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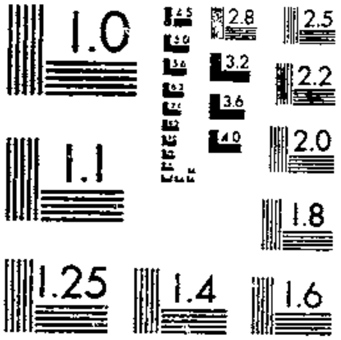

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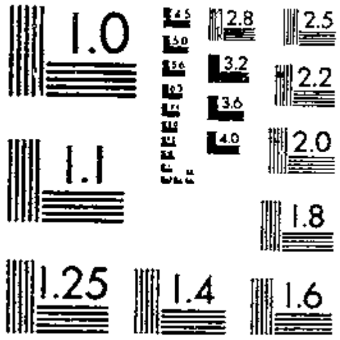

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TECHNICAL BULLETIN No. 429 JULY 1934

PILE TRESTLES AS CHANNEL OBSTRUCTIONS

By

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UNITED STATES DEPARTMENT OF AGRICULTURE
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PILE TRESTLES AS CHANNEL OBSTRUCTIONS[1]

By David L. Yarnell[2]

Senior drainage engineer, Division of Drainage and Soil Erosion Control, Bureau of Agricultural Engineering

CONTENTS

Appendix:

INTRODUCTION

This bulletin presents the results of 1,082 experiments on the effect of clean pile trestles—that is, pile trestles free of any debris—in obstructing the flow of water made at the hydraulic laboratory of the University of Iowa at Iowa City, Iowa, during 1929 and 1930.

The investigations were undertaken primarily to determine the coefficients used in certain formulas for calculating the backwater caused by such obstructions.

Tests were conducted on both small-size models and on full-size single- and double-track pile trestles. The model trestles were made in the laboratory, whereas the material for the full-size trestles was furnished by the Chicago, Rock Island & Pacific Railway Co

PURPOSE OF THE STUDY

The erection of a pile trestle or a bridge pier in a stream forces the water to flow through a reduced cross section, and in passing this section the water must acquire a velocity greater than that existing in

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[1] A report of a study made under a cooperative agreement between the Bureau of Agricultural Engineering of the U.S. Department of Agriculture and the College of Engineering of the University of Iowa.

[2] For advice and assistance in the research, the author makes acknowledgment to Sherman M. Woodward, University of Iowa, to Martin E. Nelson, engineer, U.S. Engineer's Office, and to Ralph W. Powell, Ohio State University. Aid in making the tests and computations was given by Paul L. Hopkins, junior civil engineer of the Bureau of Agricultural Engineering, and by Nolan Page, C. H. Smoke, R. N. Brudenell, R. A. Kampmeier, C. H. Morris, F. E. Edwards, and R. F. Poston.

the unobstructed channel.[3] The increase in velocity can be produced only by elevating the water surface up stream from the trestle where the contracted area of flow exists. Thus as the stream enters the contracted area, a drop in the water surface is noted accompanying the increase in velocity.

The changes in cross section and velocity in passing the trestle piling cause much disturbance in the flow of water. Eddies may be formed along the piling. The high velocities and resultant eddies may scour out the bed of the stream next to the pile bents to such an extent that the trestle itself may be endangered and even swept away.

Differences of opinion often occur as to the amount of obstruction to flow caused by highway or railway pile trestle bridges and lawsuits may result over the amount of damages. It has been a moot question whether the resistance to flow offered by a double-track trestle with the bents for both tracks in line is greater than that offered by a single-track trestle. Just how much more obstruction is offered by a double-track trestle with the bents for the two tracks set a little off line than by the same track with the bents set in line has been an unanswered question. The hitherto existing need of information in this field is relieved by the results of these investigations as set forth herein.

The amount of obstruction a pile-trestle bent offers to the flow of water may easily be expressed in the form of a trestle-bent coefficient in a backwater formula. The value of the coefficient depends upon the particular formula used. Of the many formulas known, those most commonly used are D'Aubuisson's, Weisbach's, Nagler's, and Rehbock's. In the first three the trestle-bent coefficient varies with the quantity of flow. For a given height of backwater, depth of flow, and channel contraction, if the trestle coefficient is increased 5 percent through an improved setting of the bents, the flow capacity of the trestle is increased 5 percent. The trestle-bent coefficient is, in reality, an index number of the hydraulic efficiency of a pile-trestle bent.

The discharge through pile-trestle openings during floods may be computed with a fair degree of accuracy by means of a backwater formula if the drop-down at the trestle opening is known. The converse also is true; the discharge being known, the drop-down or backwater caused by the trestle may be determined.

The specific purpose of this investigation was to determine the proper coefficients for use in certain formulas so that these formulas can be used for computing the probable discharge or the probable drop-down at trestle openings. Experiments were made on models of 1/100 size and 1/4 size, and full-size single- and double-track pile-trestle bents placed both in line with and at various angles to the current.

THEORY OF THE OBSTRUCTION OF PILE TRESTLES TO FLOW OF WATER

Figure 1 represents a pile-trestle bent with the water flowing through the contracted area. The following symbols are used:

Q = quantity of water flowing, in volume per second.
D_1 = mean depth of water upstream from head of trestle at a distance equal to length of bent.
D_2 = mean depth of water in most contracted section of channel.

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[3] It is assumed that the velocity of the water in the unobstructed channel is less than critical. If the velocity in the unobstructed channel is at the critical value or higher, then the water will rise at the point of obstruction. Such conditions of flow are seldom encountered in actual practice.

D_3 = mean depth of water in channel below contraction; that is, depth in unobstructed channel.

W_1 = mean width of channel above contraction.

W_2 = mean width of channel at most contracted section.

W_3 = mean width of channel below contraction, ordinarily equals W_1.

V_1 = mean velocity of water above contraction, Q/W_1D_1.

V_2 = mean velocity of water in most contracted section of channel, Q/W_2D_2.

V_3 = mean velocity of water in channel below contraction, Q/W_3D_3, ordinarily equal to Q/W_1D_3.

H_2 = drop of water surface at most contracted section, D_1-D_2.

H_3 = drop of water surface in passing through the contraction, D_1-D_3.

g = acceleration of gravity.

$V_1^2/2g$ = head due to velocity of water above contraction.

$V_2^2/2g$ = head due to velocity in most contracted section of channel.

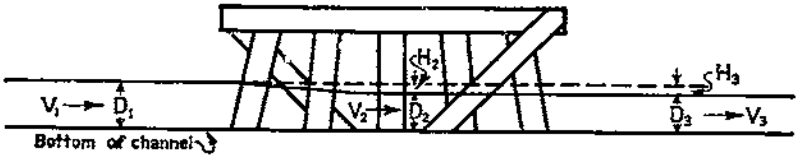
$V_3^2/2g$ = head due to velocity of water downstream from contraction.

$$\alpha = \text{channel contraction ratio} = \frac{\text{cross-sectional area of obstruction}}{\text{cross-sectional area of channel}}.$$

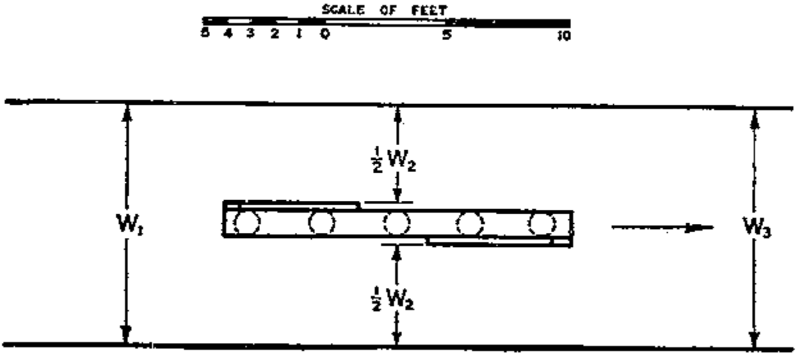
$$\omega = \frac{\text{velocity head of water below contraction}}{\text{depth of flow below contraction}} = \frac{V_3^2/2g}{D_3}.$$

K = trestle-bent coefficient covering losses due to friction, impact, eddies, etc. The subscripts $D'A$, N, W, and R designate the D'Aubuisson, Nagler, Weisbach, and Rehbock formulas, respectively.

δ_o = trestle-bent coefficient in Rehbock general bridge-pier formula. (See equation 7, p. 5.)



LONGITUDINAL PROFILE



PLAN

FIGURE 1.—Pile-trestle bent. See text for symbols used in pile-trestle formulas.

The real backwater height is shown in figure 1 as H_3. The surface drop in the contracted area, H_2, is sometimes erroneously called the backwater height.

D'Aubuisson (*2, pp. 188–191*)[4] probably first advanced the theory that the drop H_2 was merely the difference of the velocity heads for

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[4] Italic numbers in parentheses refer to Literature Cited, p. 25.

points D_1 and D_2. The formula becomes

$$H_2 = Q^2/2g\ (1/K^2_{D'A} W_2^2 D_2^2 - 1/W_1^2 D_1^2) \tag{1}$$

in which $K_{D'A}$ is the D'Aubuisson coefficient.

The true backwater is not exactly represented by H_2, but ordinarily in practical field installations there will be little difference between H_2 and H_3 and hence little difference between D_2 and D_3. Therefore only the values of the D'Aubuisson coefficient using H_3 and D_3 are given. Transposing and rearranging the terms in equation 1, substituting V_1 for Q/W_1D_1 and H_3 and D_3 for H_2 and D_2, and solving for Q, equation 1 for practical use becomes

$$Q = K_{D'A} W_2 D_3 \sqrt{2gH_3 + V_1^2} \tag{2}$$

whence

$$K_{D'A} = \sqrt{Q^2/2g W_2^2 D_3^2 (H_3 + V_1^2/2g)} \tag{3}$$

Weisbach based his formula upon the assumption that the total discharge through the contracted section may be calculated as the sum of two quantities, one quantity consisting of the flow through a submerged orifice of width W_2 and height D_2, and another quantity consisting of the flow over a weir with a crest length of W_1 and a head of H_2. The formula then becomes

$$Q = K_W \sqrt{2g}\left[\frac{2}{3} W_1 (H_2 + V_1^2/2g)^{3/2} + W_2 D_2 (H_2 + V_1^2/2g)^{1/2}\right] \tag{3a}$$

Nagler's (*3*) formula is

$$Q = K_N W_2 \sqrt{2g}[D_3 - \theta(V_3^2/2g)]\sqrt{H_3 + \beta(V_1^2/2g)} \tag{4}$$

in which the coefficients θ and β depend upon conditions at the site of the pile trestle. The coefficient θ is merely a correction coefficient, and the factor $\theta(V_3^2/2g)$ is intended to correct D_3 to give a smaller depth of flow similar to that at the most contracted section. This coefficient has little effect upon the results obtained when the depth of the stream is an appreciable quantity. Its value was taken as 0.30 throughout this investigation. Although the formula was originally proposed merely for the purpose of determining the relative efficiency of different shapes of piers with a fixed amount of channel contraction, it was suggested that the coefficient β varies with the percentage of channel contraction, the amount of change in the coefficient being greatest for channel contractions between 5 and 30 percent. This coefficient may be obtained from figure 2 prepared by Professor Nagler.

Rehbock gives a formula applicable to only one condition of flow past the piers. He divides the flow into three classes as follows:

1. Ordinary or "steady" flow, in which the water passes the obstruction with very slight or no turbulence.
2. Intermediate flow, in which the water passing the obstruction displays a moderate degree of turbulence.
3. "Changed" flow, in which the water passing the obstruction becomes "completely" turbulent.

These three classes of flow are defined, according to Rehbock, by the following two equations.

$$\alpha_A=1/(0.97-21\omega)-0.13 \tag{5}$$

$$\alpha_B=0.05+(0.9-2.5\omega)^2 \tag{6}$$

The moving water is in the first class as long as the contraction ratio of the pier site is less than the limiting value in equation 5. When the value of α of the pier site under investigation lies between the values of α_A in formula 5 and α_B in formula 6, according to Rehbock the second condition of flow prevails. When the value of α of the pier site exceeds that given in equation 6, the third condition of flow exists.

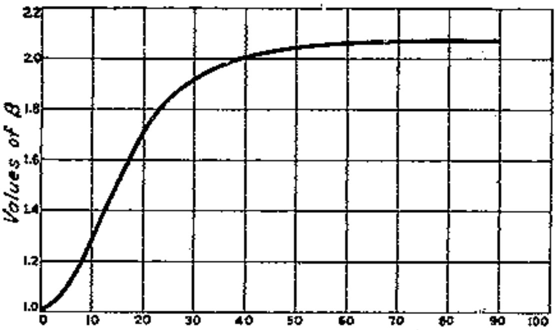


FIGURE 2.—Values of coefficient β to be used in Nagler bridge-pier formula.

The Rehbock equation (*1, pp. 122–128; 4, pp. 197–200; 5*) for computing the backwater height, H_3, for all pier shapes in a channel of rectangular cross section with ordinary or pure streaming flow, is as follows:

$$H_3=[\delta_0-\alpha(\delta_0-1)](0.4\alpha+\alpha^2+9\alpha^4)\ (1+2\omega)V_3^2/2g \tag{7}$$

A simple equation for bridge backwater is, according to Rehbock,

$$H_3=K_R\alpha(V_3^2/2g) \tag{8}$$

It is probable that the D'Aubuisson, Weisbach, and Nagler formulas apply only to the first class of flow as defined by Rehbock.

Determinations of trestle-bent coefficients for the Weisbach formula were attempted, but the extremely discordant results indicated that this formula is theoretically unsound and the effort was abandoned.

There are many other backwater formulas mentioned in foreign publications on hydraulics. Of these, the most prominent (*6*) are: Dupuit, Eytelwein, Flamant, Freytag-D'Aubuisson, Gauthey, Heinemann, Hofmann, Lesbros, Mehmcke, Montanari, Navier, Rühlmann, Tolkmitt, Turazza, and Wex. For reasons of economy, pile-trestle coefficients were not determined for these formulas which are seldom mentioned in English texts on hydraulics.

SCOPE OF TESTS

Experiments were conducted on a full-size single-track 5-pile trestle bent (pl. 1, *A*) placed at angles of 0°, 5°, 10°, 15°, 20°, and 30° with the current (fig. 3). Tests were made also on a full-size double-track 10-pile trestle bent (pl. 1, *B*) with all piles in line with one another as well as with the current, to determine the effect of additional piling on the value of the coefficient. A double-track trestle

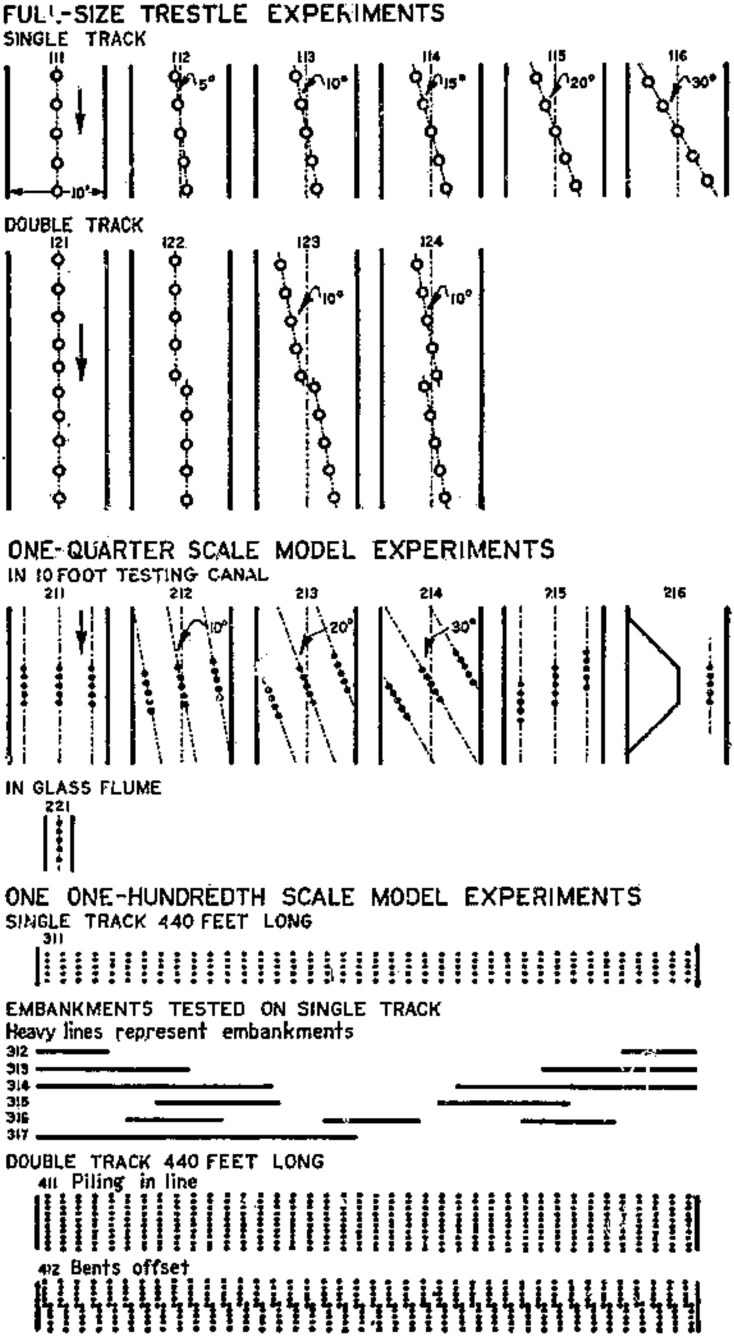
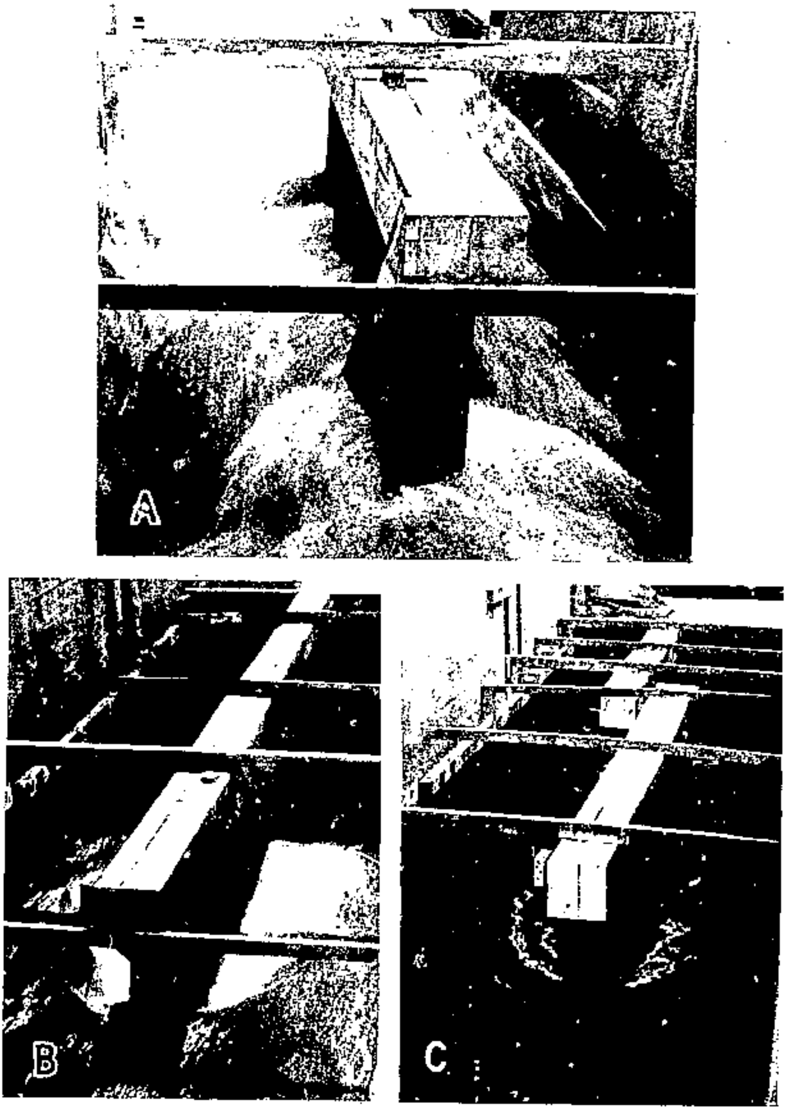
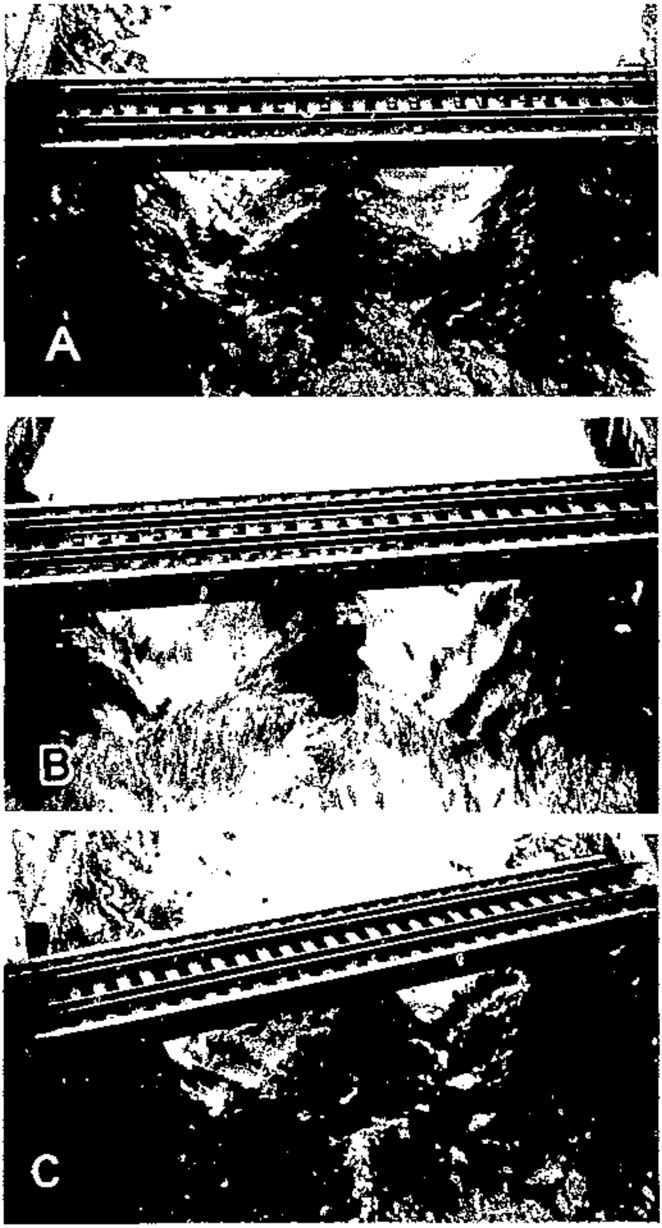


FIGURE 3.—Trestle set-ups tested.



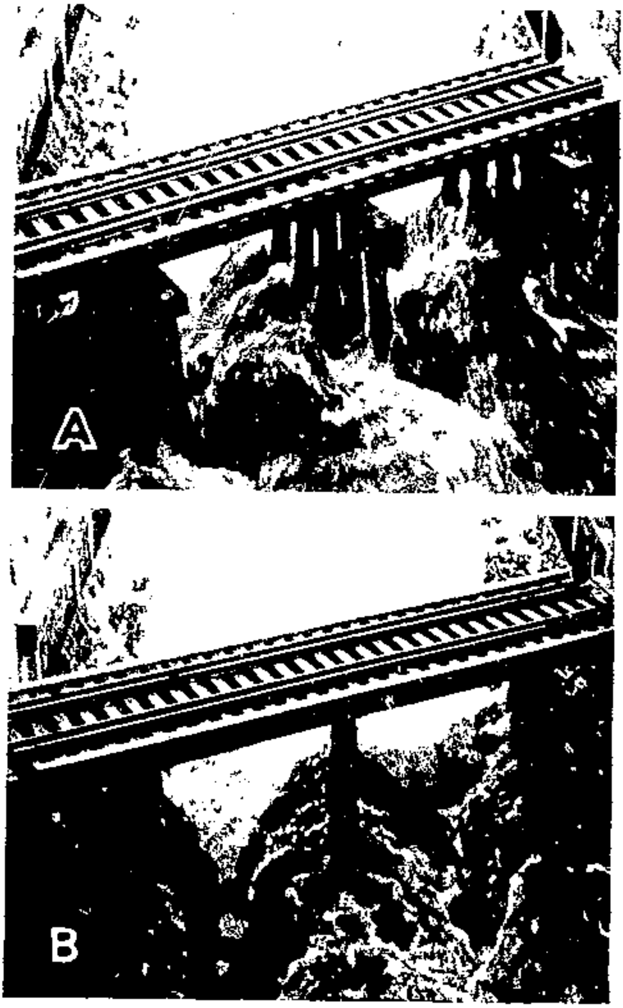
FULL-SIZE PILE TRESTLES UNDER TEST.

A, Single-track 5-pile trestle bent in line with current; channel contraction, 16.2 percent. B, Double-track 10-pile trestle bent in line with current; channel contraction, 14 percent. C, Two single-track 5-pile trestle bents in line with current, bents offset; channel contraction 14 percent.



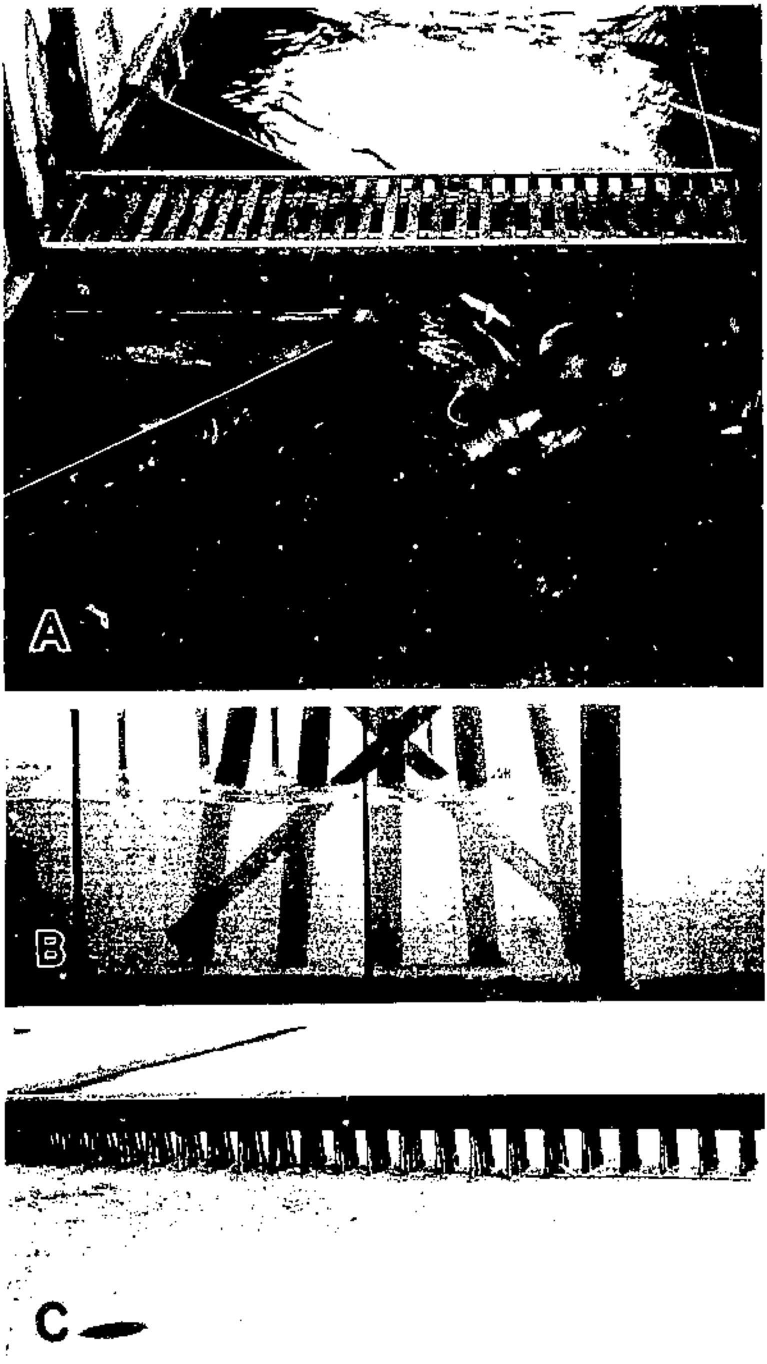
ONE-QUARTER SCALE MODEL OF 3-BENT SINGLE-TRACK PILE TRESTLE, 40 FEET LONG.

A, Bents in line with current, channel contraction, 12.5 percent. B, Bents at 10° angle with current, channel contraction taken as 12.5 percent. C, Bents at 20° angle with current, channel contraction taken as 12.5 percent.



ONE-QUARTER SCALE MODEL OF 3-BENT SINGLE-TRACK PILE TRESTLE, 40 FEET LONG.

A, Bents at 30° angle with current, channel contraction taken as 12.3 percent. B, Bents set in echelon in testing channel, angle of axis of deck with current, 60°; channel contraction as 12.3 percent.



TRESTLE MODELS UNDER TEST.

A, One-quarter scale model of a 20-foot single-track pile trestle. One end abutment and one bent in testing channel. Channel contraction taken as 56 percent. B, One-quarter scale model of a 5-pile trestle bent under test in glass-walled flume. C, One one-hundredth scale model of a single-track pile trestle 410 feet long.

bent consisting of two 5-pile bents, each offset from the other by the thickness of the piling and sway bracing, was tested with the pile lines parallel to the current and with the pile lines set at a 10° angle with the current. In the oblique position, tests were made with the bents offset first to the left and then to the right.

Tests were also conducted on a ¼-scale model representing a trestle 40 feet long with three 5-pile bents placed at angles of 0°, 10°, 20°, and 30° with the current, and also with the bents tested in echelon parallel to the current (pls. 2 and 3). In one test with this model the channel was obstructed as shown in plate 4, *A* to represent the effect of one trestle bent and one end abutment, the total channel contraction being 56 percent.

Check experiments on a ¼-scale model of a 5-pile trestle bent were run in the glass-walled flume of the laboratory, giving a channel contraction of 16 percent (pl. 4, *B*). The tests were conducted by first running a definite quantity of water through the unobstructed flume and taking readings of the water slope. Then the trestle bent was placed in the channel and the water-surface slope again read, to determine the amount of rise in the water surface upstream from the bent. Fourteen experiments were made in which the discharges ranged from 2.46 to 8.05 cubic feet per second, the depths of flow from 0.87 to 2.60 feet, and the velocities upstream from the bent from 1.09 to 1.94 feet per second.

To determine the effect of submergence upon the trestle coefficient, tests were run on the ¼-scale model with different degrees of submergence as follows: (1) With the water just touching the bottoms of the stringers; (2) with the upstream water surface at the top of the stringers; (3) with the upstream water surface to the top of the guard rail; (4) with the upstream water surface over the top of the guard rail.

To study the reliability of results obtained from tests on extremely small models, experiments were made on models constructed to a scale of 1 to 100, representing trestles 440 feet long with 5-pile bents (pl. 4, *C*). Experiments on this model were made with three quantities of flow and the following set-ups: (1) A single-track trestle, (2), a double-track trestle with bents in line, and (3), a double-track trestle with the bents offset. Other tests with the model of the 440-foot single-track trestle were made to investigate the obstruction to flow offered by an embankment with trestle openings, such as is commonly built to carry a railway or highway across a river valley subject to overflow at such height that the roadbed is above high water. Tests were run with various portions of the trestle blocked off to represent embankments of different lengths as shown for set-ups 312 to 317 in figure 3.

TEST PROCEDURE

Most of the experiments were run in the principal testing canal of the labratory, which is 312 feet long, 10 feet wide, and 10 feet deep. At its upstream end is an electrically operated head gate 10 feet wide by 10 feet deep. A calibrated weir of the suppressed type 10 feet long, for measuring flow in the canal, is located 60 feet downstream from the head gate. Numerous baffles were placed in the canal immediately below the head gate to obtain uniform velocity distribution as the water approached the weir, and a smooth flow over the crest. Similar baffles were placed immediately downstream from the weir to prevent commotion of the water as it approached the pile trestles. An adjustable weir 6 feet high, located some 80 feet downstream from the center of the pile bent, was used to regulate the water level downstream from the trestle. This weir was hung on hinges and was adjusted by means of a block and tackle.

The loss of head caused by the trestles was measured by means of 37 piezometers on the wall of the canal. The piezometer openings through the wall were spaced throughout a distance of 69 feet, and were 4 inches above a level floor built in the bottom of the testing canal. Ten openings 2½ feet apart were made upstream from the trestle site, 15 openings 6 inches apart were made at the site, and 12 openings 2½ feet apart were made downstream from the site. The piezometers were 1-inch glass tubes 3 feet long attached to white-enameled gage staffs on the outside of the canal wall, and were connected to the wall openings by means of rubber tubing. The gage staffs, 3.3 feet long, were graduated to 0.02 foot, and the markings could be read to the nearest 0.01 foot with little chance of error.

Several staff gages also were set along both walls of the canal, the zeros of all being set even with the level floor constructed in the canal, to supplement the piezometer measurements in determining the depth of flow and the water-surface gradient above and below the pier as well as the depth in the contracted section along the trestle bent.

Tests in the 10-foot canal were conducted with quantities of flow ranging from 8 to 100 cubic feet per second and with depths of flow, D_3, from 0.8 foot to 3.2 feet, resulting in velocities past the trestles ranging from 0.6 foot to 5 feet per second. The height of trestle to bottom of stringer above the testing floor was 4.9 feet for the full-size bents and 3.6 feet for the ¼-scale models.

For the tests in the 10-foot canal, experiments were begun with a head of about 0.40 foot of water discharging over the measuring weir, followed by experiments with successive increases of about 0.05 foot in head on the weir, until the greatest possible quantity was obtained. Different depths of flow at the trestle site for each head on the weir were obtained by raising or lowering the adjustable weir.

With each quantity of flow two tests were run, in most cases, for each class of flow. To obtain the desired type of flow, in order to compare the Rehbock formula (equation 7) with the D'Aubuisson and Nagler formulas (equations 2 and 4), the procedure was as follows:

After the desired head on the weir was obtained, the observer first read the hook gage above the weir; then, knowing the quantity of flow he computed by means of equation 5 a depth which would give class 1 flow. The adjustable weir was regulated to obtain this depth. Readings were then taken on the various piezometers and staff gages, and a check reading on the weir hook gage to see if the quantity of flow had varied. Another test with a different depth but same class of flow was then run in the same manner. The depth for this test was also determined by means of equation 5. Then, without varying the quantity of flow, two tests at different depths in class 2 flow and two tests in class 3 flow were run. The range of depths for each class was determined by equations 5 and 6, and the desired variations in depth were obtained by means of the adjustable weir. With each increase in quantity of flow a similar series of tests was made.

Typical profiles of the water surface in the testing canal are shown in figures 5 and 6, for the 5-pile and 10-pile bents, respectively. The generally continuous loss of head through the length of the bent, evidenced by the continuing decrease in depth, is very apparent and so is the partial recovery of velocity head immediately below the bent. The greater turbulence of the flow at higher velocities accompanying

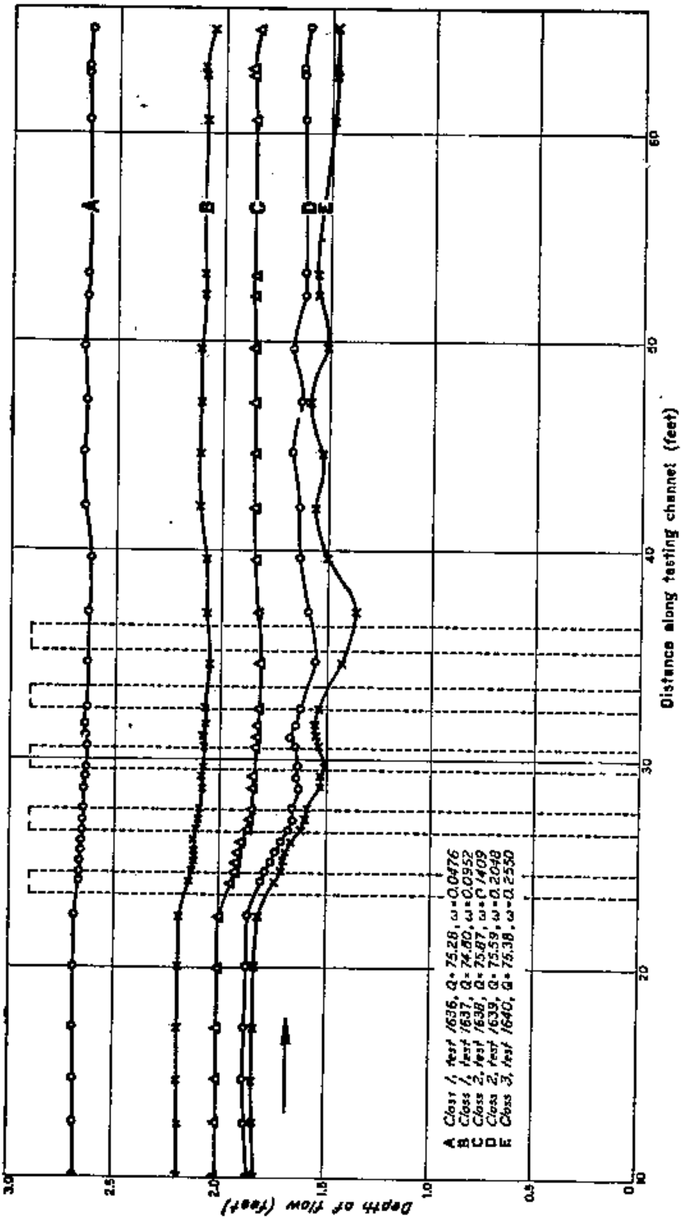


FIGURE 4.—Water-surface profiles in tests of full-size single-track 5-pile trestle bent parallel to current. Flow approximately 75 cubic feet per second; depth varied by means of adjustable weir. Channel contraction 10.2 percent. Each pile represented by two lines. Piezometer and staff gage readings shown by symbols.

the lesser depths is indicated by the irregularities of the profiles below the bridge site. The throttling effect of the obstruction is indicated

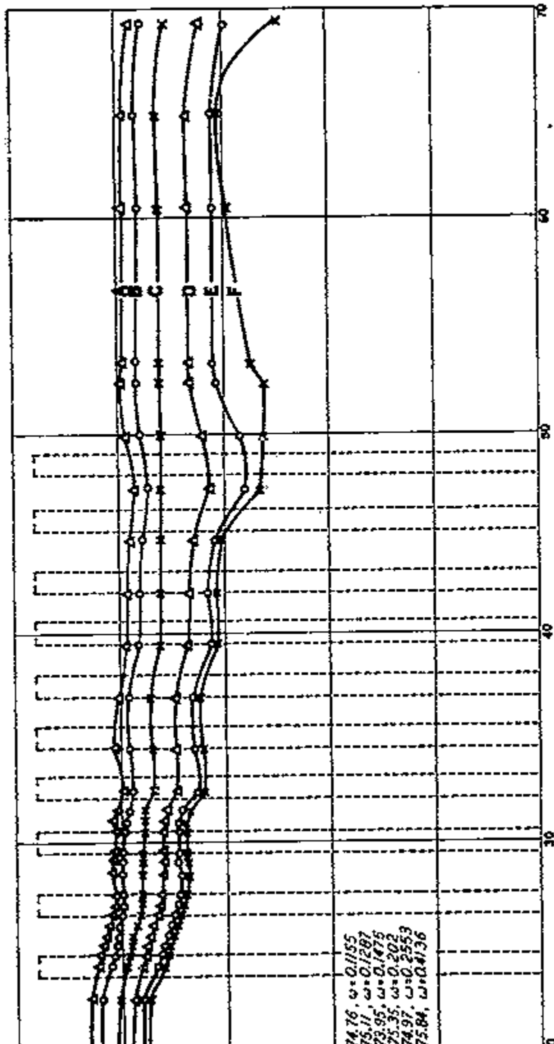


FIGURE 4.—Water-surface profiles in tests of full-size double-track 10-pile trestle bent parallel to current. Flow approximately 75 cubic feet per second; depth varied by means of adjustable weir. Channel contraction 14 percent. Each pile represented by two lines. Piezometer and staff-gage readings shown by symbols.

by the lesser changes in depth above than below the bent, with adjustment of the depth-control weir.

FIGURE 6

FOUND AT END

OF BULLETIN.

The pile-trestle coefficients for the D'Aubuisson, Nagler, and Rehbock formulas were computed by substituting the laboratory measurements of flow and surface drop and the other known factors in the equations 3, 4, 7, and 8. These coefficients were plotted against the corresponding velocities, V_1, upstream from the trestle bent, and the results are shown in figures 6 and 7. Summaries of the coefficients for the full-size and ¼-scale-model set-ups are given in tables 1 and 2. Table 1 gives the coefficients which may be used in practical work.

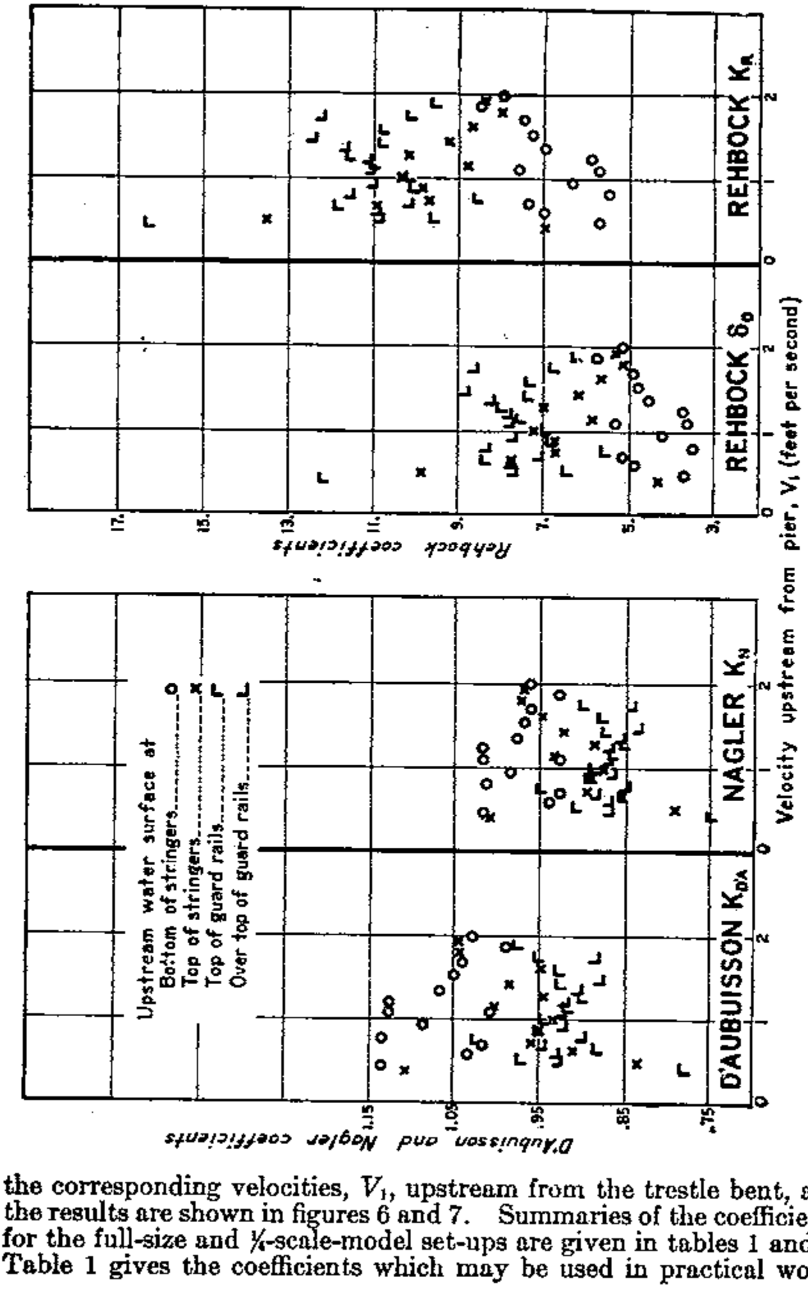


Figure 7.—Computed pile-trestle coefficients in relation to velocity upstream from bridge, showing effect of submergence of bridge.

The test results in table 2 are of only academic, theoretical interest and should not be used indiscriminately in practical work.

TABLE 1.—*Pile-trestle coefficients for bridge-pier formulas*

(For summary of recommended values, see table 9, p. 25)

<table>
<tr><th rowspan="2">Formula</th><th colspan="2">Class 1 flow</th><th colspan="2">Class 2 flow</th><th colspan="2">Class 3 flow</th><th rowspan="2">Mean coefficient for classes 1 and 2 [1]</th><th rowspan="2">Mean coefficient for all 3 classes [1]</th></tr>
<tr><th>Tests</th><th>Average coefficient</th><th>Tests</th><th>Average coefficient</th><th>Tests</th><th>Average coefficient</th></tr>
<tr><td colspan="9">FULL-SIZE SINGLE-TRACK TRESTLE, 0° ANGLE WITH CURRENT; CHANNEL CONTRACTION 16.2 PERCENT (pl. 1, <i>A</i>)</td></tr>
<tr><td></td><td><i>Number</i></td><td></td><td><i>Number</i></td><td></td><td><i>Number</i></td><td></td><td></td><td></td></tr>
<tr><td>D'Aubuisson $K_{D'A}$</td><td>21</td><td>1.003</td><td>19</td><td>0.970</td><td>11</td><td>0.957</td><td>0.987</td><td>0.981</td></tr>
<tr><td>Nagler K_N</td><td>21</td><td>.885</td><td>19</td><td>.913</td><td>11</td><td>.943</td><td>.898</td><td>.906</td></tr>
<tr><td>Rehbock δ_0</td><td>21</td><td>5.03</td><td>19</td><td>6.41</td><td>-----</td><td>(2)</td><td>5.68</td><td>-----</td></tr>
<tr><td>Rehbock K_R</td><td>21</td><td>3.02</td><td>19</td><td>4.51</td><td>11</td><td>5.34</td><td>3.72</td><td>4.12</td></tr>
<tr><td colspan="9">FULL-SIZE DOUBLE-TRACK TRESTLE, 10 PILES IN LINE; 0° ANGLE WITH CURRENT; CHANNEL CONTRACTION 14.0 PERCENT (pl. 1, <i>B</i>)</td></tr>
<tr><td>D'Aubuisson $K_{D'A}$</td><td>24</td><td>0.886</td><td>29</td><td>0.852</td><td>10</td><td>0.880</td><td>0.859</td><td>0.862</td></tr>
<tr><td>Nagler K_N</td><td>24</td><td>.817</td><td>29</td><td>.828</td><td>10</td><td>.873</td><td>.823</td><td>.831</td></tr>
<tr><td>Rehbock δ_0</td><td>24</td><td>11.84</td><td>29</td><td>12.70</td><td>-----</td><td>(2)</td><td>12.31</td><td>-----</td></tr>
<tr><td>Rehbock K_R</td><td>24</td><td>7.28</td><td>29</td><td>8.41</td><td>10</td><td>8.32</td><td>7.90</td><td>7.96</td></tr>
<tr><td colspan="9">FULL-SIZE DOUBLE-TRACK TRESTLE, DOWNSTREAM BENT OFFSET; 0° ANGLE WITH CURRENT; CHANNEL CONTRACTION 14 PERCENT (pl. 1, <i>C</i>)</td></tr>
<tr><td>D'Aubuisson $K_{D'A}$</td><td>44</td><td>0.846</td><td>12</td><td>0.828</td><td>10</td><td>0.858</td><td>0.842</td><td>0.845</td></tr>
<tr><td>Nagler K_N</td><td>44</td><td>.782</td><td>12</td><td>.814</td><td>10</td><td>.928</td><td>.789</td><td>.810</td></tr>
<tr><td>Rehbock δ_0</td><td>44</td><td>12.95</td><td>12</td><td>14.25</td><td>-----</td><td>(2)</td><td>13.23</td><td>-----</td></tr>
<tr><td>Rehbock K_R</td><td>44</td><td>7.31</td><td>12</td><td>9.55</td><td>10</td><td>9.93</td><td>7.79</td><td>8.11</td></tr>
<tr><td colspan="9">ONE FOURTH-SCALE MODEL OF 40-FOOT SINGLE-TRACK TRESTLE; THREE 5-PILE BENTS IN TESTING CHANNEL; 0° ANGLE WITH CURRENT; CHANNEL CONTRACTION 12.5 PERCENT (pl. 2, <i>A</i>)</td></tr>
<tr><td>D'Aubuisson $K_{D'A}$</td><td>28</td><td>0.978</td><td>27</td><td>0.972</td><td>11</td><td>0.971</td><td>0.975</td><td>0.974</td></tr>
<tr><td>Nagler K_N</td><td>28</td><td>.898</td><td>27</td><td>.933</td><td>11</td><td>.950</td><td>.915</td><td>.926</td></tr>
<tr><td>Rehbock δ_0</td><td>28</td><td>6.33</td><td>27</td><td>6.90</td><td>-----</td><td>(2)</td><td>6.61</td><td>-----</td></tr>
<tr><td>Rehbock K_R</td><td>28</td><td>3.72</td><td>27</td><td>4.68</td><td>11</td><td>5.64</td><td>4.19</td><td>4.43</td></tr>
<tr><td colspan="9">ONE FOURTH-SCALE MODEL OF 40-FOOT SINGLE-TRACK TRESTLE; THREE 5-PILE BENTS IN TESTING CHANNEL; 10° ANGLE WITH CURRENT; CHANNEL CONTRACTION 12.3 PERCENT (pl. 2, <i>B</i>)</td></tr>
<tr><td>D'Aubuisson $K_{D'A}$</td><td>18</td><td>0.994</td><td>18</td><td>0.989</td><td>9</td><td>0.983</td><td>0.991</td><td>0.990</td></tr>
<tr><td>Nagler K_N</td><td>18</td><td>.914</td><td>18</td><td>.939</td><td>9</td><td>.983</td><td>.927</td><td>.938</td></tr>
<tr><td>Rehbock δ_0</td><td>18</td><td>5.48</td><td>18</td><td>5.93</td><td>-----</td><td>(2)</td><td>5.71</td><td>-----</td></tr>
<tr><td>Rehbock K_R</td><td>18</td><td>3.25</td><td>18</td><td>3.93</td><td>9</td><td>5.14</td><td>3.59</td><td>3.90</td></tr>
<tr><td colspan="9">ONE FOURTH-SCALE MODEL OF 40-FOOT SINGLE-TRACK TRESTLE; THREE 5-PILE BENTS IN TESTING CHANNEL; 20° ANGLE WITH CURRENT; CHANNEL CONTRACTION 12.3 PERCENT (pl. 2, <i>C</i>)</td></tr>
<tr><td>D'Aubuisson $K_{D'A}$</td><td>18</td><td>0.952</td><td>14</td><td>0.960</td><td>9</td><td>0.958</td><td>0.956</td><td>0.956</td></tr>
<tr><td>Nagler K_N</td><td>18</td><td>.887</td><td>14</td><td>.923</td><td>9</td><td>.960</td><td>.903</td><td>.915</td></tr>
<tr><td>Rehbock δ_0</td><td>18</td><td>7.54</td><td>14</td><td>7.42</td><td>-----</td><td>(2)</td><td>7.49</td><td>-----</td></tr>
<tr><td>Rehbock K_R</td><td>18</td><td>4.45</td><td>14</td><td>4.95</td><td>9</td><td>5.84</td><td>4.67</td><td>4.93</td></tr>
</table>

[1] Computed as the average of the individual determinations for all the tests, not as the average of the average determinations for the classes as shown in preceding columns.

[2] δ_0 was not computed for class 3 flow.

Table 1.—*Pile-trestle coefficients for bridge-pier formulas*—Continued

ONE FOURTH-SCALE MODEL OF 40-FOOT SINGLE-TRACK TRESTLE; THREE 5-PILE BENTS IN TESTING CHANNEL; 30° ANGLE WITH CURRENT; CHANNEL CONTRACTION 12.3 PERCENT (pl. 3, *A*)

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2	Mean coefficient for all 3 classes
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
	Number		*Number*		*Number*			
D'Aubuisson $K_{D'A}$	21	0.920	9	0.929	9	0.932	0.923	0.925
Nagler K_N	21	.863	9	.906	9	.942	.876	.891
Rehbock δ_0	21	9.31	9	9.06		([2])	9.24	
Rehbock K_R	21	5.46	9	6.11	9	6.84	5.66	5.93

ONE FOURTH-SCALE MODEL OF 40-FOOT SINGLE-TRACK TRESTLE; THREE 5-PILE BENTS IN ECHELON IN TESTING CHANNEL, AXIS OF DECK AT ANGLE OF 60° WITH CURRENT; CHANNEL CONTRACTION 12.3 PERCENT pl. 3, *B*)

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2	Mean coefficient for all 3 classes
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
D'Aubuisson $K_{D'A}$	24	1.022	20	1.010	10	1.002	1.016	1.014
Nagler K_N	24	.934	20	.950	10	.997	.942	.952
Rehbock δ_0	24	4.23	20	5.09		([2])	4.62	
Rehbock K_R	24	2.53	20	3.39	10	4.55	2.92	3.22

ONE FOURTH-SCALE MODEL OF 20-FOOT SINGLE-TRACK TRESTLE; ONE END ABUTMENT AND ONE BENT IN TESTING CHANNEL; 0° ANGLE WITH CURRENT; CHANNEL CONTRACTION 56 PERCENT (pl. 4, *A*)

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2	Mean coefficient for all 3 classes
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
D'Aubuisson $K_{D'A}$	26	1.002	26	0.958	11	1.786	0.980	1.121
Nagler K_N	26	.925	26	.915	[3] 7	5.20	.920	1.428
Rehbock δ_0	26	5.42	26	6.02		([2])	5.72	
Rehbock K_R	26	7.70	26	8.92	11	2.73	8.31	7.33

[2] δ_0 was not computed for class 3 flow.

[3] Coefficients for 4 tests not included because very erratic.

Table 2.—*Computed coefficients for full-size pile trestles, bents placed at angle with current*

(Of academic interest only; for recommended values see table 7, p. 22)

SINGLE-TRACK TRESTLE; 5° ANGLE WITH CURRENT; CHANNEL CONTRACTION 14 PERCENT

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2 [1]	Mean coefficient for all 3 classes [1]
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
	Number		*Number*		*Number*			
D'Aubuisson $K_{D'A}$	48	0.932	37	0.913	9	0.934	0.924	0.925
Nagler K_N	48	.843	37	.877	9	.929	.858	.865
Rehbock δ_0	48	8.27	37	9.35		([2])	8.74	
Rehbock K_R	48	4.74	37	6.38	9	6.48	5.45	5.55

SINGLE-TRACK TRESTLE; 10° ANGLE WITH CURRENT; CHANNEL CONTRACTION 14 PERCENT

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2 [1]	Mean coefficient for all 3 classes [1]
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
D'Aubuisson $K_{D'A}$	64	0.904	19	0.874	13	0.887	0.967	0.896
Nagler K_N	64	.826	19	.848	13	.891	.831	.839
Rehbock δ_0	64	9.64	19	11.51		([2])	10.07	
Rehbock K_R	64	5.50	19	7.77	13	8.10	6.02	6.30

[1] Computed as the average of the individual determinations for all the tests, not as the average of the average determinations for the classes as shown in preceding columns.

[2] δ_0 was not computed for class 3 flow.

TABLE 2.—*Computed coefficients for full-size pile trestles, bents placed at angle with current*—Continued

SINGLE-TRACK TRESTLE; 15° ANGLE WITH CURRENT; CHANNEL CONTRACTION 14 PERCENT

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2	Mean coefficient for all 3 classes
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
	Number		*Number*		*Number*			
D'Aubuisson $K_{D'A}$	61	0.868	19	0.834	11	0.871	0.860	0.861
Nagler K_N	61	.793	19	.805	11	.880	.796	.806
Rehbock δ_0	61	11.80	19	13.87	--------	(1)	12.29	----------
Rehbock K_R	61	6.53	19	8.91	11	8.68	7.10	7.29

SINGLE-TRACK TRESTLE; 20° ANGLE WITH CURRENT; CHANNEL CONTRACTION 14 PERCENT

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2	Mean coefficient for all 3 classes
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
D'Aubuisson $K_{D'A}$	45	0.817	7	0.786	3	0.828	0.813	0.813
Nagler K_N	45	.754	7	.788	3	.842	.759	.763
Rehbock δ_0	45	15.18	7	16.82	--------	(1)	15.40	----------
Rehbock K_R	45	8.30	7	11.58	3	10.28	8.74	8.82

SINGLE-TRACK TRESTLE; 30° ANGLE WITH CURRENT; CHANNEL CONTRACTION 14 PERCENT

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2	Mean coefficient for all 3 classes
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
D'Aubuisson $K_{D'A}$	55	0.789	11	0.767	(2)	----------	0.785	----------
Nagler K_N	55	.729	11	.780	(2)	----------	.737	----------
Rehbock δ_0	55	17.48	11	18.21	(2)	----------	17.60	----------
Rehbock K_R	55	9.35	11	12.80	(2)	----------	9.92	----------

DOUBLE-TRACK TRESTLE; DOWNSTREAM BENT OFFSET TO LEFT, LOOKING DOWNSTREAM; 10° COUNTER-CLOCKWISE ANGLE WITH CURRENT; CHANNEL CONTRACTION 14 PERCENT

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2	Mean coefficient for all 3 classes
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
D'Aubuisson $K_{D'A}$	49	0.768	2	0.748	8	0.777	0.768	0.769
Nagler K_N	49	.706	2	.762	8	.803	.708	.721
Rehbock δ_0	49	18.96	2	23.14	--------	(1)	19.12	----------
Rehbock K_R	49	9.75	2	13.64	8	12.64	9.91	10.28

DOUBLE-TRACK TRESTLE; DOWNSTREAM BENT OFFSET TO RIGHT, LOOKING DOWNSTREAM; 10° COUNTER CLOCKWISE WITH CURRENT; CHANNEL CONTRACTION 14 PERCENT

Formula	Class 1 flow		Class 2 flow		Class 3 flow		Mean coefficient for classes 1 and 2	Mean coefficient for all 3 classes
	Tests	Average coefficient	Tests	Average coefficient	Tests	Average coefficient		
D'Aubuisson $K_{D'A}$	36	0.802	10	0.793	8	0.830	0.800	0.804
Nagler K_N	36	.746	10	.780	8	.879	.753	.772
Rehbock δ_0	36	16.27	10	16.54	--------	(1)	16.32	----------
Rehbock K_R	36	9.03	10	10.62	8	10.88	9.37	9.60

[1] δ_0 was not computed for class 3 flow.

[2] For this channel contraction there were no data in this class.

In figure 6 are plotted all the individual determinations that form the basis of table 1. Figure 7 shows the results of all tests to determine the effect of submergence upon the trestle coefficients. Table 3 shows results of experiments with the 1/100-scale model.

TABLE 3.—*Computations of pile-trestle coefficients for D'Aubuisson formula from tests on 1/100-scale models of trestles 440 feet long*

[The quantities stated in this table represent values in the prototype]

Flow Q	Depth upstream D_1	Velocity upstream V_1	Backwater height H_1	D'Aubuisson coefficient $K_{D'A}$
SINGLE-TRACK TRESTLE				
Cubic feet per second	*Feet*	*Feet per second*	*Feet*	
6,800	5.27	2.95	0.07	0.960
14,000	7.97	3.99	.12	.972
15,300	9.85	3.53	.10	.943
DOUBLE-TRACK 10 PILES IN LINE				
6,950	5.36	2.95	0.12	0.874
15,100	9.85	3.49	.12	.911
14,100	8.07	3.07	.17	.915
DOUBLE-TRACK OFFSET 5-PILE BENTS				
6,700	5.26	2.90	0.10	0.897
14,050	8.10	3.94	.21	.876
15,200	9.87	3.50	.14	.887

In the computations, the amount of channel contraction was taken as the average diameter of the piles plus the thickness of the sway bracing, except when the deck of the trestle was submerged. For those tests in which the bent was placed at an angle with the current, the channel contraction was taken the same as for the same bent placed parallel to the current and the effect of building the trestle at an angle was thrown into the coefficient. The ¼-size model contracted the 10-foot channel 12.5 percent. The ¼-size model with the abutment (pl. 4, *A*) caused a channel contraction of 56 percent. The full-size single-track trestle with piles parallel to the current contracted the 10-foot channel 16.2 percent, and the full-size, double-track trestle with 10 piles in line contracted the channel 14 percent, the former being made of larger piles. With the full-size double-track trestle with offset 5-pile bents, the channel contraction was taken as 14 percent.

For the submergence tests, which were made on the ¼-scale model with one end abutment, the channel contraction was computed by taking the total wetted cross-sectional area of the trestle obstructing the flow of the water. For example, when the water was to the top of the stringers, the vertical area of the stringers and the cross-sectional area of the caps was added to the obstructing area of the piling, to get the amount of channel contraction.

Since the Rehbock formula (no. 7) was intended to apply only to class 1 flow as defined by equation 5, a fair comparison of this formula with the others can be made only with the tests belonging to class 1 flow. Hence, the tests were classified according to type of flow by applying equations 5 and 6.

Neither D'Aubuisson nor Nagler specified the kind of flow to which his formula applied. It is probable, however, that all three formulas are applicable only to class 1 flow. In this investigation the D'Aubuisson and Nagler coefficients have been computed for classes 2 and 3 merely to determine the variation in coefficient with class of flow. It should be noted that except in some of the tests for class 3 flow with the ¼-scale model having the end abutment, the Nagler and D'Aubuisson formulas appear to apply very favorably to the experiments involving all classes of flow (fig. 6).

The Rehbock coefficient δ_0 was not computed for class 3 flow because this formula was intended to apply only to class 1 flow. The coefficients were computed for class 2 flow because cases of this class often occur, and there is not a great deal of difference between class 1 and class 2 flows. Class 3 flow seldom prevails at a bridge-pier site, except perhaps in mountain streams or at bridges having unusually large channel contractions.

The dispersion of the points in figures 6 and 7 is due to the fact that the drop or backwater caused by the trestle was often so small that unavoidable inexactness of measuring water-surface elevations caused appreciable inaccuracies in the computed coefficients. The average of the plotted points, however, should be thoroughly reliable. The rate of flow was controlled within 1 percent, hence the average coefficients in table 1 can be used with confidence in solving practical problems.

EFFECT ON COEFFICIENT OF BENTS PLACED IN LINE WITH THE CURRENT

SINGLE-TRACK TRESTLE

The full-size trestle bents in the 10-feet testing canal gave practically the same percentage of channel contraction as commonly exists in field installations. Including the thickness of the two sway braces, the average width of a trestle bent is about 1.65 feet. With such bents set on 11.75-foot centers the channel contraction is 14 percent, on 13-foot centers it is 12.7 percent, and on 13.75-foot centers the channel contraction is 11.2 percent. The full-size single-track bent used in these experiments had a channel contraction of 16 percent, but channel contractions caused by pile trestles range from 10 to 16 percent.

In making a comparison of coefficients obtained from tests on models of different sizes it is desirable to compare the coefficient for 1 or 2 formulas. In these comparisons the D'Aubuisson formula has been taken. Likewise the average coefficient for class 1 flow only has been taken for purposes of comparison.

It will be seen in table 1 that the D'Aubuisson coefficient for the full-size single-track trestle was 1.003. The D'Aubuisson coefficient for the ¼-scale model in the main testing canal, was 0.978. The average D'Aubuisson coefficient for 14 experiments on the ¼-scale model bent in the glass-walled flume was 1.00. The average D'Aubuisson coefficient for the ¹⁄₁₀₀-scale model trestle was 0.96 (table 3).

DOUBLE-TRACK TRESTLE

The D'Aubuisson coefficient for the full-size double-track trestle with the 10 piles in line was 0.866. The coefficient for the ¹⁄₁₀₀-scale model with the 10 piles in line varied from 0.874 to 0.915, an average being about 0.900

The D'Aubuisson coefficient for the full-size double-track trestle with the offset bents was 0.846. The coefficient for the ¹⁄₁₀₀-scale model with the offset bents varied from 0.876 to 0.897, and average being about 0.887.

In comparing the coefficients for the double-track trestle with those for the single-track trestle it will be noted that the coefficients for the former are somewhat less than for the latter, showing that additional piles in line increase the resistance to the flow of the water. The values of the coefficients for the two full-size 5-pile trestle bents with the bents offset are also less than those for the full-size single-track trestle.

The obstruction offered by the double-track trestle with offset type of bents is a little greater than the type with the 10 piles in line in each bent.

The coefficient charts, figures 6 and 7, on which all of the coefficients obtained have been plotted, are of especial interest as they show the variation of the coefficient with velocity. If the coefficients had been plotted against the depth of flow, D_1, a similar but less coordinated vertical variation of the coefficients would have resulted.

It will be noted that the points on the D'Aubuisson and Nagler diagrams are bunched quite closely, particularly for those tests with class 1 and class 2 flows. The points on the Rehbock diagrams are quite scattered showing that Rehbock's formulas, insofar as the coefficients are concerned, are quite sensitive.

These charts show that generally within the range of the experiments the coefficients increase with an increase in discharge or velocity for D'Aubuisson and Nagler, contrary for Rehbock. The ideal bridge-pier or pile-trestle formula would be one in which the pier or trestle coefficient is a constant for all discharges.

EFFECT ON COEFFICIENT OF BENTS PLACED AT AN ANGLE WITH THE CURRENT

To obtain useful data on trestles placed at an angle with the current in which identical field conditions could be simulated, the ¼-scale model of a pile trestle 40 feet long was used. The results of these tests are given in table 1.

It will be noted that, with one exception, the D'Aubuisson and Nagler coefficients decrease with an increase in the angle the trestle bents make with the current. The D'Aubuisson and Nagler coefficients for the three ¼-scale model trestle bents set at a 10° angle with the current are slightly higher than those for the same trestle with the bents set in line with the current. This small increase in the coefficient, 1.6 percent, is logical since the beneficial effects of the partially echelon placement of the bents may more than offset the minor additional obstruction to flow offered by the 10° angle.

As the angle of the bent with the current increases beyond 10° the additional obstruction offered by the bent is not offset so much by the echelon effect of the bents, hence the coefficients decrease slightly with an increase in the amount of the angle.

Attention is called to the D'Aubuisson and Nagler coefficients for the three ¼-scale model trestle bents when set in echelon. These coefficients are some 5 percent greater than the coefficients for the three ¼-scale model bents set in line in the channel showing that bents set in echelon offer less obstruction to the flow than bents of a trestle crossing normal to the current.

The coefficients obtained from the tests on the full-size trestles placed at an angle with the current as shown in table 2 are not applicable to field installations since the actual obstruction caused by the full-size trestle when placed at an angle in the testing channel was much greater than that which would occur in a stream of greater width. These coefficients, however, have much theoretical and academic value and for that reason are included in this report.

EFFECT ON COEFFICIENT OF CONTRACTING STREAM CHANNEL BY ABUTMENTS

When a railway or highway embankment is built across a river valley subject to overflow, usually several waterway openings are planned at various intervals so that the flood waters can be discharged through the respective openings with comparatively little loss of head. The question naturally arises as to the method of computing channel contraction in such cases. If the gross width of the stream is considered to be no wider than that occupied by the trestle, then the contraction caused by the bents is small and usually lies between 11 and 14 percent. If the embankment is considered to obstruct part of the waterway, the percentage of contraction will be large. Investigations were made of the effect on the coefficient by the consideration of the embankment as part of the waterway contraction.

In the first series of experiments, an embankment, or more properly speaking, an abutment was added to the ¼-scale model of a single-track pile trestle 40 feet long as shown in plate 4, *A*. This set-up gave a contraction of 56 percent considering the width of the waterway as a whole. The D'Aubuisson coefficient $K_{D'A}$ for this set-up was 1.00, whereas the average coefficient for the same set-up without the end abutment was 0.98. It would appear from this set of tests that there will be comparatively little difference in the coefficient if different channel contractions are used.

The second series of experiments were made on the 1/100-scale model of a single-track pile trestle 440 feet long in which portions of the trestle opening were blocked off so as to give the various percentages of channel contraction shown in set-ups nos. 312 to 317 in figure 3. The results of these tests are given in table 4.

TABLE 4.—*Variation of D'Aubuisson coefficient with contraction of waterway*

Set-up no.[1]	Contraction of 440-foot channel	End contractions	D'Aubuisson coefficient $K_{D'A}$	Set-up no.[1]	Contraction of 440-foot channel	End contractions	D'Aubuisson coefficient $K_{D'A}$
	Percent	*Number*			*Percent*	*Number*	
311	9	0	0.96	315	56	4	0.86
312	29	2	.94	316	48	6	.90
313	51	2	.95	317	46	1	.80
314	73	2	.94				

[1] See fig. 3.

It will be seen that the coefficients for the set-ups nos. 315, 316, and 317 are somewhat lower than the coefficients for the other set-ups. A duplicate test was run on set-up 315 and the value of the coefficient checked. Apparently there is little difference in the coefficients for set-ups 311 to 314, inclusive, even though the channel contraction for set-up 314 is two and one half times that for set-up 312.

It would appear from this that the amount of channel contraction does not have a great effect on the coefficient as long as critical velocity does not exist.

Disturbance of the symmetry of flow as in set-up 317 undoubtedly causes a decrease in the coefficient. The distribution of the flow through a series of multiple openings as in set-ups 315 and 316 reduces the coefficient by increasing the number of end contractions. However, when the openings have been made more numerous, the degree of contraction caused by the individual sections of the embankments may be decreased with a corresponding increase in the value of the coefficient as shown by set-up 316 in comparison with 315.

EFFECT ON COEFFICIENT OF SUBMERGENCE OF PILE TRESTLES

The experiments on the submergence of pile trestles were conducted on the ¼-scale model trestle with the end abutment. The area of obstruction to flow was computed by including the abutment and the bent and that portion of the stringers and guard rails which actually obstructed the flow of water. This additional area of resistance to flow was converted into width of equivalent obstruction so that the proper value of the effective width W_2 or the channel contraction factor could be used in the formulas.

A total of 47 experiments were made in which the deck of the trestle was submerged to varying depths. The coefficients obtained from these tests as illustrated in figure 7 show definitely that the Nagler and D'Aubuisson coefficients decrease as the amount of submergence increases, while the Rehbock coefficient δ_0 increases with an increase in submergence. The values of the coefficients for various degrees of submergence are shown in table 5.

TABLE 5.—*Summary of D'Aubuisson, Nagler, and Rehbock pile-trestle coefficients for trestles submerged varying amounts*

Water surface	Coefficient			Water surface	Coefficient		
	Nagler K_N	D'Aubuisson $K_{D'A}$	Rehbock δ_0		Nagler K_N	D'Aubuisson $K_{D'A}$	Rehbock δ_0
At bottom of stringers	0.97	1.06	4.53	At top of guard rails	0.88	0.93	7.56
At top of stringers	.91	.97	6.48	Over top of guard rails	.86	.91	7.90

USE OF DATA ILLUSTRATED BY EXAMPLES

These experiments have made available coefficients for use in hydraulic formulas for computing either the drop-down due to pile trestle bridges when the quantity is known or, knowing the drop-down, the quantity of water passing through the trestle opening. If either factor is definitely known, it is possible to compute the other factor with a reasonable degree of accuracy. This procedure can best be illustrated by practical examples.

Example 1: A stream discharging 6,600 cubic feet per second has a somewhat irregular section with a mean width of 206 feet and a mean depth of 8 feet. It is desired to compare the drop-down or backwater that would occur from the construction of the following types of obstruction in this channel.

(1) A single-track pile trestle.
(2) A double-track pile trestle, with 10 piles in line in each bent.
(3) A double-track pile trestle with bents offset but in line with the current.
(4) A single-track pile trestle with the bents set at an angle of 30° with the current.
(5) A single-track pile trestle with the axis of the deck at 60° with the current and the bents set in echelon.

For the purpose of illustrating the method of computation the backwater for set-up 1 will be given in full. The amounts of backwater computed for the other set-ups will be tabulated for purposes of comparison. The coefficients for set-ups 2 to 5 were taken from table 1 under class 1 flow.

With bents spaced 13 feet 9 inches center to center, there would be 14 bents obstructing the flow of the water in set-up 1. Including sway bracing, the average pile bent is about 1.65 feet wide. With 14 bents the total obstructed width would be 23.10 feet. The values of the known factors are as follows:

$Q = 6{,}600$ cubic feet per second
$W_1 = 206$ feet
$W_2 = 182.9$ feet
$D_3 = 8$ feet
$V_3 = 4.00$ feet per second
$\alpha = 23.1/206 = 11.2$ percent channel contraction

$$\omega = \frac{V_3^2/2g}{D_3} = 0.2487/8 = 0.031$$

Let H_3 be determined by substituting the above data in the Nagler formula (no. 4). Figure 2 shows $\beta = 1.31$. The test data give an average value of K_N as 0.90 and θ is taken as 0.30. In this formula the drop must first be assumed in order to obtain V_1. After the preliminary calculation, a check computation is made. Formula 4 shows $H_3 = 0.077$.

Substituting the above data in the D'Aubuisson formula and using $K_{D'A} = 0.99$ as determined from the test data gives $H_3 = 0.078$.

The Rehbock formula (no. 7) coefficient varies somewhat for the different scale models. Using the average coefficient obtained for the full-size trestle bent, or $\delta_0 = 5.68$, formula 7 gives $H_3 = 0.81$.

The backwater heights that would occur with the various trestle set-ups, as computed are stated in table 6.

TABLE 6.—*Backwater heights determined for example 1*

Trestle set-up	Backwater height computed by—		
	Nagler formula	D'Aubuisson formula	Rehbock formula
	Feet	*Feet*	*Feet*
1. Single-track pile trestle with axis of deck at right angles to current (pl. 1, *A*)	0.08	0.08	0.08
2. Double-track pile trestle with axis of deck at right angles to current, 10 piles in line in each bent (pl. 1, *B*)	.17	.18	.17
3. Double-track pile trestle with axis of deck at right angles to current, bents offset but in line with current (pl. 1, *C*)	.18	.24	.24
4. Single-track pile trestle with axis of deck at 60° angle with current and bents at 30° angle with current (pl. 3, *A*)	.12	.13	.13
5. Single-track pile trestle with axis of deck at 60° angle with current and bents in echelon (pl. 3, *B*)	.05	.06	.06

Example 2: A single-track pile-trestle bridge 825 feet long built across a river valley was subjected to a flood. At the crest of the flood, the drop-down in the water surface at the trestle was found to be 0.10 foot. The average depth of flow immediately downstream from the trestle was 6 feet. It is desired to compute the discharge through the trestle opening. Since the drop-down through the trestle opening was constant throughout its entire length, the discharge may be computed as a whole by considering the entire area of waterway.

With bents spaced 13 feet 9 inches center to center in a trestle opening 825 feet long there will be 59 bents obstructing the flow. Since a single bent including sway bracing will average 1.65 feet in width, the total obstructed area will be approximately 97.35 feet.

The values of the known factors are as follows:

$W_1=825.0$
$W_2=727.65$
$H_3=0.10$
$\alpha=11.8$ percent
$D_3=6.0$
$g=32.16$

The same coefficients given in the preceding set-up no. 1 will be used in these calculations.

The Nagler formula using $\theta=0.30$ and $\beta=1.32$ gives a discharge of 21,100 cubic feet per second.

The D'Aubuisson formula gives a discharge of 21,300 cubic feet per second.

The Rehbock formula gives a discharge of 21,000 cubic feet per second.

SUMMARY AND CONCLUSIONS

The investigation of the obstruction of pile-trestle bridges to the flow of water has brought out a number of facts which are of practical importance to all engineers, particularly those engaged in the solution of problems concerning the height of backwater caused by pile-trestle bridges.

The bridge-pier formulas most commonly used in this country are D'Aubuisson's:

$$Q=K_{D'A}W_2D_3\sqrt{2gH_3+V_1^2} \qquad (2)$$

Nagler's:

$$Q=K_NW^2\sqrt{2g}[D_3+\Theta(V_3^2/2g)]\sqrt{H_3+\beta(V_1^2/2g)} \qquad (4)$$

Rehbock's:

$$H_3=[\delta_0-\alpha(\delta_0-1)](0.4\alpha+\alpha^2+9\alpha^4)(1+2\omega)V_3^2/2g \qquad (7)$$

Since all bridges made of pile trestles produce practically the same relatively small amounts of channel contraction, the question as to whether the pile-trestle coefficient is the same for various degrees of channel contraction does not arise. Hence the various trestle coefficients may be used in their respective bridge-pier formulas without correction for degree of channel contraction, in calculating the height of backwater caused by any pile-trestle bridge.

TABLE 7.—*Pile-trestle coefficients recommended for use in bridge-pier formulas*

Arrangement of trestle	Pile-trestle coefficients		
	D'Aubuisson $K_{D'A}$	Nagler K_N	Rehbock δ_0
Bents in line with current:			
Single-track 5-pile trestle bent	0.99	0.90	5.77
Double-track 10-pile trestle bent	.87	.82	11.9
2 single-track 5-pile bents offset	.85	.79	13.0
Bents at angle with current:			
Single-track 5-pile trestle bent at—			
10° angle	.99	.90	5.70
20° angle	.96	.89	7.50
30° angle	.92	.87	9.30

The coefficients given in table 7 are recommended for practical use in the respective formulas except in those rare cases in which the velocity is higher than the critical value (p. 5). The solution of practical problems of backwater caused by pile-trestle bridges involving velocities less than critical may be obtained by following the procedure shown on pages 19 to 21.

In using the coefficients it must be recognized, however, that the laboratory experiments which determined them covered a range of conditions much more limited than are met in practice. Where velocities and depths of flow are much greater than those obtained in the experiments, the results of computations should be applied with judgment. Of much value to hydraulic engineers would be actual measurements of backwater elevations caused by pile trestles in streams of considerable depth and velocity, together with the other data for determining the depth, velocity, and quantity of flow and the channel-contraction ratio caused by the trestle. Notation as to the amount and effect of debris lodged against the trestle would be an important item in such data.

The following conclusions have been drawn from the results of this investigation:

The amount of obstruction to flow offered by pile trestles may be determined through the use of the proper trestle coefficient in any of the approved formulas.

The detrimental effect of setting trestle bents at an angle with the current is less than might be expected. Little decrease in the coefficient, and hence in discharge, occurs unless the angle of the bent with the current exceeds 10°.

The discharge coefficient for trestle bents set at a 30° angle with the current is about 4 percent less than that for bents parallel to the current.

Some beneficial effect can be obtained by setting trestle bents in echelon if a roadway must cross a stream at an angle.

If the axis of the roadway is at a 60° angle with the current and the bents are set in echelon, the Nagler and D'Aubuisson coefficients are about 5 percent greater than those for the same trestle crossing the stream at right angles to the current and the bents parallel to the current.

When water of the given depths and quantity flows through the trestle set-ups outlined in example 1 (p. 19) the following conclusions may be drawn:

A double-track pile trestle with 10 piles in line in each bent produces approximately twice the amount of back water that is caused by a single-track pile trestle constructed of bents with 5 piles in line.

A double-track trestle with the bents offset offers somewhat greater obstruction than a double-track trestle with 10 piles in line.

A single-track pile trestle with the bents set at a 30° angle with the current causes from 50 to 70 percent greater depth of backwater than a single-track pile trestle crossing the channel at right angles with the bents parallel to the current.

A single-track pile trestle with the axis of the deck at 60° with the current and the bents set in echelon parallel to the current causes from 53 to 60 percent less backwater than a single-track trestle with the same deck angle but with the bents set at a 30° angle with the current.

A single-track pile trestle with the axis of the deck at 60° with the current and the bents set in echelon parallel to the current gives from 27 to 40 percent less backwater than a single-track pile trestle crossing the channel at a right angle with the bents parallel to the current.

APPENDIX

ANALYSIS OF D'AUBUISSON FORMULA

The D'Aubuisson formula (2) may be written in the following form:

$$Q/W_2D_3\sqrt{2g}=K_{D'A}(H_3+V_1^2/2g)^x$$

This is the equation of a straight line when plotted on logarithmic coordinates. With the expression $H_3+V_1^2/2g$ plotted as abscissas and $Q/W_2D_3\sqrt{2g}$ plotted as ordinates, the exponent "x" is the slope of the line and the coefficient $K_{D'A}$ is the point at which the line intersects the vertical unity axis. In his formula, D'Aubuisson uses the value of 0.5 for the exponent "x." In order to check the correctness of this value for pile trestles, points for class 1 flow were plotted on logarithmic paper using the above equation. The straight line defined by the majority of the points, determined by inspection, was drawn and its slope and intercept found graphically. These values are given in columns 2 and 3 of table 8. Next, a line with a slope of 0.5 was drawn in the same manner and its intercept determined, these values being given in column 3, of table 6. Column 5 is taken from tables 1 and 2, and gives the corresponding values of the coefficient determined by computation, and is included here to facilitate comparison with columns 2 and 3. The values of the exponent "x", are so nearly 0.5 that it is not desirable to depart from this value for pile trestles, although for some solid piers with certain shapes of noses and tails, tested previously,[5] an exponent of 0.6 was found more suitable.

TABLE 8.—*Comparison of D'Aubuisson coefficients for pile trestles determined by graphical methods with coefficients obtained from the formula (class 1 flow only)*

ONE-QUARTER SCALE TRESTLE MODELS

Test set-up	Exponent and coefficient as determined graphically		Coefficient determined graphically if x=0.50 $K_{D'A}$	Computed coefficients (tables 1 and 2) $K_{D'A}$
	x	$K_{D'A}$		
Three 5-pile bents in testing channel; 0° angle with current	0.531	1.09	1.00	0.978
1 bent and 1 end-abutment in testing channel	.478	.96	1.00	1.002

[5] Unpublished data.

TABLE 8.—*Comparison of D'Aubuisson coefficients for pile trestles determined by graphical methods with coefficients obtained from the formula*—Continued

FULL-SIZE SINGLE-TRACK TRESTLE BENTS

Test set-up	Exponent and coefficient as determined graphically		Coefficient determined graphically if $x=0.50$ $K_{D}{}'_{A}$	Computed coefficients (tables 1 and 2) $K_{D}{}'_{A}$
	x	$K_{D}{}'_{A}$		
0° angle with current	0.521	1.05	1.01	1.002
5° angle with current	.557	1.03	.940	.932
10° angle with current	.538	.97	.930	.904
15° angle with current	.550	.95	.870	.868
20° angle with current	.500	.82	.820	.817
30° angle with current	.500	.79	.790	.789

FULL-SIZE DOUBLE-TRACK TRESTLE BENTS

Test set-up	x	$K_{D}{}'_{A}$	Coefficient determined graphically if $x=0.50$ $K_{D}{}'_{A}$	Computed coefficients (tables 1 and 2) $K_{D}{}'_{A}$
10 piles in line; 0° angle with current	0.575	0.97	0.89	0.896
5 piles offset; 0° angle with current	.516	1.13	1.08	.846
Downstream bent offset to left, 10° angle	.540	1.07	.95	.768
Downstream bent offset to right, 10° angle	.529	1.10	1.05	.802

COMPARATIVE ACCURACY OF THE D'AUBUISSON, NAGLER, AND REHBOCK FORMULAS

The method of classifying flow was checked by plotting the data on logarithmic charts. All tests in class 1 flow as defined by Rehbock's empirical formula 5 were plotted using the thickness of the bent as the channel contraction regardless of the angle the bent made with the current. Some of these points would have fallen in classes 2 and 3 if the projected area of the bent had been used as the channel contraction for the purpose of classifying flow. For identification purposes, these latter points were distinguished by certain symbols. If the points tended to form three separate groups the method of classification followed would have been shown to be erroneous, but as all the points tended to group about the same straight line it is reasonable to assume that the method of classification used was proper.

If the average coefficients for class 1 flow as shown in table 1 are used with the observed test data in the respective formulas and new backwater values computed the relative accuracy of the various formulas, insofar as the test data are concerned, may be determined by comparing the computed amounts of backwater with the observed amounts of backwater. This method, however, does not include any consideration of the simplicity of a formula in obtaining the desired data.

Of the many statistical methods which may be used in making a comparison of the various backwater formulas, the following three were employed. In the first method, the summation of the deviations or the differences between the computed and observed backwaters, regardless of sign, was determined for each formula and this summation divided by the number of tests gave the mean deviation. By this method, the formula having the smallest mean deviation most nearly fits the experimental data. In the second method of comparison, the summation of the squares of the deviations was determined for each formula, and this summation divided by the number of tests gave the mean of the squares of the deviations. The mean-square deviation or error might be obtained by extracting the square root of the mean of the squares of the deviations. By the third method of comparison, the summation of the percentages obtained by dividing the individual deviations by the corresponding observed backwater heights was obtained, and this summation was divided by the number of tests. The result was the average percentage deviation or error in computation by the formula under consideration. The differences between the formulas are not at all significant, as may be seen in table 9.

Table 9.—*Difference between observed backwaters and those computed by different formulas*

Formula	Mean deviation from observed H_3		
	Average of deviations	Average of squares of deviations	Average of percentage deviations
	Foot	*Square foot*	*Percent*
Nagler	0.00966	0.000188	15.5
D'Aubuisson	.0104	.000189	17.4
Rehbock	.0119	.000257	19.9

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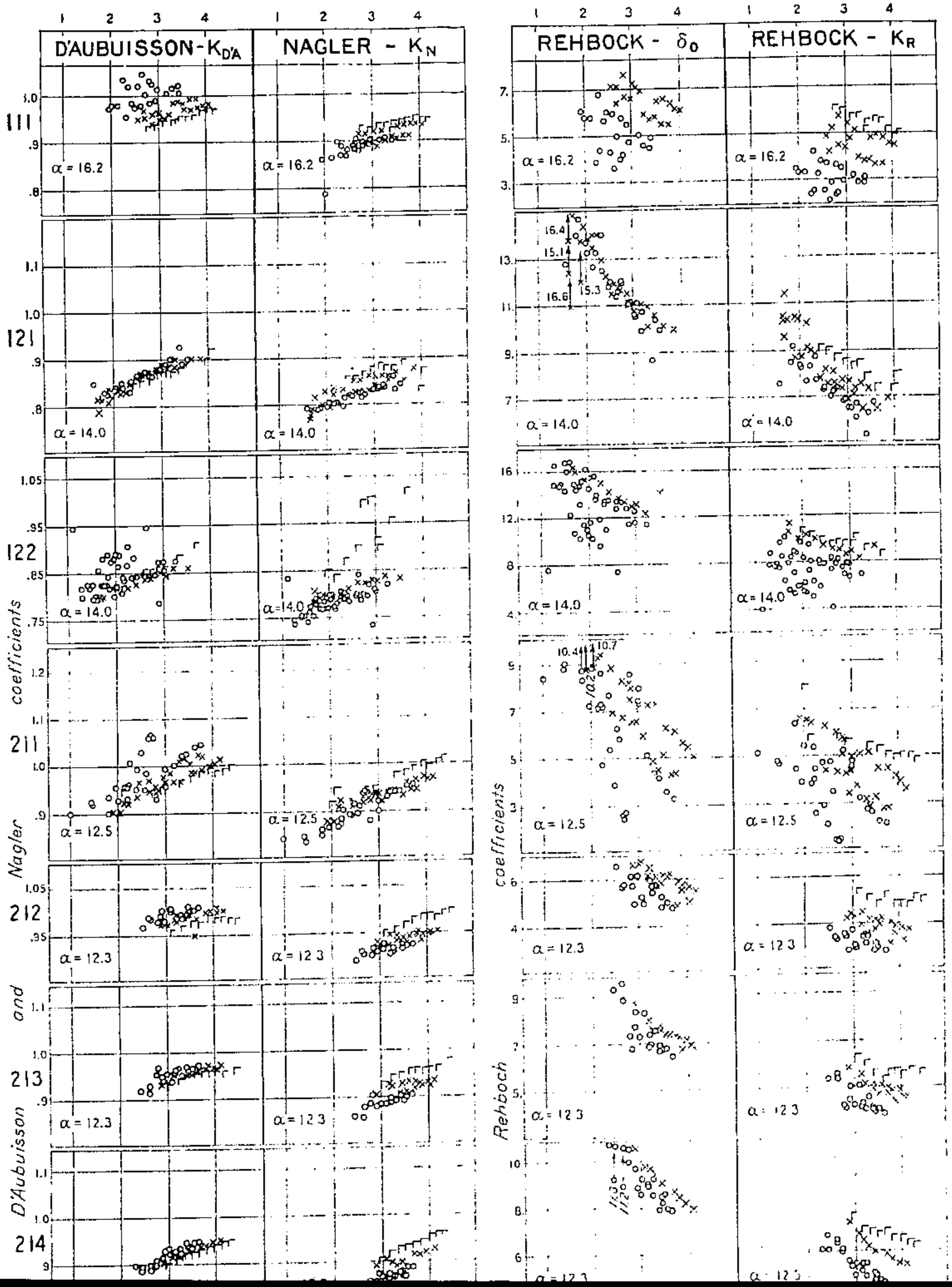D'AUBUISSON - $K_{D'A}$
NAGLER - K_N
REHBOCK - δ_0
REHBOCK - K_R
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121
122
211
212
213
214
D'Aubuisson and Nagler coefficients
Rehboch coefficients
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α = 14.0
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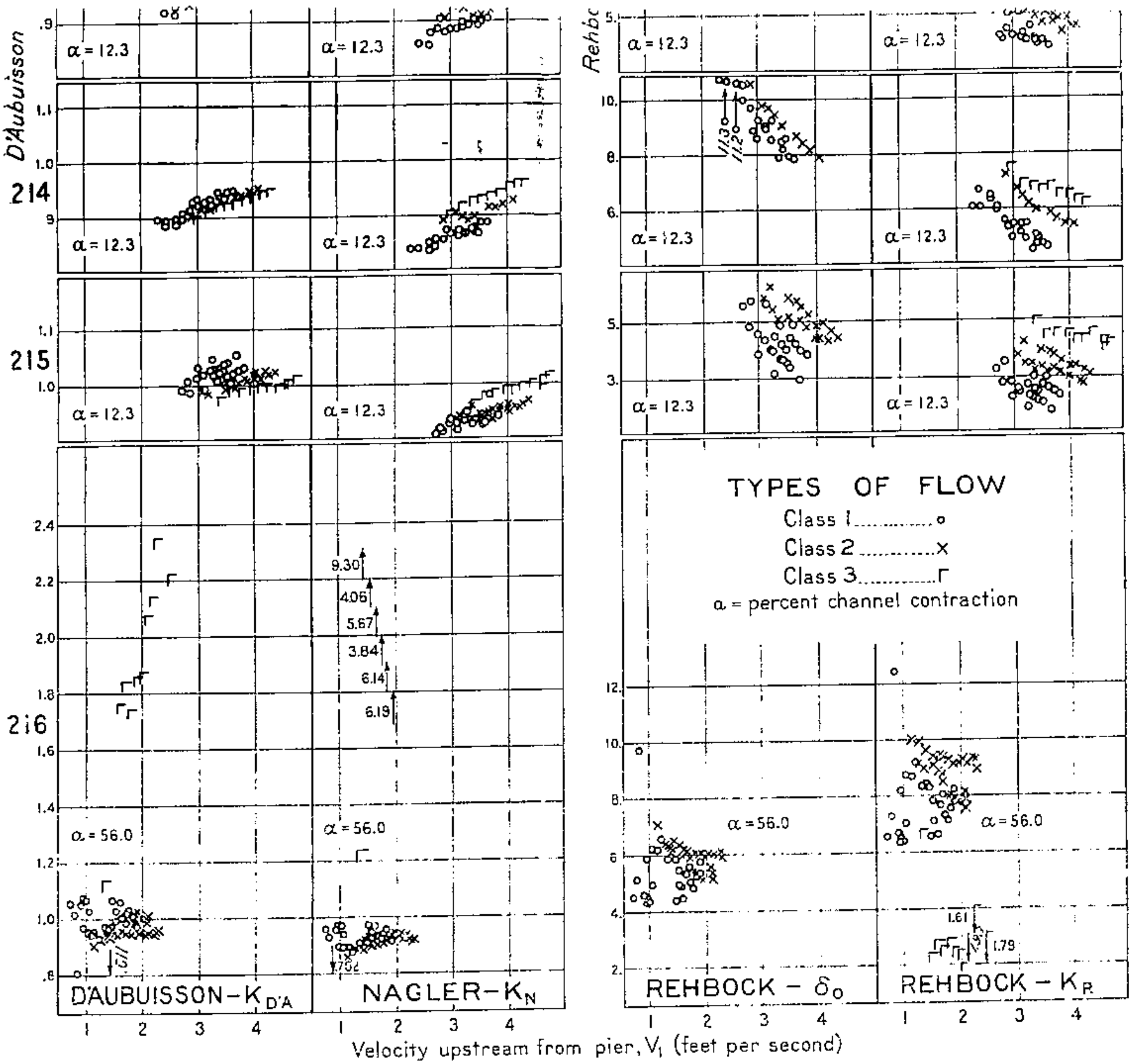

FIGURE 6.—Computed pile-trestle coefficients in relation to velocity upstream from bridge, showing effect of type and setting of bents: 111, full-size single-track trestle bent parallel to current (pl. 1, A); 121, full-size double-track trestle bent, 10 piles in line parallel to current (pl. 1, B); 122, full-size double-track trestle, downstream bent effect, each bent parallel to current (pl. 1, C); 211, ¼-scale model of single-track trestle, three 5-pile bents parallel to current (pl. 2, A); 212, ¼-scale model of single-track trestle, three 5-pile bents at 10-degree angle with current (pl. 2, B); 213, ¼-scale model of single-track trestle, three 5-pile bents at 20-degree angle with current (pl. 2, C); 214, ¼-scale model of single-track trestle, three 5-pile bents at 30-degree angle with current (pl. 3, A); 215, ¼-scale model of single-track trestle, axis of deck at 60-degree angle with current and three 5-pile bents parallel to current (pl. 3, B); 216, ¼-scale model of single-track trestle, one end abutment and one bent parallel to current (pl. 4, A).

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