Hyd-54.1

PIEZOMETER INVESTIGATION

by

C. M. ALLEN AND L. J. HOOPER

W. E. Wagner

W. E. Wagner

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By CHARLES M. ALLEN[1] and LESLIE J. HOOPER,[2] WORCESTER, MASS.

C. M. Allen

This investigation had for its object the determination of a standard piezometer for commercial use and the study of the hydraulic effect of various conditions of operation upon different forms of piezometers. Piezometers were compared in operation with suitable reference orifices, the differentials being measured with hook gages. A number of factors concerning the performance of piezometer orifices were analyzed. The paper gives results covering a variety of forms and conditions and should assist in establishing a standard form of piezometer.

L. J. Hooper

The object of this investigation was (1) to determine a stable type of piezometer suitable for use as a standard in commercial work, and (2) to determine those factors which have the greatest bearing in obtaining correct results.

The experimental work was conducted at the Alden Hydraulic Laboratory of Worcester Polytechnic Institute. The general layout of the apparatus may be seen in Fig. 1. A 12-in. pipe line was used for this work, as suitable water velocities, ease of regulation, and uniformity of flow and pressure conditions were readily obtained. This line is connected to the main 40-in. penstock above a 36-in. by 16-in. venturi meter and below the Johnson differential surge tank. The 40-in. penstock, which is about 400 ft. long, takes its water from the second or middle pond and supplies a 100-hp. water wheel under 30 ft. head in the main laboratory.

From Fig. 1 it is seen that the 12-in. line branches off from the main penstock and runs horizontally about 33 ft. across the laboratory.

Then it rises 4.2 ft. and again runs horizontally 34 ft. at right angles to its former course to a 12-in. by 6-in. venturi meter. At the end of the venturi meter is a regulating valve, and from there the water discharges either into a waste way or for calibration purposes, into a weighing tank.

At the entrance to the 12-in. line two $^3/_8$-in. mesh screens were placed to prevent leaves and sticks from entering the pipe and causing trouble with the test piezometers. As the direction of the current of water in the main penstock was across these screens, they cleaned themselves every time the 12-in. line was shut down.

For this work smooth water-flow conditions are essential. In Fig. 1 it is seen that there are two right-angle bends in the pipe above the test section. These bends were in planes normal to each other. This condition would tend to give a whirl to the water that might seriously affect the accuracy of the measurements. Therefore a water-flow straightener was placed in the pipe just below the second elbow. This was a sheet-metal vane 3 ft. long that divided the pipe into quadrants. This effectively checked any tendency of the water to whirl. To further quiet the water, stilling screens, which consisted of two $^1/_4$-in. mesh screens close together with the wires at 45 deg. to each other were placed in the pipe at the flange joint upstream from the test section.

The test section was located about 6 ft. upstream from the venturi meter and 0.4 ft. upstream from the end of the 18-ft. section of pipe. In Fig. 1 it is seen that the water straightener was 29.6 ft. and the stilling screens 17.9 ft. upstream from the piezometer section. In order to have the pipe wall and hence the surface flow as smooth as possible, the pipe was scraped for a distance of 7 ft. upstream from the test section and brushed with a stiff wire brush for 3 ft. upstream.

At the test section 12 holes were drilled radially at equal intervals around the pipe and tapped for a $^3/_8$-in. pipe thread. The orifices were made up in brass plugs which were screwed into these holes. After being put in place the inside surface of the plug was filed and scraped flush with the wall of the pipe. (See Fig. 2.)

Since there is no independent method of measuring pressure head in a pipe other than piezometers, it was necessary to choose arbitrarily comparison or reference orifices. Four of these reference orifices were installed on two diameters at right angles to each other. These orifices had $^1/_8$-in. holes, square edges, and surfaces flush with the penstock wall. Other piezometers to be compared were installed in the intermediate holes, as shown in Table 1.

The elevation of the pressure head at the test section was several feet above the roof of the building. The small differences in the readings of the various piezometer orifices made the use of sensitive hook gages imperative. Therefore a differential-pres-

[1] Professor of Hydraulic Engineering, Worcester Polytechnic Institute. Mem. A.S.M.E. Professor Allen was born at Walpole, Mass., on Dec. 12, 1871. He received his B.S. in Mechanical Engineering from Worcester Polytechnic Institute in 1894, his M.S. in 1899, and his D.Eng.Hon. in 1929. He has been on the teaching staff of the institute in part-time capacity since his graduation, for the past 20 years serving as Professor of Hydraulic Engineering. Professor Allen has been engaged for 30 years in consulting and testing-engineering practice in paper-mill and water-power lines, making power and efficiency tests throughout the United States and Canada. He has done considerable research work in connection with the friction of gears, rating of all forms of water-measuring apparatus, and, in recent years, hydraulic model testing. He is a Vice-President of the Society.

[2] With Prof. C. M. Allen, Worcester Polytechnic Institute. Jun. A.S.M.E. Mr. Hooper was born in Essex, Mass., on Feb. 15, 1903. He received his B.S. degree in Mechanical Engineering at Worcester Polytechnic Institute in 1924 and M.E. degree from the same institution in 1929. The first three years after graduation he was engaged in hydraulic test work in Brazil, and for the past four years has been engaged in hydraulic research and commercial work at the Alden Hydraulic Laboratory of the Worcester Polytechnic Institute, and has just been appointed a part-time Instructor at the institute.

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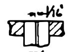
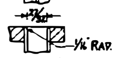
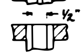
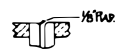
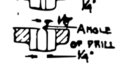
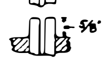
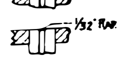
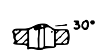
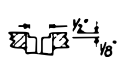
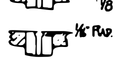
TABLE 1 PIEZOMETERS TESTED

Piez No.		Description
1		Square edged 1/8" orifice used as a reference
2		Square edged 1/8" orifice used as a reference.
3		Square edged 1/8 orifice used as a reference.
4		Square edged 1/8 orifice used as a reference
5		Square edged 1/16" orifice.
5A		Piezometer with 27/32" orifice and 1/16" radius of rounding.
6		Square edged 1/4" orifice
6A		Burr removed by countersinking with large drill point.
7		Square edged 3/8" orifice.
7A		Conical piezometer of 60 degrees.
8		Square edged 1/2" orifice
10		Piezometer with 1/8" orifice and 1/16" radius of rounding.
10A		Conical piezometer of 45°.
10B		Modification of conical piezometer
10C		Piezometer recessed 1/32"
10D		Piezometer recessed 1/16"
11		Piezometer with 1/8" orifice and 1/8" radius of rounding
11A	See Fig 14	Inserted tube piezometer Similar to a pitot tube but lacking the impact orifice. Tube 5" long and 1/2" O.D. Four 1/8" square edged orifices 3" from point.
11B		Burr removed by two light countersinking operations.
11C		Piezometer recessed 1/4"
11D		Piezometer counterbored from inside
12		Piezometer plug projecting 1/8"
12A		Piezometer plug projecting 5/8"
12B		Piezometer with 1/8" orifice and 1/32" radius of rounding
12C		Conical piezometer of 30 degrees
12D		Similar to trailing pitometer orifice
13		Piezometer plug projecting 1/16"
13A	See Fig. 14	Teaball piezometer One inch sphere on end of a 1/8" pipe. No 60 holes drilled all over the ball at regular intervals
13B		Piezometer plug recessed 1/8"
13C		Cup shaped recess in piezometer tube

Note - All piezometers have 1/8" orifice except where noted

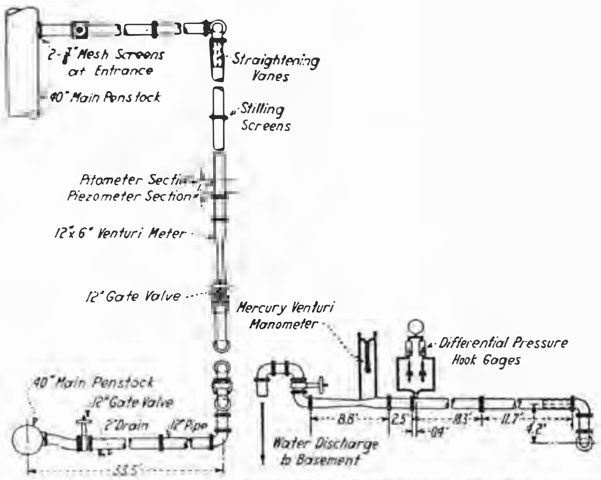


Fig. 1 Layout of Apparatus in Comparison of Piezometer Orifices

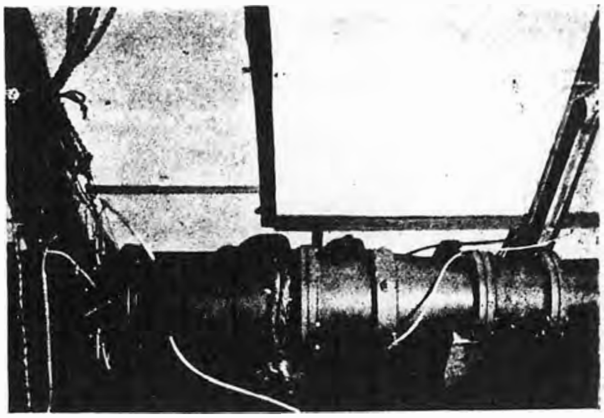


Fig. 2 Piezometer Section and 12-In. by 6-In. Venturi Meter

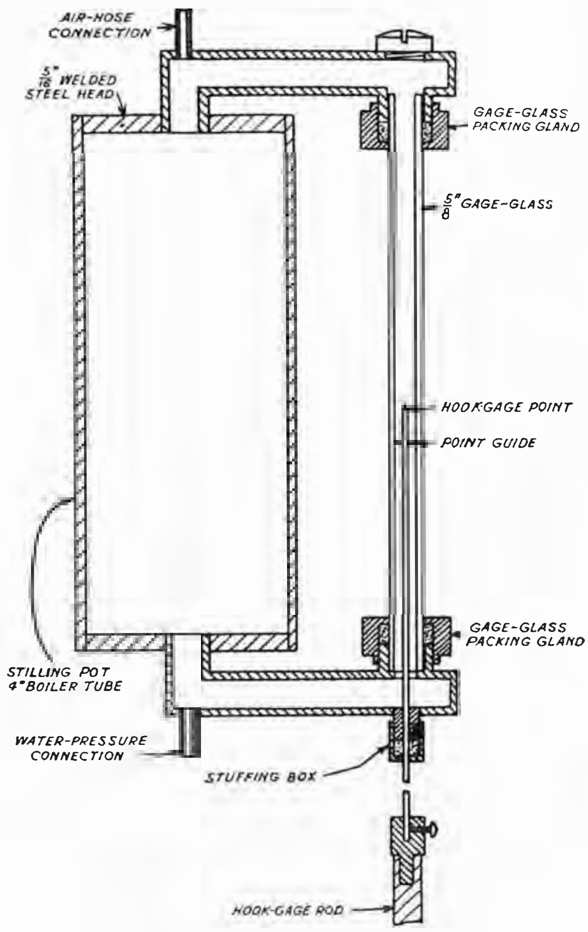


Fig. 3 Differential-Pressure Hook Gage

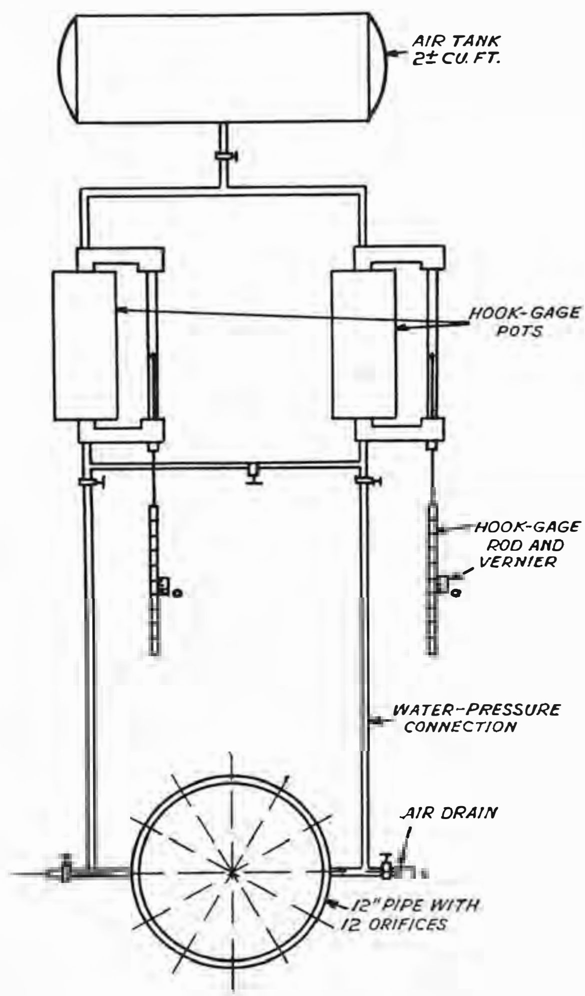


Fig. 4 Connections for the Differential-Pressure Hook Gages

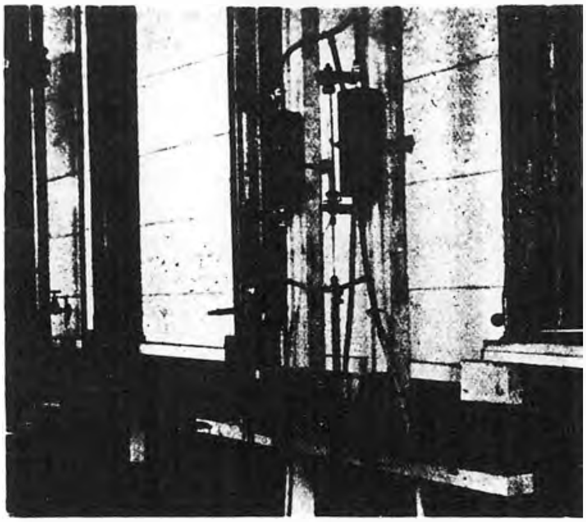


Fig. 5 Differential-Pressure Hook-Gage Manometer

sure manometer with two hook gages was made up for this test work.

A sectional view of one of the head gage pots is shown in Fig. 3. The stilling pot was made up of a piece of 4-in. boiler tube with two heads welded in, $^1/_2$-in. pipe fittings being used to connect regular water-column fittings to the stilling pot. The lower water-glass fitting was equipped with a small stuffing box, through which passed the hook-gage point. About 1 in. down from the point a small guide was soldered so that the point was kept in a central position in the tube.

Fig. 4 is a diagrammatic sketch of connections for these gage pots. Two of these instruments were mounted side by side on a suitable base, as shown in Fig. 5. The air connections at the top were joined, and a common line went into an air tank of about 2 cu. ft. capacity. An ordinary tire pump was used to raise the pressure in the air tank so as to balance the water pressure. The water-pressure connections were first tied by an equalizer, and then passed through valves to the orifice connections on the 12-in. pipe.

In normal operation all the air passages were open, so that equal air pressure existed in both hook-gage pots and the air tank. The water-pressure equalizing tube was closed and the water-pressure tubes were connected to the desired piezometers. Between runs the water-pressure tubes were closed and the water-pressure equalizing connection was open so as to obtain a zero reading. From time to time the zero reading was checked by removing the gage glasses and laying a machinist's spirit level on the hook-gage points.

Before trying out the gages it was feared that there might be some difficulty in seeing the "pimple" on the water surface through the glass. It was found that not only was the point clearly observable in the usual manner, but that there were two other equally accurate ways of taking the reading of the water surface. By observation from below, the image of the point is very plainly seen. As the point approaches the water surface the image and the point approach each other. The point at which they meet can be seen very clearly, and the water level is accurately determined. In the third method a small frosted lamp bulb was held directly behind the water column, throwing the point and the meniscus into strong silhouette. Here again the meeting of the point with the water surface is very clearly seen. Fig. 6 shows the meniscus and the point at time of reading according to the third method. All three of these methods were compared for accuracy and there was no choice among them.

Procedure

In preparation for a run the air was first blown out of the venturi-meter connections and the zero reading was checked on the mercury U-tube of the venturi meter. Then the regulating valve was opened until the desired flow was obtained in the 12-in. pipe. In the meantime the water-equalizing valve on the hook-gage pots had been opened so that a zero reading could be taken. Then the water-pressure hose from each gage was connected to the desired orifices, and care was taken to remove the air all along the water-pressure line. Before opening the line valves wide, the air pressure in the tank was raised until it balanced the water pressure. After the line valves were opened to insure stable hydraulic conditions, 10 to 15 min. elapsed before taking any readings. Then two check readings were taken with about a 2-min. interval between. A reading of the venturi meter was recorded at the same time.

With the readings of an orifice completed, No. 2 hook gage was connected to the next orifice to be read, while No. 1 was left connected to the main reference orifice throughout the tests. As each orifice was connected the air was blown out of the tubing before starting to take a reading.

Following a run, the flange bolts were removed and that section of pipe containing the piezometer section was revolved 180 deg., and another run was made at the same velocity and using the same reference orifice. Since the water-flow straighteners and stilling screens were not moved, it seems safe to assume that the water came down the pipe in much the same way for both runs. By averaging the results of the two similar runs the effect of oblique or turbulent flow on the piezometers was removed.

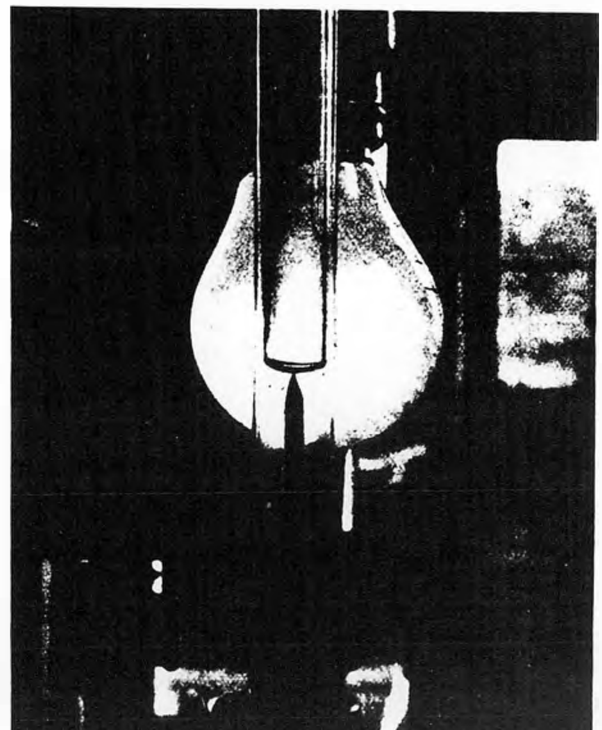


Fig. 6 Reading the Differential-Pressure Hook-Gage Manometer

At the start, the reference orifices did not agree as well as might be expected. During the course of tests the four reference piezometers were improved until at the end of 19 runs they all read practically the same when they were located at the same point with respect to the flow. After six more runs had been made, the procedure in regard to revolving the pipe was abandoned, inasmuch as the same answer was obtained by averaging the reading of the reference piezometers.

Data and Computations

Three sample data sheets, which contain the data for one complete set of runs, are shown in Tables 3, 4, and 5. The computations were made as follows, the first set of readings in Table 3 being used as an example:

Difference in level = reference reading — test reading — zero correction
= 1.480 — 1.379 — 0.108 = —0.007

Mean velocity head = computed from venturi deflection
= $V^2/2g$
= $Q^2/A_1^2 2g$
= (venturi constant)^2 (deflection)/(A_1^2 $2g$)
= $(5.66)^2$ (0.95)/(0.6168) (64.4)
= 0.81 ft. of water.

Deviation = difference in level/velocity head
= —0.007/0.81
= —0.9 per cent of the mean velocity head

Results

Table 2 presents a summary of all the results that were obtained in this piezometer study. The more obvious conclusions indicated by this study are described in detail.

Care in Making Connections. The utmost care is necessary in removing air and leaks from all pressure connections. In startin the tests, the zero correction by water level did not check tha

TABLE 2 RESULTS OF PIEZOMETER STUDY

Run No.	Mean Pipe Velocity ft./sec.	Piezometer Error in Percent of Mean Velocity Head #1	#2	#3	#4	#5	#6	#7	#8	#10	#11	#12	#13	Remarks
4-5	8.5	REF	-0.7	-0.8	-1.8	0.0	0.2	0.2	-0.3	-0.5	3.0	-9.6	-7.5	Pipe scraped 7 ft. and brushed 3 ft. upstream Standards (Nos. 1, 2, 3 and 4) Painted
6-8	7.3	↓	0.6	0.6	1.7	0.2	1.4	1.0	1.2	1.6	3.1	-10.9	-7.9	Sandpapered paint from standards and
7-9	4.0		-0.2	0.0	-2.2	-1.4	0.3	0.2	-1.8	-0.3	1.3	-9.4	-7.5	cleaned edges with a match
10-11	7.0		-0.3	-0.3	-2.1	0.2	0.7	-0.3	-0.1	-0.8	2.7	-10.5	-7.3	Stilling screens installed 18 ft upstream.
12-14	7.2		0.1	0.1	-1.1	-0.3	0.4	0.0	0.9	-0.1	+2.2	-10.0	-6.4	Piez Nos. 2, 3 & 4 squared and polished
13-15	4.0		-0.9	-0.5	-1.0	-0.4	0.2	0.0	-0.3	0.4	2.0	-9.1	-6.9	under microscope Nos 5, 6, 7 & 8 squared No 10 smoothed and rescraped.
16-18	7.3		0.1	0.1	-0.3	-0.2	0.2	-0.2	-0.2	-0.3	2.0	-11.0	-6.9	No. 4 filed down flush and squared
17-19	4.0		0.4	0.1	-0.3		-0.2	0.0	0.0	0.0	1.4	-9.0	-7.9	
22-24	7.2	↓	-0.1	4.0	3.5	3.8	5.6	5.0	5.4	5.3	8.3	-4.0	-0.5	Tubercles placed 1¼" on ℄ in front of all
23-25	4.0	REF	0.6	3.0	4.2	1.8	6.4	5.6	4.9	5.9	8.2	-3.1	-0.2	orifices except No. 1 and No. 2. Tubercles ¼" high and ¼" in diameter.
26	4.0	-0.8	REF	0.8	0.9	-0.4	2.0	1.2	1.2	0.0	2.0	-9.2	-7.2	As above
27	7.2	-0.6	↑	0.2	0.1	2.1	1.7	1.5	1.0	0.2	2.3	-9.8	-7.2	Tubercles ⅝" OD x ⅛" high
28	4.0	-0.2		1.0	0.8	1.0	1.6	1.2	1.2	0.4	2.5	-8.0	-5.8	Second row of tubercles added at 2½" ℄
29	7.2	-0.1		0.4	0.6	0.5	1.7	1.1	1.1	0.5	3.1	-8.5	-5.7	Size ¾" OD x 3/16" high
30	7.2	0.2		-0.4	0.4	1.7	1.6	0.5	0.2	-0.3	2.1	-8.6	-5.8	Two more rows of tubercles added at ℄
31	4.0	0.0		-0.3	0.8	1.6	1.7	0.7	0.1	-0.2	2.2	-8.8	-6.4	distances of 3¾" and 5¼" — Total 4 rows Size 1" x ¼"
32	7.2	0.1		-0.9	0.1	1.5	2.3	0.6	0.2	-0.5	3.1	-8.5	-5.9	Added two more rows at ℄ distances of 5¾" and 7¼". Total of 6 rows
33	4.0	-0.4		-0.8	0.2	0.4	1.9	0.6	-0.4	-0.4	2.6	-8.0	-4.8	Size - 1" x ¼"
34	7.2	-0.6	↓	-1.2	-0.8	1.6	1.4	0.5	-0.8	-1.5	-1.1	-9.8	-7.7	Small tubercles in first row removed from in front of orifice Nos 3, 4, 8, 10, 11, 12 & 13
35	4.0	0.0	REF	-0.8	-0.4	-0.5	2.0	1.0	-0.3	-0.9	0.9	-9.2	-8.8	
36	7.2	2.7	2.9	-0.6	REF	2.4	3.0	2.5	0.5	-0.5	1.7	-9.0	0.1	Six rows of tubercles arranged as above
37	4.0	3.2	2.4	-0.4	REF	1.6	3.0	3.1	0.8	0.0	1.2	-8.8	0.5	but orifice Nos 3, 4, 8, 10, 11 & 12 left free
38	7.2	-0.4	REF	-1.1	-2.3	0.9	0.4	-0.5	-2.4	-2.3	-0.3	-3.5	-0.7	Strips of ¼" mesh screen over all orifices except Nos 1 & 2
39	4.0	0.0	↑	-0.8	-2.4	-1.6	0.6	0.0	-1.6	-2.0	0.4	-3.2	-0.4	
40	7.2	-3.5		0.0	-3.5	-2.6	-0.6	0.7	4.0	1.6	0.0	-11.8	-13.7	Whirling water Vanes 4" x ¾" fastened on
41	4.0	-3.2		0.0	-2.4	-3.7	-0.6	1.2	3.2	2.0	-0.4	-9.6	-15.4	pipe at an angle of about 40° Orifice Nos 1, 2, 5, 6 & 13 left free.
42	7.0	0.0		-1.0	-0.8					-43.7	0.3	-34.4	-86.0	Smooth water. No. 10 - 45° cone No 11 - inserted tube No 12 - ⅝" plug projecting ⅝"
43	7.0	-1.2	↓	0.1	-3.2					-42.9	-0.6			No 13 - teaball
44	7.0	0.4	REF	-0.9	-0.3					-32.8	-1.0	-1.2		No 10B No. 11B No 12B No 13A
45	7.0	-5.0	15.0	13.5	9.8	13.7	14.6	15.6	11.9	-22.9	7.4	6.0	REF	Whirling Water - 4" x 1" plates attached to pipe wall at an angle of 35° to axis End
46	3.95	-4.9	11.1	12.2	17.9	10.3	8.7	11.1	9.6	-14.7	13.9	18.0	↕	of vane 4" upstream from piezometers
47	4.0	18.0	20.8	17.2	16.8	20.8	18.4	18.8	20.8	-44.0	20.0	17.6		Six bladed spinner placed in pipe 17 ft
48	7.0	12.1	17.5	12.3	13.2	15.8	13.5	14.0	16.2	-52.2	13.0	13.6	REF	upstream from piezometers
49	7.05	-30.4	REF	-18.5	-0.6	-2.9	0.5	-4.4	-18.8	-50.0	-1.6	-3.5		Butterfly Valve 0.5 ft. upstream on ℄
50	7.0	6.0	↑	7.9	-0.5	-0.6	0.8	-3.2	0.2	-25.9	-2.1	-2.8		Butterfly valve 1.0 ft. upstream on ℄
51	7.0	1.2		-6.8	-11.4	4.8	2.2	-1.8	-1.4	-49.0	-12.7	-15.8	1.9 @ ℄	Butterfly valve 1.5 ft upstream on ℄.
52	7.0	-1.8		-0.9	-1.0		0.4			3.3				No. 6A. No. 10C No 11 backed out
53	7.0	0.0	↓	-1.9	-1.5	0.4	0.5	-41.0	-1.7	-1.8	-3.3	-34.2	-3.0	No 5A. No 7A. No 10D No. 11C No. 12C No. 13B
54	7.0	0.1	REF	-0.1	-0.7						0.6	-13.6	-2.5	No. 13C No. 12D No. 11D

Note - Ref. is the reference or comparison orifice for the indicated series of tests.

TABLE 3 SAMPLE DATA TEST SHEET NO. 9

(Piezometer Tests, March 6, 1928)

Zero Readings:				
	No. 1	1.583	1.584	1.531
	No. 2	1.475	1.476	1.422
	Diff.	0.108	0.108	0.109

Piezometer No.	Reference reading	Test reading	Venturi deflection	Difference of level	Mean velocity, H	Deviation, per cent	Remarks
4	1.480	1.379	0.95	—0.007	0.81		a
	80	80		—0.008		—0.9	
3	1.478	1.377	0.94	—0.007	0.80		b
	77	77		—0.008		—0.9	
2	1.529	1.423	0.96	—0.003	0.82		
	32	27		—0.004		—0.4	
5	1.524	1.414	0.95	0.001	0.81		
	23	13		0.001		0.1	
6	1.535	1.425	0.96	0.001	0.82		
	33	23		0.001		0.1	
7	1.521	1.419	0.97	—0.007	0.83		
	20	18		—0.007		—0.8	
8	1.514	1.412	0.96	—0.007	0.82		
	11	09		—0.007		—0.8	
10	1.504	1.406	0.96	—0.011	0.82		
	02	05		—0.012		—1.4	
11	1.492	1.375	0.96	0.008	0.82		
	91	73		0.009		1.0	
13	1.456	1.415	0.96	—0.068	0.82		
	54	13		—0.068		—8.1	
12	1.424	1.405	0.96	—0.090	0.82		
	24	05		—0.090		—11.0	
4	1.481	1.373	0.30	—0.001	0.25		c
	66	59		—0.002		—0.6	
3	1.4465	1.340	0.30	—0.0025			
	435	37		—0.0025		—1.0	
2	1.426	1.317	0.30	0.000			
	24	15		0.000		0.0	
5	1.374	1.280	0.30	—0.015			
	74	80		—0.015		—6.0	
7	1.352	1.244	0.30	—0.001			
	51	43		—0.001		—0.4	
6	1.328	1.220	0.30	—0.001			
	26	18		—0.001		—0.4	
8	1.356	1.249	0.292	—0.002			
	54	46		—0.001			
	52	45		—0.002		—0.8	
10	1.450	1.343	0.30	—0.002			
	485	42		—0.0025		—0.9	
11	1.434	1.323	0.30	0.002			
	34	23		0.002		0.8	
13	1.4355	1.347	0.30	—0.021			
	365	48		—0.021		—8.4	
12	1.456	1.370	0.30	—0.023			
	58	72		—0.023		—9.2	

[a] No. 1 up. Run No. 16.
[b] No. 4 leveled and carefully squared. Found surface projected 0.005 in.
[c] No. 1 up. Run No. 17. Conditions as for No. 16.

found by the machinist's level by 0.002 ft. A bubble of air about the size of a pea was worked out of one of the pipes, and thereafter the readings were checked. In another case the readings of one test on piezometer No. 5 with an opening of $^1/_{16}$ in. were lower by 0.005 ft. than those of a previous test under identical conditions. The trouble was found to be a leak in a pressure-tube connection, and the quantity of water escaping was only one drop per second.

Expression of Error. An examination of the results, Table 2, indicates that the error of any piezometer remained constant when expressed as a per cent of the velocity head. Runs were made at two velocities, and for like conditions the percentage errors remained constant within the limits of accuracy of measurement. As might be expected, the error of a piezometer is caused by the local water velocity passing by the orifice, and the error therefore is correctly expressed as a per cent of the local velocity head at the piezometer. A partial traverse made with a teaball piezometer proved this to be a fact. But due to the difficulty

TABLE 4 SAMPLE DATA SHEET NO. 10

(Piezometer Tests, March 6, 1928)

Zero Readings:				
	No. 1	1.469	1.470	1.470
	No. 2	1.361	1.361	1.361
	Diff.	0.108	0.109	0.109

Piezometer No.	Reference reading	Test reading	Venturi deflection	Difference of level	Mean velocity, H	Deviation per cent	Remarks
4	1.543	1.432	0.97	0.002	0.83		a
	42	31		0.002		0.2	
3	1.531	1.413	0.97	0.009			
	28	09		0.010		1.1	
2	1.512	1.398	0.97	0.005			
	10	96		0.005		0.6	
5	1.490	1.384	0.97	—0.003			
	89	83		—0.003		—0.4	
6	1.474	1.361	0.97	0.004			
	70	58		0.003		0.4	
7	1.452	1.3385	0.97	0.0045			
	50	37		0.004		0.5	
8	1.434	1.321	0.97	0.004			
	32	19		0.004		0.5	
10	1.416	1.300	0.97	0.007			
	15	1.299		0.007		0.9	
11	1.406	1.272	0.97	0.025			
	04	70		0.025		3.0	
13	1.373	1.317	0.97	—0.047			
	72	16		—0.047		—5.7	
12	1.341	1.313	0.97	—0.091			
	39	11		—0.091	0.83	—11.0	
2	1.455	1.344	0.30	0.002	0.25		b
	54	43		0.002		0.8	
3	1.455	1.343	0.30	0.003			
	55	43		0.003		1.2	
4	1.430	1.321	0.30	0.000			
	27	18		0.000		0.0	
5	1.451	1.339	0.30	0.003			
	51	40		0.002		1.0	
6	1.468	1.359	0.30	0.000			
	67	58		0.000		0.0	
7	1.468	1.3585	0.30	0.001			
	69	59		0.001		0.4	
8	1.472	1.362	0.30	0.001			
	71	61		0.001		0.4	
10	1.473	1.362	0.30	0.002			
	73	62		0.002		0.8	
11	1.477	1.363	0.30	0.005			
	77	63		0.005		2.0	
13	1.439	1.348	0.30	—0.018			
	38	47		—0.018		—7.3	
12	1.412	1.325	0.30	—0.022			
	12	25		—0.022		—8.7	

[a] No. 3 up. Run No. 18. Conditions as in No. 16.
[b] No. 3 up. Run No. 19. Conditions as in No. 16.

TABLE 5 SAMPLE DATA SHEET NO. 11

(Piezometer Tests, April 7, 1928)

Zero Readings:			
	No. 1	1.584	1.570
	No. 2	1.478	1.464
	Diff.	0.106	0.106

1	1.433	1.327	0.93	0.000	0.79		a
	33	27		0.000		0.0	
3	1.433	1.336	0.93	—0.009	0.79		
	33	36		—.0009		—1.0	
4	1.455	1.355	0.94	—0.006	0.80		
	56	56		—0.006		—0.8	
10	1.337	1.579	0.93	—0.345	0.79		b
	37	79		—0.345		—43.7	
12	1.373	1.546	0.95	—0.279	0.81		
	72	45		—0.279		—34.4	
11	1.545	1.437	0.95	0.002	0.81		c
	45	37		0.002		0.2	
13	1.133	1.696	0.91	—0.671	0.78		d
	33	96		—0.671		—86.0	

[a] No. 1 up. Run No. 42. Conditions as in No. 16.
[b] $^1/_8$-in. hole, but with 45 beveled sides. Plug projecting $^5/_8$ in.
[c] Pitot tube rated at center of pipe.
[d] Tea-ball piezometer at center of pipe.

of determining the actual velocity of the water immediately adjacent to the pipe wall, except where noted the piezometer errors in this report are expressed in terms of the mean velocity head existing at the test section. (See Figs. 7 and 8.)

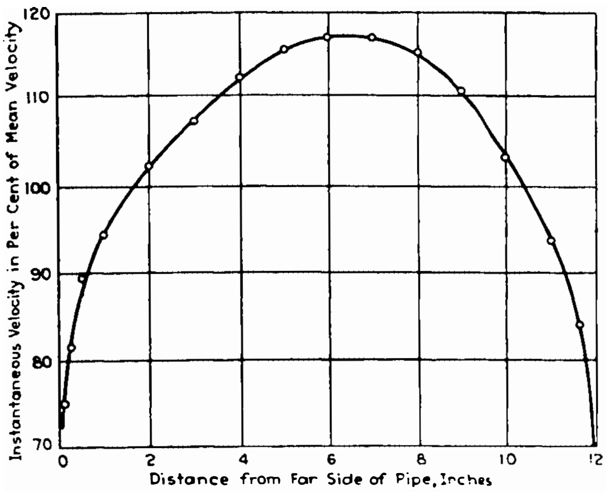


FIG. 7 MEAN OF FOUR PITOMETER TRAVERSES OF THE 12-IN. PIPE LINE
(Pipe factor, —0.85.)

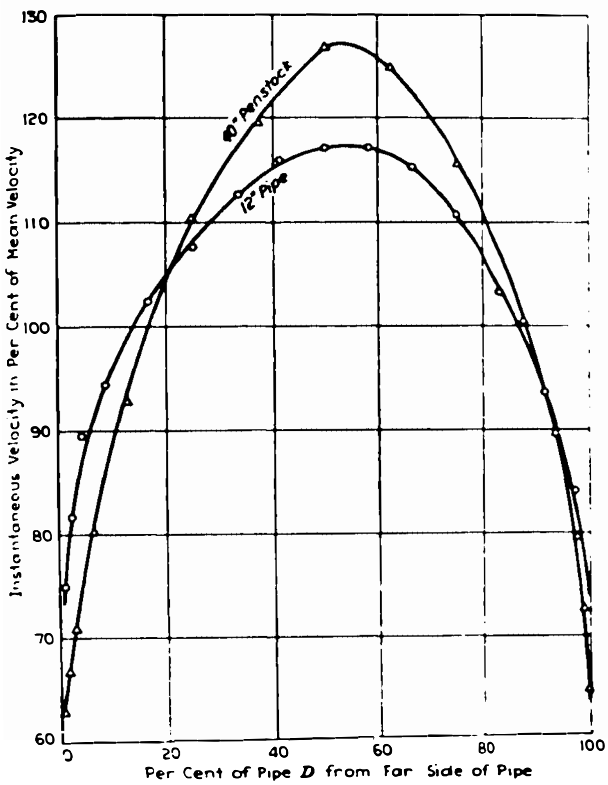


FIG. 8 INSTANTANEOUS VELOCITY CURVES IN STEEL PIPES
Dotted triangles, 40-in. tuberculated steel penstock, pipe factor, —0.79
Dotted circles, 12-in. smooth steel pipe, pipe factor, —0.85.)

Agreement of Reference Piezometers. As first installed, there were variations as high as 4 per cent among the four reference piezometers. In removing these discrepancies a great deal was learned about the action of square-edged orifices.

Burr. From a study of the results of runs Nos. 10 to 19, inclusive, Table 2, it is seen that orifices Nos. 2 and 3 actually changed 0.4 per cent due practically entirely to the removal of the burr, since the surfaces of these piezometers were little changed. This burr was not on the surface of the piezometer plug, i.e., projecting into the flow of the water, but overhung the hole of the orifice about 0.001 in., and was caused by the dragging effect of the file when the orifice plug was being dressed down to the pipe surface.

The presence of this burr was expected, but following the filing process a piece of hardwood that fitted very snugly was forced and twisted into the hole, and it was thought that the burr was removed by this treatment. To the unassisted eye the edge was smooth and square. The true state of the orifice edge was seen

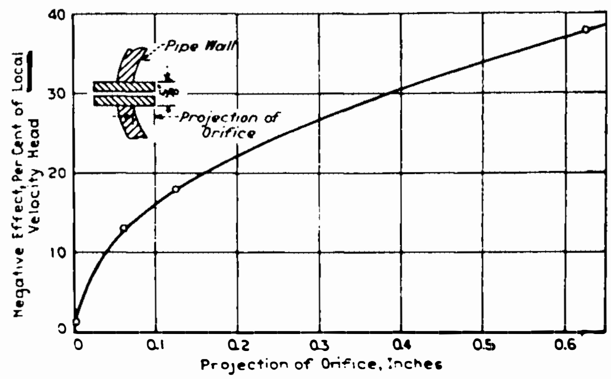


FIG. 9 EFFECT OF PROJECTION OF ORIFICE PLUG UPON PRESSURE READINGS

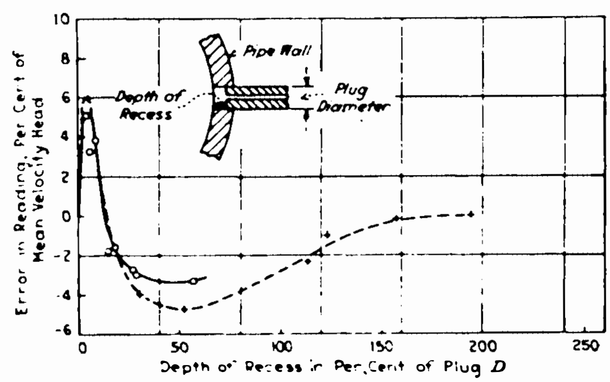


FIG. 10 EFFECT OF RECESSED PIEZOMETER PLUG

only under a microscope and was remedied with a fine rat-tail file.

Surface Finish of Plug. In examining the reference orifices under a binocular microscope it was noted that the surface left on the piezometer plug by a smooth file was relatively rough. Therefore while the burr was removed from all square-edged orifices, the surfaces of piezometers Nos. 1, 2, and 4 were polished with crocus cloth and the surface of No. 3 was left untouched. In subsequent tests it was noted that No. 1 and No. 3 gave the same reading when in the same place. Since one was polished and the other was not, it would indicate that a piezometer plug is not sensitive to minute abrasions on its surface.

Projection of Plug. Probably the greatest source of error was that caused by the orifice plug projecting beyond the surface of the pipe. Orifices Nos. 12 and 13 were purposely projected $^1/_8$ in. and $^1/_{16}$ in., respectively, and the average error was found to be about 10.0 per cent and 7.4 per cent. In the first few runs orifice No. 4 had a 2.2 per cent error. This was later reduced to -1.1 per cent, but the reason for the improvement was not guessed at the time. Finally the true reason for the discrepancy was surmised. It was found that the center of the orifice plug projected 0.005 in. beyond the pipe surface. This surface was leveled as near as possible, and the error was decreased to −0.3 per cent. In Fig. 9 the negative error, expressed as a percentage of the local velocity head, is plotted against the projection in inches of the piezometer plugs. It will be noted that the curve at first rises rapidly from the origin. Then, in Fig. 10, the effect of allowing the piezometer plug to be recessed in the pipe wall is noted. Here again the curve rises very abruptly from the origin. This should emphasize the great importance of getting a piezometer plug or plate absolutely flush with the penstock wall.

Final Agreement of Reference Piezometers. When the known sources of error were removed, the four $^1/_8$-in. square-edged orifices checked each other to well within 1 per cent. Further, the discrepancies remaining are largely due to oblique or turbulent flow of the water since piezometers No. 1 and No. 3 check each other to 0.1 per cent when in the same place, i.e., when the pipe was rolled over, but there is a variation of 0.5 per cent between them on opposite sides of the pipe.

Size of Orifice. From a comparison of performance of piezometers Nos. 1 to 8 and including No. 5A, Table 2, it is seen that within the limits tested the error of a piezometer is not a function of the size of the orifice. All these piezometers mutually check within 0.7 per cent. The variation in size between the piezometer orifices was from $^1/_{16}$ in. to $^{27}/_{32}$ in. It may be noted, however, that a very small orifice, such as No. 5, which had a $^1/_{16}$-in. hole, may be overdamped and sluggish in action, leading to erroneous readings, since the operator assumes that the reading is correct because it is steady. Also the effect of a minute leak in the piping may cause a considerable error in the reading in the smaller piezometers.

Length of Straight Piezometer Tube. Referring to Fig. 10, another factor governing the performance of piezometers is brought out. In addition to illustrating the fact that the piezometer plug must be flush, this curve shows that the piezometer orifice that pierces this plug should be continued for over two diameters into the plug before its shape is changed. This fact is of great importance when piezometers are constructed in thin wall pipe.

Piezometers With Rounded Edges. Orifices No. 10 and No. 11 were made with $^1/_8$-in. holes and a radius of rounding on the edge of $^1/_{16}$ in. for No. 10 and $^1/_8$ in. for No. 11. It is seen that No. 10 checks the standard readings very consistently and accurately throughout. No. 11 has a positive error of 2.1 per cent. Piezometer No. 10 was rescraped because it looked rough under the microscope, yet the performance of the orifice was changed very slightly. The relatively large radius of rounding on the edge of piezometer No. 11 apparently allowed the water to eddy into the opening to give a small positive error. A rounding of $^1/_{16}$ in. and of $^1/_{32}$ in. on a $^1/_8$-in. hole gave the same results as the standard orifices. From these results, for a commercial standard, a piezometer having a $^1/_8$-in. hole and a $^1/_{32}$-in. radius of rounding is recommended for small pipes, while for larger pipes a piezometer having a $^1/_4$-in. hole and a $^1/_{16}$-in. rounding is recommended.

Effect of Pipe-Wall Roughness on Piezometers. In runs Nos. 22 to 39, inclusive the effect of various combinations of wall roughness on the piezometers was studied. In runs Nos. 22 to 25 inclusive a single tubercle made of tar, $1^1/_4$ in. in diameter and $^1/_4$ in. high, was placed $1^1/_4$ in. on center line in front of each of the test orifices. It will be noted that the effect of such a large tubercle immediately upstream from the piezometer was to cause a positive error of about 5 per cent. Various other arrangements of tubercles were tried, as will be noted in Table 2. However, the effect of adding rows of tubercles upstream from the piezometers, as shown in Fig. 11, is to reduce the error gradually until it becomes slightly negative. Leaving 3 in. of clean and smooth pipe wall between the orifice and any roughness or tubercles was sufficient in these tests to insure correct readings. In commercial practice, therefore, it would seem that if a strip of pipe wall about 6 in. wide and 12 in. upstream from the orifice was scraped smooth, correct results would be assured.

In runs Nos. 38 and 39 strips of $^1/_4$-in.-mesh wire screen were laid over all test orifices, as shown in Fig. 12, and the effect for the most part was a very slightly increased negative reading. This checked the action of a large number of tubercles in the pipe immediately upstream from the orifice.

Effect of Whirling Water. In runs Nos. 40 and 41 and Nos. 45 to 48, inclusive, the effect of whirling water upon the piezometers was studied. (See Fig. 13.) The reference orifice in this case was the so-called tea-ball piezometer, which was rated and held at the center of the pipe for these tests. The only conclusion that can be drawn is that under such conditions large positive errors can be obtained. Referring to Fig. 18, the effect of whirling water was tried upon the 12-in. by 6-in. venturi meter. In this case it will be seen that the coefficient of the meter was increased at low discharges and decreased at the high discharges.

Pressure Distribution Below a Butterfly Valve. In runs Nos. 49 to 51, inclusive, the effect upon the piezometers of a butterfly valve above the test section was studied. The valve was 12 in. in diameter and $2^1/_2$ in. thick, and modeled after the butterfly disks which are in common commercial use. The center line of the butterfly valve was located 0.5 ft., 1.0 ft., and 1.5 ft. above the center line of the piezometers. The pressure distribution found at the piezometer section during these tests was very different from that existing with smooth water-flow conditions. The errors are erratic and sometimes relatively large. The data available do not indicate any remedy for this condition except to take a greater distance between the butterfly valve and the piezometer section.

Inserted Tube. The inserted tube, which is shown in Fig. 14, was rated by placing it at the center of the pipe with its axis parallel to that of the pipe. The error was found to be 0.3 per cent, which is an exact check with the reference orifices. The error became −7.0 per cent, however, when the tube was rotated about 10 deg. out of its proper position. It is therefore evident that such a piezometer must be used with the greatest care.

A traverse was made across the pipe with this tube. The deviation was from -1.3 per cent to +1.3 per cent and directly proportional to the true position. This deviation is probably accounted for by the fact that the water flow was not absolutely smooth and axial. Quantitatively, the traverse indicated that the pressure head is constant all across the pipe.

Tea-Ball Piezometer. This type of piezometer, illustrated in Fig. 14, was rated at the center of the pipe and showed a large negative error. While it does not read the true pressure head, it is not sensitive to the direction of the water flow.

Conical Piezometers. As the name implies, this type of piezometer, illustrated in Figs. 15 and 16, consists of a cone which projects into the water flow, with the orifice located at the apex of the cone. Various angles of the side of the cone with the flow of the water from 0 deg. to 90 deg. were tried, both at the wall and mounted on a rod in various parts of the pipe. Very large negative effects can be obtained in this manner up to as much as 15 times the local velocity head acting at the apex of the cone. However, wherever one of these conical piezometers is used, it must be rated, as the amount of the negative effect cannot be

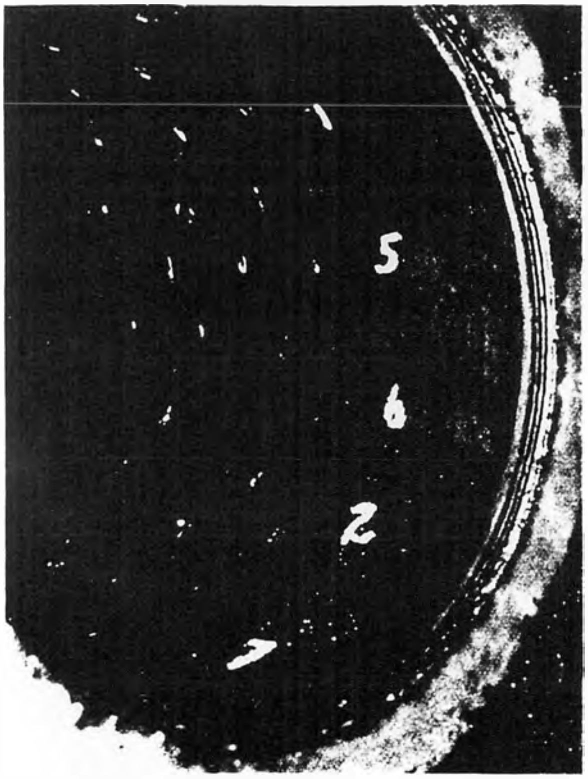


Fig. 11 Tubercles of Tar Attached to Pipe Wall

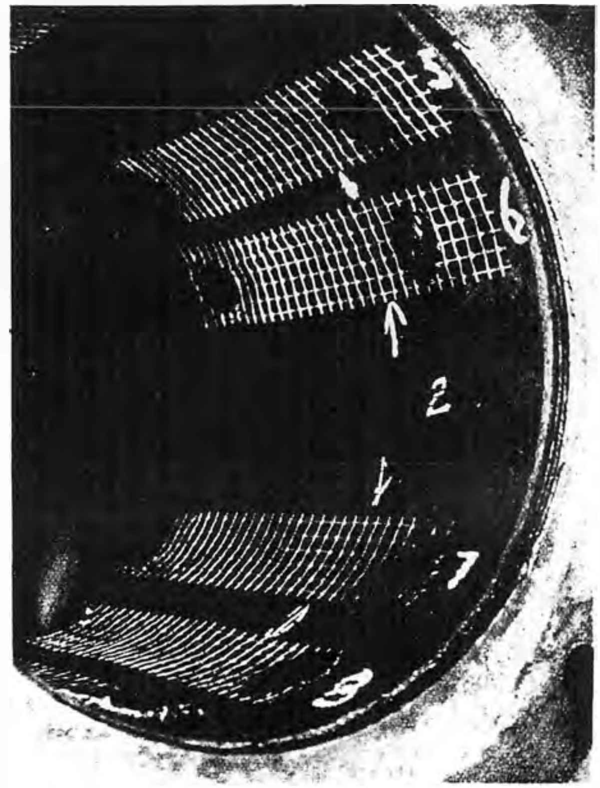


Fig. 12 Wire Screen Laid Over Piezometers to Simulate Pipe Roughness

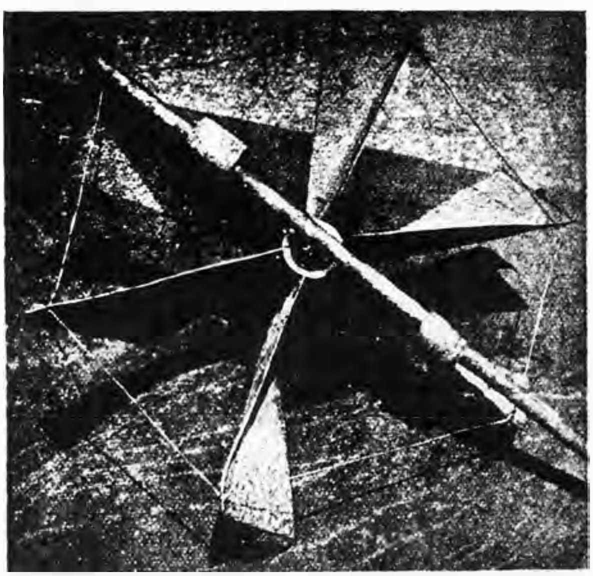


Fig. 13 Spinner Used to Give Whirling Water for Piezometer and Venturi Tests

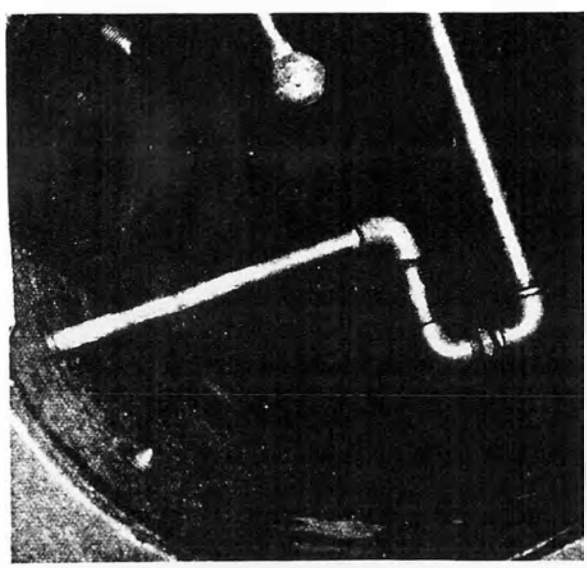


Fig. 14 Inserted-Tube and Tea-Ball Piezometers

predicted. This is due to the fact that the flow past the tip is the resultant of the primary flow in the pipe and a secondary flow along the tip. This secondary flow is caused by the difference in velocities along the pipe traverse. The dynamic pressure of the water striking the side of the tip is directly proportional to the velocity of the water at that point. Inasmuch as the velocity is constantly changing in the traverse there is a difference in pressure from the bottom of the cone and the apex which is dependent upon the position of the cone in the pipe. Where there is a difference in pressure in a free fluid, there must be a flow which is the secondary flow referred to. Therefore it is seen that a conical piezometer will have a varying rating according to position in the pipe and also according to the distribution of velocities in the pipe.

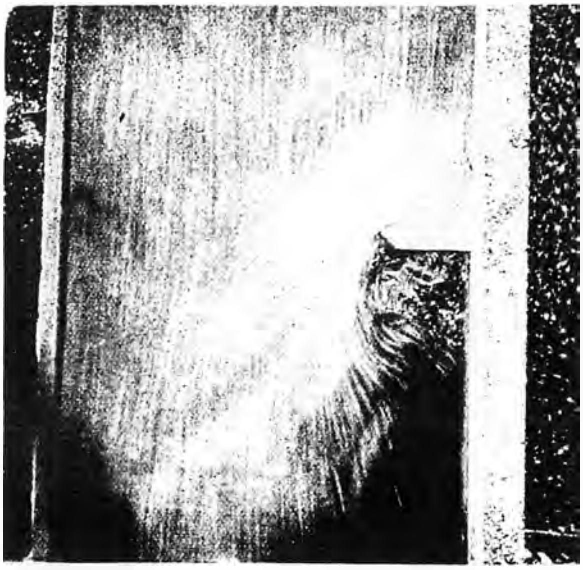


FIG. 15 FLOW PAST A PIEZOMETER MOUNTED ON A ROD

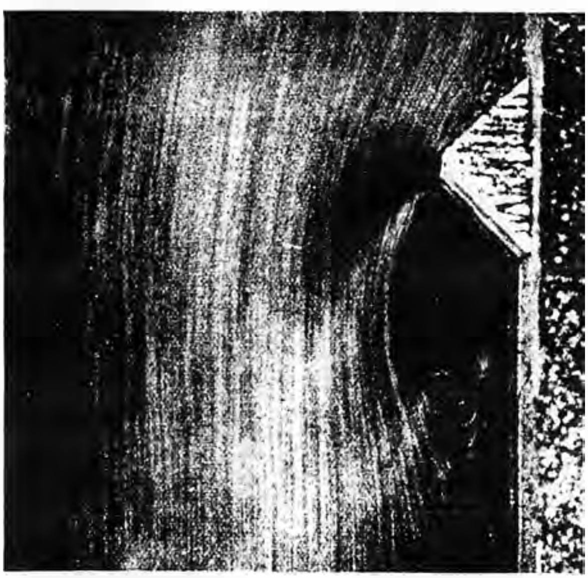


FIG. 16 FLOW PAST A 45-DEG. CONICAL PIEZOMETER ON THE WALL OF THE PIPE

From the foregoing discussion it is seen that conical piezometers can be used to increase greatly the deflection in a water-gaging or venturi section and for other similar uses. However, due to its sensitivity to more than the ordinary number of factors, it should be used with great care and thoroughly rated.

TABLE 6 RECESSED PLUG

(Tests on Sept. 15, 1931)

Depth of recess, per cent of plug D	Deflection, per cent of mean Hv	Remarks
5.0	−6.0	[illegible]
30.0	4.0	
51.5	1.7	
113.0	2.4	
123.0	1.0	
158.0	0.2	
194.0	0.0	
4.4	+5.1	[illegible]
8.8	+3.8	
13.3	−0.1	
17.8	−1.6	
26.7	−2.8	
6.2	+3.3	[illegible]
14.2	−1.8	[illegible]
37.2	−3.3	[illegible]
28.6	−3.0	[illegible]

[a] These tests were made with a [illegible]-in. plug containing a [illegible]-in. standard piezometer. The plug could be moved inside a sleeve screwed into the pipe, which in itself was a standard piezometer. Thus the amount of recess was readily varied.

[b] Piezometer No. 11 in run No. 52 was backed out on its thread.

[c] Piezometer No. 10, run No. 52.

[d] Piezometer No. 10, run No. 53.

[e] Piezometer No. 11, run No. 53.

[f] Piezometer No. 13, run No. 53.

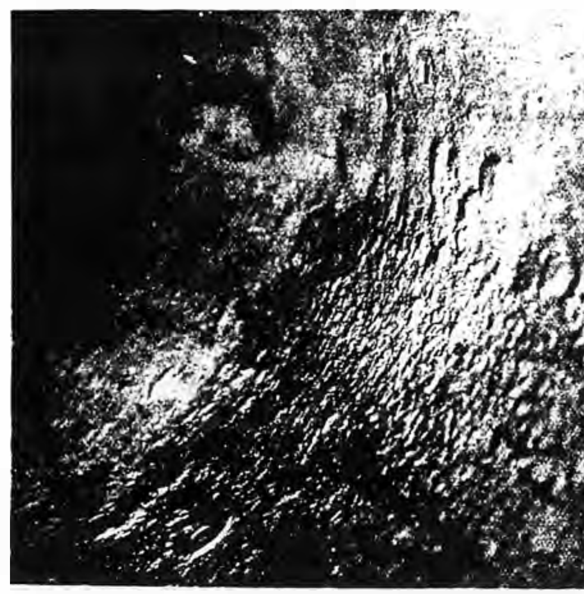


FIG. 17 INLET PIEZOMETERS OF VENTURI METER AFTER TUBERCLES WERE REMOVED

Venturi-Meter Study. During the piezometer investigation, the effect of wall roughness, whirling water, and improvement of meter-inlet piezometers upon the operation of the 12-in. by 6-in. venturi meter was studied. Fig. 17 shows the condition of two inlet piezometers after the tubercles had been removed and before the piezometer plugs were filed down smooth and flush. The results of these tests are shown in Figs. 18 and 19.

CONCLUSIONS

The following results were indicated by these tests on piezometer openings:

1 The error of a piezometer is a constant percentage of the local velocity head existing at the orifice.

2 The size of the opening has no effect within the limits tested, which were from $^1/_{16}$-in. to $^{27}/_{32}$-in. opening and mean velocities up to 7.3 ft. per sec. in a 12-in. pipe.

3 A true square-edged orifice is accurate, but very sensitive to slight changes in construction and position.

4 A standard piezometer plug or plate must be absolutely flush with the conduit wall.

5 A piezometer that projects beyond the pipe-wall surface has a large negative error.

6 The burr must be carefully removed from a square-edged orifice.

7 A piezometer plate or plug is not sensitive to minute abrasions on its surface.

8 A piezometer orifice must continue with parallel sides for over two diameters into the plug before its shape is changed.

9 The inside penstock wall should be scraped clean for at least 1 ft. upstream from a piezometer.

10 The piezometers to determine true pressure head should not be installed where there is any chance of the water whirling

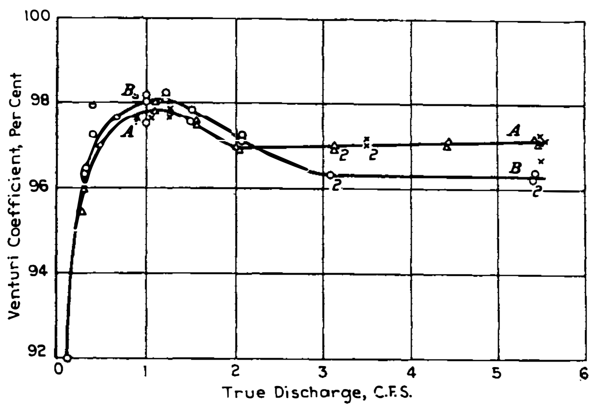


FIG. 18 TESTS OF 12-IN. BY 6-IN. VENTURI METER
(Curve *A*, with and without butterfly valve; curve *B*, with spinner. Circles, six-vane spinner in pipe, 5.3 ft. upstream; crosses, butterfly valve in pipe, 5.3 ft. upstream; triangles, calibration under normal circumstances.)

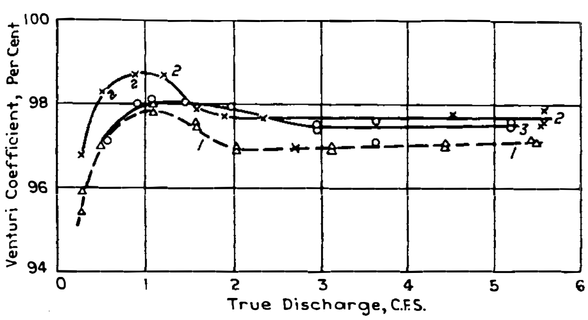


FIG. 19 TESTS OF 12-IN. BY 6-IN. VENTURI METER
(Order of tests: Curve 1, as used in piezometer study; curve 2, with tubercles removed; curve 3, with inlet piezometers improved.)

in the pipe or immediately downstream from an obstruction, such as a butterfly valve, a rivet head, or a plate joint.

11 An inserted tube pointed on the upstream end and with piezometers on the side gives a correct pressure-head reading, but it is very sensitive to angularity.

12 A tea-ball piezometer has a large negative error, but it is not sensitive to the direction of flow of the water.

13 A conical piezometer has a very large negative effect, but must be used with extreme care and calibrated.

14 An orifice with a large radius of rounding has a small positive error.

15 An orifice with $^1/_4$-in. hole and $^1/_{16}$-in. radius of rounding is recommended for standard practice.

Discussion

ARTHUR L. COLLINS.[3] The work of the authors on piezometers has been made public at an opportune time, and the information should be a valuable guide to engineers who are interested in measurements where they must make use of pressures obtained through the piezometer.

The authors have stated that the object of this investigation was (1) to determine a stable type of piezometer suitable for use as a standard in commercial work and (2) to determine those factors which have the greatest bearing in obtaining correct results. It does not appear that the first object has been satisfactorily accomplished, because the data do not indicate how a piezometer can be constructed so that it will provide a means for taking a pressure measurement without the measurement being affected by the velocity in the pipe. It will be a matter of coincidence when such a piezometer is discovered. This is apparent since the reference orifices when first installed had variations as great as 4 per cent between them. Even then there was no way to prove that all four piezometers were not in error.

In some classes of measurements where the piezometer is depended upon, such as the pitot tube, orifice plate, and venturi, and where the low differential pressures are required in pipe-line tests for coefficient of roughness, these errors are very important.

Difficulty in obtaining an ideal piezometer may not be the fault of the design of the piezometer so much as it is the rolling action of the water at the pipe wall. Under a normal flow, where the velocity distribution is unaffected by various factors, the slope of the distribution curve has a tendency to follow the parabola. Under this condition the liquid probably strikes the wall in a direction oblique to the axis of the pipe.

The failure of the piezometer to function accurately has already had its effect upon many hydraulic problems. For example, it has prohibited to a large extent the use of the pitot tube, which should be one of the simplest and most accurate instruments that can be used for flow measurements in pipes. Also, the piezometer is bringing into disrepute in many cases measurements made by the orifice plate where it is used on the end of a pipe as a nozzle or between the flanges, and the taps for the piezometer are made by tapping into the pipe. In the orifice plate the way to minimize the effect of the piezometer on differential pressure is to have a high ratio of pipe diameter to orifice diameter. Of course, the objection to the high ratio is the loss of head and dissipation of energy through the restricted area.

The manufacturers of the deep-well turbine pump in California are the most extensive users of the orifice plate for field tests. It was introduced to them about 1920. The end orifice plate is generally used with a low ratio of pipe diameter to orifice diameter, in order not to build up a false head on the pump being tested. The piezometer is drilled in the field, and of course may create readings which are far from correct. Where the differential head is only a few inches and the initial pipe velocity is quite high, the measurement cannot be very reliable. However, innumerable acceptance tests are made with the orifice plate, and the results are not questioned, because some reliable company is credited with having calibrated the orifice plate under laboratory conditions and found it to be correct. Such tests mislead both the manufacturer and the buyer, and no doubt will be abandoned when better methods of water measurement are introduced.

A few examples of how the piezometer has affected the general information on pitot tubes will be called to attention. The A.S.

[3] Consulting Engineer, San Francisco, Calif.

M.E. Fluid Meter Bulletin, Part 1, 1924, pages 39, 40, and 42, illustrates by Figs. 17A, 17B, 18, 19, 21, and 23, types of tubes the reliability of which can now be judged by these piezometer studies. The A.S.M.E. Power Test Code of 1926 particularly recommends 17B. The coefficient for this tube is given as 0.98. No doubt the 0.02 correction is due to the piezometer, and the value may change depending upon various conditions. It is noted that in the revised Third Edition, Part 1, 1931, the 17B design is now shown on page 42, Fig. 17, and the coefficient has not been mentioned, but multiple piezometers are recommended.

The next example is the Testing Code, approved by the Machinery Builders Society, dated Oct. 17, 1917. Under Pitot Tubes it reads: "The static pressure over the cross-section shall be measured by from four to eight carefully constructed piezometers." . . . "and condition of piezometer orifices shall be such that no piezometer shall vary its readings by more than 10 per cent of the velocity head from the average of all piezometers." Then the code further states that after the measurement has been conducted the velocity is multiplied by 0.976 to correct for oblique or sinuous flow.

Inasmuch as an error in the piezometer due to the velocity means an error in the measurement, one is now also able to judge to a certain extent the risk taken in a pitot-tube measurement when the piezometer is used. It is quite noticeable that the pitot-tube coefficients are less than 1.00, which naturally favors the waterwheel manufacturer, inasmuch as a low measurement is in their favor. However, the pump manufacturer in a performance test is on the other side of the fence and favors the high-capacity readings, and should demand a tube coefficient of 1.00 plus, to be on the safe side.

In the writer's field experience with the pitot tube he has proved that the type of tube using the piezometer in the pipe wall will give readings which may be in error as much as 5 per cent. This error is not permissible, and since the method is specified in the Power Code, it practically prohibits the use of the system. In order to overcome the handicap offered by the piezometer, it is necessary to use a type of pitot tube where the piezometer feature has been eliminated.

There is another point worth mentioning along this same line. The pitot-tube traverses shown in the paper apparently were taken with the overhung type of tube which crowds the water to the opposite side. On one side of the pipe the velocity will be much higher than the velocity on the other side of the pipe, due to the insertion of the tube. For that reason the curve of velocity distribution does not indicate the true velocity in the pipe. As a matter of general information the writer would like to ask for a description of the pitot tube and its coefficients. Is the coefficient the same for the 12-in. pipe and the 40-in. pipe?

F. G. Switzer.[4] The measurement of pressure certainly seems a very simple thing at first, but it needed further investigation to bring out some of the difficulties. The authors deserve credit for a difficult job well done.

In the connections from the pressure tap to the pressure-measuring device such as a water or mercury column, it is customary to insert a valve, which is partly closed, to reduce pulsations. It should be noted that such practice may introduce errors which mount rapidly with increasing tendency to pulsation. Pulsations are usually not entirely eliminated, but merely reduced to a point where accurate observations of column height may be made. Hence there is flow back and forth through the throttling valve. Loss of head through this valve is proportional to nearly the square of the velocity. Velocities above and below the average will therefore be damped by different percentages. The average pressure on the manometer side will not be quite the same as the average pressure in the pipe under observation. While this difference may not be great, its presence may be noticeable in work of a high degree of accuracy. Some method of viscous damping is much to be preferred. One method of accomplishing this is to insert a bundle of fine wire into a short section of the connecting tubing. This makes the removal of air bubbles very difficult, no matter how the piping is arranged with air vents. It is not to be recommended unless extreme care is used in installation and observation. It is suggested that a more practical method of securing viscous damping be devised.

For measuring air pressures, an entirely different device has been used which apparently can be made to measure pressures in liquids also. No reference to this device can be cited. It consists of a tube with a large number of small holes drilled through the walls from all directions. Around that portion of the tube there is wound a closely coiled helix of fuzzy material such as twine used for tying up packages. This arrangement has been used in experimental work at Cornell University with great success. Its chief advantage is that it can be used anywhere in a flowing stream and is not directional, no matter in what direction the tube is placed with respect to the flow lines. This makes it possible to measure pressure distribution in any cross-section.

E. B. Strowger.[5] Although according to the writer's experience it has been customary to insist on rather rigid specifications for the installation of piezometer openings, yet to date there seemed to be available no definite information as to the errors introduced by various modifications. The paper quite definitely establishes the effects of various modifications in the piezometer opening, some of which may be either artificially or accidentally produced in the ordinary course of construction.

Of the conclusions stated by the authors, those numbered 8, 9, and 15 are perhaps the outstanding ones from a practical viewpoint. These three conclusions are concerned with the length of the orifice wall, the condition of the penstock wall just upstream from a piezometer, and the rounding of the orifice edge to prevent burrs. The results found will serve to preclude controversies on these points.

The possibility of errors in head measurement due to the vagaries of the individual piezometers indicates the advisability of having more than one piezometer at the section where the head is to be measured, and also indicates the advisability of bringing each piezometer pipe separately to the head-measuring instrument rather than joining the piezometers to a piezometer ring.

The use of a throttling valve in addition to a shut-off valve in a piezometer line is perhaps worthy of note. Where the pressure to be measured may have a variation in one direction for a certain length of time, the use of a gate valve for throttling may introduce a serious error in the pressure readings. This condition may be exemplified by a piezometer line to a penstock which is connected to a surge tank, a gate valve for throttling purposes being in the piezometer line. If the valve disk is nearly closed, it may become locked closed by the action of the changing pressure tending to deflect the disk over against the seat and thus cut off more or less completely the opening to the penstock. One precaution is to drill a hole through the center of the disk to insure a positive opening under all conditions of throttling.

It should be pointed out that the function of piezometers for use in connection with taking Gibson diagrams is somewhat different in principle from their function in measuring absolute pressure head. In the former case, the piezometer is used for transferring the supernormal pressures existing in the penstock by virtue of

[4] Professor of Hydraulic Engineering, Sibley School of Mechanical Engineering, Cornell University, Ithaca, N. Y. Mem. A.S.M.E.

[5] Assistant Hydraulic Engineer, Buffalo, Niagara & Eastern Power Corporation, Buffalo, N. Y.

the water hammer produced by destroying the momentum of the water. Any slight modification of the piezometer opening while changing the absolute head reading for "steady state" conditions, in the case of the diagram, only results in altering the position of the "running line," the impulse area recorded being unaltered. This has been established by many experiments, using combinations of various piezometers located around the periphery of the pipe on the piezometer sections.

JOHN W. BRASKO.[6] Due to the care which must be exercised with piezometers, the writer is curious to learn what results, in the opinion of the authors, may be expected from the use of a piezometer consisting of a 1/2-in. H pipe nipple screwed into a 1/2-in. H coupling, which is welded over a 3/8 drilled hole in the wall of standard thickness pipe.

We have adopted this method of pressure-tapping pipes as a much more satisfactory mechanical job than that of screwing a nipple into a tapped hole in the pipe. We feel, also, that the elimination of the problem of making the piezometer flush with the pipe wall and the consequent reduction of burr formations are strong points in favor of this method.

If such a piezometer gives inaccurate readings, is it reasonable to assume, in cases of flow measurement by orifice plate where the pressure differential across the orifice is to be measured, that the error in the one piezometer is cancelled by the same error in the other piezometer by reason of a manometer arrangement.

JOHN. B. DRISKO[7] AND HUNTER ROUSE.[7] A short series of investigations similar to those performed by the authors, dealing with only five types of piezometer openings, was carried out in 1905 in Dresden, Germany, by Dr.-Ing. Paul Schuster.

Schuster's work[8] was essentially an investigation of flow through a Francis turbine. Preliminary tests of various pitot tubes and piezometer openings were carried out in the towing tank of the Uebigau Shipyard. The piezometer openings investigated were five in number:

(1) Square-edged hole with diameter of 1.75 mm. (0.069 in.).

(2) Hole with diameter of 1.75 mm., corners removed with 90-deg. countersink to a maximum diameter of 1.8 times the hole diameter

(3) Square-edged hole with diameter of 2.7 mm. (0.106 in.).

(4) Hole with diameter of 2.7 mm., corners removed with 90-deg. countersink to a maximum diameter of 1.5 times the hole diameter

(5) Hole with diameter of 2.7 mm., corners rounded on a radius of 0.4 times the hole diameter.

The five piezometer openings were mounted at intervals of 25 mm. in a vertical row on a brass plate 4 mm. thick. The plate, the leading edge of which was sharpened with the bevel on the back side, was mounted on the towing carriage exactly parallel to the direction of travel and was towed in still water.

The velocities of the carriage were recorded chronographically. Glass tubes of 6.5 mm. inside diameter containing the piezometer water columns were mounted on a board faced with millimeter cross-section paper, by means of which the column heights were determined. Test data are as follows:

Velocity		Piezometer error due to dynamic pressure head, in mm.				
m. per sec.	ft. per sec.	(1)	(2)	(3)	(4)	(5)
0.76	2.49	—1	—1	—2	—1	—1
0.84	2.76	—1	—1	1	0	0
1.02	3.34	—2	—2	0	—1	1
2.05	6.72	0	—2	0	—1	0
2.57	8.42	—10	—8	—10	—8	—4

Schuster concludes that the suction effect of moving water is best avoided and hence the pressure is indicated most accurately by the use of a well-rounded opening. He gives the following approximate values for the error of piezometer column heights due to the velocity effect:

Square-edged opening, —3 per cent of velocity head
Countersunk opening, —2.5 per cent of velocity head
Well rounded opening, —1 per cent of velocity head

Similar errors as found by Allen and Hooper are:

Square-edged orifice, 0 per cent of velocity head
Round-edged orifice No. 11, 2.1 per cent of velocity head

Allen and Hooper arbitrarily chose square-edged orifices as references; hence rounded orifices have a positive error. Schuster found the rounded openings more nearly correct, which would give the square-edged openings a negative error. A comparison of the foregoing tables indicates that in both cases the well-rounded orifice gave higher readings.

The values of "piezometer error in per cent of mean velocity head" from Allen and Hooper are probably smaller than if based upon actual velocity, inasmuch as they were figured for mean pipe velocity and not for the lesser velocity actually existing near the piezometer openings in the pipe wall. The corresponding Schuster values were figured for a velocity which actually existed close to the piezometer openings and are hence somewhat larger than the former values.

The fact that Schuster's piezometer openings were set into a flat plate and that those of Allen and Hooper were set into a cylindrical surface may account for some of the discrepancy noted.

It is barely possible that some of Schuster's work was done in water quiet enough to give laminar flow conditions. In general, it is found that the first one or two runs made in a towing tank after the water has been undisturbed for some time, as for instance overnight, are unsatisfactory because the water has become quiescent and conditions correspond to those of laminar flow. Once having been disturbed, the water in the tank may be said to be turbulent, and gives corresponding results. Since the flow with which Allen and Hooper were working was undoubtedly turbulent, the possible dissimilarity of flow conditions under which the two series of investigations were done may be given as a remote source of difference in the results.

It is to be regretted that the wide range of piezometer inlets discussed in the paper did not include various forms of openings leading to tubes set at angles differing from 90 deg. with the pipe wall. The fact has long been known that a tube pointing slightly against the direction of flow, however flush it may be with the pipe surface, will give values above the actual pressure head, because of the additional effect of a component of the velocity head—similar conditions causing a decreased reading for a tube pointing somewhat downstream. In addition to having quantitative data on the influence of such angularity, it would also be interesting to know whether the proposed rounding of the opening would tend to reduce this effect.

The danger of inaccuracies due to this cause, especially in cases where openings must be drilled by hand with no means of procuring absolutely normal holes, may be fully understood only through such careful tests as are contained in this paper. One of the writers recently conducted a series of experiments involving 75 hand-drilled piezometer connections on the side of an open flume for measuring the effect of curving flow; as the pressures

[6] Steam Engineer, Atlantic Refining Company, Philadelphia, Pa. Jun. A.S.M.E.

[7] River Hydraulic Laboratory of Massachusetts Institute of Technology, Cambridge, Mass.

[8] Published in 1910 by the Verein deutscher Ingenieure, "Mitteilungen über Forschungsarbeiten," Heft 82.

were often below the atmospheric and the velocities correspondingly high, many of the tubes were rendered useless by their imperfect construction, despite great care in finishing the openings at the wetted face.

Allen and Hooper's ingenious method of arranging the gage box brings to mind a number of gage forms which have proved satisfactory in various laboratories for very delicate setting. It is claimed of the gage point lowered from above that small particles of dust or drops of water will cause the springing of the meniscus before the metal point is actually in contact with the water surface. This difficulty is overcome by the hook gage immersed in the water, but the latter is often sharply pointed and the contact noted from above when the surface is punctured; needless to say, this instant of contact cannot be observed with great accuracy from above the surface, while the sharpness of the point makes it equally difficult from below.

The apparatus used at the Worcester laboratory apparently includes a gage whose point is not so acute as to involve the latter difficulty. A slightly arched chisel edge has been used at the Walchensee experiment station of the Forschungsinstitut of Bavaria, with which one may measure without great difficulty to within 0.02 mm. (0.0008 in.). A small lamp illuminates the hook, whose reflection is sharply visible in the under side of the water surface; the hook is raised until it apparently just touches its reflection above, but without quite puncturing the surface.

Many experimenters believe that the glass gage pipe should be from $1^1/_2$ to 2 in. in diameter, not only to insure a flat portion of the water surface between the meniscus curves at the sides of the glass, but also to overcome the lag due to capillarity, and the variable capillary rise if the pipe varies slightly in diameter. This usually makes the tube large enough to serve both as stilling box and gage glass, and hence lessens the effect of changing volume as the gage is raised or lowered.

H. S. Bean.[9] The paper is the most comprehensive study of pressure measurements with a piezometer that has come to attention. Since K. Büchner[10] published the results of his observations, and possibly before, there have been many references to more or less causal observations on the use of piezometers, but in all cases these observations have been incidental to the attainment of some other objective.

The effects of the various designs and flow conditions that were tried and the conclusions drawn are very much what would be expected. It is gratifying to see that the piezometers used in the Chicago tests, by the A.G.A. Committee on the Measurement of Large Volumes of Gas,[11] conformed exactly to the recommendation of the authors.

The authors do not specifically state whether they used other sizes of lines than those shown in Fig. 1. Presumably they did not. Also, they recommend the use of a piezometer with a $^1/_8$-in. hole and a $^1/_{32}$-in. radius of rounding for small pipes, while for larger pipes a piezometer with a $^1/_4$-in. hole and a $^1/_{16}$-in. rounding is recommended. However, they have not suggested a dividing line between "small" and "larger" pipes. It will be very helpful to know what their recommendations on this point would be.

John R. Freeman.[12] The paper interests me, because about 55 years ago I had a hand in a much more fundamental and more precise research on piezometers. The principal results of this research were published in the *Transactions* of the American Academy of Arts and Sciences in Boston in the year 1878, pages 28 to 53, and illustrated by four plates of drawings and diagrams.

These researches were carried on by Mr. Hiram F. Mills, Chief Engineer of the Essex Water Power Company at Lawrence, Mass., who was one of the most eminent hydraulic experimenters in America in the epoch of 50 years ago. They were made as a preliminary to a long series of other experiments on the flow of water in pipes, only a few of which have ever been published.

These researches on piezometers by Mr. Mills, unfortunately, have remained almost unknown to the engineering profession, because presented to a society which at that time contained relatively few engineers in its membership.

The writer had the rare good fortune to be one of Mr. Mills' young assistant engineers at the time these experiments were made, and soon afterward became his principal assistant, and continued in that capacity for about 10 years in a great variety of hydraulic work, including much of an experimental nature.

These experiments by Mr. Mills were much more fundamental than those of Allen and Hooper because they compared the piezometric level with that of a free water surface flowing in an open channel, whereas Allen and Hooper's experiments simply compare one piezometer with another, and have all their piezometric orifices arranged around the same cross-section of a closed pipe flowing full of water under pressure. Thus they simply show the errors which may be introduced in such measurements by the careless projection of a burr on the inside of the piezometric orifice or the lowering of the water column caused by carelessly permitting the end of a connecting pipe to protrude inside of the channel, which errors are, however, often permitted by those who fail to realize the truths brought out by Professor Allen's experiments.

The precision of measurement in the Mills experiments was also greater inasmuch as the micrometer gages used in the comparisons were all carefully read to about 0.0001 in., under excellent conditions for measuring head in the piezometer chamber, whereas the limit of measurement in the Allen-Hooper experiments was 0.01 in. For most practical purposes this difference of precision is unimportant.

Mr. Mills' experiments aimed to accurately determine once and for all the truth about a moot point in physics which had been raised by Darcy in a statement in his monumental work "Recherches Hydraulique," published about 75 years ago, which (translated) reads: "Piezometers do not indicate the entire head of a conduit at the point where they are attached, but the head diminished by a certain amount, the diminution being due to the velocity at the base of the piezometers, where the water by its cohesion acts on the manometric column, the height of which it lowers."

Darcy also stated that in a piezometer attached to a reservoir of large diameter, feeding a pipe in which water was flowing, the lowering of the piezometric column by suction would be less than in a piezometric column attached to the pipe.

The idea at the bottom of this piezometer question in physics is that water has a definite cohesive strength (which with proper apparatus may be measured as a tensile strength amounting, as I remember it, to about 75 lb. per sq. in.). And it appeared not unreasonable to Darcy and others to suppose that this cohesion would lower the piezometric column when water was flowing rapidly past the orifices.

Dubuat, ablest of the hydraulic experimenters of 120 years ago, had erroneously concluded that water would press against the side of an open conduit in which water was flowing, with a pressure less than that due to its depth by the amount of pressure that would produce its mean velocity. Mr. Mills stated that although Navier in 1819 had controverted this idea, Dubuat's

[9] Physicist, Bureau of Standards, Washington, D. C. Mem. A.S.M.E.

[10] *Z.V.D.I.*, vol. 48, II, 1904, p. 1097 (especially p. 1100).

[11] Bureau of Standards Research Paper No. 335, "Experiments on Metering Large Volumes of Air," *Journal of Research*, no. 7, July, 1931.

[12] Consulting Engineer, Providence, R. I. Mem. A.S.M.E.

conclusion had been commonly presented in treatises on hydraulics up to the time of Darcy.

Mr. Mills therefore sought the origin of this wrong idea of Dubuat, that the piezometric height would be less than the true height, by connecting certain of his piezometers to a pipe with an open end, which could be projected through the wall of the conduit; and he found, just as Allen and Hooper have now found, that the water column in the piezometer chamber was thereby lowered proportionately to the velocity of the water passing the end of the projecting pipe, because of the deflection of the current by this projection.

The apparatus designed by Mr. Mills for the purpose of definitely settling this question of whether or not there was a lowering of the piezometric column by suction, when connected to an orifice truly in the plane of a conduit wall, comprised in brief an open trough, nearly 30 ft. in length, about 1 ft. in depth, and about 4 in. in width of channel, constructed of clear, well-seasoned pine wood with greatest care by an uncommonly expert mechanic, within the walls of which about 20 orifices of different forms were cut, on opposite sides of the trough, of various sizes and shapes and having various inclinations.

We are now chiefly concerned with the results of the three series of experiments:

(A) With orifice in the plane of the wall of the flume and with the connecting passage at right-angles to that wall
(B) With orifice truly in the plane of wall of the flume, but with passage leading from the orifice to piezometer inclined at an angle to wall
(C) With orifice in end of pipes which projected into the conduit by various amounts.

Nearly 6000 separate observations were made, covering velocities all the way from about $^1/_2$ ft. per sec. to about 9 ft. per sec. The flume was frequently emptied and inspected for possible changes in shapes due to swelling of the wood, by means of steel straight-edges, some short and some long, under conditions of lighting so arranged that deviations of 0.001 in. in or out from the plane of the orifice could readily be perceived. Some of the orifices were in smooth brass plates carefully inserted in the conduit wall.

The piezometric water columns were measured in small reservoirs averaging perhaps 6 in. in diameter, constructed of tin boxes, attached to the side of the flume, with great precautions to prevent leakage.

The principal cause for possible errors in measurement of comparative heights lay in the "wrinkles" in the surface of the water in the open conduit when flowing at high velocities. Notwithstanding the care taken to maintain a constant level at the entrance of the flume, this surface at higher velocities became somewhat "wrinkled" along its course by small diagonal standing waves.

Every practicable precaution was taken to obtain accuracy. To eliminate the personal equation, the observers at the several stations along the trough, all of whom were skilled and experienced in such experiments, frequently shifted their location.

As a result of this elaborate series of experiments, Mr. Mills concluded that the height of the water shown by piezometers of class A was the same as the height of water at the middle of the stream flowing in the trough, as nearly as it was practicable to measure, and that there was no lowering of the piezometric column by suction or cohesion of the water flowing past the piezometric orifice.

For class B, by experiments on four orifices he found, notwithstanding the edges of the orifice coincided as nearly as practicable with the plane of the conduit wall, that when the connecting passage was inclined 45 deg. facing upstream, the effect was to slightly raise the piezometric column, and when inclined downstream to slightly lower it, probably because of some slight sinuosity in the current past the orifice.

For class C, with orifices in the end of a pipe, Mr. Mills found, as Allen and Hooper have found, a definite lowering proportional to the velocity head of the water flowing past the end of the pipe.

As the final result of nearly 6000 observations on about 20 different orifices, Mr. Mills concluded his paper with the words: "From these results, it is evident that it is entirely within the practicable limits of construction to make piezometers that will indicate the true height of the stream, within the practicable limits of observation."

During the 10 years or more following these experiments, in my work for Mr. Mills in measuring water used by the factories at Lawrence, Mass., and Manchester, N. H., in various turbine tests, and in a great variety of experiments on the flow of water in conduits, great care was always taken when setting up piezometers for water-measuring apparatus to make sure that the piezometric orifice was truly in the plane of the surface of the pipe, and in order that there could not be any possibility of a burr or projection, the edges of the orifice were always very slightly rounded. Great care was taken when a pipe was screwed into a conduit wall that by no possibility should it project inside the surface of this wall.

I am prompted to make a few further comments relative to the precautions necessary to obtaining the greatest practicable accuracy in piezometric observations.

First, as to the size of the glass tubes for observing the height of water, I assisted Mr. Mills in a long series of experiments on this matter, using glass tubes of many sizes up to 2 in. in diameter, with water of various temperatures, with the water surface in the reservoir rising in some cases, falling in others, and in experiments in which the actual mean level in the reservoir did not change, but was simply agitated, as by small waves. Unfortunately, no description of these experiments was ever published.

My recollection is that we found it necessary to have our glass tubes at least 1 in. in internal diameter, in order to fully avoid the effects of surface tension, or capillarity, from the inner walls of the glass tubes.

We found this degree of surface tension and error which existed in the small tubes of, say, $^1/_2$ in. internal diameter, varied with both temperature and with the degree of cleanliness of the inner wall of the tube.

Subsequent to these experiments, in all of our precise work, care was taken to have tubes not less than about 1 in. in diameter. With these and proper apparatus of loop-vernier index, proper lighting, and accurate scale, the height can quickly be measured with certainty to within about 0.001 in.

Another matter which commonly does not receive sufficient attention, in precise work, and which may have led to a lack of precision in Professor Allen's experiments, is that the conduit channels between the piezometric chamber and the pipe should be such that water should flow just as easily in one direction as in another; otherwise a sort of check-valve action occurs which, if there are pulsations in the water of the conduit, may materially affect the accuracy of the piezometric measurement.

In the Mills' experiments previously discussed, great care was taken to have the orifices in the walls of the conduit and the connections to the piezometric chamber so shaped that the coefficient of contraction at all edges of the connecting channel should be the same for inward flow as for outward flow.

Another matter which Professor Allen has touched on is the importance of avoiding even the faintest leakage in piezometric connections. I have had frequent occasion to observe that the importance of this precaution is often not appreciated. It is of highest importance for precise experimentation that there be no leakage whatever. Possibly the fact that water possesses slight velocity may be at the bottom of this possible source of error.

Long tubes and tubes of small diameter in many cases present opportunities for error in piezometric observations by reason of air bubbles released from solution which collect in these tubes.

On one occasion, perhaps 25 or 30 years ago, in some experiments in the large hydraulic flume and measuring weir in the hydraulic laboratory of Cornell University, I found that the hook gage in the still-box measurements of depth over the weir, supposed to be "absolutely correct," was about 1 in. in error, as determined by holding an ordinary leveling rod, first on the crest of the weir and then at the water level of the weir box, using an engineer's Y-level under such conditions as to insure accuracy.

This test was made with a foot or more in depth flowing over the weir in order that any effect from settlement under the weight imposed by operating conditions should be discovered. The experienced engineer at that time in charge of Cornell's hydraulic flume could hardly believe his eyes when this amazing error was revealed. Probably it was due to an air trap or an accumulation of small bubbles in the connections.

In our many water experiments and measurements at Lawrence 50 years ago, under Mr. Mills, we learned to take the utmost care to arrange our piezometric connections so that they could be flushed out by a swift current, immediately before beginning observations, also at frequent intervals, and, moreover, found it necessary to carefully avoid slopes in connecting pipes which might interfere with the free rising of bubbles, and also found it necessary at intervals of half an hour more or less, in many cases, to hammer our rubber-tube connections in a way to produce violent pulsations of the water column, for the purpose of loosening air bubbles disengaged from solution in the water, while it stood in the connection.

Precise experimentation in hydraulics involves an everlasting setting of traps to guard against unconscious error of many kinds.

Authors' Closure

Arthur L. Collins: In answer to the statement which Mr. Collins makes that "it does not appear that the first object of the investigation has been satisfactorily accomplished," may we call attention to the work of Mr. Hiram Mills referred to in Mr. John R. Freeman's discussion. Results of his work, which was done in an open flume where the actual elevation of the free-water surface was checked against the piezometer heads, check the work described in this paper very closely. In addition, the four reference piezometers, when properly installed, check within 1 per cent of the mean velocity head of each other, and later four other piezometers, Nos. 5A, 6A, 11B, and 12B, were installed according to the specifications developed in the paper, and they checked the reference piezometers within 1 per cent of the mean-velocity head.

In regard to the use of pitot tubes in this investigation, the static piezometers of the tube referred to as No. 11A and shown in Fig. 14 were compared as to performance with the reference piezometers, and in this case checked very well. However, a pitometer was used in making the traverses in the 12-in. and 40-in. pipes, the curves of which were printed in the paper, and the indicated velocities were corrected for the change in area occasioned by the presence of the rod. Pitometers have been carefully calibrated recently in the 12-in. line and in the 16-in. throat of a 36-in. by 16-in. venturi meter against weighing-tank measurements, and the value of the coefficient was the same in both cases. A pitot tube should not be in error as much as 5 per cent if it is carefully calibrated under hydraulic conditions similar to those in which it is to be used.

F. G. Switzer and E. B. Strowger: The damping devices referred to in the discussions of Professor Switzer and Mr. Strowger are probably satisfactory, but at the Alden Hydraulic Laboratory it is customary to pinch a rubber hose to give the desired degree of damping. This system, we believe, has merit on account of its simplicity, flexibility, and availability. In the first place, it is very easy to obtain full discharge in the pressure line for the elimination of dirt or trapped air, or to change the water in the line because of temperature conditions. Secondly, the channel of approach to the throttling section is just the same on both sides. Then, if the hose is pinched so that the water column or pressure gage is just alive, it is probable that the flow through the throttling section is viscous. And finally the throttling is very readily changed to meet the pressure conditions.

John W. Brasko: Fig. 10 of the paper shows that a $^3/_8$-in. hole must have parallel sides for $^3/_4$ in. before any change of diameter of the piezometer tube occurs. Therefore, for a large number of cases where the pipe-wall thickness may be considerably less than $^3/_4$ in., this form of piezometer will undoubtedly be in error. Also the importance of removing the burr from the inside edge of the piezometer opening cannot be overemphasized.

John B. Drisko and Hunter Rouse: With reference to the tests of Dr. Ing. Paul Schuster in 1905, it is evident that the hydraulic conditions of the two investigations are so dissimilar that comparisons are probably of little value.

H. S. Bean: If reference be made to the results of tests on piezometers Nos. 5A and 12B, it will be seen that they give the same results. Hence the choice of the size of the orifice depends upon other considerations than accuracy.

John R. Freeman: With reference to Mr. Freeman's statement of relative accuracy of Mr. Mills' and this work, it should be understood that the error given in this paper was an over-all figure (about 1 per cent), whereas the figure given for Mr. Mills' work really applies only to the measurement of the elevation of the water surface in the piezometer stilling pots. Referring to Plates Nos. 3 and 4 of Mr. Mills' paper, it will be found that there are a number of points which lie more than 2.0 per cent of the mean velocity head away from the smooth curve of all the points, and each of these points is the average of ten readings. The determination of the free-water surface, a very difficult thing to measure accurately, introduced errors which makes the two papers comparable as to accuracy.

It is to be regretted that Mr. Mills' paper on piezometers was so thoroughly hidden that the material therein was practically unknown to the engineering profession for so long. The authors were unable to obtain a copy of his paper until after the present paper was written, but find, fortunately, that his work and the results of this paper practically check.