FLOW MEASUREMENT IN FREE SURFACE FLOW

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Contents

Summary

Flow measurement in free surface flow is essential for determining the hydrographic yield of a catchment area by gauging a stream or river at a selected site, for obtaining flood hydrographs, and for monitoring flow rates in canals, channels or flumes in water supply projects or in the laboratory. This article describes the various direct and indirect methods of flow gauging by means of velocity-integration, and slope area flow measurement. The accuracy and sources of error, in comparison with closed conduit flow metering, are analyzed. Various control and calibration methods are dealt with, and practical guidelines given towards obtaining satisfactory results. (see also chapter *Hydrological Data Acquisition Systems*).

1. Introduction

Free-surface flow measurement is important for hydrological purposes to assess the yield of a water resource, such as a river catchment area, for gauging flood flows, and for monitoring the flow in open channels built for water supply and drainage purposes (see chapter *Water Conveyance Systems and Flood Control Works*).

The present article deals with flow measurement in open-channels with a free water surface, such as canals or natural streams. A separate article deals with the measurement of discharge in closed conduits, such as pipelines that are flowing full (see chapter *Flow Measurement in Closed Conduits*).

There are two important additional variables or parameters entering in the subject of free-surface flow measurement, which makes it a more complicated case to deal with than closed conduit flow metering. These two additional variables are: the flow depth or prism storage effect, which causes the flow cross-sectional area to vary with the flow rate; and the time-variability effect of unconfined flow, which gives rise to a temporary wedge storage in the conveyance channel with a free surface, and hence causes time-lag effects to occur between the measured and the actual discharges.

These characteristics do not compare well with the unchanging cross-sectional area in a closed conduit, and the less variable flow in that case, which has a fixed area and a nearly constant energy gradient. For these reasons, the measurement of discharge in free surface flow is more difficult and less accurate than closed conduit flow metering, and different flow-gauging techniques are employed (see chapter *Flow Measuring Techniques*).

2. Chemical Flow Measuring Techniques

While the chemical flow measuring methods outlined below do not in a sense pertain to flow metering, they can be used effectively for flow measurement purposes, both for closed conduit flow, as well as for free surface flow conditions.

2.1 Salt Velocity Method

In this method, which is similar to the timed float method, but is more accurate, the flow velocity is measured by timing the passage of the concentration peak of a dosed amount of table salt or other electrolyte conducting chemical past two points displaced along the flow path a known distance apart. The distance divided by the time interval of the peak passage thus obtained directly measures the average velocity.

For determining the discharge, i.e., the rate of flow, the stream cross-section also has to be known, This, when multiplied by the measured average velocity, yields the flow rate or discharge. Reliable results may thus be obtained, provided that the salt dosage is introduced instantaneously at some distance ahead of the upstream timing point and has by then become well mixed across the flow cross-section. This method is especially suited to measuring flow rates in large conduits, pipelines or tunnels, as well as in channels, streams and even over floodplains and in long-shore coastal currents.

2.2 Salt Dilution Method

In this method the conduit flow rate is measured by injecting at a constant rate a tracer chemical such as sodium chloride solution or other inexpensive chemical, or a safe radioactive tracer, into the flow field in a conduit of unknown cross-section (pipeline, tunnel, channel or stream). At a downstream point, samples are taken of the fluid flowing in the conduit. The resultant dilution of the chemical multiplied by its injection rate yields the desired flow rate.

The principle of mass conservation has to hold for the results to be valid, that is the chemical or physical tracer must not be absorbed, altered, or combined with the surface of the conduit or with substances in the flow field. Note that the cross-sectional area of the conduit does not have to be known for this method to be effective.

2.3 Gulp Method

This method is not as well-known as the previous two, but is very convenient for the direct determination of the volumetric throughput in a conduit, whether it be enclosed or flowing with a free surface, and the cross sectional area does not have to be known. It may thus be used for variable area sewer flow, river flow, coastal current flow and even groundwater flow. The principle of conservation of mass still has to be valid, as in the previous case, as any amount of absorption, alteration or combination of the tracer material with foreign substances would invalidate the results.

The flow rate is given by the ratio of the mass of tracer material, injected at an upstream point, divided by the integral of the area under the curve of concentration versus time, as measured at the downstream point (taken sufficiently far downstream to ensure complete mixing through the flow field). Since mass divided by concentration equals volume, the answer is directly given as the volumetric flow over the time t (from the beginning to the end of the concentration curve), which when divided by the time t, gives the average discharge for steady state conditions.

2.4 Combined Methods

Combining the salt velocity method with either the salt-dilution or the gulp method, enables indirect determination of the cross-sectional flow area, since area equals discharge divided by velocity. This is useful in undefined channel gauging, such as floodplain streams, or in pipelines that may be heavily corroded or tuberculated. However, as mentioned before, the chemical or tracer must not be absorbed or altered, or combine with materials in suspension or residing at the flow boundaries, for the results to be valid.

3. Flow Meters for Free Surface Flow Conditions

The type of flow meters use in free surface flow differ radically from those used for closed conduit flow metering, described in a previous article (see chapter *Flow Measurement in Closed Conduits*).

In free surface flow the most practical direct flow measurement to be made is the flow velocity past a fixed point. For this purpose a current meter is employed. This consists of a freely rotating element and a vane to line up the axis of rotation parallel to the flow. A revolution counter is incorporated in the meter, and the number of revolutions in a certain time interval is timed with the aid of a stop watch or electronic timing device. By integrating velocity measurements made systematically over the flow cross-sectional area the discharge may then be obtained. This direct method is cumbersome and slow, and generally used mostly for calibrating faster indirect methods.

Indirect methods of measuring discharge in free surface flow are based on either volumetric determinations over set time intervals (e.g., daily reservoir levels and hence volume rates of flow per day) or the measurement of flow depths over calibrated hydrological weirs.

The calibration of free surface flow measuring devices is essential for accurate and reliable results, and is dealt with next.

3.1 Calibration

The direct calibration of a current meter is done initially by the manufacturer by towing it at constant speeds along a towing tank and recording the number of revolutions made over a given distance towed. The following methods are available for calibrating flow meters such as used in free-surface flow measurement.

Velocity integration of the flow profile across the flume may be done *in situ* to calibrate a flow meter. By means of a current meter or similar instrument the velocity is measured for a number of equal-area portions of the flow cross-section and added and multiplied by the elemental area (area-integrated). This indicated discharge is then compared with the actual discharge, which is independently determined by means a volumetric or gravimetric tank, to which the flow is directed over a timed interval, by means of a rapidly operated swing spout. Volumetric measurement control of the meter-indicated flow rate is usually made in a laboratory (by means of a calibrated volumetric tank over a measured time interval); a rapidly operated swing spout is essential. Gravimetric determination of the metered flow delivered over a measured time interval may also be made in the laboratory by means of a weighing tank supported on scales or load cells. In the latter case the temperature is also recorded for making a correction, usually of the order of 0.1%, due to the slight density variation. Such a calibrated meter may then be inserted in line with the meter still to be calibrated in a closed conduit flowing full, or may be towed along with it in a towing tank at constant speed. In-service calibrations are often also needed to make small site-specific corrections to shop or laboratory calibrations, which are usually done under ideal circumstances.

In-service conditions for free surface flow measurement may differ from the ideal,—cleanliness and steadiness of flow may not necessarily be possible, hence *in situ* calibrations are necessary to be made under site conditions at regular intervals, comparing various current meters against each other, etc. This also monitors the physical state of the meter, e.g., coating or fouling of the interior working surfaces of a current meter, which may give false readings.

4. Indicating, Recording, Telemetry and Processing of Flow-Meter Data

The flow meter may give a direct indication of rate of flow, velocity, volume or mass delivered, by analog (dial) or digital (numerical) signal (e.g., for domestic water supply). It can also be coupled with a circular chart or strip recorder giving a recording of flow rate versus time (day, week, year). Such recorders used to be mechanical, but now are electrical or electronic.

Data may be instantaneously transmitted by land-line, optical-fiber, digital or analog radio-link or satellite, to a central data processing point, or it may be stored in a data-logger for subsequent downloading and analysis. Data transmission may be conveyed in analog form (mechanical, electrical or electronic) or in digital form (by data-logger or via transmission line).

Usually, a combination of visual indication, recording and data storage, and retrieval is necessary in water treatment plants. Continuous feedback is often necessary to adjust the chemical feeding rate, or the control valves, and to issue timely warnings (light or sonic signals), or to effect emergency shutdown in case of abnormal functioning, or merely for status information.

For accounting purposes, physical or electronic printouts of meter readings in graphical or tabular form are also necessary. As a general rule, every meter used for flow measuring purposes should have a back-up meter as a control, and all meters should have a valid calibration certificate, that is regularly updated.

5. Free-Surface Flow (Open-Channel Flow) Measurement

For free surface flow measurement at a rating section, such as a hydrological weir, a self-contained stage measuring device, suitably equipped with an automatic recorder and enclosed in a secured cubicle, is used rather than a current meter.

Ideally, a single-position stage measurement should suffice to determine the flow rate in a free-surface flow conveyance under proper conditions. Quite often this is not possible, and two-position measurements (upstream and downstream of the rating section) have to be made. For calibration purposes it is sometimes necessary to make a complete velocity traverse by means of a current meter, and integrate this, to obtain the discharge over a measured cross-section. This is generally necessary for purposes of discharge correlation with stage readings, and for the establishment of a rating curve for the hydrological measuring station.

5.1 Single-Point Measurement

For a single-point stage measurement to be valid for discharge determination in free-surface flow, critical flow must occur immediately downstream of the stage measuring point. Should this not be the case, two-point stage measurements (upstream and downstream) are necessary whereby the velocity head can reliably be determined, and hence the velocity and discharge derived. Single point measuring devices require that the flow pass through the critical condition just after the point of measurement, in other words that the kinetic energy head exceeds half the value of the potential energy head; and that the downstream pressure is atmospheric. Such single point measuring devices are the following:

- For measuring freely-discharging free-surface flow:

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Biographical Sketch

Jan Jordaan is a retired professor of civil engineering and professional engineer in civil engineering hydraulics. He graduated from the University of the Witwatersrand (B.Sc. Eng.) and obtained the degrees M.S. (Wisconsin), Civil Engineer (MIT) and Sc.D. (MIT). He lectured at the Universities of Hawaii, Delaware and Pretoria. His professional career included hydraulic and coastal engineering research with the Council for Scientific and Industrial Research in Pretoria, South Africa, and the US Naval Civil Engineering Laboratory, Port Hueneme CA, USA. He specialized in hydraulic engineering practice for a period of twenty-eight years with the Department of Water Affairs in South Africa and Namibia, and was active as Technical Assessor for the proposed Misicuni Multiple Purpose Hydro-electric and Water Project, Cochabamba, Bolivia, South America.