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Special Methods of Determining Flow in Large Conduits

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SPECIAL METHODS OF DETERMINING FLOW IN LARGE CONDUITS

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Comparatively small quantities of water are most accurately measured by weighing. Other means, such as weirs, flow meters, orifices, and moving screens, to mention only a few, have been developed to meet certain needs and have been investigated quite thoroughly for use in laboratories and for small and medium rates of flow.

The measurement of large flows of water in the field is still in a relatively undeveloped state. By comparison, measurements on a laboratory scale are more highly developed because universities, colleges, and industrial research organizations have amplified this latter phase. These organizations have emphasized the study of those phases of hydraulic measurement that may be worked on indoors, but it has seemed both inconvenient and expensive to conduct field studies. Also, the relatively inexact nature of the nonlaboratory investigation has not appealed to many of our scientists. The temptation to continue laboratory work for the perfection of a piece of equipment or development of a technique has an appeal which has kept men in the laboratories when they might have made greater contributions by moving into the field where they could observe the operational performance of the methods and equipment under conditions of use. The increasing demand for improved accuracy in the field may focus attention on further development of this phase.

I do not wish to imply that analytical and laboratory studies are not important, because in the final analysis, neither method is as expensive as field applications in terms of both money and prestige. Also, many of our field procedures and techniques are based on analytical and laboratory studies. In other instances, our field studies have advanced to a point where it became necessary to investigate fundamental behavior by analytical or laboratory means before further progress could be made.

Any means of measuring discharge in large conduits must, of course, be applicable in the field since we do not find this type of installation in a laboratory. Development of the techniques employed are usually results of extended analytical and laboratory studies.

Let us examine briefly the means that are presently available for determining flows in large conduits. In our present stage of development along this line we do not have a wide choice of methods. We are, however, more fortunate in this field than in some others in that more than one means is initially available for examination. We may consider the use of the Gibson method, the Pitot tube in its various forms, current meters, flow meters, chemical titration, color-velocity, or the salt-velocity methods.

I will not attempt to evaluate the methods of measurement enumerated above. To do so would require a lengthy symposium and considerable discussion would result. Experienced engineers are not in unison in regard to the apparatus or the techniques used in hydraulic measurements. On the contrary, opposing opinions are many times expressed and maintained with a vigor ordinarily associated with political issues. We find that one engineer will put unqualified trust in certain instruments or methods while another of equal repute will refuse to accept results procured in such a manner. These conflicting views are not unreasonable when it is considered that large scale measurements of liquids may be an art as well as a science. If the procedures can be reduced to pure science, the results may be more definitely evaluated without making allowances for the experience and skill of the observers. Also the hydraulic phenomena being measured are not ordinarily uniformly and smoothly flowing streams of liquid, but turbulent processions of eddying liquid elements each following its own devious and incalculable path. Thus the results expressing a rate of flow may be considered a statistical average.

In considering the means of measuring large flows, I will mention the Pitot tube and the color-velocity methods briefly and in the remainder of the paper will discuss more fully the salt-velocity method.

Pitot-tube traverses for obtaining velocity and discharge have been used extensively in smaller conduits, and to a lesser extent in some large conduits. The Bureau of Reclamation has used a reinforced Cole Pitometer very successfully in pipes up to 5 feet in diameter and in velocities of the order of 5 to 20 feet per second. Where low velocities exist, the differential pressures are small and the error in reading greatly influences the results. Flow conditions may vary in the considerable length of time required in making the Pitot-tube traverses.

Most of the large conduits that require testing by the Bureau of Reclamation are used for conveyance of irrigation water. The fact that this water, many times, carries foreign material, such as sand, silt, weeds, and trash, makes the use of the Pitot tube difficult. As an example of this the Cole Pitometer was employed to determine the efficiency of the pumps at Pasco Pumping Plant on the Columbia River. The discharge line is of steel with a 60-inch internal diameter designed to carry the flow from two pumps. With only one pump operating, velocities are in the order of 2 to 4 feet per second. This low velocity gives small differential pressures on the Pitot tube and makes testing difficult. The pump also delivers from the river, in addition to the water, considerable sand having a mean grain size approximately the same as the upstream opening of the Pitometer. The length of time necessary to make the traverse and clean the openings of the tube became so great that the technique was abandoned. The Pitometer in position on the 60-inch discharge line is shown in Figure 1.

The color-velocity and salt-velocity methods of measuring discharge in large conduits are somewhat similar in basic principles. It is my belief that this method is not used as extensively as it might be. The technique consists essentially of introducing color into the water prism at a known point and timing its transit from this point until it appears at some outlet farther down the pipe. The developed length of pipe intervening, in feet, divided by the elapsed time, in seconds, gives the mean velocity of water in feet per second. The procedure in determining the passage of the color cloud is purely visual. In irrigation systems the pipes are usually in the form of inverted siphons leading from an open channel and into another open channel. In these instances it is very easy to use the color method, and quite accurate results may be obtained. Previously, obtaining a good color material, such as fluorescein or some of the red dyes, was a little difficult, but during the war large quantities of fluorescein were produced and packaged for the Navy. This fluorescein was used for sea-marking material by personnel in life rafts and life boats. The surplus packages are now available from Navy depots and can be obtained quite easily particularly by Government agencies.

To obtain highly accurate results the color-velocity method requires experience in viewing the passing cloud. By continued experience one may acquire the art of determining just when the color has passed the observation point, but I know of no way to adequately describe this technique so that others may follow it.

I do believe there are many of our engineers who are not familiar enough with this method to realize the many advantages offered by its use. As an example, on one of the Bureau projects is an inverted steel siphon extending approximately 3,590 feet across a creek valley. The tube has an internal diameter of 104 inches, Figure 2. There are no measuring devices in the canal. The siphon was rated by use of the color-velocity method. A recorder placed at the downstream end gives fairly accurate measurement of the water in the canal. I am sure there are many other similar instances where this method could be used very advantageously.

The salt-velocity method may be considered as a refinement of the color method. Instead of introducing color into the flow, salt is used and the passage of the cloud is determined by electrical instruments rather than visually, thus permitting a closer delineation of the cloud. A definite technique can be set forth prescribing the use of instruments for detecting passage of the salt whereas it is difficult to explain how an individual should use his eyes to detect passage of the color cloud. The human element is thus somewhat minimized and the procedure becomes more nearly a science rather than an art.

In examining the possible methods of determining flow in large conduits, it was felt that the salt-velocity method was more universally applicable to the many types of structures built by the Bureau of Reclamation. Although a certain amount of equipment is necessary to apply this means of measurement, the many advantages offered indicated that it would probably best fit the needs. Therefore this method was selected for use and development and will probably be used until some better method is developed.

The technique employed is to introduce a concentrated salt brine into the flow in a short interval of time at the intake or at some location along the conduit. Pairs of electrodes, each pair being connected through associated circuits to a source of current and an electrical indicator, or recorder, are installed at one or more points of observation downstream from the point of salt injection. An increase in electric current is indicated when the water prism containing the salt passes the electrode. Careful determination of the time required for passage of the brine between the test stations, the volume of the conduit in the same reach, and proper interpretation of the records permit calculation of the rate of flow.

On the observation of the passage of the salt cloud, the primary principle involved is the basic law of the flow of electrical current; that is $I = \frac{E}{R}$ where I is the current flowing, E is the electromotive force, and R is the resistance. If the electromotive force or voltage applied across two electrodes placed in water is held constant the current can be varied only by a change in the resistance. The addition of salt to the water decreases the resistance and the current increases. The passage of the salt in the flow can be detected by the use of electrical current measuring instruments, and if the instruments are sensitive enough the nature of the cloud may also be determined.

To grasp an idea of the formation and travel of the salt cloud, consider for a moment the movement of the particles of water in the conduit before any of the chemical is added. Each particle of water is tossed about by the many small eddy currents which characterize turbulent flow. If we were to take a single particle of water and paint it red to enable us to observe the movement, we would see this particle moving in various directions and at an infinite number of velocities as it progresses downstream. Although we cannot see the small particles of water containing the ions of the salt solution we may trace their course with electrical instruments. The velocity, as we normally think of it, is an average of the infinite number of velocities and the direction may likewise be considered as an average. All of the water particles considered together represent an enormous mixing with each other. This is not to be confused with molecular motion which is so small that it is not considered in this discussion.

The normal salt-velocity procedure involves the use of a saturated solution made by dissolving semicrushed, or rock salt in water. The brine is then introduced into the flow by means of a pressure tank, a quick acting valve, a piping system, and pop valves. In large conduits operating under pressure this equipment becomes very bulky. A mixing tank of considerable proportions is also necessary in which to prepare the brine.

The recommended current supply to the electrodes has in the past been alternating current ranging from approximately 24 to 115 volts. Electric meters or recorders normally used had a range from 0 to 20 amperes and some from 0 to 5 amperes. This voltage and relatively high current has caused difficulties in obtaining satisfactory insulation on the electrodes and the associated circuits. It is also necessary to use a relatively large amount of salt to get suitable records.

The power test code prescribes that:

> "The timing shall be done with a calibrated clock or other timing device that beats seconds. These seconds shall be recorded on the electrical instrument chart simultaneously with the indications of the passage of the brine by the electrodes."

This foregoing procedure was developed over a period of years by analytical, laboratory, and field study. During the same interim, instruments for measuring time and electrical current were improved and other pieces of equipment became readily available. These improvements provided new tools and permitted modification of the technique applied.

In making an analysis of the method, considering the new tools available, and studying the test results obtained it appeared that improvement could be made. For instance, in applying the method to measurement of very high-velocity flow, a timing device registering seconds was found inadequate. A recording oscillograph was utilized to record the passage of the brine cloud and as an accurate means of timing. Twelve and 24 trace oscillographs are now generally available for geophysical exploratory work. These instruments provide accurate time lines at each 1/100 or 1/60 of a second, and the galvanometers give recorded deflections in the order of 1 to 2 inches for each milliampere change in current, depending upon the type of galvanometer being used.

The high sensitivity of the galvanometers permitted use of potentials in the order of 1 to 6 volts and a very small amount of salt. One difficulty was that the normal salt content of the flow caused a high initial deflection of the very sensitive galvanometer. Resistance added to the circuit reduced the initial deflection but had the disadvantage of reducing the sensitivity and hence the height of the curve. To correct this, a Wheatstone bridge was included in the circuit.

The amount of salt in the flow being tested varies from place to place. In general, the quality of water found in the northwest is much better than that in the southwest. This variation in quality of water can be cared for by using a multitap transformer for current supply and variable resistors in the legs of the bridge circuits.

The use of direct current on the electrodes caused a tendency for the electrodes to polarize. It was also found under certain conditions that the use of alternating current, instead of the direct current, gave a higher sensitivity to the passage of the brine cloud.

Figure 3 shows a line diagram of the improved electrical circuits now being used. On the left is shown the multitap transformer for varying the voltage. A voltage divider on the primary may also be used to regulate the output from the secondary in steps of from 1 to 15 volts. Two sets of variable resistors are used in the Wheatstone bridge circuit. One set has values from 0 to 50 ohms and the other from 0 to 200 ohms. Switches permit changing the circuit from one to the other.

A galvanometer is shown as the recording element. Practical limitations do not permit reduction of the paper speed in the oscillograph below about 1-1/2 inches per second so in long test reaches or low velocities the photographic records became excessively long. Under these conditions Esterline-Angus recorders with measuring elements calibrated from zero to 1 milliampere may be substituted. A wide variety of paper speeds are available in this instrument ranging from 3/4 inch per hour to 3 inches per second. These recorders are equipped with chronograph pens for recording time on the edges of the charts. The pens are driven by an external jeweled escapement motor having an accuracy of approximately one part in 2,000. A direct reading meter graduated from 0 to 1 milliampere and a stopwatch may also be substituted to observe passage of the salt cloud and elapsed time where accuracy limitations permit.

Figure 4 shows a sample record obtained from an oscillograph and the associated circuits shown in Figure 3. The upper record was made using alternating current in all the circuits and shows from left to right, the opening of the valve, the passage of the salt cloud at the first set of electrodes and at the second set of electrodes. Separate galvanometers were used to record each event. The lower portion of the figure shows similar results using direct current.

In analyzing the records the time distance between the centroids of the deflection curves is used as elapsed time. Records from the alternating current may be analyzed by using the entire envelope or the upper half whichever appears to be the most convenient.

Figure 5 shows a portion of a record from the oscillograph that was made for the purpose of checking the accuracy of the external second timer used to drive the chronograph pen on the Esterline-Angus recorder. The upper line was obtained by feeding the output signal from a short-wave radio receiver into one galvanometer circuit of the oscillograph. The lower line represents the output from the timing device as recorded by another galvanometer. The radio was tuned to WWV, the National Bureau of Standards short wave station broadcasting time in seconds.

The oscillograph equipment and the improved circuits permit the use of low voltages, low current and a very small amount of salt per shot. The former materially alleviates the insulation problems, both in the electrodes and in the circuits. The latter permits a major reduction of the size of brine pressure tank, the piping system, and the pop valves.

Since salt is a rather cheap commodity, the quantity used does not appear to be relatively important. However, this is not the case. In considering the use of the salt-velocity method, to test the pumps at Grand Coulee Dam, preliminary calculations indicate that 17 pounds of salt are necessary for each shot if commonly used circuits are employed. This amount of salt in solution requires a 6-inch piping system operating at 130 psi pressure for injection in a permissible time period of 1 second. Similar calculations for the Tracy pumps on the Central Valley Project show much larger quantities of salt and, consequently, larger piping systems. This is not so much due to larger discharge lines at Tracy, 15 feet, as compared with 12 feet internal diameter at Grand Coulee, but rather due to the difference in initial resistance of the water at the two locations.

Figure 6 shows the amount of salt necessary per shot to give an acceptable diagram using circuits prescribed by the code.

Improved circuits now being used will permit use of less than one-tenth of the amount of salt shown in the diagram. This reduction in the amount of salt needed greatly simplifies the entire mixing and injection system. Acceptable records can be obtained with as little as 1/20 to 1/25 of the amount of the salt shown. By use of the multitap transformer to vary the voltage on the electrodes and the variable resistors in the bridge circuit, deflections that are easily read can be obtained with the almost minute quantities of brine.

In order to further reduce the amount of equipment and time necessary to prepare the brine, flour salt, the kind used to salt peanuts, is used. This product is readily soluble but costs slightly more than the lower grades of salt. Since the quantity used is so small, the increased cost of a series of tests is negligible.

Another advantage gained by using the very small amounts of salt is that the specific gravity of the cloud is almost 1.0. This is a very favorable improvement, since the method has been criticized because of the fact that a brine cloud having a density appreciably greater than 1.0 would settle to the bottom of the conduit. In this case electrodes traversing the pipe would not give a true indication of the velocities but would indicate a velocity somewhat lower or higher depending on the velocity distribution in the conduit.

The use of the small amount of brine causes the cloud to disperse in a more nearly symmetrical manner as it moves down the conduit, indicating the shorter reaches should be used. With the improved timing devices, this is permissible. The rate of flow is calculated by using the formula: discharge equals volume divided by time. Hence, it may be seen that with a constant volume the discharge is in error the same amount as any error in the time determination.

The same statement may be made in regard to the accuracy of determination of the volume. Tolerances permitted in the fabrication of large conduits make it necessary to secure actual measurements of internal diameter and length of test reaches if accurate results are to be obtained.

There are certain advantages to be gained by using the salt-velocity method: First, dependent upon the accuracy desired, the method is capable of a great range of application from throwing a ball of moist flour salt into the flow and observing its passage with two metal strips, a dry-cell battery, and a milliammeter, to installations requiring a large number of pop valves and an elaborate electrode and circuit assembly; second, a large number of measurements can be made in a very short time once the initial installation has been completed. Third, equipment can be fabricated before the test and very little preparation is required in the field. As soon as the equipment is installed the system can resume operation and tests may be conducted simultaneously. This latter point is very important in any system that can be taken out of service only at a considerable loss in delivery and consequent loss in revenue. Fourth, there is no empirical coefficient or correction used in the calculations. Hence, the results can be quickly evaluated, at least to the point where the tests may be continued with an assurance that the final results will be consistent.

Figures 7 and 8 show a very simple installation of the salt-velocity equipment on a 60-inch steel pump discharge line approximately 1,500 feet in length. The brine injection tank and piping is shown in Figure 7 and the copper strip electrodes fastened to 2- by 4-inch timbers may be seen in Figure 8. A milliammeter was used to detect the passage of the salt cloud. A stop-watch that had been checked against the Bureau of Standards time signal was used for timing. All control for the tests was provided by SCR 536 portable voice radios.

A discussion of the salt-velocity method would not be complete without pointing out some of the possible errors. The consensus of those using the method appears to be that more study is needed to determine the effects of very low velocities on the accuracy. The method is dependent upon turbulence to keep the brine cloud dispersed throughout the cross section of flow. A decrease in the turbulence usually accompanies the low velocities. A laboratory study is now in progress to determine what relationship, if any, exists between accuracy and relative velocity.

From an academic point of view, the exact size and shape of the electrodes is a moot question. Experience in the field indicates that considerable deviation from theoretically perfect electrodes is permissible without materially affecting the accuracy of results.

In closing, let me say that we, as engineers, should not be satisfied with methods of water measurement now in use, but should be ever on the alert for new methods or for improvements in present methods. We should utilize to the fullest all analytical, laboratory and field facilities to develop and perfect our equipment and procedures. Many times some means of effecting a solution may be available. Naturally, with more basic data the accuracy will improve, but in many cases it is better to be within the right order of magnitude now than to be very precise 10 years hence after many structures have been completed.

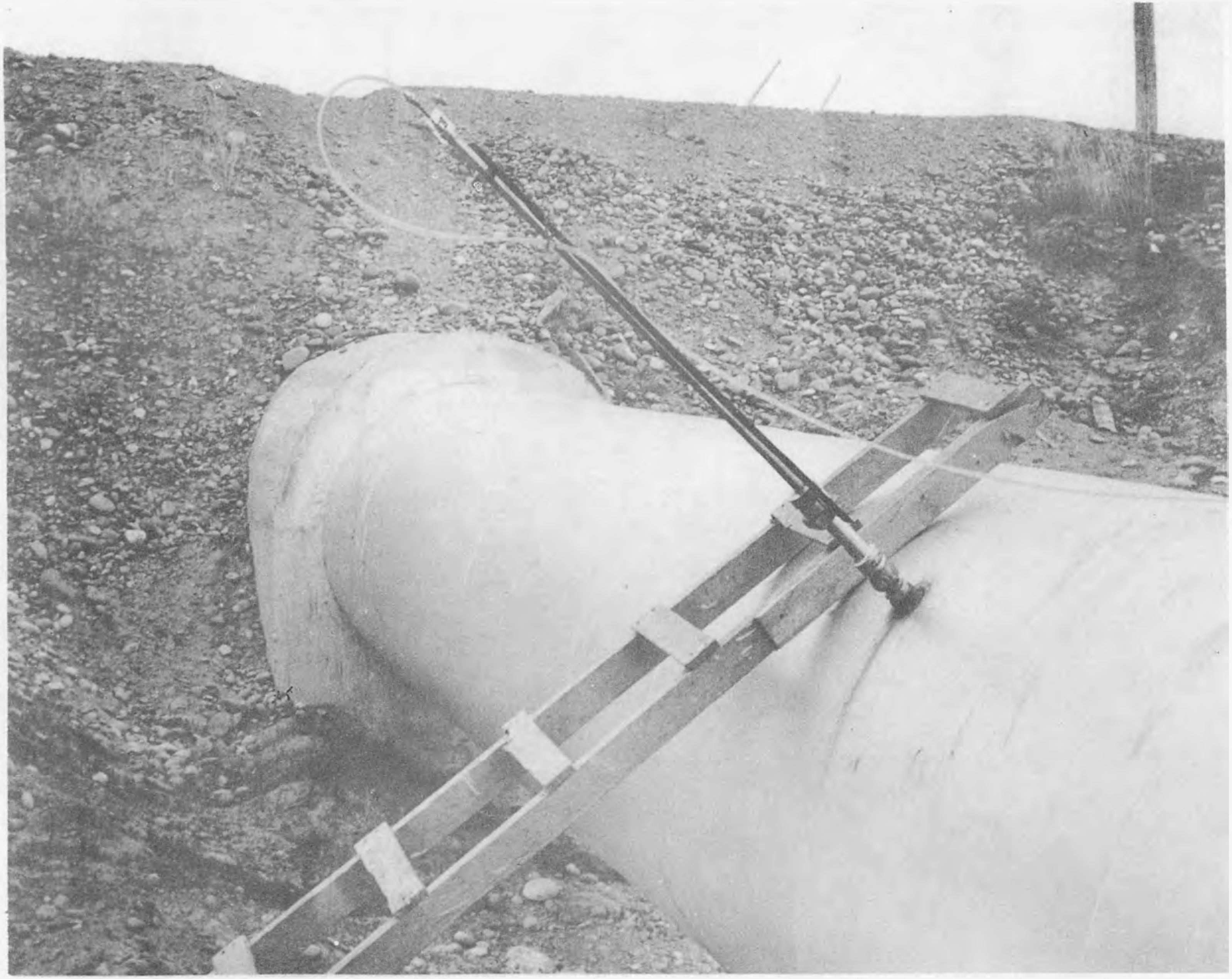
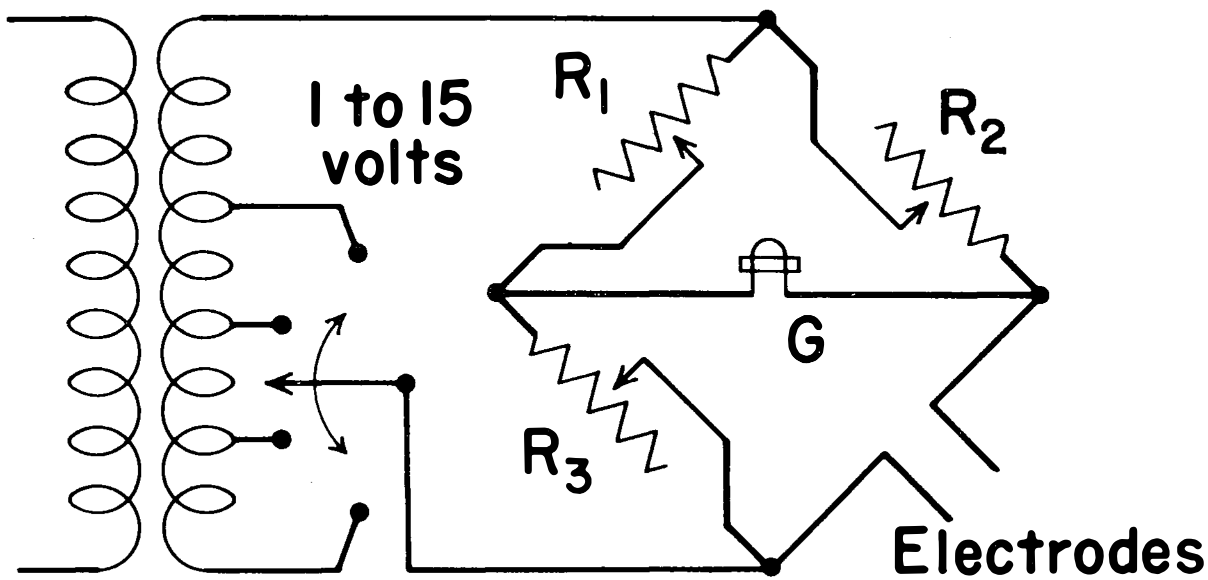


FIGURE 1 Cole Pitometer being used on 60-inch Internal Diameter steel pump discharge line to determine rate of flow.

FIGURE 2 Inverted siphon crossing creek valley. Tube is of steel having a 104-inch Internal Diameter, and approximate length of 3500 feet.



Line diagram of improved electrical circuits used in salt-velocity method of measuring discharge.

FIGURE 3

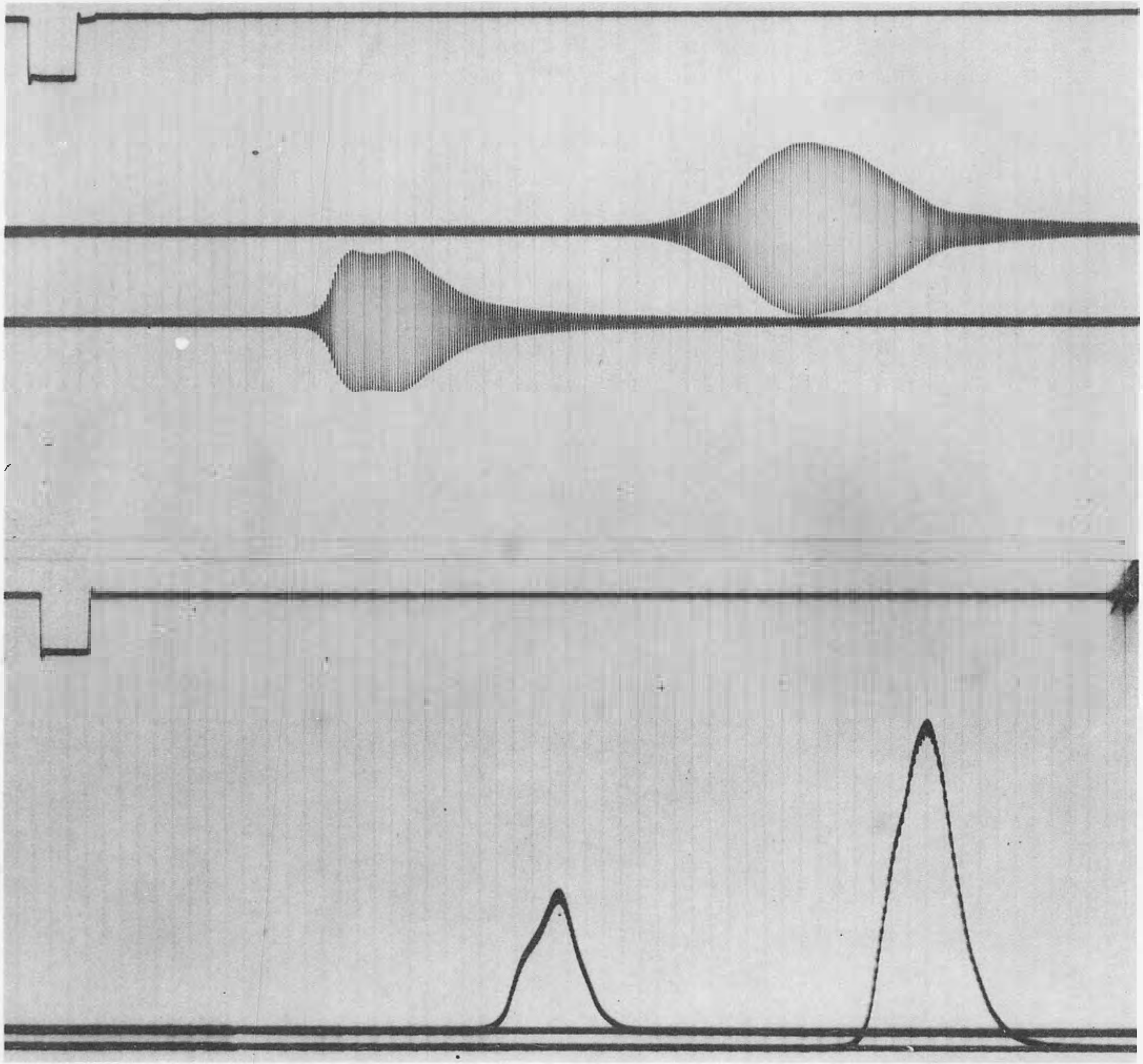
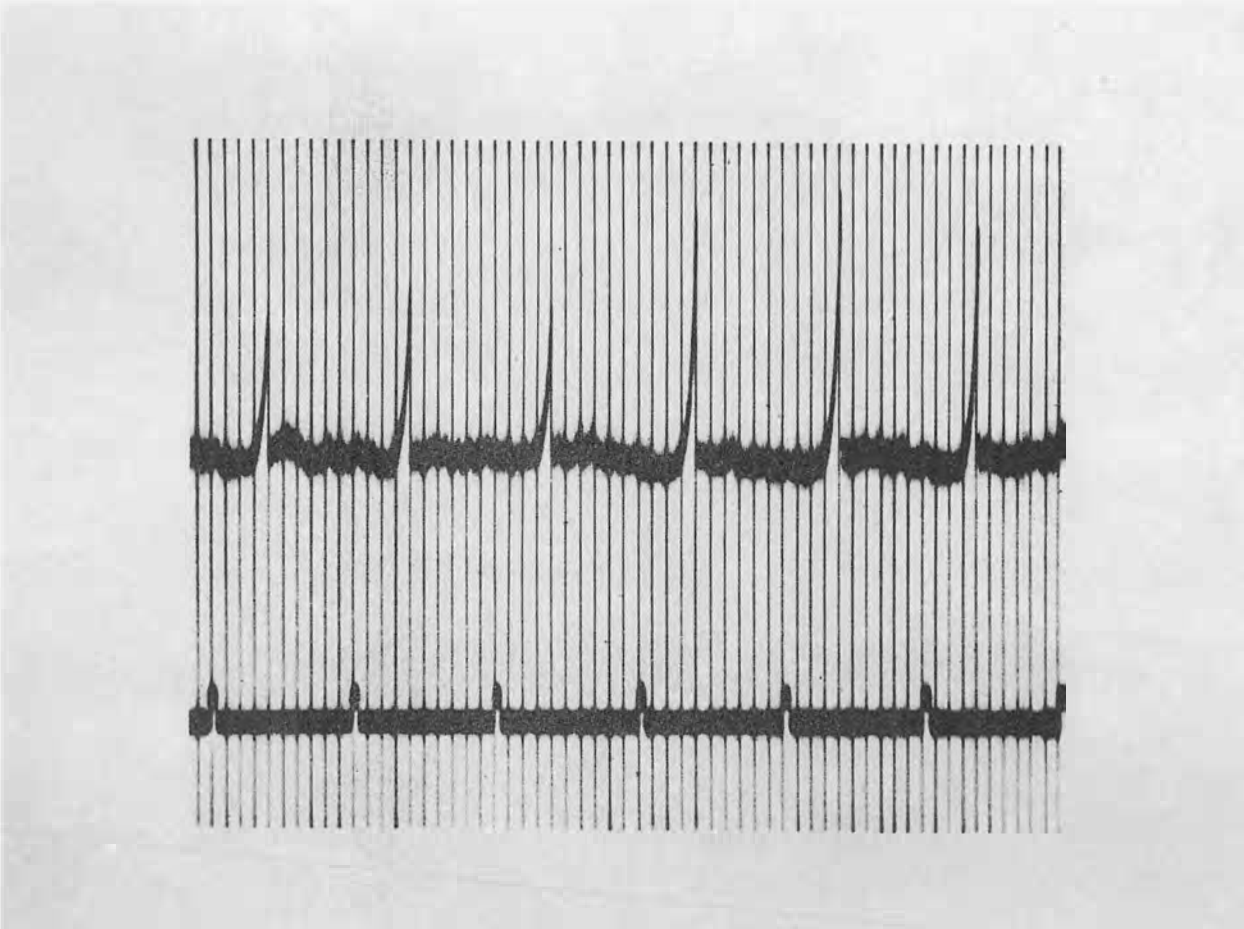
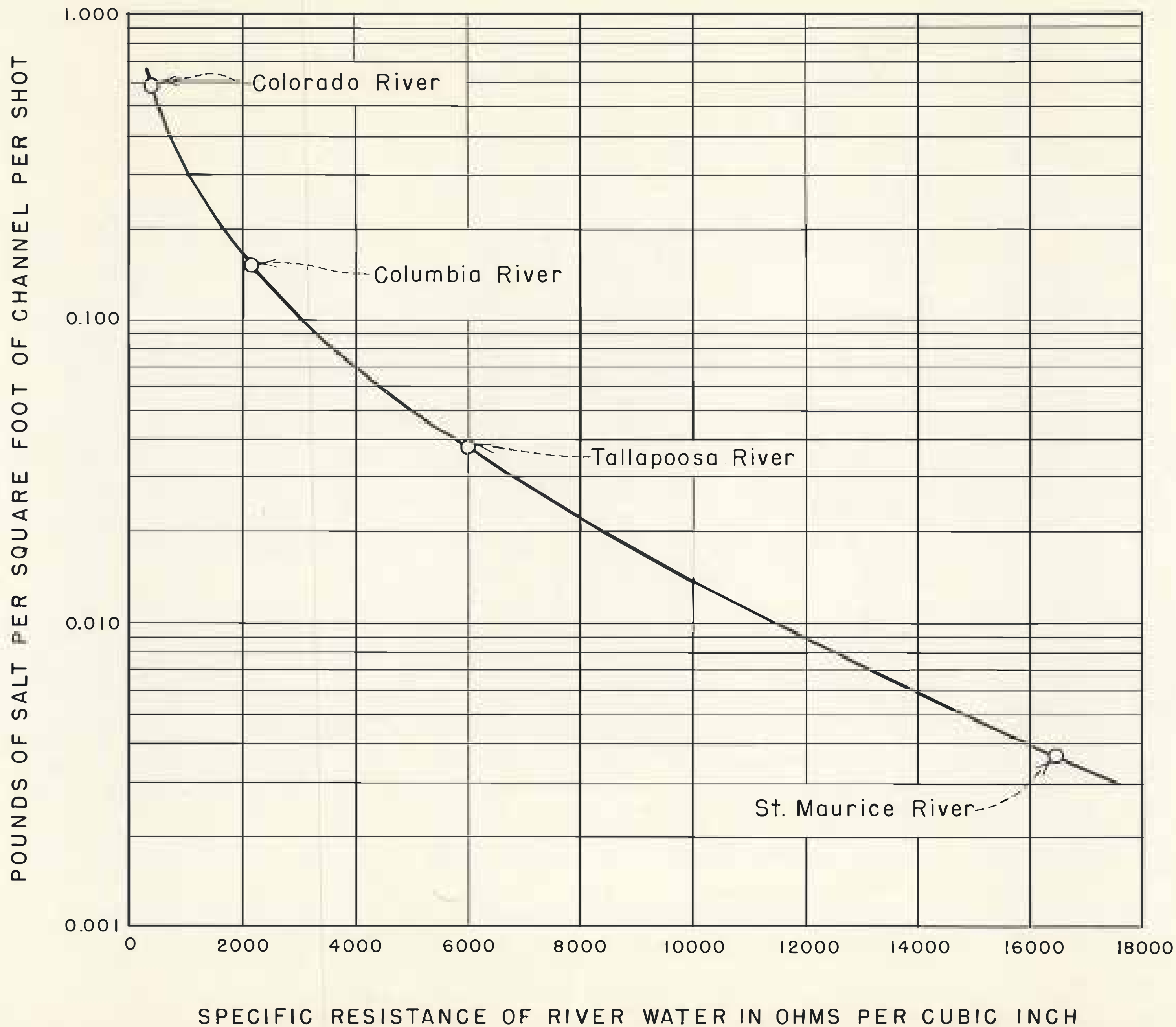


FIGURE 4 Photographic records from recording oscillograph used to register and time passage of salt cloud.

FIGURE 5



Record produced by oscillograph used to check chronograph against Bureau of Standards time signal.



POUNDS OF SALT PER SQUARE FOOT OF CHANNEL PER SHOT
1.000
0.100
0.010
0.001
Colorado River
Columbia River
Tallapoosa River
St. Maurice River
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
SPECIFIC RESISTANCE OF RIVER WATER IN OHMS PER CUBIC INCH

FIGURE 6

FIGURE 7 Brine tank and injection equipment on 60-inch steel pump discharge line approximately 1500 feet long.

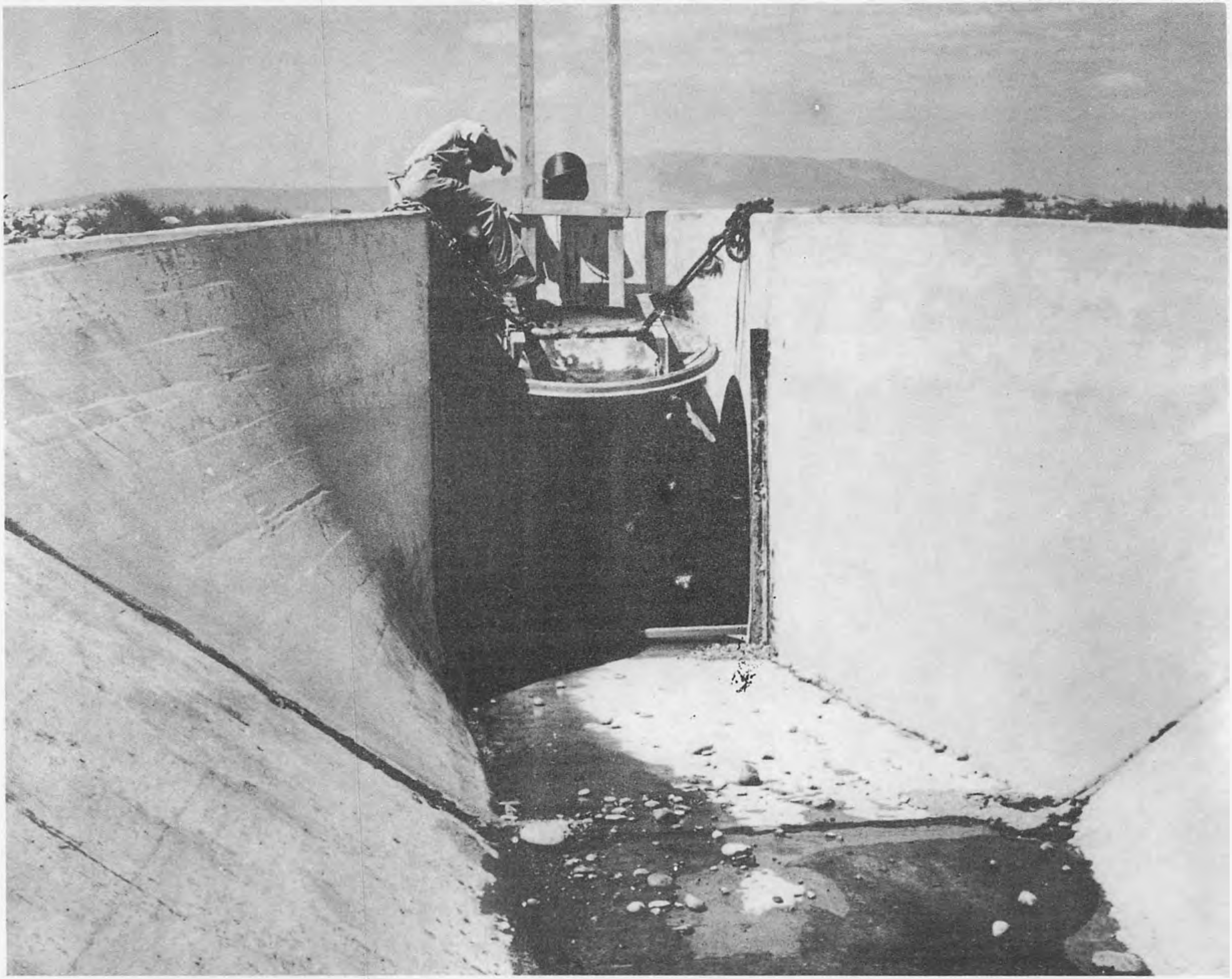


FIGURE 8 Electrodes secured to 2- x 4-inch timber at end of pump discharge line.