FLOW MEASUREMENT IN OPEN CHANNELS

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METHODS OF FLOW MEASUREMENT

The subject of water measurement in open channels involves discussion of a large number of structures and devices developed for a variety of flow situations. It includes all techniques of measurement of flows in which a free water surface is involved. These free surface flows include conveyance in lined and unlined canals, natural streams and closed conduits flowing partly full. Even to the earliest times, possibly to 3000 B.C. when dams were constructed on the Nile in Egypt for the purpose of irrigation, some form of water measurement has been practiced. Through the years many types of devices have been used. The progress in the development of methods of open channel flow measurement has not kept pace with such relatively new fields as electrical and nuclear measurement. Flow measurement in open channels is very approximate--devices presently in field use are crude when compared to the field of electrical measurement.

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Many flow measurement devices and techniques are in use throughout the world. All of these can be classified as one of the following types:

1) Structures which control the channel geometry.
2) Instruments which float on, or are immersed in the flow field.
3) Techniques which require measurements of materials which disperse when placed in the flow field.

The most universally used and accepted devices are those associated with controlling channel geometry usually employing the concept of critical depth, with the flow passing through a section of minimum specific energy in a defined cross-section. This method of measurement includes the weirs, both sharp and broad crested, suppressed or fully contracted. Many times the weir is the crest of a dam or spillway; where there is a definite relation between depth and discharge. At other times, it is a specially constructed weir employing a metal blade with sharp edge and carefully prepared approach conditions.

Another method of flow measurement employing the use of open channel constriction is the measuring flume. Like the weir these flumes are in use throughout the world and are commonly called Venturi flumes, standing wave flumes, critical depth flumes, and Parshall measuring flumes. In the United States, Parshall flumes are used in canals almost exclusive of the other types of flumes. Modules and meter gates are also examples of structures for flow measurement which control the channel geometry.

There are many other types of devices which are used for measurement of open channel flows. Perhaps nearly as common in field use as flumes are instruments which float or are immersed in the flow. Many such meters depend on a rotating wheel to indicate the flow--such as the current meter and Dethridge meter. Other methods of flow measurement employ the displacement or drag on a body.

There are methods which employ the use of radioactive materials, dyes or salt solutions to measure the discharge. In these cases, dispersion or dilution and/or movement of the material can be related to discharge (7). Another method uses the Doppler principle with sonic transducers.

There is an increasing need and demand for good measuring devices, both from the standpoint of accuracy and adaptability. Accurate devices are needed to evaluate runoff or water supply from watersheds, distribution of water, and studies concerned with the proper, alternative, and ultimate use of the water supplies. The accuracy of many devices now in use is probably only ± 5 to 10 percent, even under the best conditions. This accuracy certainly needs to be improved. There is a demand for devices to fit a large range of conditions.

In the United States the Parshall measuring flume has long been considered the final answer to most of the measurement problems found in open channels where a structure was involved. This is not true. Actually the Parshall flume is limited by conditions under which it will accurately measure. Many times it is difficult to install a flume of this type, mainly because of the geometric shape of the channel or the alluvial bed of the stream. Recently, it has been found that trapezoidal measuring flumes are at times superior in operation to the Venturi or Parshall type flume. There is a great need for a simple flume which will measure a large range of flows accurately where the approach conditions and velocities do not affect its operation. Flows which are heavily silt laden must also be accurately measured.

Some desirable features of a flume-type measuring device can be listed as follows:

1) There must be no deposition of sediment in the structure which will change the discharge relationship.
2) The discharge measurement should be dependent on measurements at only one section of the channel for the free-flow condition.
3) The device must provide the desired accuracy under all design conditions of flow. This accuracy range should be within $\pm$ 2 percent if possible.
4) The calibration can be safely extrapolated or extended for the nonstandard condition.
5) The device must be relatively inexpensive in order to gain universal usage.

Current meters are used very frequently. The Price meter, while in common use, is the subject of considerable controversy. There is an argument as to the relative merits of meters with vertical axis of rotation versus meters with horizontal axis of rotation. Further, many feel that a vane type propeller is superior to a cup or screw type propeller. Many studies are reported in the literature--but the differences in opinion still persist. Thus, more basic research seems indicated rather than a continuation of early research techniques.

This paper discusses several studies in open channel flow measurement which have been made at Colorado State University and at other locations. Since the hydraulic research program in flow measurement at Colorado State University is primarily concerned with problems in irrigation, the devices discussed herein were generally developed to fulfill a need for measurement of irrigation water. This review is intended to give the status of developments to the present time and to point out the continuing needs in this field.

REVIEW OF PREVIOUS RESEARCH

Parshall Measuring Flumes

Starting about 1915, experiments on a device called the Venturi flume were made by V. M. Cone (1) at the hydraulics laboratory of Colorado State University. Experiments on the same device starting about 1920, were made by R. L. Parshall and Carl Rohwer (8). The device which is now known as the Parshall Measuring Flume (9), resulted from studies by Parshall over a period of approximately 30 years. Some changes were made by Parshall on the old Venturi type flume originally studied by Cone. These consisted of a depressed section in the throat or contracted portion of the flume and changes in the angles of contraction and expansion. The Parshall Flume is a measuring device which relys on experimentation to determine correction coefficients so that the Bernoulli equation can be applied as the basis for calibration curves. Since the flume is basically an empirical device, it was considered necessary to calibrate each particular size. There is a definite ratio of basic dimensions for flumes in the range of 1 to 8 feet. The design of the smaller flumes do not follow such a relationship. Those larger than 8 feet also follow a somewhat different relationship.

Many Parshall flumes are in operation at the present time with throat widths up to 50 feet and capacities in excess of 3000 cfs (10). Most of these flumes have been very satisfactory in operation and are giving a reasonably accurate measure of discharge. Successful operation of the flume usually depends upon the correct setting of the crest above channel grade and upon precise construction to correct dimensions.

One distinct advantage of flumes such as the Parshall as compared to weirs is their ability to operate with a small loss in head. This generally means that there is only a small drop in the water surface through the flume and the flume is operating under submergence. Under such conditions the flow through the flume is not passing through critical depth. In this case it is necessary to measure the depth at two prescribed points and from these depths determine the correct flow. Charts have been developed and are available (9) (10) for obtaining the flow under submerged conditions.

Recently, there arose a need for flumes to measure very small flows. Several Parshall flumes were designed and calibrated in sizes down to a throat width of one inch (11). Here again relationships were determined for the flow under submerged conditions. One feature of this study was the removal of the downstream, diverging section of the flumes. It was found that if the flume was not operated under submergence, the diverging section could be removed without changing the relationship of head to discharge.

A recent study by S. Davis (4) has shown that a single semi-theoretical equation can be used to estimate the discharge for all sizes of Parshall flumes. This equation relates the flow to depth at any point along the drawdown curve for a given size of Parshall flume. This equation is a useful and significant development since the calibration curves can be determined for flumes that do not conform to a standard width or upstream distance to the point for measuring depth.

Trapezoidal Flumes

Although a wealth of information exists concerning flumes of rectangular shape, very little has been published until recently on flumes with trapezoidal cross-sections. Possibly the first comprehensive study of the trapezoidal flume in the United States was made by Chamberlain (2)(3). From this study it was found that the trapezoidal flume had characteristics which frequently made it superior to flumes with rectangular sections.

A series of studies have been made for the development of trapezoidal flumes for both irrigation canals and for use in natural streams. Trapezoidal flumes for measurement in canals and flat slope channels were reported by Robinson and Chamberlain (12). This study covered relatively small trapezoidal flumes with variable sidewall angles and lengths. A method was devised for relating the upstream geometry and flow conditions to a discharge coefficient. With this coefficient, the discharge relationship for a particular design could be determined based on the energy and continuity relationships.

A number of advantages were noted in the operation of trapezoidal flumes over rectangular types. These advantages were summarized as follows:

1) Approach conditions seemed to exert a minor effect on the head-discharge relationship. Material deposited in the approach section did not change this relationship to any degree.

2) A large range of flows can be measured with a relatively small change in depth thus minimizing the amount of free-board needed on the canal.

3) The trapezoidal shape fits the common canal section more closely than does the rectangular flume. For the lined section this simplifies the transition design and construction.

4) Trapezoidal flumes operate under higher degrees of submergence than will the rectangular flume without corrections being necessary to the standard rating.

The trapezoidal flume has also been developed for the measurement of streamflow, particularly for the study of small watershed runoff (13). The Rocky Mountain Forest and Range Experiment Station requested the development of measuring structures for evaluating the effect of different treatment practices on the runoff from mountain watersheds. A series of model studies was initiated, the first of which was used to develop the general design of the structure. After several field structures were built and observations made of the operation, other models were used together with the field results to determine a standard rating. The flumes have a flat bottom, five feet wide at the entrance narrowing to one foot in the throat section. The sidewalls have an angle of 30^0 from horizontal and the bottom slope is 5 percent. The general design of flat sidewalls together with a sloping bottom was used because of: (1) steep gradient streams, (2) heavy debris loads including sediment, rocks and logs, and (3) the need to measure a large range of flows.

As the flumes are now designed and equipped, flows ranging from 0.10 to 300 cfs are measured. Intake pipes at the center of the contracted throat section lead to recorder wells. Recorders maintain a continuous record of streamflow even during the winter months when heaters are required in the wells to prevent freezing. After three seasons of operation, the performance of these flumes is reported to be entirely satisfactory.

Artificial Controls

In alluvial channel rivers or streams, the problem exists of locating a gaging station in the proper location so that a stable stage-discharge relationship will be maintained. In most streams there are no ideal locations. This usually means that the stage-discharge relation is continually changing, requiring frequent current meter discharge measurements. Frequent measurements are necessary to define the temporary rating curve. Even at best the stability of the stage-discharge relation under these conditions is questionable and the probable deviation may vary widely.

In order to improve the accuracy of stream gaging on the Rio Grande for the division of water between the United States and Mexico, the United States Section of the International Boundary and Water Commission contracted with Colorado State University to investigate the feasibility of artificial controls. The lower Rio Grande is subject to natural shifting of channel controls due to aggradation and degradation. A stable stage-discharge relationship was desired in the range of 100 to 10,000 cfs with a minimum interference from aggradation and deposition of material near the structure.

A survey team determined that artificial controls were feasible at certain locations on the Rio Grande. A model study was then conducted to determine the general design of a control and to make recommendations regarding the installation (5). From this study a structure having a top width of 10 feet and a sill 1-foot high and 1-foot wide on the downstream side of the crest was recommended. Slopes of 2:1 and 3:1 for the respective upstream and downstream faces were also recommended. With this design, an almost constant coefficient of discharge was maintained for a range of upstream bed elevations caused by channel aggradation.

Impact Type Meters

Observations of velocity of flow by means of the force exerted on a solid object placed in the flow field has been practiced for many years. Many types of devices have been used including disk flow-meters, torsion flow-meters and pendulums of various shapes. A combination torsion, pendulum meter was developed by Karl F. Keeler of the International Boundary and Water Commission (6). This meter is being used to measure the flow in some canals in the lower Rio Grande basin and is a very effective device.

In the late 1940's, R. L. Parshall started experimenting with a device which was called a deflection vane meter. As the name implies, the device was a vane made of metal, suspended by pivots in a channel section of prescribed size. In general, the channel section was made of wood or concrete with dimensions 2-feet wide, 2-feet deep and 5-feet long. Other sizes of measurement sections could be accommodated by changing the shape of the vane. The discharge was determined directly from a calibrated bubble tube mounted in the head of the device. With a constant discharge and within a recommended operating range, the meter would indicate the same discharge for a range of depths and velocities.

The vane meter has been improved and developed over the years until it has recently become available commercially; known as the Pendvane Meter (16). The meter is portable and when in use rests on pivots mounted on brackets in a liner section 6-foot long. The section can be either trapezoidal or rectangular. One meter can serve any number of installations equipped with liners of the same size. There are about thirty sizes available; for discharges up to 30 cfs. Each meter handles a range of flows and automatically compensates for velocity and depth changes due to the shape of the vane. There is a negligible loss in head with the device. Since this loss is small, the device will operate on ditches with very flat gradients and low velocities.

Current Meters

Many thousands of experiments are reported in the literature on current meters dating from about 1790 when Woltman invented a revolving current meter. Since that date many changes or modifications have been made in current meters, but the fundamental concept of relating a speed of rotation of a rotor to a flow velocity has not changed.

A very comprehensive set of experiments were conducted on several meters at Colorado State University by Rohwer (15). Reported are experiments of the behavior of meters near solid boundaries, a free water surface and shallow depths. Also reported is the behavior of misaligned meters and meters being moved in a vertical direction.

More recently, 1957, the U. S. Geological Survey conducted exploratory experiments at Fort Collins to evaluate a group of experimental vane type current meters. Conclusions comparable to those of Rohwer seem to be indicated. Meters of the size of Price meters require the application of correction coefficients if the flows are less than 0.7 feet deep. The cups or vanes of a current meter can be very close to a solid boundary without influencing the rating. However, gross errors in velocity are measured if the meter is closer than about 0.4 feet to the free water surface.

PRESENT STUDIES AND RESULTS

Parshall Flume

Although the development of the Parshall flume was initiated over 40 years ago, studies are continuing to clarify and solve operational problems. Recently questions have been raised from the field regarding the operation of the flume under submerged conditions. Examination has shown that the previously published procedures for determining the discharge under submergence are difficult to apply and are frequently misunderstood. In some cases they are not entirely correct.

Because of the difficulty and misunderstandings, the correct determination of flow under submerged conditions is seldom made. Instead, one depth of flow is taken and the discharge found from the free-flow tables. Discharge determined in this manner is always greater than the actual flow. With this type of measurement technique, the deviation from the correct flow increases as the percent of submergence increases. Actually this situation seems to be a fairly common occurrence in irrigation canals late in the season. This is due to greater depths of flow for the same discharge because of vegetative growth in the canals.

With a recently completed study at Colorado State University, this situation should be alleviated. All of the previously available data on Parshall flumes flowing submerged has been reanalyzed and additional data obtained from both field and laboratory studies. This study, which will soon be published, will present a simplified procedure for determining the correct flow.

During the past year Mr. Sydney Davis conducted a study in the hydraulics laboratory at Colorado State University, which he is continuing at the Davis Campus, University of California. This study of the Parshall flume is concerned with variable angles of convergence as well as non-standard location of the upstream measuring point. Limits will be determined for the variance in the contracted section within which the standard flume rating can be used. With this information it is anticipated that the upstream converging section of the Parshall flume can be changed slightly, if needed, in order to simplify design problems.

Trapezoidal Flumes

Laboratory studies are continuing on the development of trapezoidal measuring flumes. The most recent work has been with flumes for lined canals. Flumes for canals with a 1.25:1 sidewall slope and 2-, 2.5- and 3-feet bottom width have been studied. Presently in progress is the development of a trapezoidal flume for a channel with 1:1 side slopes and a 1-foot bottom width. These flumes are tested for a complete range of flow conditions, including submergence.

The laboratory studies are considered to be models of prototype field structures. The results can be used for field structures of the same size or projected to geometrically similar flumes of different sizes. A publication of these investigations will be prepared and published in the near future.

Impact-Type Meters

An evaluation of the operation and relative accuracy of the Pendvane meter (14) has recently been completed. As mentioned previously, the vane meter is an impact-type measuring device which recently became commercially available. These evaluation tests were performed both in laboratory test facilities and by a field check. Results have shown that an accuracy of ± 5 percent could be expected for the recommended range of operation. The maximum variation was ± 7 percent but these flows were near the limits of the recommended zone. Approach conditions had an effect on the operation of the meter. The length of the specified section in which the meter is suspended is relatively short so that a standard flow condition is not always developed.

NEEDS IN OPEN CHANNEL FLOW MEASUREMENT

There is a continuing need for more accurate measuring devices capable of measuring under broader ranges of conditions in open channel flow systems. Particularly for irrigation water measurement has this field been neglected. In many instances, the division and distribution of water is still made without measurement of the flow rate. In view of the increasing demand on water supplies, there is a corresponding increase in interest in water measurement and efficient use of water. Because of this increased demand, it is necessary that the existing supply be conserved and better utilized. Existing water measuring devices must be improved and new devices developed in order to efficiently use the water resources.

There is need for a better combined turnout-measuring device for irrigation releases. This function is frequently accomplished using two devices, with the flow measurement usually being neglected. There are investigations presently underway on dilution methods of measurement using radioactive substances. Because of real or believed health hazards, there is little possibility that this method will be widely used for public water supplies although the accuracy may be very good. It may be feasible to use colors or dyes in essentially the same way and measure the amount of dilution using colorimeters. Ultrasonic and electromagnetic techniques, now being developed principally for closed conduit flows, need to be adapted for open channels.

There is need for more automation in control and measurement of water; utilizing differential transformers, pressure transducers and servo-mechanisms. Data processing methods using computers should be further developed and incorporated into flow measurement along distribution systems.

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