents an equipotential line (the head h consists of the pressure, h_p and elevation, h_e heads whose sum is constant for all points of the slope). Clearly, the impervious bottom represents one boundary flow line. The second boundary flow line must start at the intersection of the slope with the upstream water level.

However, since there are no physical obstacles in its path, its geometry is not defined. The top flow line is under atmospheric pressure and it seeks its path according to certain physical laws. These must be taken into account since they act in the same way as the geometrical constraints that were present in the previous case but missing in this.

To mathematically determine the shape of such free flow lines from the governing physical laws is not always simple. For this reason an experiment is often a very valuable and important alternative method of tackling the problem.

Exercise A - Seepage Underneath a Sheet Pile Wall

Objective



Seepage underneath a sheet pile wall is one of the seepage problems that are most common in practice. Sheet pile walls are used to reduce seepage under all types of dams, sea walls, dividing walls, lock walls, coffer-dams and similar structures. They are also used to reduce leakage from canals, rivers and the sub soils surrounding an excavation and the like.

It is also this type of seepage which most clearly illustrates the concept of a flow net where the flow net has a simple and intuitively clear pattern and fully defined boundary conditions.

i. Flow Line Visualisation

Prepare about $\frac{1}{2}$ litre of fluorescein solution by slowly adding the chemical into water until the solution becomes a semi-transparent opal-like liquid of orange-greenish colour.

Fill the tank with pure sand to a level of about 300mm above the bottom of the tank.

Adjust the upstream overflow so that its top is about 100mm below the top of the tank and the downstream overflow so that its top is about 25mm above the surface of the sand bed.

Adjust the impermeable screen at the middle of tank. Leave about 125 to 150mm of clearance between screen and bottom of the tank. Seal the contacts between the screen and tank walls with grease or other easily removable seal.

Apply the seal on downstream side to prevent leakage in case screen moves under the final pressure difference.

Pour water slowly into the tank. Start with the downstream pool and transfer the input into the upstream after the lower pool is full. After overflow occurs both upstream and downstream reduce water input to the minimum needed to

maintain constant water level in the upstream pool (in this case there will be a small continuous overflow from the upper pool). Smooth out any sharp irregularities of the sand bed which may have formed while filling the pool.

Fix the bottle with dye on the stand in such a position that the liquid level is approximately at the same elevation as the water level in the upper pool. Then, depending on the desired number of flow lines (3 to 4 recommended), insert the corresponding number of dye-injection needles vertically about 6mm into the sand along one of the transparent walls of the upper pool. In order to obtain an approximately "square" flow net, the spacing between the needles should progressively increase in the upstream direction from the impermeable screen. The suggested needle distances from the screen for 4 flow lines, are approximately 50, 115, 230, 380mm. Tape the needles (or the tubes connecting them with the bottle) to the tank wall just above the water.

After the dye-injection needles have been fixed, lift the bottle with dye and position it so that the liquid level is about 12mm above the water level in the upper pool. The position of the bottle should be adjusted according to the appearance of the flow lines. If lines are wide, the bottle is too high. If no dye appears or its flow is irregular, the bottle is too low. The formation of flow lines may require several minutes to an hour or two, depending on the permeability of the sand used.

To stop the experiment, shut off the dye input by lowering dye container until dye surface is about 50mm below water level in pool. Let the flow lines wash away. Do not take out the needles before the dye input has been shut off as indicated. Otherwise dye will get into water in the pool while needles are being removed.

ii. Flow Net Construction

Trace the flow line pattern and the boundary conditions (the perimeter of the cross section of the body of sand in the tank) on tracing paper taped to the transparent wall of the tank. Use a felt marker to prevent erasing the contours which are to serve as a firm skeleton of the net when sketching in the completed net with a pencil later on.

To obtain a square flow net, try first to fit the squares between one pair of the experimentally obtained flow lines. Proceed with the sketching of the equipotential lines from the upstream to the downstream boundary (ie. upstream sand surface to downstream sand surface) using care to obtain right angle intersections.

On the first trial, a narrow residual rectangle will probably occur at the end. The correction can be made in two ways. The width of the "channel" formed by the two experimental flow lines can be either increased or reduced by drawing a parallel trial line close to one of the original lines.

Using this corrected flow line instead of one of the experimental ones, a new set of squares is fitted into the "channel". If the new "channel" is wider than the original, the length of the residual rectangle will reduce eventually to zero. If it is narrower, the residual rectangle will eventually be lengthened until it approximates a square.

Once the square net between one pair of flow lines has been established, the equipotential lines can be extended across the whole flow field so that they

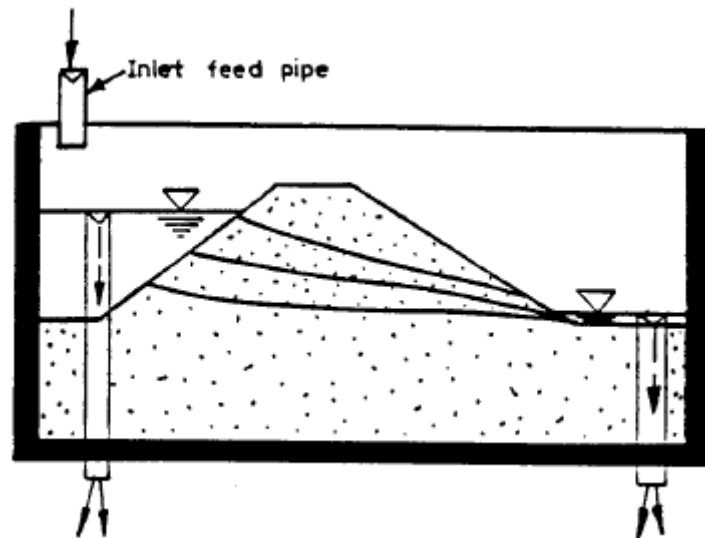
intersect all the experimental flow lines at right angles. Then flow lines are interpolated between the experimental ones so as to form, with the equipotential lines, a square network.

Since the "channels" near the boundary flow lines need not be square at the first trial, the whole flow net may be adjusted. A way to avoid this is to set up a separate rectangular flow net in each of the two boundary "channels". This can be done by appropriately changing the position of some equipotential lines.

iii. Seepage Rate

First, the pressure drop dh is determined from equation (9). Then the seepage rate in each flow "channel" is determined using equation (5) in case of a square network, or equation (10) in case of a rectangular network. The total seepage flow rate per running foot underneath the steel pile is the sum of all the rates through the individual flow "channels".

Exercise B - Seepage Through an Earth Dam



Objective

A frequently encountered type of seepage in hydraulic engineering is seepage through an earth dam. The term "earth dam" includes dams constructed from materials ranging from rock-fill to silt and clay. The services earth dams render are not limited to the impounding of water as in a reservoir. They also serve as dykes, levees, banks of canals, banks of aqueducts (with water level above the surrounding terrain), part or all of the perimeter of a catch basin. Even the earthworks for highways or railways sometimes function as dams, especially when culverts and bridge openings become clogged from heavy rains and water is impounded behind the earth fill.

Apart from its practical importance, seepage through an earth dam is interesting from a theoretical point of view. It typifies a group of engineering problems in which boundary conditions are not completely specified by the geometry as they are in problems similar to that of seepage under a sheet pile wall.

The objectives of the experiment are as follows:

1. To determine the position and shape of the flow line representing the uppermost free water surface inside the body of the dam.
2. To visualise the flow lines system and to show each flow line starts perpendicular to the upstream slope of the dam and the slope is a boundary equipotential line.
3. To determine the rate of seepage through the dam.

Equipment Set Up

A segment of a dam of trapezoidal cross section is formed from sand in the tank so that the base of the dam is about 150mm above the bottom of the tank. The upstream slope can generally be steeper than the downstream one and its toe should be approximately at the overflow outlet.

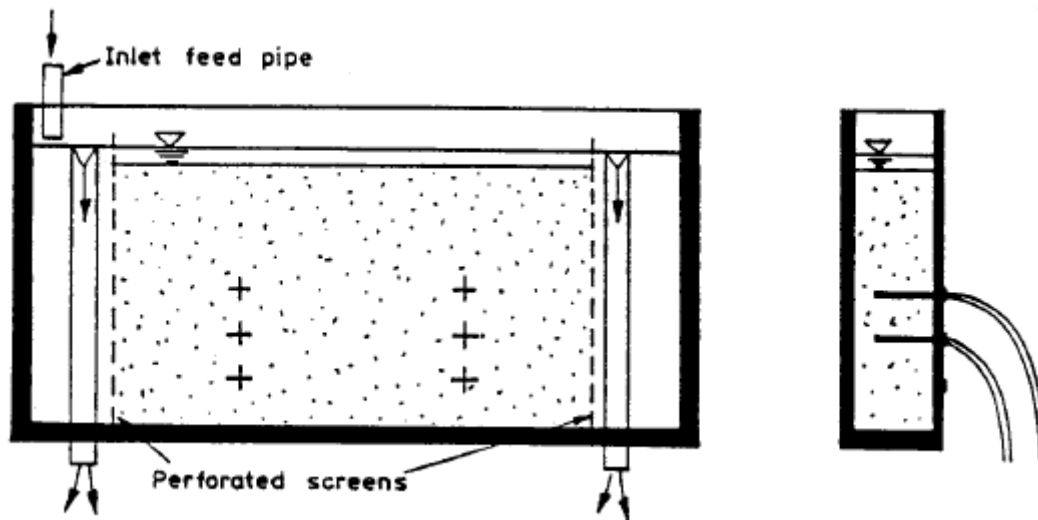
For current laboratory sands, a stable dam cross section will have an upstream slope of approximately 1:3 to 2:3 and a downstream slope of about 1:5 to 1:4. The height of the dam should be about 250mm, the crest width approximately 75mm. The

upstream water level should be stabilised 25mm below the dam crest; the downstream level about 12mm above the bottom.

After the dam segment has been formed, water is first poured into the downstream pool. Only after it is full should the upstream pool be filled. The rate of filling should be slow. Otherwise the dam segment can easily collapse.

When the upstream water level is stabilised, needles with dye are inserted along the upstream slope (next to the transparent side of the tank), the first being fixed immediately at the water surface. The procedure to be followed in visualising the flow lines construction of equipotential lines and calculation of seepage rate, is the same as described in [Exercise A - Seepage Underneath A Sheet Pile Wall](#).

Exercise C - Draining Effect of a Tile Line



Objective

Tile lines, horizontal galleries, trenches and, sometimes, vertical wells are widely used to control seepage of water through permeable soils. This type of control differs in principle from control achieved by sheet pile walls. Sheet pile walls control by elongating the flow lines so as to reduce the hydraulic gradient and, hence, the seepage. Now we want to control by changing the location of the ending, or outlet sections of the flow lines. This can only be done at the expense of an increase in hydraulic gradient and thus also the seepage rate. The reason for this is simple and follows from Darcy's Law.

As we already know, water penetrates through soil along paths of highest hydraulic gradient. Therefore, if we want to change the position of the end sections of flow lines we must arrange new paths that have greater gradient than the original ones.

The gradient increase is most easily achieved by (a) removing part of the soil (ie. the medium obstructing the water movement) and/or (b) by making the head difference between an upper pool and the desired end-points of flow lines greater than the original. A tile line, a trench, or a well accomplishes the first effect automatically. The second is achieved only by maintaining a tail water level at a lower elevation than the original tail water. This is usually done by pumping or by draining.

Tile lines, galleries, trenches and the like are used to drain water from surface layers of swamps, and from damp agricultural land; to protect excavation sites from flooding by ground water, to collect water supplies from water bearing strata.

The objective of this experiment is to show, by visualising the flow lines, how a tile line works (ie. how it forces the end-sections of flow lines to concentrate on one point).

Equipment Set Up

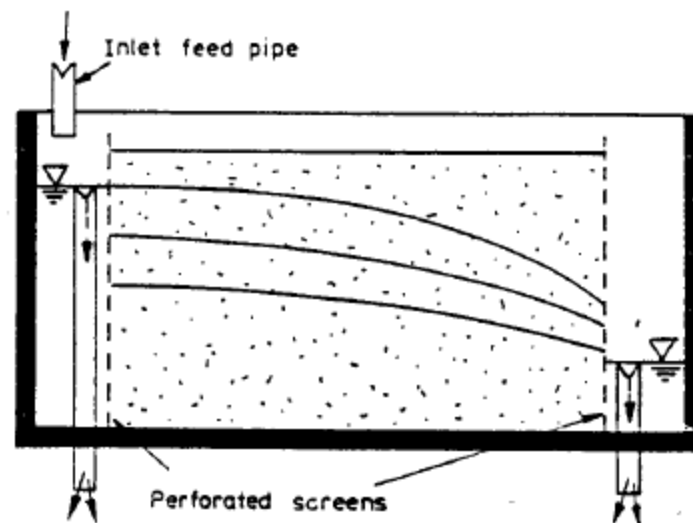
Purpose made tile drains can be inserted in any of six locations in the aluminium side of the permeability tank. Two tile drains are normally used in this experiment.

The drains are fitted into the tank at two of the six positions. Space around the overflows is kept free by using vertical sheets of perforated metal, which can be supported by the overflow pipes.

The space in the tank between the perforated metal sheets is then filled with sand to a depth of about 450mm. The overflows are set with their tops about 25mm above sand level, before water is poured slowly into the space around the upstream overflow.

After steady flow conditions have been achieved, dye is introduced in the usual manner at different points along the sand surface and, also along the edge of the upstream membrane.

Exercise D - Draining Effect of an Open Trench



Objective

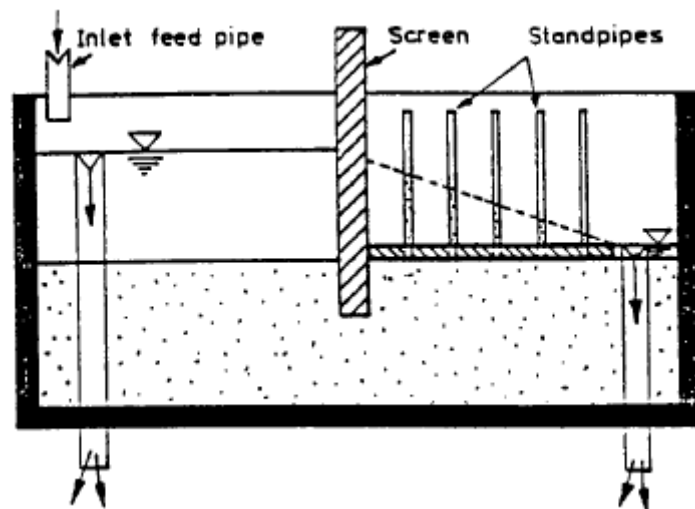
See [Exercise C - Draining Effect of a Tile Line](#).

Equipment Set Up

In this experiment we simulate the drainage effect of a trench along one of its walls. We assume that the trench is in homogeneous material so that all dimensions and the flow pattern are symmetrical with respect to the centre line of the trench which will be represented by the downstream end wall of the tank.

The trench wall will be considered to be vertical and will be simulated by a perforated metal sheet just like that used in [Exercise C - Draining Effect of a Tile Line](#), to separate the upper pool from the body of sand. In this experiment one sheet supported by the downstream overflow pipe, separates the sand body from the downstream pool representing half of the trench cross-section, while the other separates the sand body from the upper pool as in [Exercise C - Draining Effect of a Tile Line](#). In order to prevent sand being washed into the trench segment, the contact area between the downstream perforated sheet and the tank walls should be similarly sealed off.

Exercise E - Uplift Pressure on Foundation of Structures



Objective

Whenever a structure (dam, weir, retaining wall, etc.) is built on permeable material and separates two water pools with different elevations of water level, seepage occurs underneath and the water exerts pressure on the structure along its whole submerged perimeter. That part of the pressure that acts upwards and tries to lift the structure is called the uplift pressure and is extremely important in the stability analysis. As explained earlier, the submerged perimeter of a structure represents a flow line and the pressure at any point can be determined from the flow net. However, it can also be measured directly by means of standpipes.

The objective of the present experiment is to demonstrate how such direct pressure measurements are made, using the horizontal bottom of a submerged structure as the basis for the experiment. In this special case all the pressure is uplift pressure.

Equipment Set Up

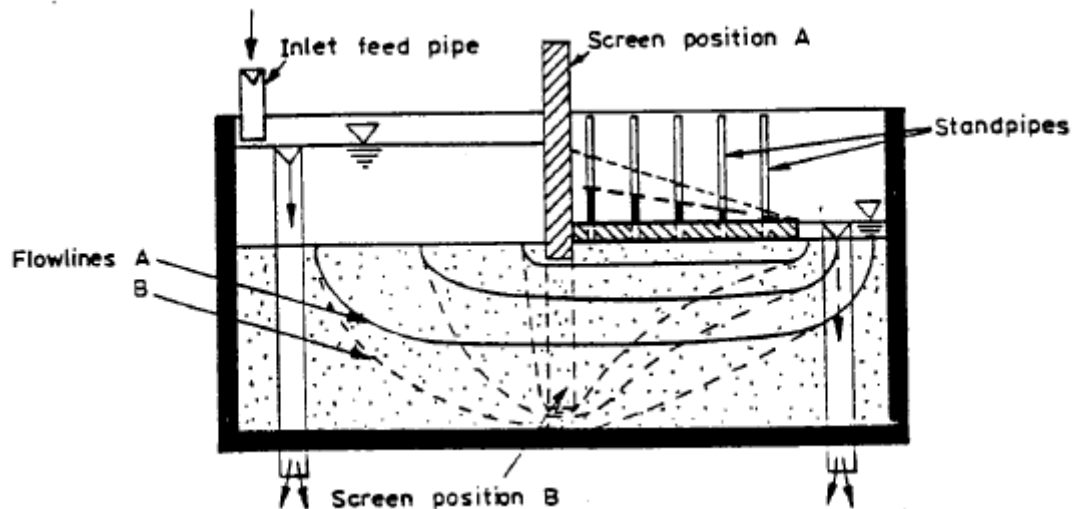
The set-up is basically the same as in [Exercise B - Seepage Through an Earth Dam](#), with an additional element consisting of a simulated foundation of a structure.

The "foundation" is simulated by means of a PVC sheet about 6mm thick, 460mm long and 150mm wide, with both long edges covered with the elastic rubber packing. Simulated foundation has 5 standpipes fitted along the centre line as shown in Additional Apparatus.

The "foundation", with standpipes in place, is positioned horizontally immediately downstream of the vertical impermeable screen and on top of the sand.

The contact between the rubber edges of the "foundation" and the tank walls should also be sealed by grease if this appears to be necessary. In order to prevent the "foundation" from being lifted, some weights can be put on it. Finally, water is poured in. The uplift pressure profile is shown by the rise of water in the standpipes.

Exercise F - Changing Uplift Pressure by Changing Length of Flow Lines

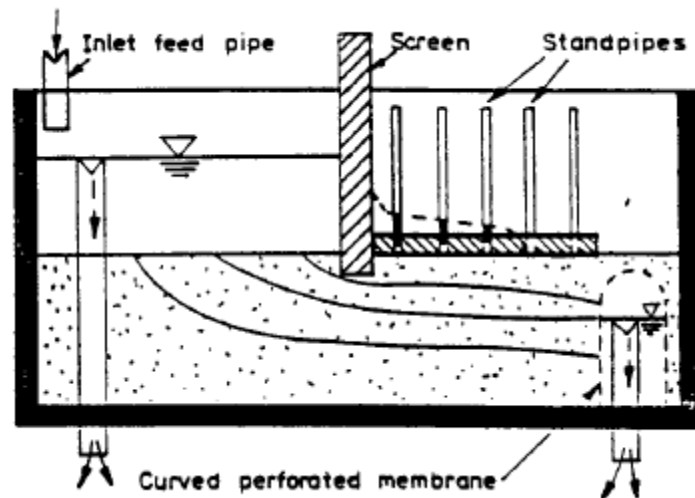


The pressure at any point along a flow line, and for that matter, pressure at any point along the submerged perimeter of a structure, changes with any change of the overall length of the flow line. This fact is often used to reduce the uplift pressure on structures by stretching out the flow lines. This can be done with vertical or horizontal impermeable membranes (aprons). In most instances these are located upstream of the structure.

The influence of the flow line length on uplift pressure can be easily demonstrated. In [Exercise E - Uplift Pressure on Foundation of Structures](#), simply change the depth of penetration into the sand of the impermeable vertical screen.

For each of several depths the uplift pressures registered in the standpipes can be recorded and the flow lines visualised in the ordinary way.

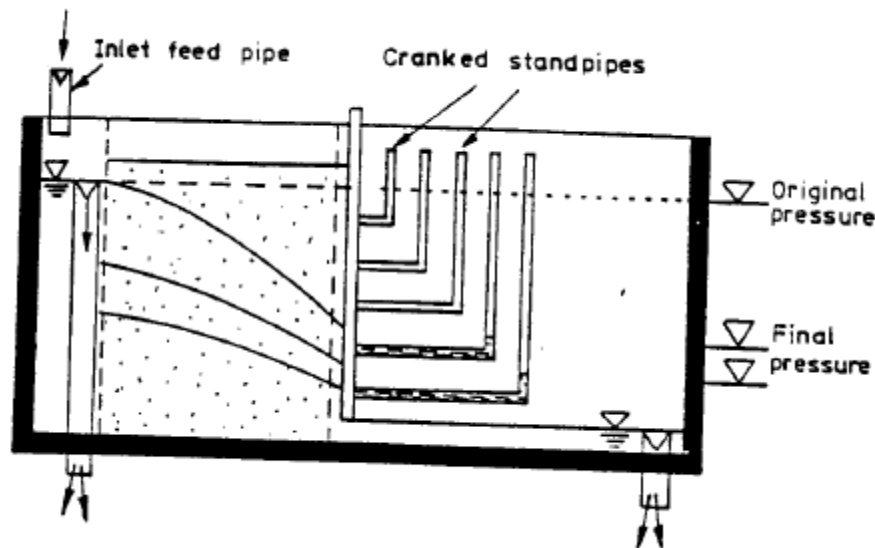
Exercise G - Reduction of Uplift Pressure by Draining



Objective

If we want to reduce uplift pressure but are not interested in reducing the rate of seepage at the same time, the most convenient way to do it is by using a downstream drain in the form of a tile line or a trench. In this manner, the flow lines are drawn downwards and the uplift pressure is reduced or even entirely eliminated. This can be easily demonstrated by modifying the outlet from the downstream pool as in [Exercise D - Draining Effect of an Open Trench](#), by employing the open trench principle.

Exercise H - Reduction of Lateral Thrust on a Retaining Wall by Draining



Objective

If water collected behind a retaining wall has no outlet, its hydrostatic pressure contributes to the lateral thrust of the soil and increases the total pressure load on the wall. Therefore, wherever possible, we try to drain water which may collect behind the wall and thus reduce not only the load on the wall but also the dimensions and cost of the wall.

The current way to drain water from behind a retaining wall is to place a layer of permeable material (sand, gravel) between the wall and the soil and then to provide openings in the wall near the bottom.

The objective of this experiment is to demonstrate flow and pressure conditions in a permeable layer behind a retaining wall.

Equipment Set Up

The wall segment will be simulated by an impermeable PVC plate of the same type used in [Exercise E - Uplift Pressure on Foundation of Structures](#) for simulating the foundation of a structure. In this case, however, the plate is positioned vertically and should be at least 720mm long so that it can be fixed at the top of the tank by the special fittings provided at the mid-point of the tank.

The wall segment is fixed vertically into the middle of the tank with standpipes oriented downstream. A suitable seal is used between the lower end of the plate and the tank bottom in order to seal off completely the upper pool from the lower pool.

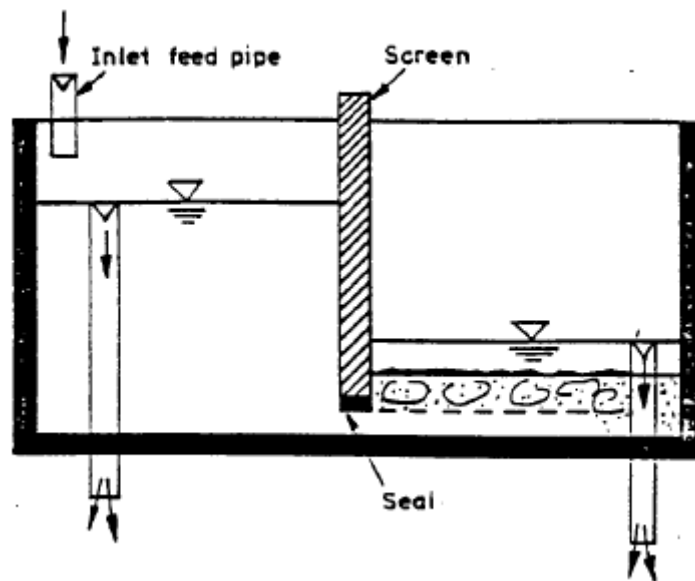
The perforated metal sheet used in [Exercise C - Draining Effect of a Tile Line](#) is placed against the upstream side of the wall segment so that it reaches right down to the bottom of the tank. The sheet serves to prevent the sand from the upper pool being washed into the lower pool after the seal has been removed from underneath the wall segment. Therefore, its lower end must not rest on the seal as does the wall segment.

Another perforated metal sheet is placed at the upstream overflow pipe as in [Exercise C - Draining Effect of a Tile Line](#). Now the space between the two perforated sheets is filled with sand up to about 50mm below the top of the tank. Upstream overflow is adjusted to about 25mm below the sand surface while the downstream overflow is adjusted to about 12mm above the tank bottom.

The upper pool is then filled with water. A small continuing input of water is established which will be drained away by the upstream overflow. At this stage no water should be coming into the lower pool and water levels in all standpipes connected to the wall segment should stabilise at the elevation of water in the upper pool. This indicates that the wall is under full hydrostatic pressure.

In the second step remove the sealing strip from underneath the wall segment and let the water flow into the lower pool. This is equivalent to draining off the toe of a retaining wall. Next insert dye at several points in the upstream perforated metal sheet and let the flow lines form. At the same time watch the drop of water levels in the standpipes. Levels should now be different in each. The pattern of the flow lines explains why the pressure on a wall is reduced when there is a drain at its bottom. The profile of water pressure from top to bottom of the wall is indicated by the height of the columns of water in the standpipes.

Exercise J - Quicksand



Objective

Quicksand develops when, in a saturated mass of sand, the uplift pressure reaches the weight of the sand body. The sand then starts to "float" and loses all its natural stability. It frequently occurs at the bottom of wells and downstream of engineering structures serving as water dams. The occurrence of quicksand, or "quick", always indicates a very dangerous situation for nearby structures which lose the support of the underlying material and collapse.

The objective of this experiment is to demonstrate the formation and behaviour of the "quick".

Equipment Set Up

The perforated metal sheet with its bent edges down, is laid on the tank bottom so that there is about 38mm free space between the plate and the bottom. The impermeable membrane is then adjusted in a vertical position at the upstream end of the perforated sheet so that the lower end of the former rests on top of the latter. The contact area between the two plates should be sealed off. The space downstream of the vertical plate is then filled with sand to about 75mm depth. The sand rests on the perforated plate and at the far end of tank on the tank bottom. The downstream overflow is adjusted to about 25mm above the sand surface while the upstream overflow is set about 50mm below the top of the tank.

Water is poured into the upper pool at a moderate rate which, however, must be higher than the rate of seepage in order that the level in the upper pool keeps rising slowly.

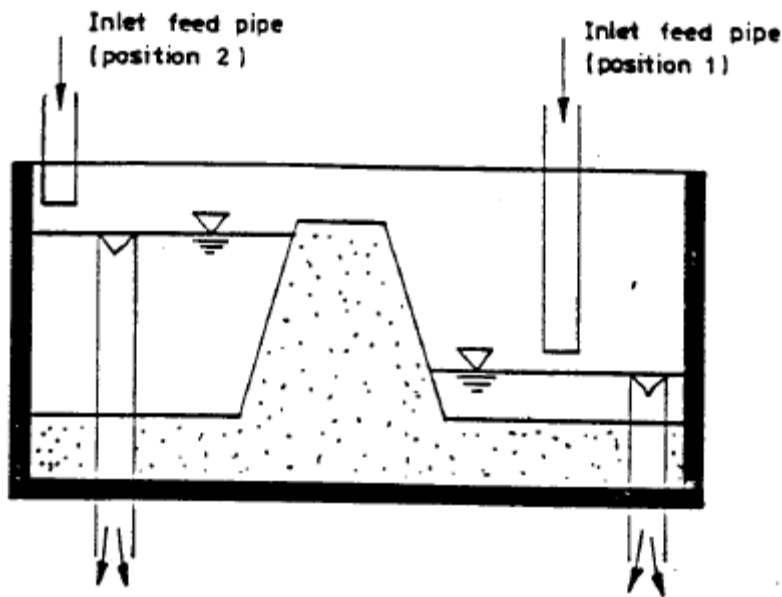
At some point the sand exposed in the lower basin to the uplift pressure of the vertically penetrating water, starts showing a pattern of instability.

Its surface will look something like boiling water and periodically vortices will form, travel across the sand surface, then disappear.

At this point the head difference between the two water pools is correct and water input should be so adjusted so as to keep it constant. The sand is now under the

conditions of "quick" and if some object, a concrete or steel cube, for instance, is placed on its top it will sink since the sand is floating and does not have any stability.

Exercise K - Stability of an Earth Dam



Objective

The continuing safety of an earth dam structure depends on the stability of its slopes. The stability of the slope is in turn dependent on:

1. the properties of the material of which the dam is constructed;
2. whether it is 'exposed' to water or air; and
3. on conditions of seepage through the dam.

This experiment is to demonstrate the process of collapse of an improperly designed earth dam with slopes too steep for the material used. At the same time it may be noticed how the water itself adjusts a dam's surface to the steepest slope allowable for given conditions. This slope is called the critical slope.

Equipment Set Up

A segment of an earth dam is formed out of moist sand in the middle of the tank with slopes as steep as the material permits, the overflow pipes being adjusted as in [Exercise B - Seepage Through an Earth Dam](#).

Water is poured into the lower pool and, after it has reached the top of the overflow, the input is transferred into the upper pool and maintained at a moderate rate. The rising water level in the upper pool will gradually undercut the upstream slope of the dam and level it out into its "critical slope".

At the same time the increasing rate of seepage will start washing away sand particles at the toe of the downward slope, depositing them at a critical slope.

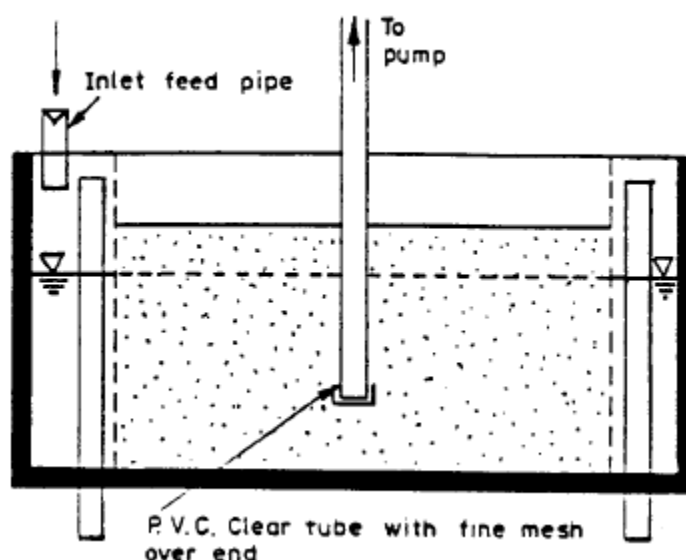
It should be noticed that the upstream and the downstream critical slopes are different, the upstream slope being steeper.

This difference is due to the variant contributions to stability of the hydrodynamic pressure of the penetrating water. Upstream the water exerts pressure on the dam

surface and so contributes to its stability. Downstream it acts to "pull" the sand more-or-less horizontally out of the dam.

The process continues gradually until the upper part of the dam loses stability and collapses. Then the whole process starts again and proceeds upwards to the dam crest.

Exercise L - Well Draining



Objective

A deep excavation for the construction of a foundation or other below ground activity, will frequently penetrate below the normal level for the water table in that area.

If the works are in permeable ground and suitable measures are adopted, the excavation will fill with water to the local water table level.

One method of de-watering is to sink a ring of wells around the perimeter of the excavation site and by pumping, lower the water table level locally.

The object of this experiment is to show the core of excavation of water local to a single well.

Equipment Set Up

Additional equipment necessary for this experiment is as follows (not supplied):

1. 6mm bore PVC clear tube x 2m long.
2. Positive Displacement Pump.
3. Motor for Pump.
4. Fine Mesh Terylene Cloth.

The clear PVC tube with the end covered in fine mesh Terylene cloth to prevent the ingress of soil, is suspended in the centre of the tank, with its covered end about 100mm from the bottom of the tank.

Space around the overflows is kept free by using vertical sheets of perforated metal as in [Exercise C - Draining Effect of a Tile Line](#). The overflows are to be set with their tops approximately 25mm below the top of the tank. Sand is to be put in the tank around the PVC tube and between the perforated metal sheets until the level surface is approximately 75mm below the top of the tank.

Water is poured slowly into the space around the upstream overflow until the water reaches a level approximately 75mm below the surface of the sand.

Dye is then introduced as in [Exercise C - Draining Effect of a Tile Line](#). The pump connected to the PVC clear tube is then operated and the inlet feed water adjusted to give a balanced water table level around the overflow.

The experiment may be extended to demonstrate de-watering of a site by using two adjacent wells.

In this instance it will be necessary to feed water to the area adjacent to the overflow at each end of the tank. This will preserve the water table adjacent to the de-watered site.

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