TECHNICAL REPORT 9213

Published 1988-02-01

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION•МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ•ORGANISATION INTERNATIONALE DE NORMALISATION

Measurement of total discharge — Electromagnetic method using a full-channel-width coil

Mesurage du débit total — Méthode électromagnétique à l'aide d'une bobine d'induction couvrant toute la largeur du chenal

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work.

The main task of ISO technical committees is to prepare International Standards. In exceptional circumstances a technical committee may propose the publication of a technical report of one of the following types :

- type 1, when the necessary support within the technical committee cannot be obtained for the publication of an International Standard, despite repeated efforts;
- type 2, when the subject is still under technical development requiring wider exposure;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical reports are accepted for publication directly by ISO Council. Technical reports types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical reports type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 9213 was prepared by Technical Committee ISO/TC 113, *Measurement of liquid flow in open channels.*

The reasons which led to the decision to publish this document in the form of a technical report type 2 are explained in the Introduction.

0 Introduction

The method of total discharge measurement described in this Technical Report is still under technical development. The method is based on experimental data obtained from field observations carried out in the United Kingdom. These data are presented in annex D, which does not form an integral part of this Technical Report.

The theory of the electromagnetic gauge is presented in annex A and specifications for a site survey are given in annex B; these annexes form integral parts of this Technical Report. In annex C the design aspects of the electromagnetic coil are presented; this annex does not form an integral part of this Technical Report.

UDC 532.57.082.74

Ref. No. ISO/TR 9213 : 1988 (E)

Descriptors: liquid flow, open channel flow, flow measurement, gauging stations, specifications.

Printed in Switzerland

Price based on 15 pages

ISO/TR 9213 : 1988 (E)

1 Scope and field of application

This Technical Report deals with the establishment and operation of an electromagnetic gauging station for the measurement of discharge in an open channel, or a closed conduit with a free water surface.

The application of the method is restricted to sites where the magnetic field is generated by an electromagnetic coil which traverses the full channel width.

This Technical Report is not applicable to discharge measurements using flow-meters which operate by using the Earth's magnetic field.

2 References

ISO 772, *Liquid flow measurement in open channels — Vocabulary and symbols.*

ISO 1100-2, *Liquid flow measurement in open channels — Part 2: Determination of stage-discharge relation.*

ISO 4373, *Measurement of liquid flow in open channels — Water level measuring devices.*

ISO 5168, *Measurement of fluid flow — Estimation of uncertainty of a flow-rate measurement.*

ISO 7066-1, *Assessment of uncertainty in the calibration and use of flow measurement devices — Part 1 : Linear calibration relationships.* [1)]

3 Definitions

For the purposes of this Technical Report, the definitions given in ISO 772 apply.

4 Principle of the method

4.1 Principle of operation

A vertical magnetic field is produced using a coil which is either buried in the channel bed or bridged across the channel at a cross-section of the open channel or closed conduit with free water surface. The water in the channel is insulated from the channel bed and banks using a membrane. The small potential set up between opposite banks of the channel, which is caused by electromagnetic induction as the water flows, is measured.

The potential generated is proportional to the width, in metres, of the river times the sum of the magnetic field strength, in tesla, and the average velocity of the river water, in metres per second. The magnetic field strength is proportional to the number of ampere turns in the coil divided by a linear dimension of the coil (i.e. the length of one side of the coil).

Therefore, the following relationship can be written:

$$E = K \bar{v} \frac{N}{l} b \qquad \ldots (1)$$

where

E is the induced potential, in microvolts;

K is a constant;

$\bar{v}$ is the average water velocity, in metres per second;

N is the number of ampere turns in the coil;

l is the side length of the square coil, in metres;

b is the channel width, in metres.

1) At present at the stage of draft.

Normally, l is equal to b, and therefore equation (1) becomes

$$E = K\bar{v}N$$

K has been deduced empirically to have a value of approximately 0,5. Therefore, for a typical coil of 500 ampere turns, the induced potential between the opposite banks of the channel would be 250 μV for an average water velocity of 1 m/s.

The total discharge is obtained by using the velocity-area principle in which the velocity inferred from the electrode potential is multiplied by the cross-sectional area of the channel. The cross-sectional area of the channel is a function of the recorded water level.

4.2 Factors to be taken into consideration

4.2.1 In most applications the vertical magnetic field is generated using an electromagnetic coil which traverses the whole of the channel cross-section.

4.2.2 The coil may be either buried in the channel bed (see figure 1) or bridged across the channel at a height above the highest water level (see figure 2) at which flow measurements are required. A bridged coil configuration is normally used where the coil is not subject to vandalism and its physical presence is aesthetically acceptable. However, on wide channels, a bridged coil may be impractical, and the use of a buried coil may be impractical in existing reinforced-concrete channels.

The method of installation of the coil will normally be chosen on the basis of financial considerations since technically there is no significant difference between the two methods.

The magnitude of the magnetic field produced is proportional to the electric current flowing through the coil. This current will normally remain substantially constant but may vary slightly owing to ambient temperature fluctuations and fluctuations in the mains voltage. The current should therefore be measured and corrections should be made to the results as necessary.

4.2.3 Each element of water flowing through the channel cross-section will contribute to the electrode voltage, and for an ideal arrangement the voltage is proportional to the true spatial integration of the velocity across the cross-section. In practice, the magnetic field is non-uniform and there are deviations from the ideal spatial integration, but these deviations are usually small and therefore the method is suitable for sites where the velocity profiles are irregular and variable. This means that the method is suitable for sites where there is considerable weed growth and limited variable accretion and can be used successfully downstream of bends and large obstructions in the channel.

4.2.4 In most natural channels the bed will be an electrical conductor and hence will partially reduce the induced voltage owing to electrical leakage currents. It may be necessary to line the channel with an electrically insulating impervious membrane to reduce the leakage currents to an acceptable level (see figure 1).

4.2.5 The theory of the electromagnetic method is presented in annex A.

5 Selection of site

5.1 Owing to cost considerations, the method is suitable for a maximum width of river of approximately 30 m. This limit is set mainly by the need to insulate the channel with a membrane. Different criteria apply to sites where a degraded version of the gauge is satisfactory (see 5.9), in which case the maximum river width is approximately 40 m.

5.2 A site survey should be carried out as outlined in annex B to measure any external electrical interference (e.g. power cables, radio stations and electric railways). Areas of high electrical interference should be avoided (see also 5.9).

5.3 An electrical energy source of 2 kW should be available.

5.4 The site should afford adequate on-bank working space for the handling of the membrane and cable.

5.5 There should be good access to the site for installation, operation and maintenance of the station.

5.6 The site characteristics should be such that the calibration of the station can be checked using an alternative method.

5.7 Sites should be selected where there is no spatial variation in water conductivity. Whether or not the channel is insulated, the accuracy of the method will be reduced if the spatial conductivity is not uniform throughout the cross-section. Temporal variations are unimportant provided that the spatial uniformity of the conductivity is maintained. This requirement makes an electromagnetic gauge unsuitable for channels in which fresh water flows over saline water, which often occurs in small estuaries. Provided that these requirements are met, the quality of the water, ranging from mountain water to foul sewage, does not affect the operation of the gauge and, similarly, the conductivity of the water will not affect the operation of the gauge.

5.8 For non-insulated channels, the signal attenuation increases as the width-to-depth ratio increases. It is recommended that the width-to-depth ratio of channels does not exceed 10:1.

5.9 In a non-insulated channel the accuracy of measurement is reduced. A preliminary survey should be carried out to measure the conductivity of the water and bed to estimate the signal loss before deciding whether the site is suitable. The allowable signal loss should not normally exceed a factor of 5 (see annex B).

6 Applications

Electromagnetic gauges are particularly suited for measuring the flow of untreated domestic effluent, treated effluent being discharged into rivers, potable water in a treatment works and cooling water in power stations. It should be noted that with this method there is no head loss in the channel and hence pumping costs in a treatment or reclamation works can be considerably reduced.

Other applications include the gauging of natural channels and small streams up to a width of approximately 30 m. Within the size limitations, the method is suitable for measuring flow in any type of river and overcomes many of the problems associated with traditional methods. A version of the electromagnetic gauge is suitable for measuring flow in part-filled pipes or culverts carrying storm water, raw effluent or foul sewage.

The attributes of the method include the following:

a) it is unaffected by weed growth;

b) it is unaffected by entrained air;

c) it is unaffected by temperature stratification;

d) it is unaffected by suspended sediment or floating debris;

e) it is tolerant of deposited sediment or other accretion on the membrane;

f) it is unaffected by variable backwater from a confluence;

g) it is tolerant of upstream inflows which can cause unusual flow profiles [if the conductivity of the inflow is significantly different from that of the water in the main channel, there shall be sufficient distance for adequate mixing (see 5.7)];

h) it can detect a minimum velocity of approximately 2 mm/s;

i) it is very tolerant of unusual velocity profiles, including skew flow and severe eddy currents, in the measurement area;

j) it is suitable for very shallow water;

k) it inherently integrates the velocity profile over the whole channel cross-section;

l) it can measure a wide range of stage and discharge;

m) it gives a high accuracy of measurement;

n) it does not produce a constriction to the flow;

o) it measures reverse flow.

As stated previously, the major disadvantage is that the method is limited to fairly small rivers and artificial channels because of the cost associated with the need to install a large coil across the full channel width and a membrane to insulate the flowing water from the bed of the channel.

7 Design and construction

An electromagnetic gauging station should consist of the following elements (see figures 1 and 2):

a) a field coil installed below or above the channel;

b) a pair of electrodes, one on each side of the channel;

c) an insulating membrane, where necessary;

d) an instrumentation unit, including a coil power supply unit;

e) a water level measuring device;

f) a reference gauge and station bench mark.

7.1 The coil

The coil should be wound with a known number of turns of wire which will depend on the accuracy required, the river width, the minimum water velocity and the coil power supply. Normally a coil with between 50 and 300 turns will be required. The design aspects of a typical coil are presented in annex C.

The coil should be installed in ducting (of diameter approximately 250 mm) to afford access for maintenance of the cable. Constructional constraints normally require the coil to be rectangular in plan.

For a coil installed in the bed of a channel, the cable insulation shall be suitable for permanent immersion in water (e.g. polyethylene).

For a bridged coil, a lesser grade of insulation is acceptable [e.g. poly(vinyl chloride) may be used for insulation]. The coil should span the full width of the channel at a height above the maximum stage for which measurements are required. The coil should be designed, therefore, to provide sufficient flux density for the full range of flows to be measured (see annex C).

The coil should normally be wound with a multiway cable to simplify installation. The cable shall not be armoured with steel armouring since this partially contains the field. Non-ferrous armouring is permissible, but the armouring shall be insulated from the water to avoid leakage paths for the induced signal.

7.2 The electrodes

The electrodes should preferably be made from stainless steel strip or tube and should be covered by a mechanical filter to reduce surface movement of the water at the electrodes. This filter reduces varying oxidation potentials. Typically, the width of flat electrodes should be in the range from 50 to 150 mm. The diameter of tubular electrodes should be from 10 to 20 mm.

The electrodes should follow the geometry of the banks from the bed level to the maximum surface level and should be supported on the water side if an insulating membrane is used. They should extend from the bed level to above the highest expected stage.

The potential between the electrodes is likely to reach several hundred volts in the event of a lightning strike in the vicinity of the gauge. To protect the instrumentation from such an event a Zener barrier is essential between the electrodes and the input to the instrumentation. (A Zener barrier is a voltage and current limiting circuit which gives protection against high voltage inputs from lightning strikes.)

The inductive coupling between the signal cable and the coil shall be a minimum. This can be achieved by passing the feed from the electrode on the far bank in a straight line through the coil centre to bisect the plan area of the coil. An alternative arrangement is to take two signal cables from the far bank electrode: one electrode cable passes through the same ducting as the upstream coil cable and the second electrode cable passes through the downstream coil ducting. Ducting for the electrode cables shall be installed across the channel below the insulated membrane (where used) or it shall be bridged across the channel.

In open channels the electrodes should be supported in guides mounted on the walls or banks on either side of the channel. These mountings should extend throughout the full depth of flow.

In closed conduits the electrodes should be installed as part of the preformed pipe section (see 7.3 and figure 3).

In open channels the guides may consist of slotted plastic rods for flat electrodes or perforated plastic tubing for tubular electrodes. The guides should be secured to the channel walls or banks, but the membrane should not be punctured (see figure 1).

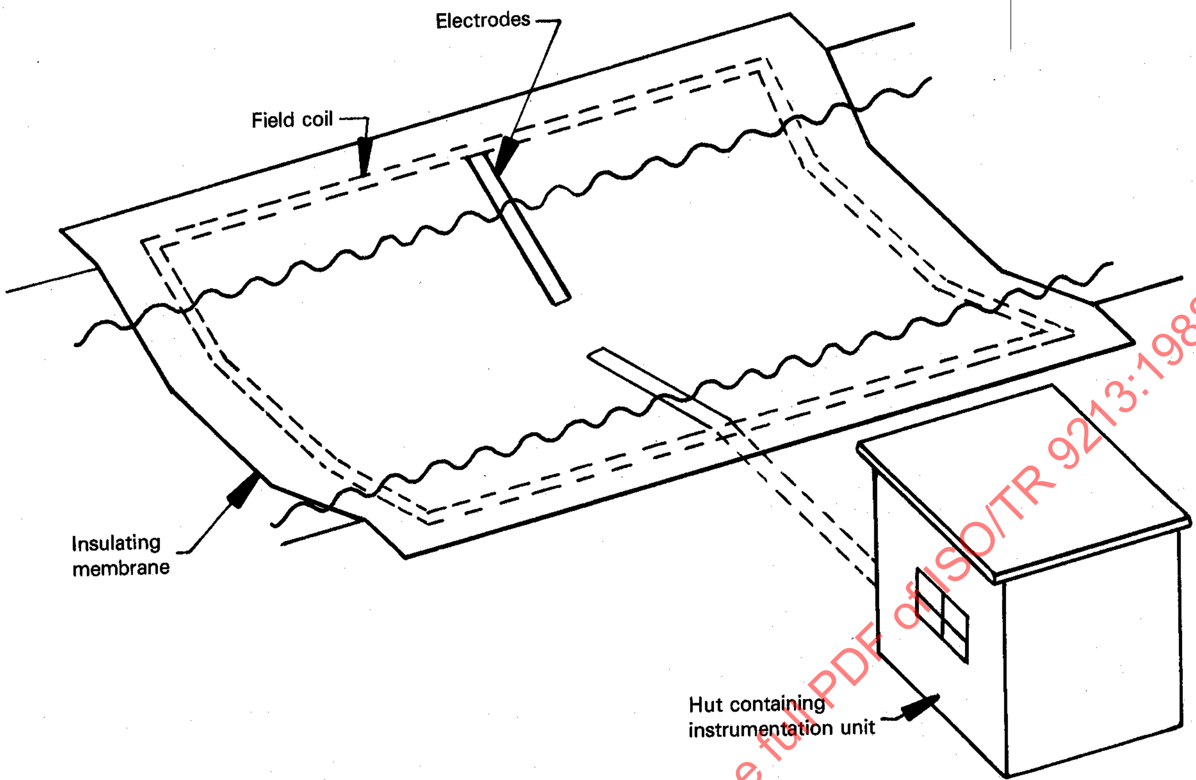

Figure 1 — Buried coil configuration

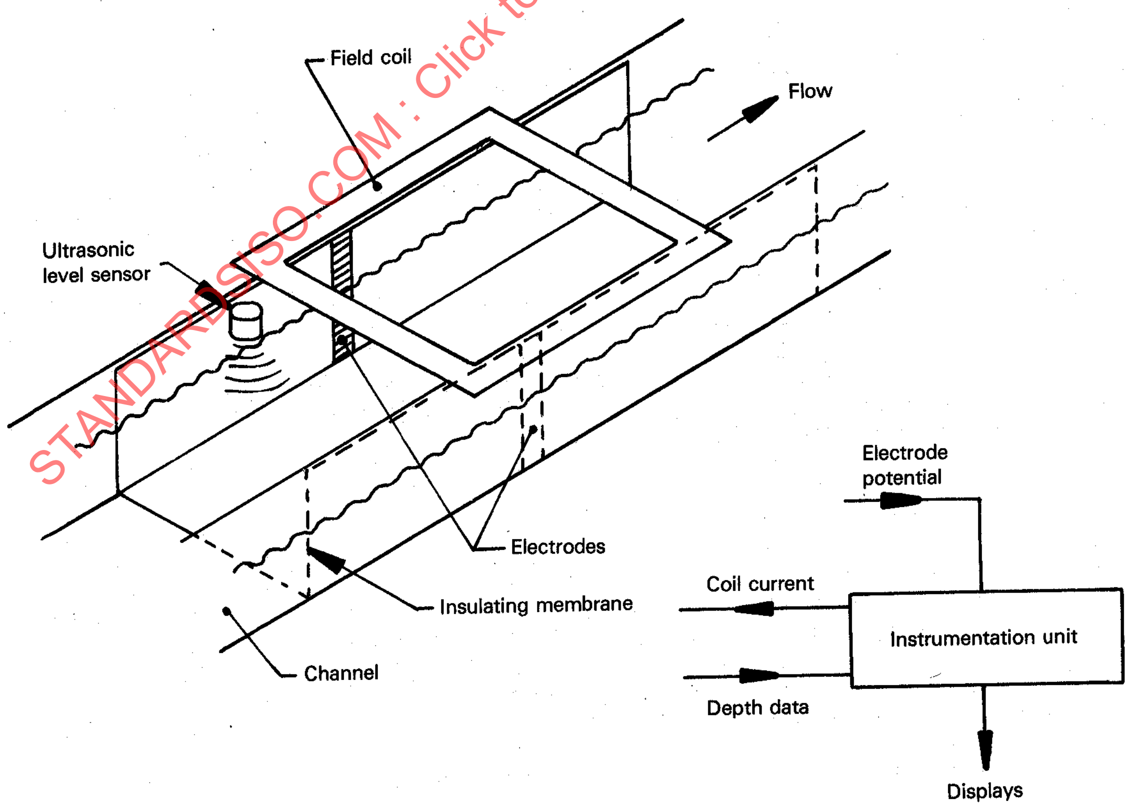

Figure 2 — Bridged coil configuration

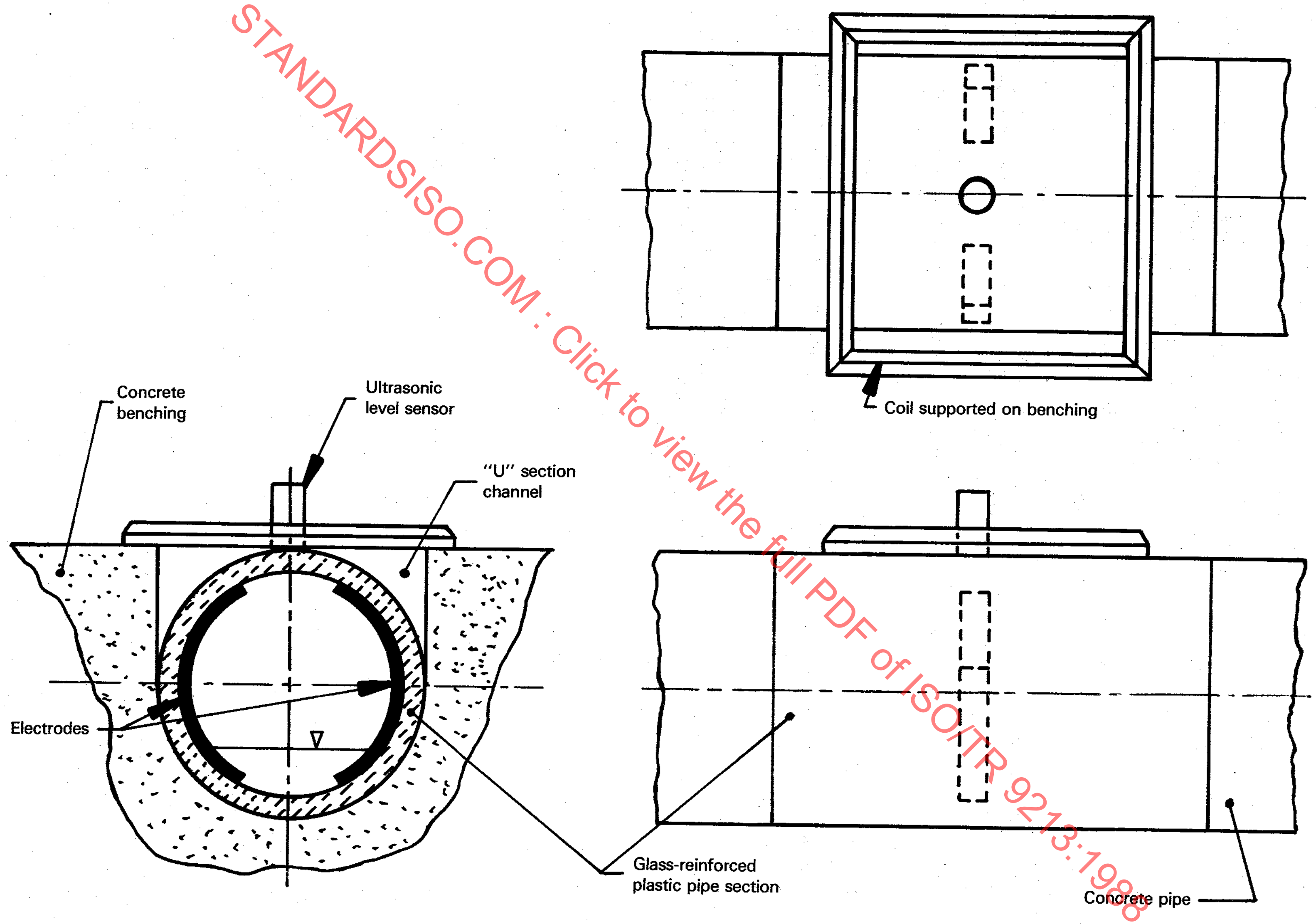

Figure 3 — Coil configuration for partially filled pipes

7.3 The insulating membrane

If the channel is to be lined, the insulating membrane used should be tough enough to withstand the stresses involved. A heavy duty polyethylene, or equivalent material, should be employed and the resistivity of the material should be greater than 10^{12} Ω·m.

The membrane lining should be anchored mechanically and sealed at the leading and side edges to protect against local scour and seepage. The lining should be laid and secured in such a way as to prevent subsequent movement. The bed at the trailing edge should be protected against damage by local scour.

In practice, the membrane may be covered by a variety of materials to protect it against damage. Where the membrane lies on the river bed, a layer of concrete (which should not be reinforced) 10 cm thick is a suitable means of protection. The membrane on the banks of the river may be protected by gabions or, in some instances, a layer of concrete. In a rectangular channel, the membrane may be set behind a vertical wall of concrete or similar material, such as concrete blocks or clay bricks.

The membrane should not be punctured except along the edges for anchoring purposes (see also 7.2). For this reason the take-off point to a stilling well should be beyond the limits of the membrane.

In a concrete channel the upstream leading edge and sides of the membrane should be battened to the concrete or fixed by similar means. In a river, the edges of the membrane may be anchored by concrete bagging to trap the membrane in a trench. The length of membrane should preferably be not less than 1,5 times the water surface width at the maximum stage at which measurements are to be made. The membrane should be centred with respect to the coil centre.

In closed conduits a special preformed pipe section should be inserted in the pipeline, as shown in figure 3. The resistivity of the material should be greater than 10^{12} Ω·m.

7.4 The instrumentation unit

The instrumentation should consist of a power supply to drive the coil, a sensitive detector to measure the electrode voltage and other electronic processing units to compute the discharge from the site parameters and water depth. An *in situ* data-logging system may be included with the instrument to record data on one or more of a variety of recording devices.

A digital output display should give a continuous display of discharge and depth measurements, with built-in indicator alarms to flag up electronic faults. It should also be possible to display other fundamental parameters such as the electrode potential, coil current and power supply voltages of the instrumentation. Where a non-insulated channel is used, the display should also be capable of indicating the water resistivity (conductivity) and the bed resistance (conductance).

7.5 The water level measuring device

A water level measuring device which complies with the specifications of ISO 4373 should be interfaced with the electromagnetic processor.

7.6 The reference gauge and station bench mark

A reference gauge and station bench mark which comply with the specifications of ISO 4373 should be provided.

8 Calibration

8.1 To calibrate the electromagnetic gauge the following variables shall be measured:

a) for an insulated channel
- the electrode voltage E (in microvolts),
- the depth h (in metres),
- the coil current I (in amperes), and
- the discharge Q (in cubic metres per second);

b) for a non-insulated channel
- the electrode voltage E (in microvolts),
- the depth h (in metres),
- the coil current I (in amperes),
- the water resistivity ϱ_w (in ohm metres),
- the bed resistance R_b (in ohms), and
- the discharge Q (in cubic metres per second).

8.2 The general relation between the discharge Q and the other variables listed in 8.1 may be expressed as follows:

a) for an insulated channel,

$$Q = f\left(\frac{E}{I}, h\right) \qquad \ldots (2)$$

b) for a non-insulated channel,

$$Q = f\left(\frac{E}{I}, h, \frac{\varrho_w}{R_b}\right) \qquad \ldots (3)$$

NOTE — In some sites where it is acceptable to use a non-insulated channel it may be unnecessary to measure the water resistivity and the bed resistance on a continuous basis. For example, in some rivers the resistivity of the water is fairly constant on a seasonal basis (and hence does not need to be measured) and under these conditions the bed resistance is also likely to be constant. There may be other sites where measurement of the water resistivity or the bed resistance is difficult, and a nominal value for these parameters may be built into the rating equation for the site. Although this may cause errors in the measurement of discharge, these errors may be acceptable.

8.3 The site calibration of the electromagnetic station requires the establishment of the relations given in equations (2) and (3) by some other means. The procedure is similar to that outlined in ISO 1100-2 for a velocity-area station.

8.4 When the rating equation has been established it may be programmed into the instrumentation so that the output may be displayed on the console and recorded.

8.5 Experience with the electromagnetic method has shown that the calibration remains stable over long periods of time (e.g. more than 4 years). It is possible, however, that flaws in the membrane or the coil insulation may occur. The instrumentation should also be stable. Therefore it is necessary to carry out occasional check calibrations using current-meters or other means.

9 Operation

9.1 The production of a satisfactory record depends on the station being maintained in full operating order at all times. This requires proper maintenance and calibration of the station and its equipment.

9.2 The instructions given in the manufacturer's manual (which should be provided with the gauge) should be followed when carrying out checks on the display unit to ensure that the depth, velocity and discharge, together with engineering parameters, as specified by the manufacturer, are displayed accurately. Any on-site recording should be checked to ensure that the record corresponds to the display on the console.

9.3 Fault warning lights, where provided, should be checked and any sign of malfunction reported.

10 Uncertainties in measurement

10.1 Calibration graph

The analysis of the uncertainties in the calibration graph shall be carried out in accordance with the principles laid down in ISO 7066-1 and ISO 1100-2.

Generally, for an insulated channel the standard error and standard error of the mean relation are of the order of ± 10 % and ± 2 % respectively at the 95 % confidence level. These figures are based on observations made at a large number of sites.

The corresponding uncertainties for a non-insulated channel may be much greater depending on the individual site and the number of observations taken during calibration. The corresponding uncertainties determined from observations made at two sites only are ± 15 % and ± 2 % respectively at the 95 % confidence level.

10.2 Single determination of discharge

The uncertainty in a single determination of discharge may be calculated in accordance with ISO 5168 by combining the component uncertainties in equations (2) and (3) using the root-sum-square method. It is not possible to provide precise values for these component uncertainties and they should be estimated independently for each site. Generally, it may be stated that the uncertainty in a single determination of discharge will be of the same order of magnitude as that in a current-meter measurement.

Annex A

Theory of the electromagnetic gauge

(This annex forms an integral part of the Technical Report.)

A.1 Basic principles

The basic principle on which the electromagnetic gauging station functions is the Faraday Generator Effect, which may be generally stated as follows:

"... when there is a perpendicular component of relative motion between an electrical conductor and a magnetic field, an electrical potential is induced in that conductor. The magnitude of the electrical potential is proportional to the magnetic field intensity, the magnitude of the perpendicular component of relative velocity, and the conductor length".

The way in which this basic principle is applied to the operation of an electromagnetic gauging station is illustrated in figure 1. The water which is moving with an average horizontal velocity, $\bar{v}$, causes an induced electrical potential, V, to appear across the river banks when a vertical magnetic field, B, is present. This magnetic field could be the Earth's vertical component or some other artificially produced magnetic field.

The basic equation is

$$V = B \bar{v} b \qquad \text{... (A.1)}$$

where

V is the probe voltage, in volts, i.e. the electrical potential induced across the banks of the channel;

B is the magnetic field strength (for an infinite and homogeneous field), in tesla;

$\bar{v}$ is the average water velocity, in metres per second;

b is the channel width, in metres.

Equation (A.1) also assumes that the river bed has infinite electrical resistivity, i.e. equation (A.1) is only applicable to the case of an electrically insulated river bed.

A.2 Effect of a spatially limited excitation field

When an electromagnetic gauging station uses an artificially produced magnetic field, i.e. a magnetic field produced by a current-carrying coil, this field must from practical considerations be spatially limited and non-uniform. The theoretical calculation of the induced voltage for a particular coil and channel cross-section is therefore complex.

The basic theory assumes a uniform field strength (measured in tesla). In practice, however, a coil is used with a chosen number of ampere turns which generates a non-uniform field but which has an "average" field strength proportional to the number of ampere turns in the coil divided by the length of one side of a square coil. Owing to the complexity of the theoretical calculation, the following empirical relationship may be adopted:

$$E = 0{,}5\, \bar{v} N$$

where

E is the induced potential;

$\bar{v}$ is the average velocity of the water;

N is the number of ampere turns in the coil.

Empirical measurements are based on a rectangular cross-section with the coil mounted above the channel and the induced voltage equal to 500 µV per metre per second water velocity for a square coil of 1 000 ampere turns and a channel width of 1,5 m. This figure is approximate and is depth dependent. For wider channels the induced voltage will remain at 500 µV per metre per second water velocity per 1 000 ampere turns.

The induced voltage sensitivity given above compares favourably with the figure of approximately 50 µV per metre per second water velocity per metre width of channel which is obtained using the Earth's vertical magnetic field and which is width dependent.

The artificially induced voltage from the coil is not width dependent since the field strength reduces linearly and cancels the increase in voltage with increased channel width.

A.3 Effect of river bed conductivity

Most river beds will have some significant electrical conductivity which will allow electric currents to flow in the bed. These electric currents have the effect of attenuating the signal predicted from equation (A.1) by a theoretically predictable factor called the resistivity attenuation factor, β.

This factor β can be shown to approximate to

$$\beta = \left(1 + \frac{b/\varrho_w}{2h/\varrho_b}\right)^{-1}$$

where

b is the river width;

h is the river depth;

ϱ_b is the river bed resistivity;

ϱ_w is the river water resistivity.

In an operational electromagnetic gauging station the river and river bed resistivities would be continuously monitored and the output signal corrected accordingly.

Annex B

Site survey

(This annex forms an integral part of the Technical Report.)

B.1 Electrical interference

When choosing a potential site for an electromagnetic gauging station it is preferable that there should be no major source of electrical interference. Typical sources include power cables, radio transmitters and electric railways. The minimum distance between the grid cables or electric railways and the gauging station should preferably be at least 100 m. The distance from a radio station will depend on the power of that station but generally the distance should be of the order of at least 2 or 3 km. In cases where doubt exists as to the suitability of a site it is necessary to carry out a survey. This survey should consist of the installation of two electrodes in the proposed positions of the flow gauge electrodes and measurement of the interference picked up by these electrodes using a battery operated oscilloscope isolated from earth. For an acceptable gauge operation the interference, seen as an envelope on the oscilloscope, should be less than 5 mV peak to peak.

Higher levels of interference may be acceptable since the installation of an insulating membrane will reduce the interference by two orders of magnitude. However, in such circumstances the suitability of a site is doubtful and the supplier of the equipment will normally need to be consulted. The time of day and the date on which the interference measurements are made should be noted as the level of interference may vary significantly diurnally or annually for several reasons.

If the source of interference is known to be due to railways, for example, measurements should be made when trains are passing in the vicinity of the proposed site. The operation of level-crossing gates has been noted to cause electrical interference and this effect should also be observed if relevant.

Where the source of interference is likely to be due to a radio station, efforts should be made to establish that the particular radio station is operating at full power at the time of the survey.

Where a radio telemetry outstation link is to be used, it is important to establish the level of interference likely to be caused by the telemetry transmitter.

Another major source of mains interference is likely to be phased multiple earth systems where the neutral of the mains supply is connected to earth at various points. When the power is eventually brought to the instrumentation hut, special arrangements may need to be made with the local electricity supplier.

B.2 Conductivity

Where a large river is to be gauged using the electromagnetic method it may not be practical to install an insulating membrane. For this type of proposed installation the specific conductivity of the water and the bed of the channel should be established, together with the maximum and minimum levels likely to be obtained for the water conductivity. Sites near estuaries should be avoided where saline intrusion from the sea may significantly contaminate the bed of the channel and cause very high conductivity of the bed.

The resistivity attenuation factor should not reduce the signal by more than a factor of 5 otherwise compensation and measurable signal levels are unacceptable.