AD-A048 263 ELECTRO MAGNETIC PROCESSES INC CHATSWORTH CALIF F/G 13/9
A SURVEY OF AVAILABLE DATA ON THE NORMAL DRAG COEFFICIENT OF CA--ETC(U)
AUG 77 W L DALTON N62583-77-M-R443
UNCLASSIFIED MAR-192 CEL-CR-78.001 NL

1 OF 1
AD
A048263

END
DATE
FILMED
1 -78
DDC

(12)

CR 78.001

CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND
and
NOAA DATA BUOY OFFICE

A SURVEY OF AVAILABLE DATA ON THE NORMAL DRAG COEFFICIENT OF CABLES SUBJECTED TO CROSS-FLOW

August 1977

An Investigation Conducted by

MAR, INCORPORATED
Rockville, Maryland

N62583-77-M-R443

(18) CEL

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (19) CR-78.001	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER (9)
4. TITLE (and Subtitle) (6) A SURVEY OF AVAILABLE DATA ON THE NORMAL DRAG COEFFICIENT OF CABLES SUBJECTED TO CROSS-FLOW.		5. TYPE OF REPORT & PERIOD COVERED Final rept., August 1977
		6. PERFORMING ORG. REPORT NUMBER 192
7. AUTHOR(s) (10) William L. Dalton		8. CONTRACT OR GRANT NUMBER(s) (15) N62583-77-M-R443
9. PERFORMING ORGANIZATION NAME AND ADDRESS MAR, Incorporated 1335 Rockville Pike Rockville, MD 20852		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62759N; (16) F52556 (17) YF52556091 01.200
11. CONTROLLING OFFICE NAME AND ADDRESS Civil Engineering Laboratory Naval Construction Battalion Center Port Hueneme, CA 93043		12. REPORT DATE (11) Aug[redacted]977
		13. NUMBER OF PAGES 65 (12) 66p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Facilities Engineering Command 200 Stovall Street Alexandria, VA 22332		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(14) MAR-192

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cables, ropes, chain, drag coefficient, moorings, hydrodynamics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Civil Engineering Laboratory is conducting a research program with the goal of developing mathematical models to aid in the computer simulation of the behavior of cable structures in the ocean. One of the major goals of the program has been prediction of the normal drag of a vibrating cable. Two simulation models have been independently developed which, when used together, result in the capability of predicting the normal drag

→ over

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

390447

Jmcc

Block 20. Cont'd

of a vibrating cable. The models predict the frequency and amplitude of the cable vibrations based upon the mechanical properties of the cable and the fluid flow properties; a factor is then computed which, when multiplied by the non-vibrating drag coefficient for the cable, results in the effective drag coefficient for the cable. Thus, the non-vibrating drag coefficient must be known. A survey has been conducted to identify available drag coefficient of non-vibrating cables and to assess the quality of the data as to its applicability for use in design of undersea cable structures.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

Section 1

INTRODUCTION

The Civil Engineering Laboratory is conducting a research program with the goal of developing mathematical models to aid in the computer simulation of the behavior of cable structures in the ocean. One of the major aspects of the program has been in the area of predicting the normal drag of a vibrating cable. Two simulation models have been independently developed which, when used together, result in the capability of predicting the normal drag of a vibrating cable. The first of the two models predicts the frequency and amplitude of the cable vibrations based upon the mechanical properties of the cable and the fluid flow field properties. The second model uses the frequency and amplitude of the cable vibrations and computes a factor which, when multiplied by the non-vibrating drag coefficient for the cable, results in the vibrating drag coefficient for the cable. Therefore, in order to compute the drag coefficient of a vibrating cable using these two models the non-vibrating drag coefficient must be known. As a result, a survey was conducted to identify what drag coefficient data of non-vibrating cables are available and to assess the quality of the data as to its applicability for use in the models described above.

Section 2

PRESENTATION AND DISCUSSION OF DATA ITEMS

In this section the data which were collected during the course of the survey are presented in tabulated and plotted forms. The data items are organized in terms of the source of the data, that is, by the author of the report or the investigator. Where possible, a discussion of the experimental techniques used to generate the data and an assessment of the quality of the data is presented for each data item. Each data item may contain drag coefficient data for more than one type of cable. For those cases in which more than one cable is presented and where the cables are greatly dissimiliar in type or construction, then the data are presented in separate tables and graphs.

2.1 DATA ITEM 1

Source: Relf, E.F., and Powell, C. H., "Tests on Smooth and Stranded Wires Inclined to the Wind Direction, and a Comparison of Results on Stranded Wire in Air and Water", Advisory Committee for Aeronautics, Great Britain, Reports and Memoranda (New Series) No. 307, January 1917.

Cables Tested: The investigators tested three (3) cables which are described as follows:

a. 1¼ inch British Cable, measured circumference 1.22 inches,
6 x 24 construction

b. 1½ inch British Cable, measured circumference 1.57 inches,
6 x 37 construction

c. 1-3/8 inch German Cable, measured circumference 1.38 inches,
7 x 7 construction.

In addition, data from previous tests for two (2) other cables are presented in the report by Relf and Powell. These are:

d. 3 inch circumference cable unknown construction, and

e. 4/5 inch diameter stranded wire, 7 x 14 construction. (This diameter is an approximate value, determined from known Reynolds number and air flow velocity values and a mean kinematic viscosity from the four previous cable tests.)

Experimental Procedure: A 30 inch long sample of cable was mounted horizontally in a wind tunnel by a 1/8-inch spindle at the center of the sample. The normal drag force was measured and corrected for end effects. The data were presented by Relf and Powell in terms of:

$$\frac{\text{normal drag per foot}}{\rho \, d \, V^2}$$

versus Reynolds number. The data presented in this report have been recalculated to obtain the normal drag coefficient

$$C_d = \frac{\text{normal drag per foot}}{\frac{1}{2} \rho \, d \, V^2}$$

Assessment of the Data: The actual amount of data presented is very small with only one data point per cable, however, there is no evidence to indicate that the data is of poor quality. No measurement of cable vibrations were made, nor were observations of vibrations reported.

Drag Coefficient Data: The cable normal drag coefficient data is presented in Table 2-1 and Figure 2-1.

Table 2-1. Drag Coefficient Data for Data Item 1

CABLE	R_{e_d}	C_d
1¼" British Cable	8.128×10^3	1.204
1½" British Cable	1.045×10^4	1.124
1-3/8" German Cable	9.183×10^3	1.228
3" Cable	1.483×10^4	1.080
4/5" Stranded Wire	4.000×10^3	0.978
	5.333×10^3	1.028

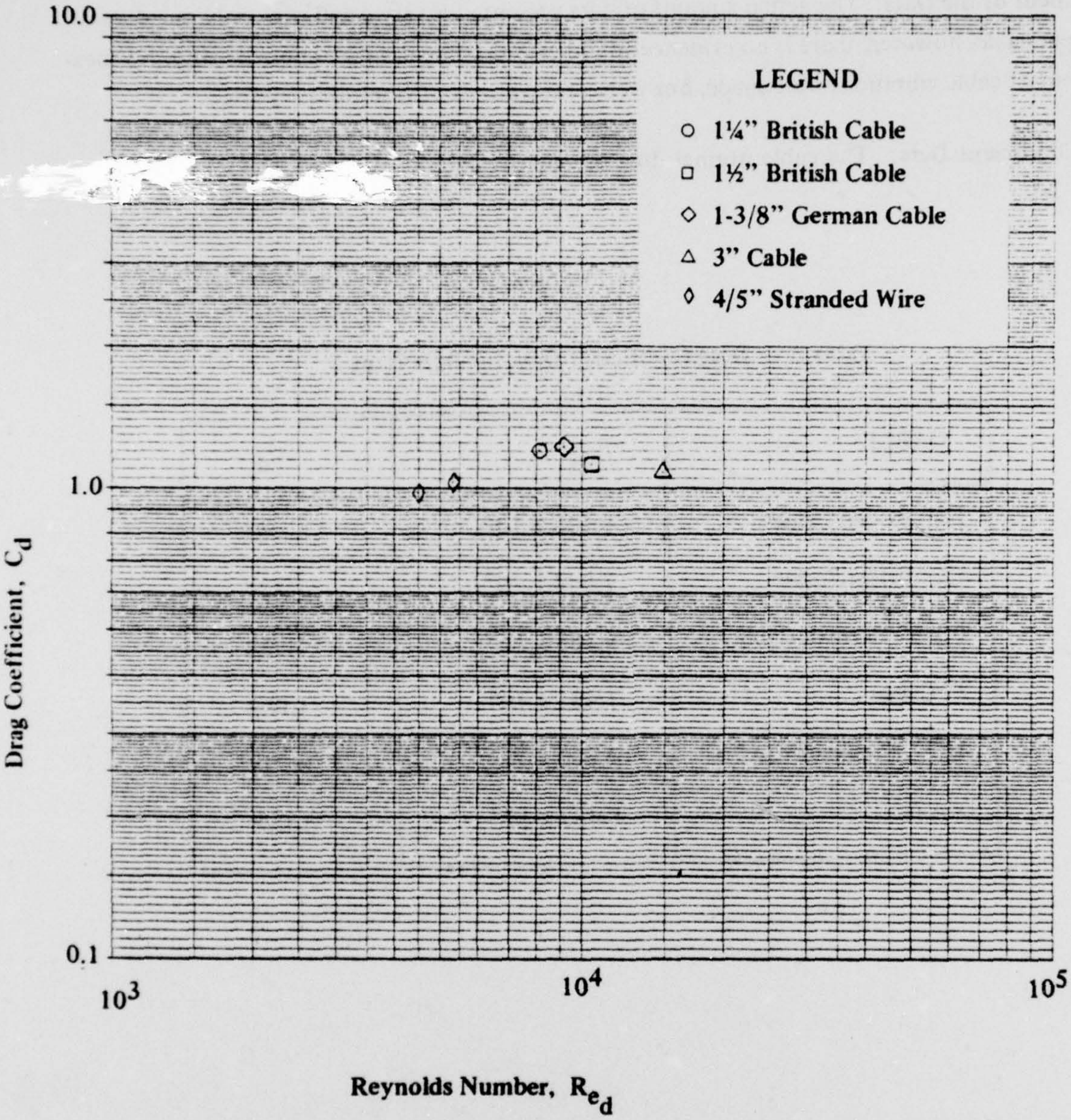

Figure 2-1. Drag Coefficient Data by Relf and Powell of Stranded Wire Cables

2.2 DATA ITEM 2

Source: Pode, Leonard, "An Experimental Investigation of the Hydrodynamic Forces on Stranded Cables", David Taylor Model Basin, Report 713, May 1950.

Cables Tested: Eight samples of cable were tested, four of 1/16-inch diameter, three of 1/8-inch diameter, and one of ¼-inch diameter. The eight cables tested are as follows:

a.	1/16-inch	19 wire strand construction
b.	1/16-inch	7 x 7 construction
c.	1/16-inch	7 x 7 construction
d.	1/16-inch	7 x 7 construction
e.	1/8-inch	7 x 7 construction
f.	1/8-inch	7 x 19 construction
g.	1/8-inch	7 x 19 construction
h.	1/4-inch	7 x 19 construction

Experimental Procedure: Samples of the cables approximately sixty (60) feet in length were towed from the towing carriage in the NSRDC deep water basin at speeds ranging from 3 knots to 16 knots. The true cable angle was measured using an arrangement of two optical devices: a travelling telescope and a sighting transit. These measurements enabled the computation of the direction cosines of the line of the cable. Knowing the cable angles and the weight of the cable in water, the drag coefficient can be determined from a summation of forces normal to the cable,

$$N = W m \cot \phi$$

where N is the normal hydrodynamic force per unit length, W is the cable weight per unit length in water, m is the direction cosine of the cable in the direction of gravity, and ϕ is the angle between the cable and the velocity stream. Having computed the normal force, N, the normal force coefficient, C_N, can be computed by

$$C_N = \frac{N}{\frac{1}{2} \rho V^2 d}$$

where ρ is the fluid density, V is the towspeed and d is the cable diameter. The drag coefficient of a cable perpendicular to the velocity vector can then be computed using the sine squared principle,

$$C_d = \frac{C_N}{\sin^2 \phi}$$

Assessment of the Data: Although it is felt that the quality of Pode's data is good, there are certain factors which should be brought out concerning the meaning of the data. First, the data represents towing configurations in the critical angle range. That is, the cable angles were very shallow, ranging from about one (1) degree to less than ten (10) degrees. This regime of cable angles does not reflect the typical mooring scenario. Second, the sine squared law was used to compute the drag coefficient, C_d. Although this is a common practice for steep angle configurations, there is no conclusive evidence that the sine squared principle is valid for very shallow angles. It can be shown that a one-half degree error in the measurement of the cable angle can result in as much as a 25 percent error in the value of C_d. Lastly, Pode makes no mention of cable vibrations. Based upon similiar experiments by other investigators, it is felt that it is highly likely that the cables did vibrate under some test conditions.

Drag Coefficient Data: Pode's drag coefficient data are presented in Table 2-2. The cable designations A through H are as described previously. Figure 2-2 shows the plotted drag coefficients as a function of Reynolds number.

Table 2-2. Drag Coefficient Data For Eight Stranded Wire Ropes by Pode

CABLE	REYNOLDS NUMBER	C_d
A	2.886×10^3	1.53
	3.607×10^3	1.62
	4.314×10^3	1.80
	5.050×10^3	1.79
	5.786×10^3	1.85
	6.507×10^3	1.99
	7.200×10^3	2.13
B	2.171×10^3	1.81
	2.900×10^3	1.76
	3.629×10^3	1.60
	4.328×10^3	1.36
	5.072×10^3	1.36
	5.800×10^3	1.43
	6.514×10^3	1.53
	7.207×10^3	1.69
C	2.886×10^3	1.58
	3.621×10^3	1.46
	4.328×10^3	1.39
	4.336×10^3	1.35
	5.079×10^3	1.36
	5.757×10^3	1.55
	5.786×10^3	1.41
	6.507×10^3	1.47
	7.214×10^3	1.59
	7.214×10^3	1.51

Table 2-2. Drag Coefficient Data For Eight Stranded Wire Ropes by Pode (Cont.)

CABLE	REYNOLDS NUMBER	C_d
D	2.878×10^3	1.71
	2.886×10^3	1.73
	2.886×10^3	1.69
	3.607×10^3	1.31
	3.614×10^3	1.57
	4.328×10^3	1.37
	4.328×10^3	1.66
	4.328×10^3	1.44
	5.043×10^3	1.50
	5.064×10^3	1.42
	5.757×10^3	1.58
	5.778×10^3	1.46
	6.478×10^3	1.66
	6.493×10^3	1.52
	7.200×10^3	1.88
	7.214×10^3	1.61
	7.936×10^3	2.02
	8.657×10^3	2.06
	9.378×10^3	2.44
	9.955×10^3	2.47
E	7.185×10^3	1.46
	7.214×10^3	1.40
	8.657×10^3	1.37
	8.671×10^3	1.42
	8.686×10^3	1.40
	1.010×10^4	1.29
	1.011×10^4	1.33
	1.014×10^4	1.28

Table 2-2. Drag Coefficient Data For Eight Stranded Wire Ropes by Pode (Cont.)

CABLE	REYNOLDS NUMBER	C_d
E	1.156×10^4	1.17
	1.157×10^4	1.10
	1.159×10^4	1.08
	1.291×10^4	1.20
	1.299×10^4	1.10
	1.301×10^4	1.12
	1.440×10^4	1.17
	1.443×10^4	1.12
	1.444×10^4	1.17
	1.576×10^4	1.23
	1.580×10^4	1.25
	1.721×10^4	1.30
	1.721×10^4	1.38
	1.868×10^4	1.49
	1.873×10^4	1.25
	2.010×10^4	1.61
	2.010×10^4	1.49
	2.158×10^4	1.67
	2.158×10^4	1.65
	2.304×10^4	1.69
	2.307×10^4	1.53
F	7.214×10^3	1.37
	7.229×10^3	1.33
	7.243×10^3	1.43
	8.556×10^3	1.45
	8.642×10^3	1.34
	8.686×10^3	1.36
	1.010×10^4	1.25

Table 2-2. Drag Coefficient Data For Eight Stranded Wire Ropes by Pode (Cont.)

CABLE	REYNOLDS NUMBER	C_d
F	1.014×10^4	1.21
↓	1.153×10^4	1.06
	1.154×10^4	0.92
	1.157×10^4	0.93
	1.297×10^4	1.09
	1.299×10^4	0.93
	1.300×10^4	0.98
	1.438×10^4	0.97
	1.440×10^4	1.49
	1.587×10^4	1.18
	1.731×10^4	1.21
	1.731×10^4	1.09
	1.876×10^4	1.16
	2.020×10^4	1.23
	2.158×10^4	1.38
	2.301×10^4	1.53
G	7.214×10^3	1.30
↓	7.214×10^3	1.26
	8.657×10^3	1.34
	8.657×10^3	1.29
	8.686×10^3	1.27
	1.010×10^4	1.14
	1.010×10^4	1.17
	1.013×10^4	1.16
	1.51×10^4	1.03
	1.153×10^4	1.01
	1.157×10^4	0.99

Table 2-2, Drag Coefficient Data For Eight Stranded Wire Ropes by Pode (Cont.)

CABLE	REYNOLDS NUMBER	C_d
G	1.296×10^4	1.10
↓	1.299×10^4	1.10
	1.301×10^4	1.17
	1.438×10^4	1.25
	1.440×10^4	0.81
	1.443×10^4	1.04
	1.443×10^4	0.89
	1.577×10^4	0.84
	1.721×10^4	1.14
	1.726×10^4	1.02
	1.863×10^4	0.98
	1.866×10^4	1.63
	2.010×10^4	1.25
	2.013×10^4	1.57
	2.150×10^4	1.50
	2.164×10^4	1.90
	2.304×10^4	1.07
↓	2.306×10^4	2.40
H	2.020×10^4	1.22
↓	2.303×10^4	1.30
	2.309×10^4	1.23
	2.583×10^4	1.30
	2.591×10^4	1.19
	2.880×10^4	1.20
	2.886×10^4	1.25
	2.886×10^4	1.34
	2.886×10^4	1.26
↓	3.160×10^4	1.41

Table 2-2. Drag Coefficient Data For Eight Stranded Wire Ropes by Pode (Cont.)

CABLE	REYNOLDS NUMBER	C_d
H	3.166×10^4	1.26
↓	3.174×10^4	1.19
	3.451×10^4	1.29
	3.463×10^4	1.40
	3.463×10^4	1.28
	3.737×10^4	1.14
	3.751×10^4	1.39
	4.017×10^4	1.58
	4.025×10^4	1.45
	4.028×10^4	1.43
	4.040×10^4	1.40
	4.271×10^4	1.42
	4.328×10^4	1.34
	4.591×10^4	1.57
	4.608×10^4	1.45
	4.617×10^4	1.34

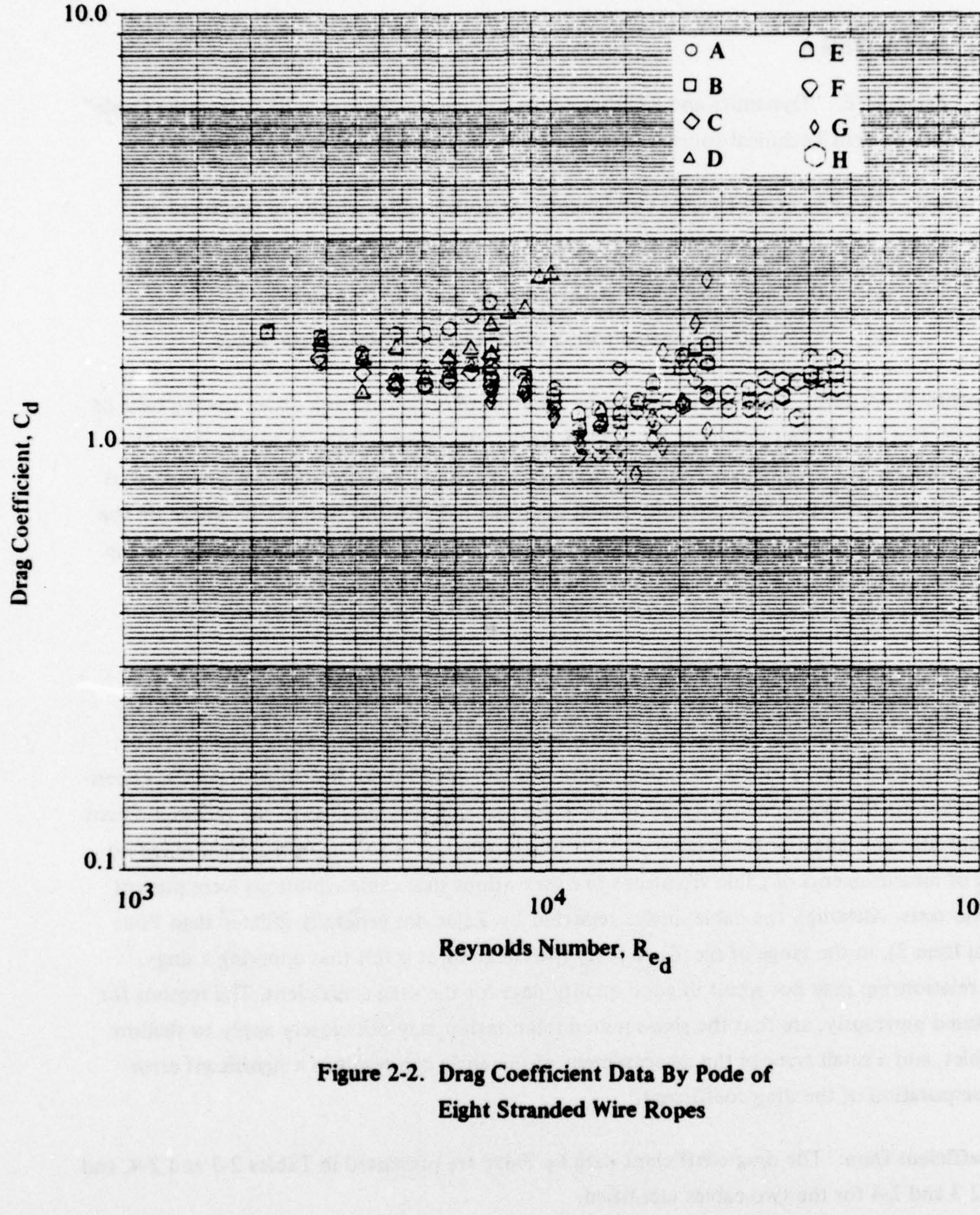

Figure 2-2. Drag Coefficient Data By Pode of Eight Stranded Wire Ropes

2.3 DATA ITEM 3

Source: Zajac, E. E., "Dynamics and Kinetics of the Laying and Recovery of Submarine Cable", Bell System Technical Journal, Volume 36(5), September 1957, pp. 1129-1207.

Cables Tested: The investigator tested two jacketed armored cables which are described as follows:

a. 0.75 inch steel cable with a smooth polyethylene jacket

b. 1.25 inch steel cable with a rough tar-impregnated jute jacket.

Experimental Procedure: The data presented by Zajac were obtained from at-sea towing tests of cables of 20 feet to 100 feet in length. The cables were towed over a range of speeds from 1½ knots to 9 knots. The cable angle (critical angle) was measured and the data are presented as plots of critical angle versus towing speed. Based upon the data for the weights in water of the cables and the water density, the drag coefficients were calculated using the relationship for the balance of the forces normal to the cable and the sine- squared relationship. That is,

$$C_d = \frac{w \cos \phi}{\frac{1}{2} \rho V^2 d \sin^2 \phi}$$

Assessment of the Data: Virtually no information was provided by the investigator on the experimental technique to assess the quality of the data. No mention was made as to the technique used to measure the cable angle or the accuracy of the measurements. Also, the investigator made no mention of measurements of cable vibrations or observations that cable vibrations were present during the tests. Although the cable angles reported by Zajac are generally greater than Pode (see Data Item 2), in the range of six (6) to forty (40) degrees, it is felt that applying a sine-squared relationship may not result in good quality data for the drag coefficient. The reasons for this as stated previously, are that the sine-squared relationship may not closely apply to shallow angle cables, and a small error in the measurement of the angle can result in a significant error in the computation of the drag coefficient.

Drag Coefficient Data: The drag coefficient data by Zajac are presented in Tables 2-3 and 2-4, and Figures 2-3 and 2-4 for the two cables identified.

Table 2-3. Drag Coefficient Data by Zajac for a Smooth Jacketed Steel Cable

REYNOLDS NUMBER	C_d
7.89×10^3	1.16
8.42×10^3	1.56
9.21×10^3	1.18
1.05×10^4	1.10
1.37×10^4	0.95
1.58×10^4	1.60
1.58×10^4	1.70
2.10×10^4	0.72
2.10×10^4	1.42
2.10×10^4	1.78
2.63×10^4	0.79
2.63×10^4	1.24
3.16×10^4	1.02
3.16×10^4	1.24
3.16×10^4	1.53
3.68×10^4	0.91
3.68×10^4	0.91
3.68×10^4	1.13
4.21×10^4	0.86
4.21×10^4	0.97
4.21×10^4	1.09
4.74×10^4	0.76
4.74×10^4	0.98
4.74×10^4	1.07

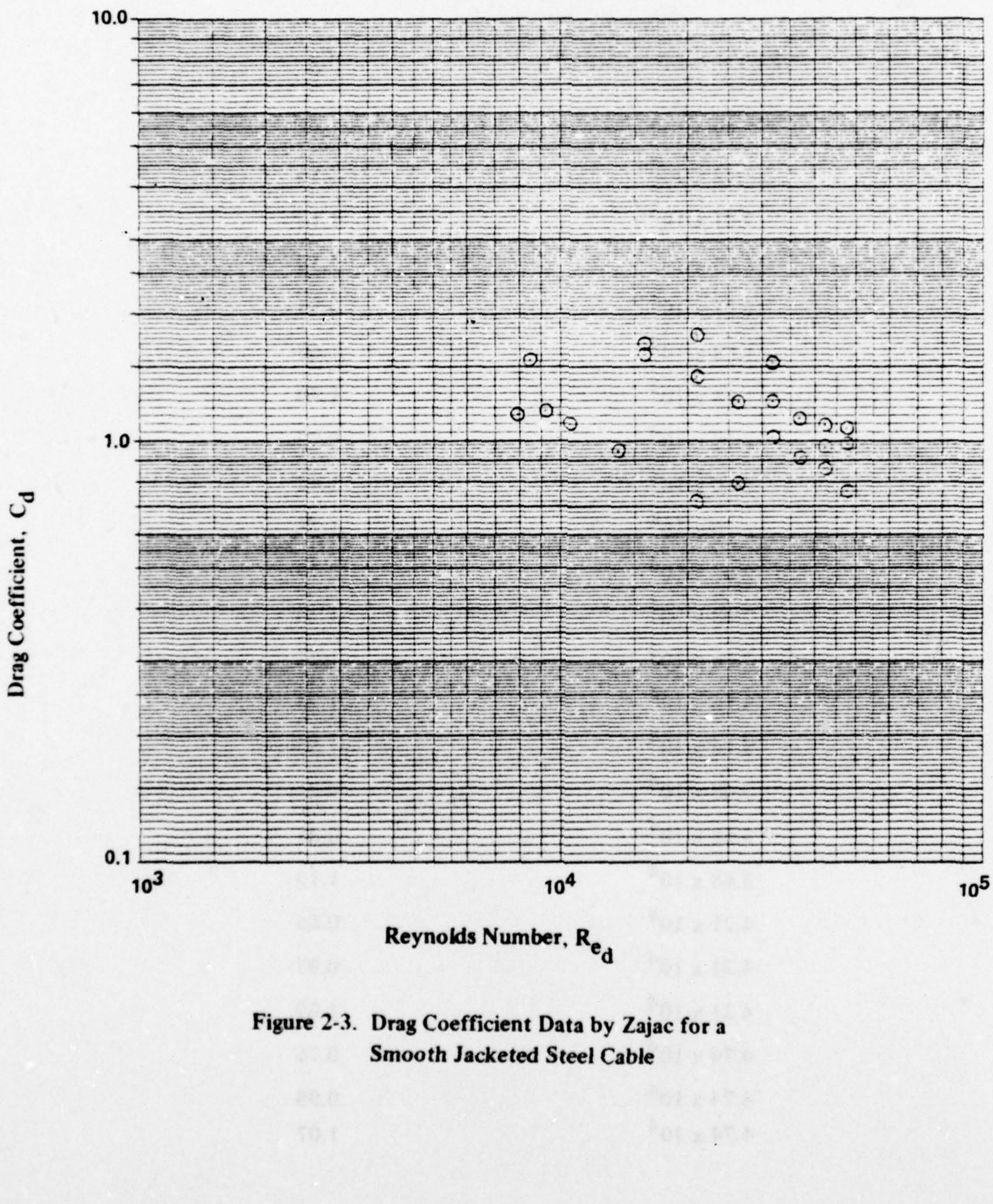

Figure 2-3. Drag Coefficient Data by Zajac for a Smooth Jacketed Steel Cable

Table 2-4. Drag Coefficient Data by Zajac for a Tar Impregnated Jute Jacketed Steel Cable

REYNOLDS NUMBER	C_d
1.75×10^4	1.24
1.75×10^4	1.27
1.75×10^4	1.30
2.63×10^4	1.44
2.63×10^4	1.46
2.63×10^4	1.52
3.51×10^4	1.17
3.51×10^4	1.19
4.39×10^4	1.37
4.39×10^4	1.37
5.26×10^4	1.50
6.14×10^4	1.10
6.14×10^4	1.59
6.14×10^4	1.88
7.02×10^4	1.68
7.89×10^4	1.50
7.89×10^4	1.96
7.89×10^4	2.28

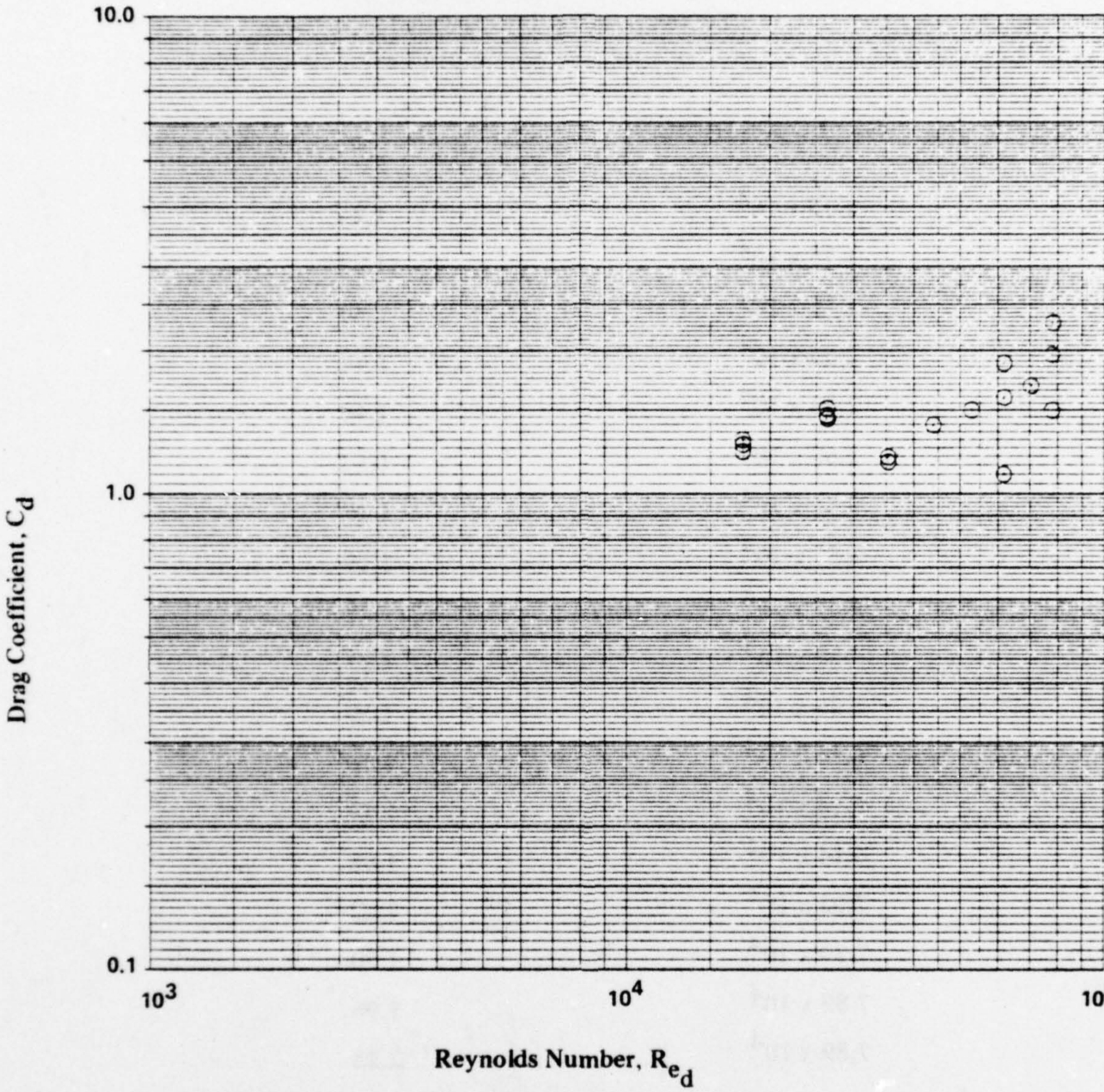

Figure 2-4. Drag Coefficient Data by Zajac for a Tar Impregnated Jute Jacketed Steel Cable

2.4 DATA ITEM 4

Source: Schultz, M. P., "Wind Tunnel Determination of the Aerodynamic Characteristics of Several Twisted Wire Ropes", David Taylor Model Basin, Report 1645, Aero Report 1028, June 1962.

Cables Tested: Three different cable diameters of a 12-strand, right-hand lay twisted wire rope were tested. Of the three diameters tested (0.266 inch, 0.330 inch, and 0.396 inch), only the data for the 0.396 inch cable were usable for this survey.

Experimental Procedure: The twisted wire ropes were mounted in the wind tunnel test section by attaching the samples to lengths of piano wire which, in turn, were mounted to a rigid frame. In order to obtain a measurable drag force, several samples of the same diameter cable were mounted in the test section at the same time. The supporting framework was attached to the wind tunnel force balance so that the entire unit could be rotated from zero degrees to 360 degrees. Measurements of lift, drag, and sideforce were taken at 20 degree intervals. Each cable was tested at four tunnel speeds.

Assessment of the Data: Although the forces exerted on the piano wire and support structure were deducted from the forces exerted on the entire assembly, no other corrections were made to the data to account for effects of jet boundary, wake blockage, etc. The investigator made no mention of cable vibrations, however, unsteady lift forces were noted and may be due to cable vibrations. Only the 0.396 inch cable sample was tested at an angle of 90 degrees to the flow. Therefore, the data for the remaining two cables are not presented here.

Drag Coefficient Data: The cable drag coefficient data for the 0.396 inch stranded wire rope are presented in Table 2-5 and Figure 2-5.

Table 2-5. Drag Coefficient Data by Schultz for A 0.396-Inch Stranded Wire Rope

REYNOLDS NUMBER	C_d
2.54×10^4	1.29
3.91×10^4	1.23
4.53×10^4	1.19
5.35×10^4	1.21

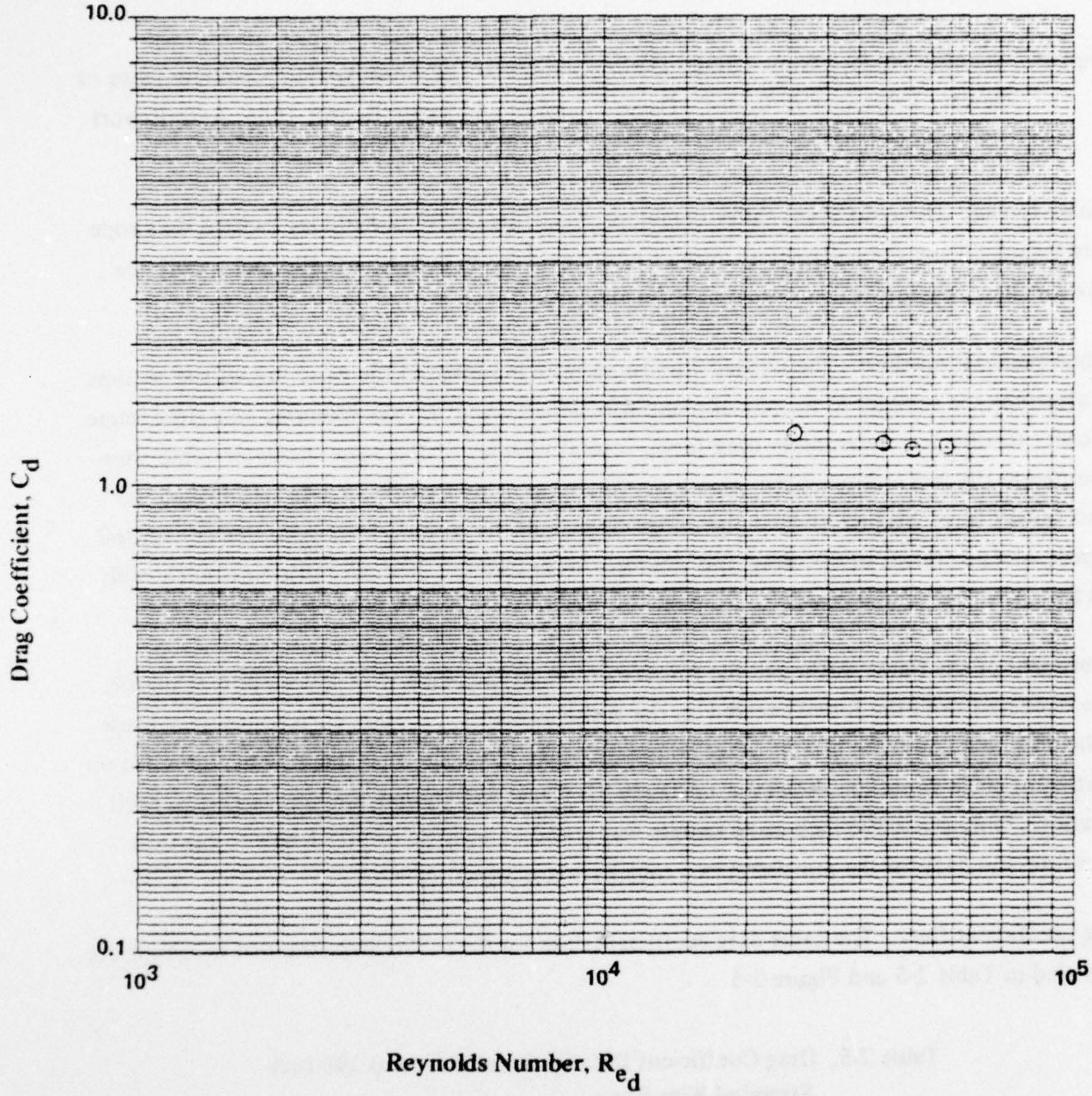

Figure 2-5. Drag Coefficient Data by Schultz for A 0.396-Inch Stranded Wire Rope

2.5 DATA ITEM 5

Source: "Drag Measurements of Bare and Faired Cables", David Taylor Model Basin, Enclosure to TMB Letter 9250 (549:TG), May 1964.

Cables Tested: The cable tested was a model made up of a solid steel rod wrapped with copper wire to simulate a double-armored bare cable. The model had a diameter of 1.16 inches and was two (2) feet in length. The number of wire strands used to simulate the armored cable was not stated in the report.

Experimental Procedure: The cable model was mounted in the test section of the two-dimensional dynamometer such that the model was oriented 90 degrees to the flow when towed through the water basin. The tests were conducted over a speed range from 1 to 12 knots. The data were presented in the report in the form of a curve of drag per foot as a function of towing speed. The data were converted to coefficient form for presentation in this report.

Assessment of the Data: It is felt that the quality of the data is good with the exception of the three data points below a Reynolds Number of 5×10^4. Those data points are suspect because the magnitudes of the measured forces were very small and probably influenced by the accuracy of the dynamometer measuring system. The investigator stated that the model was rigid and did not vibrate. Due to the shortness of the cable model (two (2) feet), three-dimensional effects might possibly be influencing the data resulting in the data having values lower than would a long cable.

Drag Coefficient Data: The drag coefficient data for the 1.16 inch stranded cable are presented in Table 2-6 and Figure 2-6.

Table 2-6. Drag Coefficient Data for A 1.16 Inch Simulated Double-Armored Cable

REYNOLDS NUMBER	C_d
1.484×10^4	1.822
2.969×10^4	1.367
4.453×10^4	1.114
5.937×10^4	0.934
7.421×10^4	0.933
8.906×10^4	0.931
1.039×10^5	0.941
1.187×10^5	0.940
1.336×10^5	0.936
1.484×10^5	0.933
1.633×10^5	0.925
1.781×10^5	0.917

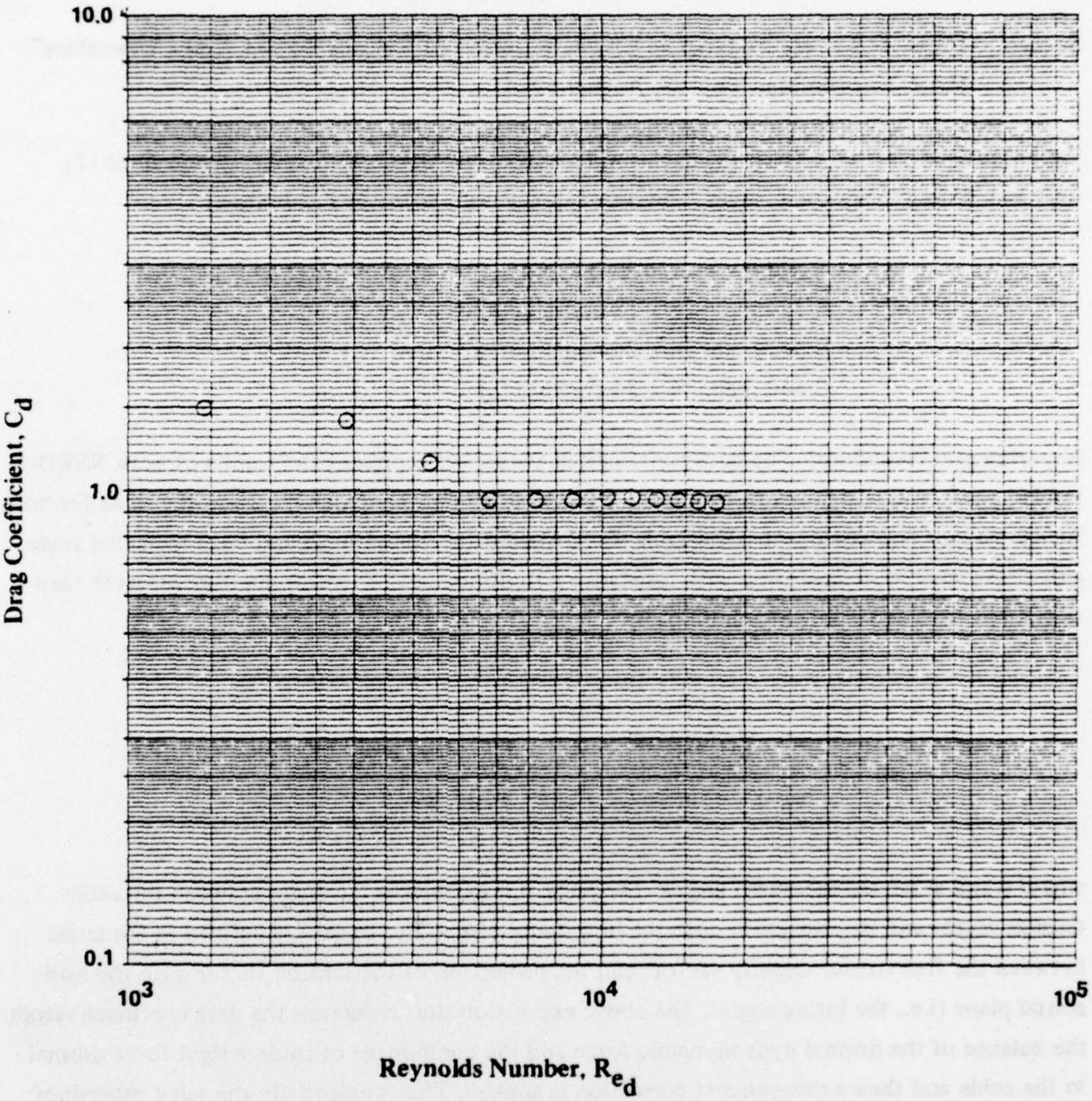

Figure 2-6. Drag Coefficient Data for A 1.16 Inch Simulated Double-Armored Cable

2.6 DATA ITEM 6

Source: Diggs, J. S., "Hydrodynamic Characterization of Various Towed Array Towcables", MAR, Incorporated TR-128, August 1974.

Cables Tested: A total of four (4) cables were tested, one (1) smooth jacketed and three (3) unjacketed double-armored cables. The four (4) cables are identified as follows:

a. 0.375 inch smooth jacketed
b. 0.322 inch, 18 x 18 construction
c. 0.542 inch, 24 x 24 construction
d. 0.840 inch, 24 x 24 construction.

Experimental Procedure: The data contained in the report represent the results of both NSRDC towing basin tests and at-sea towing tests. The measurement technique used was the same for both the laboratory and at-sea tests. The cable was towed at its critical angle and both the cable angle and kiting angle were measured with resistance potentiometers. The drag coefficients were then computed from the following relationship:

$$C_d = \frac{W \cos\phi \cos\psi}{\frac{1}{2}\rho\, d\, V^2 \sin^2\phi\,(1 + \cot^2\phi \sin^2\psi)^{3/2}}$$

where ϕ and ψ are the measured angles. The angle ϕ is defined as the angle between the cable tension vector and its projection onto the horizontal plane. The angle ψ is defined as the angle between the free stream velocity vector and the projection of the tension vector onto the horizontal plane (i.e., the kiting angle). The above expression thus computes the drag coefficient from the balance of the normal hydrodynamic force and the component of cable weight force normal to the cable and then a sine-squared correction is applied. This is essentially the same procedure used by Pode. (See Section 2.2.)

Assessment of the Data: As was described in Section 2.2, there are two (2) inherent problems in determining cable drag coefficients from critical angle towing tests. The first is that a small error in the measurement of the cable angle can result in a large error in the computation of the drag coefficient. The second, not related to the experimental accuracy, is that for shallow angles there is no evidence that the sine-sqared relationship for the variation of the normal hydrodynamic force is valid. Also, it was verified by discussions with the author that the cable strumming was present when much of the data was taken.

Drag Coefficient Data: The drag coefficient data for the smooth jacketed cable are presented in Table 2-7 and Figure 2-7, and the remaining data for the unjacketed cables are presented in Table 2-8 and Figure 2-8.

Table 2-7. Drag Coefficient Data by Diggs For A 0.375 inch Smooth Jacketed Cable

REYNOLDS NUMBER	C_d
2.90×10^4	1.03
4.20×10^4	1.09
5.85×10^4	1.15
7.35×10^4	1.20
8.80×10^4	1.29

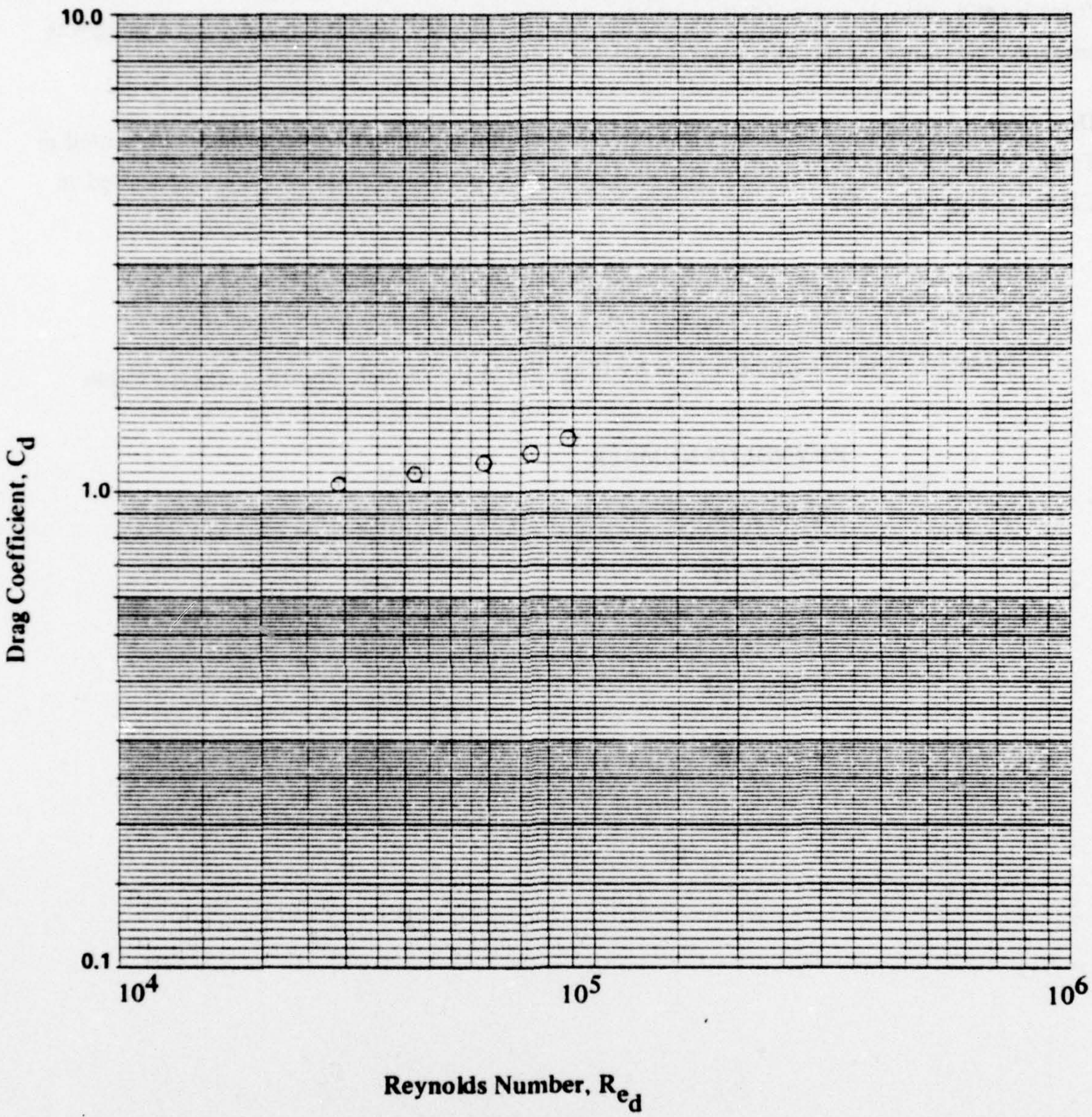

Figure 2-7. Drag Coefficient Data by Diggs for A 0.375 Inch Smooth Jacketed Cable

Table 2-8. Drag Coefficient Data by Diggs for Several Bare Double-Armored Cables

CABLES	REYNOLDS NUMBER	C_d
0.322 inch, 18 x 18	2.90×10^4	1.54
↓	4.25×10^4	2.03
	5.90×10^4	1.91
	8.40×10^4	0.30
0.542 inch, 24 x 24	4.30×10^4	1.27
↓	7.17×10^4	1.74
	9.80×10^4	3.60
	1.14×10^5	2.05
	1.43×10^5	1.84
0.840 inch, 24 x 24	7.20×10^4	0.82
↓	1.06×10^5	1.03
	1.43×10^5	1.44
	1.76×10^5	2.00
	6.35×10^4	1.91
	9.70×10^4	1.84
	1.26×10^5	1.92
	6.80×10^4	1.55
	1.03×10^5	1.40
	1.34×10^5	1.39
	1.70×10^5	1.18
	7.50×10^4	1.71
	1.05×10^5	1.61
	1.42×10^5	1.70
	1.76×10^5	1.91

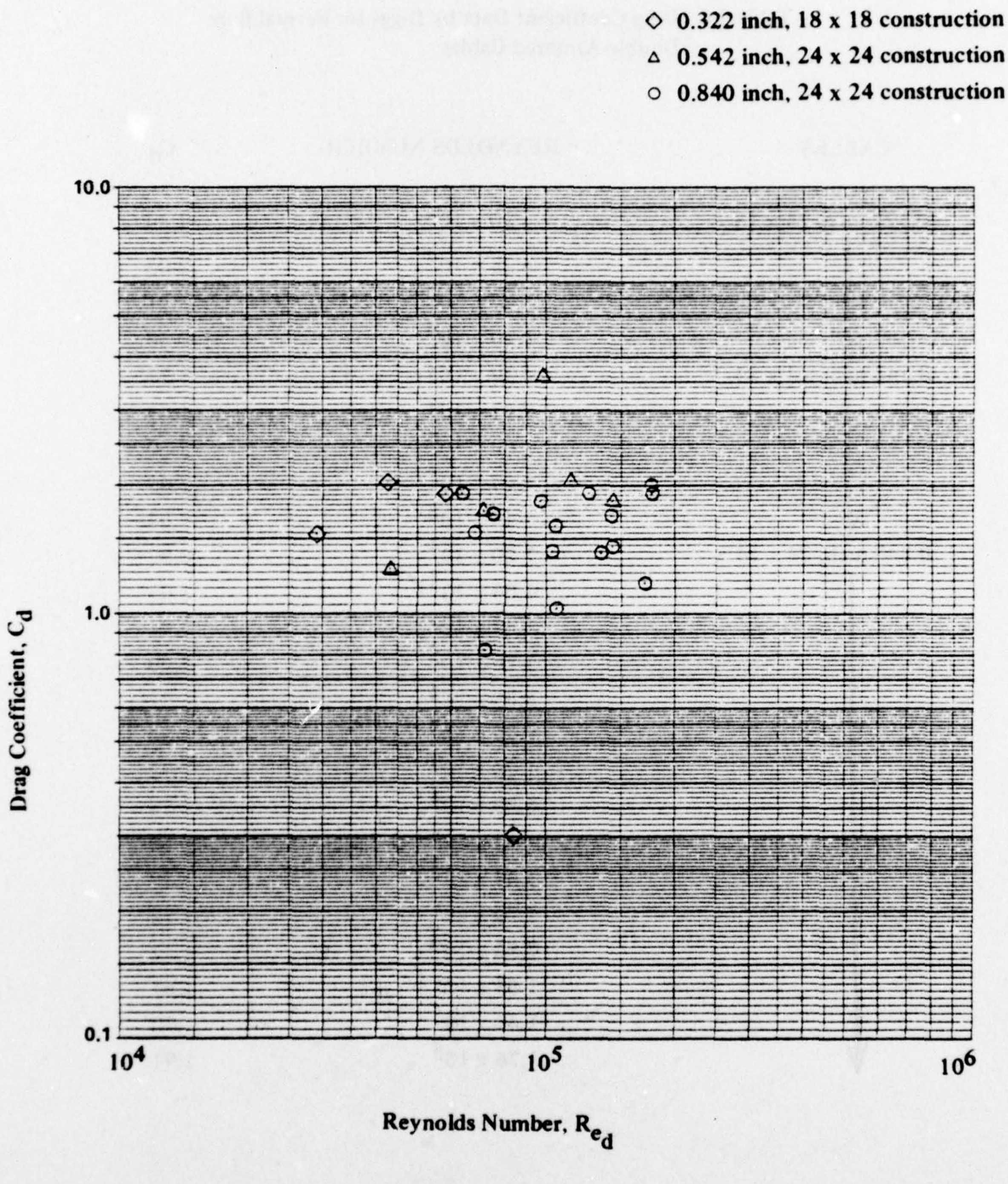

Figure 2-8. Drag Coefficient Data by Diggs for Several Bare Double-Armored Cables

2.7 DATA ITEM 7

Source: Charnews, D. P., "Drag Coefficients of Vibrating Synthetic Rope", MIT/WHOI, September, 1971.

Cables Tested: Four (4) synthetic ropes, all without jackets, were tested by Charnews. Three (3) of the ropes were of a plaited construction and the remaining rope was of a single braided construction. The cables tested are identified as follows:

a. 9/16 inch, nylon, 8 strand plaited

b. 5/8 inch, nylon, 8 strand plaited

c. 3/4 inch, nylon, 8 strand plaited

d. 3/8 inch, dacron, single braided.

Experimental Procedure: The tests were conducted at the Variable Pressure Water Tunnel at the Massachusetts Institute of Technology. The cables passed through the tunnel test section and were maintained under tension with a tensioning frame. The drag force on the rope was measured using a strain gauge dynomometer. The frequency of cable vibration was determined with a strobotac. Drag measurements were made for each rope for various cable tension (50 pounds to 2000 pounds) and water speeds. In addition, the diameter of the rope was measured at each tension step.

Assessment of the Data: The original purpose of the experiments was to measure the drag of vibrating synthetic ropes. However, due to the bearing surfaces used to measure the drag, the cables only vibrated at low tensions. The majority of the data was for non-vibrating conditions. Only the non-vibrating data are presented in this report. Except for the data points at the low Reynolds Numbers where considerable scatter can be noticed, the data shows good agreement for all tensions and diameters. The scatter at the low Reynolds Numbers which corresponds to low water speeds is probably due to the low values of drag which were measured.

Drag Coefficient Data: The tabulated and plotted drag coefficient data are based upon the actual cable diameter under load as measured by the investigator and not the nominal diameter. The data for the three (3) plaited ropes are presented in Table 2-9 and Figure 2-9. Since all of the plaited ropes are of identical construction and good agreement exists between the data for the three different diameters, the plotted data values are presented without distinguishing one diameter from another. The data for the 3/8-inch single braided rope are presented in Table 2-10 and Figure 2-10.

Table 2-9. Drag Coefficient Data by Charnews for Several Plaited, Synthetic Ropes

DIAMETER	REYNOLDS NUMBER	C_d
9/16 inch	4.536×10^3	0.794
	9.072×10^3	0.992
	1.456×10^4	1.001
	1.910×10^4	0.985
	2.387×10^4	0.974
	2.889×10^4	0.959
	3.342×10^4	0.965
	3.820×10^4	0.963
	4.297×10^4	0.964
	4.775×10^3	1.433
	9.550×10^3	1.075
	1.456×10^4	1.001
	1.934×10^4	1.048
	2.387×10^4	1.003
	2.889×10^4	0.959
	3.342×10^4	0.936
	3.820×10^4	0.940
	4.250×10^4	0.922
	4.775×10^4	0.931
	4.729×10^3	1.447
	9.458×10^3	1.085
	1.419×10^4	0.964
	1.915×10^4	0.970
	2.412×10^4	0.973
	2.837×10^4	0.984

Table 2-9. Drag Coefficient Data by Charnews for Several Plaited, Synthetic Ropes (Cont.)

DIAMETER	REYNOLDS NUMBER	C_d
9/16 inch	3.310×10^4	0.974
	3.783×10^4	0.972
	4.256×10^4	0.982
	4.705×10^4	0.986
	4.379×10^3	1.644
	9.219×10^3	0.928
	1.383×10^4	0.989
	1.844×10^4	1.020
	2.305×10^4	1.009
	2.766×10^4	0.989
	3.227×10^4	0.969
	3.688×10^4	0.986
	4.172×10^4	0.988
	4.610×10^4	0.979
5/8 inch	5.528×10^3	1.253
	1.164×10^4	0.989
	1.804×10^4	0.882
	2.327×10^4	0.954
	2.909×10^4	0.905
	4.073×10^4	0.923
	4.655×10^4	0.989
	5.267×10^3	1.315
	1.053×10^4	1.150
	1.691×10^4	1.020
	2.246×10^4	1.049

Table 2-9. Drag Coefficient Data by Charnews for Several Plaited, Synthetic Ropes (Cont.)

DIAMETER	REYNOLDS NUMBER	C_d
5/8 inch	2.772×10^4	1.068
↓	3.327×10^4	1.038
	3.937×10^4	0.989
	4.436×10^4	1.010
	5.483×10^3	1.200
	1.069×10^4	1.104
	1.700×10^4	0.999
	2.221×10^4	1.024
	2.769×10^4	1.012
	3.345×10^4	1.000
	3.838×10^4	0.992
	4.386×10^4	1.003
	5.518×10^3	1.192
	1.104×10^4	1.043
	1.655×10^4	1.060
	2.262×10^4	1.028
	2.814×10^4	0.986
	3.311×10^4	1.010
	3.863×10^4	0.998
↓	4.415×10^4	1.015
3/4 inch	6.456×10^3	1.007
↓	1.227×10^4	1.116
	1.904×10^4	1.027
	2.582×10^4	1.024
↓	3.228×10^4	0.993

Table 2-9. Drag Coefficient Data by Charnews for Several Plaited, Synthetic Ropes (Cont.)

DIAMETER	REYNOLDS NUMBER	C_d
3/4 inch	3.873×10^4	0.993
↓	4.454×10^4	1.002
	6.210×10^3	1.108
	1.307×10^4	1.000
	1.994×10^4	0.968
	2.647×10^4	1.006
	3.268×10^4	0.980
	3.922×10^4	0.972
	4.575×10^4	0.949
	5.229×10^4	0.945
	6.584×10^3	1.004
	1.284×10^4	0.924
	1.975×10^4	1.004
	2.634×10^4	1.004
	3.325×10^4	0.985
	3.950×10^4	0.990
	4.609×10^4	0.974
↓	5.267×10^4	0.973

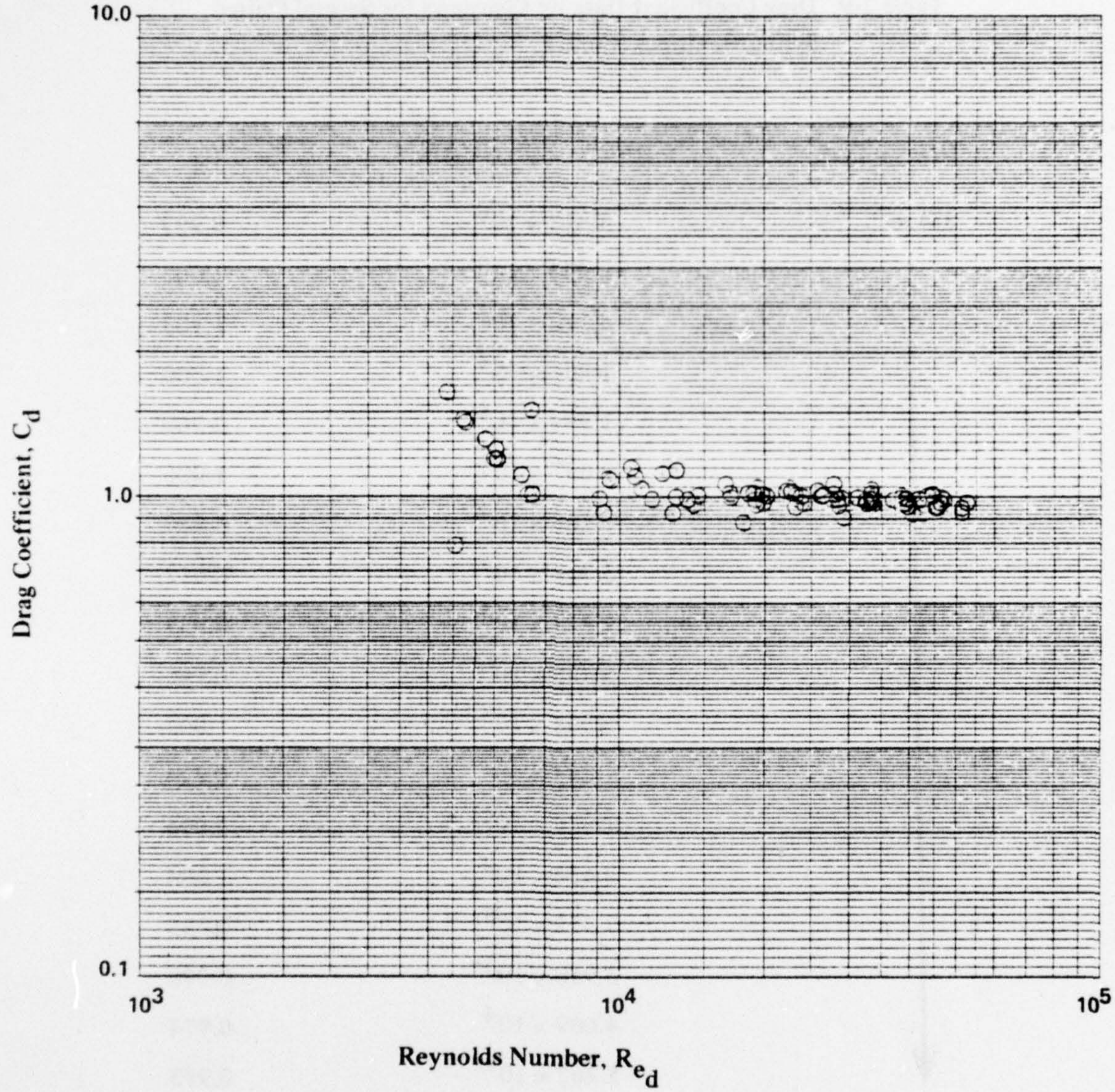

Figure 2-9. Drag Coefficient Data by Charnews for Several Plaited Synthetic Ropes

Table 2-10. Drag Coefficient Data by Charnews for A 3/8 Inch Single Braided Synthetic Line

REYNOLDS NUMBER	C_d
2.957×10^3	1.099
5.915×10^3	0.824
9.168×10^3	1.029
1.213×10^4	1.111
1.508×10^4	1.141
1.789×10^4	1.201
2.085×10^4	1.105
2.381×10^4	1.153
3.119×10^3	0.947
5.670×10^3	1.146
8.789×10^3	1.073
1.162×10^4	0.955
1.446×10^4	1.014
1.729×10^4	1.078
2.013×10^4	1.069
2.297×10^4	1.171
3.119×10^3	1.895
5.812×10^3	1.364
8.789×10^3	1.193
1.162×10^4	1.227
1.446×10^4	1.278
1.729×10^4	1.140
1.999×10^4	1.084
2.297×10^4	1.031

Table 2-10. Drag Coefficient Data by Charnews for A 3/8 Inch Single Braided Synthetic Line (Cont.)

REYNOLDS NUMBER	C_d
2.835×10^3	1.146
5.670×10^3	1.146
8.647×10^3	1.109
1.162×10^4	1.159
1.446×10^4	1.146
1.729×10^4	1.140
2.013×10^4	1.114
2.297×10^4	1.153

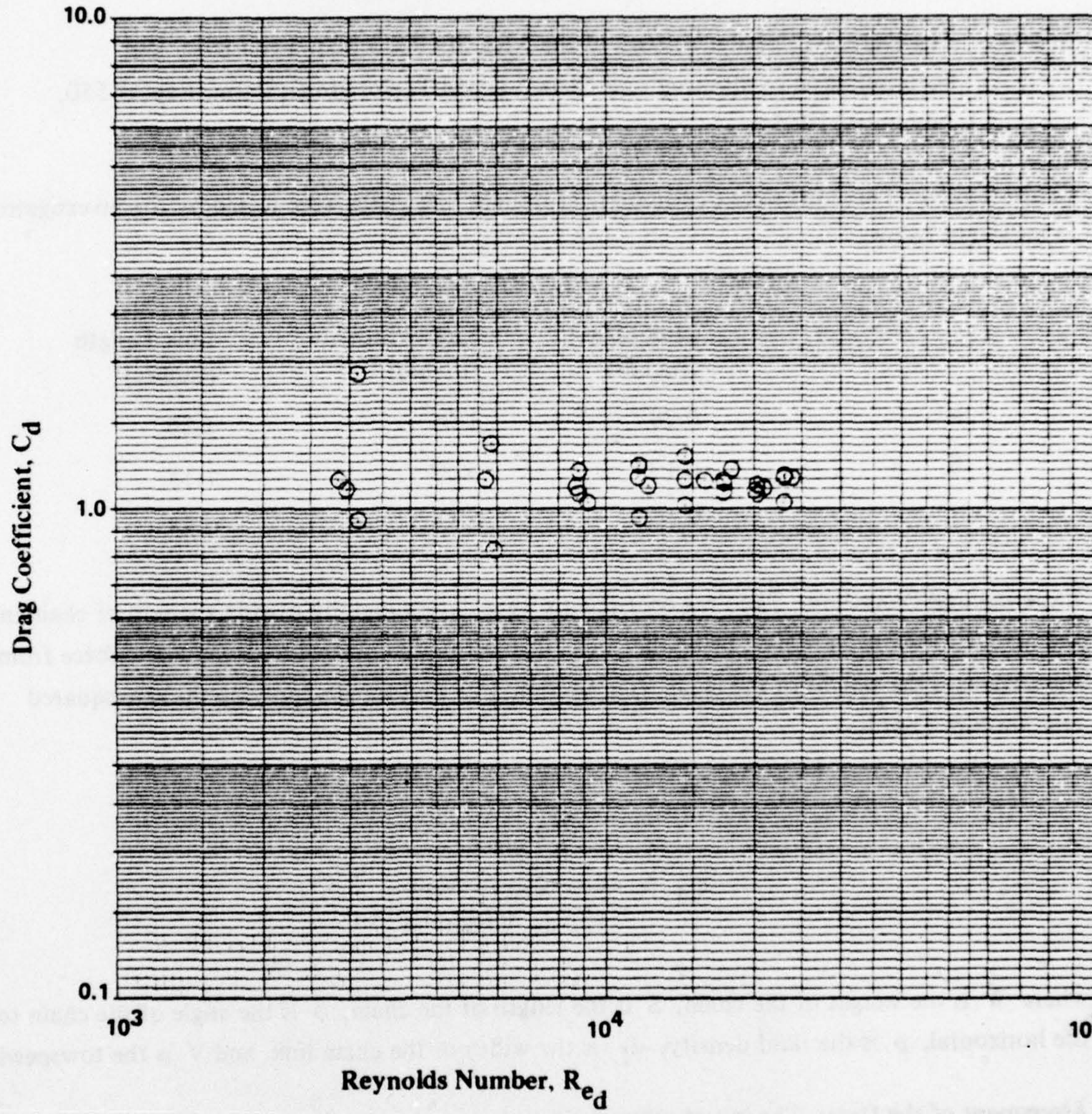

Figure 2-10. Drag Coefficient Data by Charnews for A 3/8 Inch Single Braided Synthetic Rope

2.8 DATA ITEM 8

Source: Eisenberg, P., "Characteristics of the NRL MARK 3 Boat-Type Buoy and Determination of Mooring Line Sizes", David Taylor Model Basin, Report 550, September 1945.

Cables Tested: Three (3) sizes of commercial straight link chain were tested by the investigator as indicated below.

	Link Size (Inches)	Link Width (Inches)	Link Length (Inches)
a.	0.28	1.05	1.56
b.	0.19	0.68	1.15
c.	0.15	0.54	0.88

Experimental Procedure: The drag coefficients were determined by towing a length of chain in the NSRDC towing basin measuring the angle, computing the normal hydrodynamic force from the angle and the weight of the chain, (see Section 2.2), and finally applying the sine-squared relationship. That is

$$C_d = \frac{\frac{W}{S} \cos \phi}{\frac{1}{2} \rho \, d_L V^2 \sin^2 \phi}$$

where W is the weight of the chain, S is the length of the chain, ϕ is the angle of the chain to the horizontal, ρ is the fluid density, d_L is the width of the chain link, and V is the towspeed.

Assessment of the Data: The investigator made no mention of the chain vibrating. Again, a sine-squared relationship was used to compute the drag coefficient data. The document does not give sufficient information to compute the towing angles, however, it is suspected that the angles measured were greater than 25 degrees and the sine-squared relationship is probably a reasonable assumption.

Drag Coefficient Data: Tabulated values of the drag coefficient data for the three (3) sizes of straight link chain tested are presented in Table 2-11. Plotted values are presented in Figure 2-11. Note that the drag coefficients and Reynolds Numbers are based upon the width of the chain link.

Table 2-11. Drag Coefficient Data by Eisenberg for Straight Link Chain

CHAIN WIDTH	REYNOLDS NUMBER	C_d
1.05 inch	2.7×10^4	0.85
	5.4×10^4	0.93
	8.2×10^4	0.86
	8.2×10^4	0.89
	9.5×10^4	0.93
	9.5×10^4	0.96
	1.09×10^5	0.91
	1.09×10^5	0.98
	1.37×10^5	0.90
0.68 inch	1.8×10^4	0.79
	3.5×10^4	0.83
	5.3×10^4	0.84
	5.3×10^4	0.87
	7.1×10^4	0.96
0.54 inch	1.4×10^4	0.70
	2.1×10^4	0.74
	2.9×10^4	0.82
	3.5×10^4	0.88
	4.2×10^4	0.91

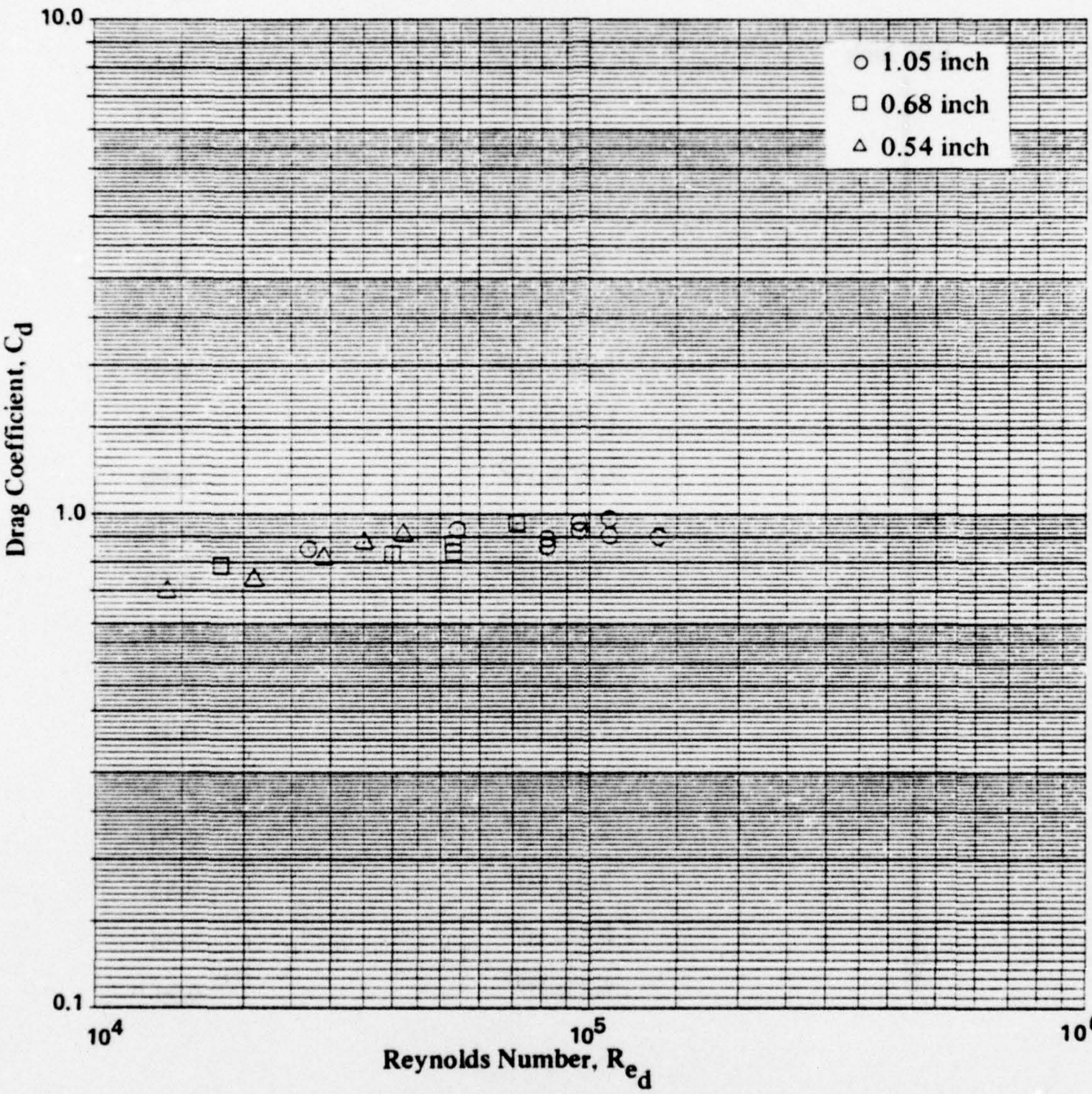

Figure 2-11. Drag Coefficient Data by Eisenberg Based on Chain Width for Straight Link Chain

2.9 DATA ITEM 9

Source: Bonde, L.W., "Determination of Stud Link Anchor Chain (Die-Lock Type) Drag Coefficients From Tow Test Data", Hydrospace Research Corporation, Report No. 133, November 1965.

Cables Tested: Three (3) sizes of stud link chain were tested as indicated below.

	CHAIN SIZE (Inches)	LINK WIDTH (Inches)	LINK LENGTH (Inches)
a.	3/4	2.69	4.5
b.	1	3.59	6.0
c.	1¼	4.50	7.5

Each stud link chain was of the die-lock type.

Experimental Procedure: Seventy (70) foot lengths of chain were towed from the stern of a small boat. Measurement of the weight of the chain, the towspeed, and the towing angle of the chain were made. The drag coefficients were computed from the balance of the forces acting normal to the chain with a sine-squared relationship applied. (See Sections 2.2 and 2.8.)

$$C_d = \frac{W \cos \phi}{\frac{1}{2} \rho \, d \, V^2 \sin^2 \phi}$$

The investigator presented the data for the drag coefficients and Reynolds Numbers in terms of the chain size.

Assessment of the Data: The investigator made no mention of the chain vibrating during the tow tests. The chain was towed at angles as shallow as 10 degrees and it is felt that the sine-squared relationship does not hold true for angles that shallow, especially when the shape of chain as compared to a wire rope or synthetic rope is considered. As a result, that portion of the data corresponding to angles below 20 degrees are not included in this report. Another reason for not including that portion of the data is the boat wake noted by the investigator which affected the chain when towing at the higher speeds (i.e., shallow towing angles).

Drag Coefficient Data: The tabulated and plotted drag coefficient data are presented in Table 2-12 and Figure 2-12, respectively. It should be noted that, although the investigator presented the drag coefficient and Reynolds Number data in terms of the chain size, that data have been recomputed and are presented herein in terms of the link width in order to be consistent with the data by Eisenberg (Section 2.8).

Table 2-12. Drag Coefficient Data by Bonde for Stud Link Anchor Chain

CHAIN SIZE	REYNOLDS NUMBER (Based on Chain Width)	C_d (Based on Chain Width)
3/4 inch	1.07×10^5	0.87
	1.58×10^5	0.78
	1.61×10^5	0.81
	1.79×10^5	0.63
	1.83×10^5	0.60
	2.04×10^5	0.60
	2.27×10^5	0.84
	2.36×10^5	0.74
	2.36×10^5	0.77
	2.76×10^5	0.88
	3.15×10^5	0.91
	3.15×10^5	0.95
1 inch	1.26×10^5	0.89
	1.26×10^5	0.92
	1.40×10^5	0.74
	1.54×10^5	0.90
	1.54×10^5	0.92
	1.80×10^5	0.96
	1.80×10^5	0.97

Table 2-12. Drag Coefficient Data by Bonde for Stud Link Anchor Chain (Cont.)

CHAIN SIZE	REYNOLDS NUMBER (Based on Chain Width)	C_d (Based on Chain Width)
1 inch	1.90×10^5	0.85
	2.01×10^5	0.65
	2.05×10^5	0.88
	2.23×10^5	0.83
	2.37×10^5	0.88
	2.48×10^5	0.78
	2.50×10^5	0.67
	2.51×10^5	0.90
	2.59×10^5	0.82
	2.87×10^5	0.85
	2.91×10^5	0.78
	2.94×10^5	0.90
	2.96×10^5	0.95
	3.09×10^5	0.88
	3.30×10^5	0.82
	3.45×10^5	0.88
	3.45×10^5	0.99
	3.59×10^5	0.93
	3.59×10^5	0.74
1¼ inch	2.16×10^5	0.81
	2.48×10^5	0.72
	2.52×10^5	0.64
	2.56×10^5	0.69
	2.63×10^5	0.79
	3.24×10^5	0.81
	3.31×10^5	0.78

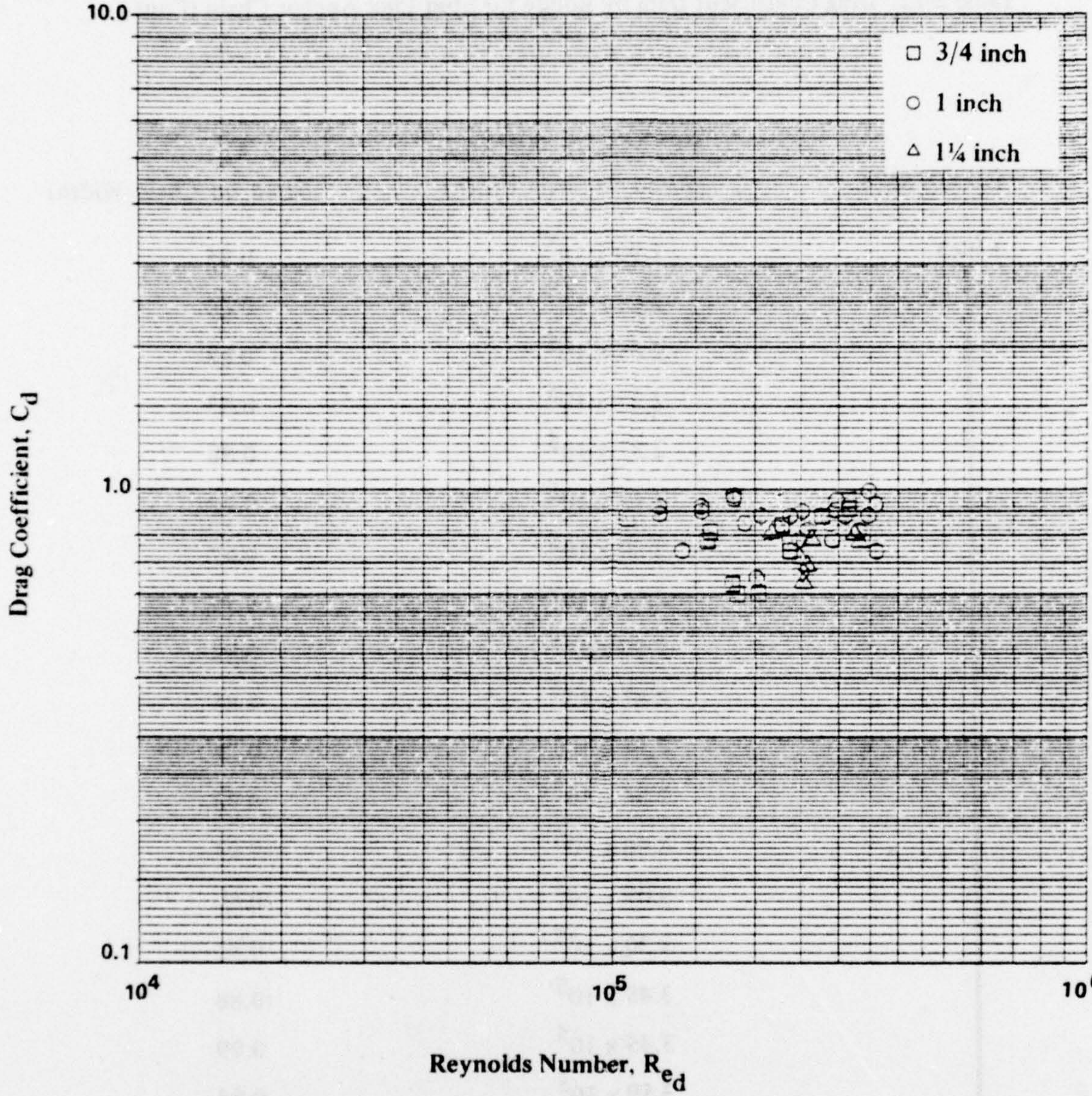

Figure 2-12. Drag Coefficient Data by Bonde Based Upon Chain Width for Stud Link Chain (Die-Lock Type)

2.10 DATA ITEM 10

Source: Kretschmer, T.R., Edgerton, G.A. and Albertson, N.D., "Seafloor Construction Experiment, SEACON II - An Instrumented Tri-Moor for Evaluating Undersea Cable Structure Technology," Civil Engineering Laboratory, Naval Construction Battalion Center, Technical Report R - 848, December 1976.

Cables Tested: The SEACON II cable consists of a 0.50 inch 3x19 wire rope with a polyethylene jacket giving an overall outer diameter of 0.72 inches.

Experimental Procedure: The SEACON II cable was tested at two separate facilities. The majority of the data were taken in the Naval Post Graduate School water tunnel. A four (4) inch long section was tested in the water tunnel. The second set of data were measured at the Naval Ship Research and Development Center. A fifteen (15) foot section was towed in the towing basin. Both tests represent situations where the cable was oriented normal to the flow direction. In the case of the NSRDC data only the data for which the cable was observed to be non-vibrating are presented.

Assessment of the Data: The data have been verified to be measurements of a non-vibrating cable. The lack of scatter would indicate that the quality of the data is quite good, especially considering the data were taken in two separate tests.

Drag Coefficient Data: The tabulated and plotted drag coefficient data are presented in Table 2-13 and Figure 2-13.

Table 2-13. Drag coefficient Data for the SEACON II Cable

Source	Reynolds Number	C_d
NPGS	8.10×10^2	1.68
↓	1.51×10^3	1.51
	2.00×10^3	1.54
	3.96×10^3	1.57
	6.00×10^3	1.61
	8.00×10^3	1.64
NSRDC	2.52×10^3	1.52
↓	3.32×10^3	1.59
	4.29×10^3	1.58

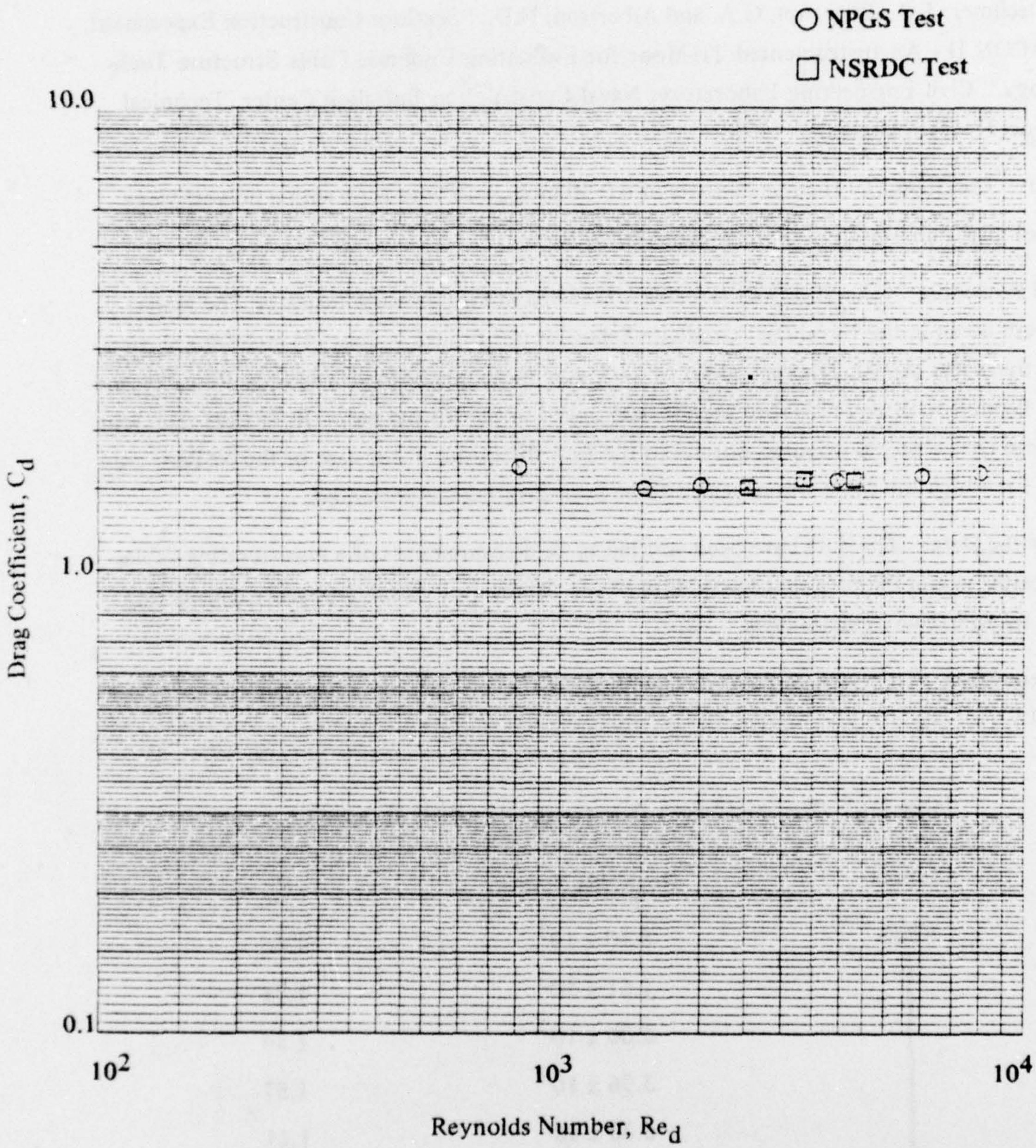

Figure 2-13. Drag Coefficient Data for the SEACON II Cable

Section 3

SUMMARY OF EXISTING DRAG COEFFICIENT DATA

The purpose of this section is to summarize the drag coefficient data by type of cable and to identify the range(s) of Reynolds number for which data is lacking or inadequate.

3.1 NON-JACKETED, STRANDED STEEL CABLES

The available data for non-jacketed, stranded steel cables are summarized in Figure 3-1 and represent the results of the following investigators and/or sources: Relf and Powell, Pode, Schultz, DTMB, and Diggs.

As a baseline reference for comparison, an empirical relationship between normal drag coefficient and Reynolds number, for a smooth circular cylinder of infinite length and in a uniform flow field, is illustrated by the Wieselsberger curve (full-line). The Wieselsberger curve is widely accepted as a valid baseline for cable normal drag comparison. Also shown is a representative curve (dash-line) of a stranded cable, developed by Wilson, reference 84, from the towing test data of Zajac, reference 87; Pode, reference 60, Mosely (1952); and Kullenberg (1951). It should be noted that the data utilized to formulate this curve, were from towing configurations in the critical angle regime and that the sine-squared law was utilized to compute the normal drag coefficients. As mentioned earlier, results of this type of analysis are of questionable validity.

It is a very difficult task to make an assessment of the data shown in Figure 3-1 as to the value of the data for use in computer programs. As a potential user of the data, it is not clear what drag coefficient should be selected for a given Reynolds number. All of the cables for which data is included are of sufficient similarity in construction. All of the cables are of 7 x 7 (or 6 x 7 with an independent core) construction or greater, and therefore, have a relatively circular cross-section. No cables having a largely different cross-section than circular (e.g., 3 x 19) are represented in the family of data. Therefore, it is felt that the construction of the cable is not a major factor in the scatter of data shown in Figure 3-1.

Based upon knowledge of the experimental procedures used by the various investigators, certain statements can be made concerning the data. First, a large percentage of the data by Diggs is certainly influenced by cable vibrations. This is probably also the case for Pode's data. Second, the data by Pode and Diggs are also affected by the fact that the data represent a very shallow

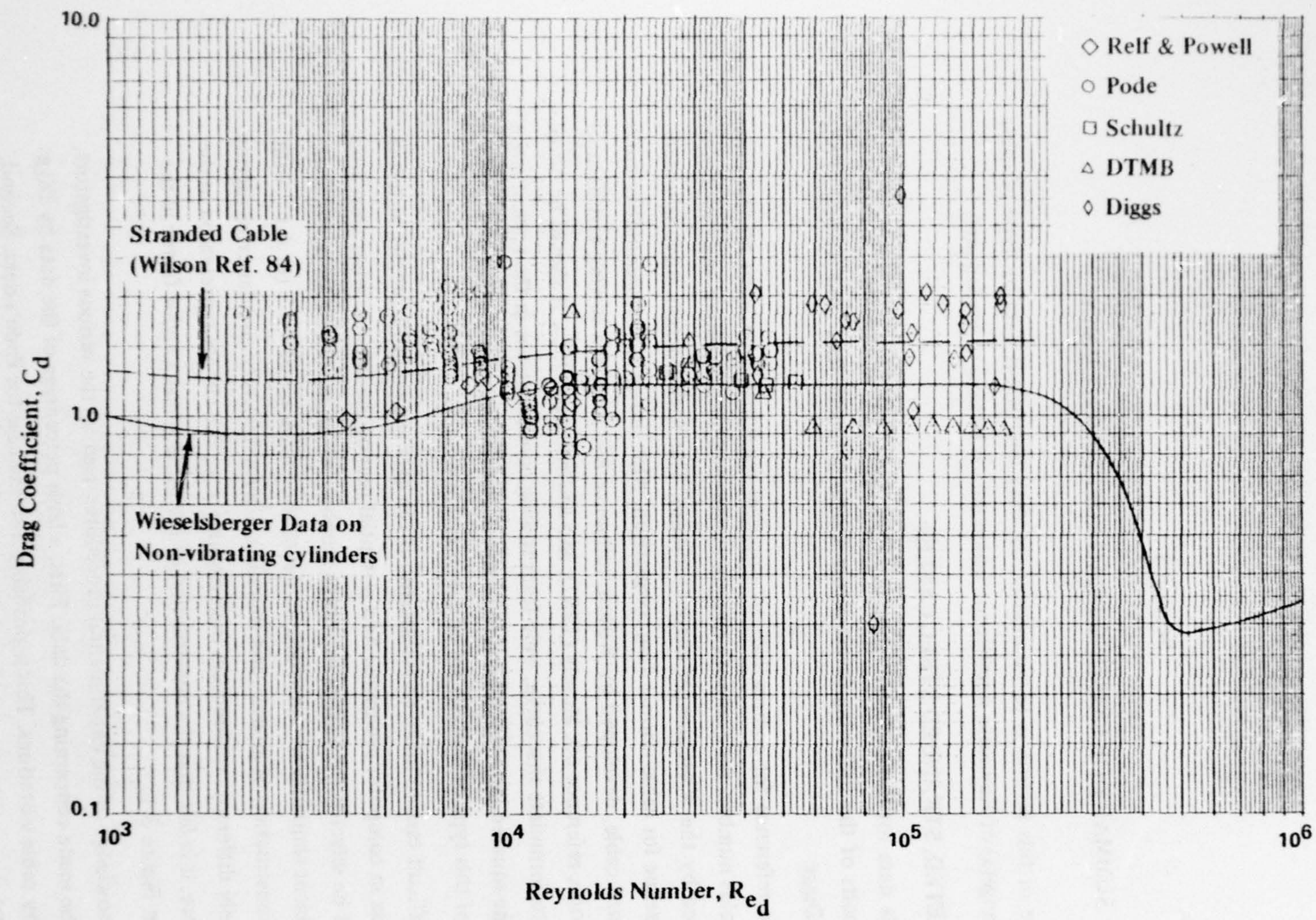

Figure 3-1. Summary of Drag coefficient Data for Non-Jacketed, Stranded Steel Cables

angle towing regime (critical angle). The inherent inaccuracy of the computed drag coefficient (a large error is possible) due to a small error in the measurement of the cable angle, and the uncertainty of the sine-squared principle for small cable angles both lend little credibility to the data. The DTMB data are slightly suspect due to possible three-dimensional data by Relf & Powell. The data by Schultz are believed to be of good quality, however, the amount of data (a total of ten (10) points over the Reynolds Number range from 4.5×10^3 to 5.3×10^4) is felt inadequate to justify its use. Finally, no data covering the Reynolds Number range from 10^2 to 2×10^3 have been identified.

3.2 JACKETED CABLES

The available data for jacketed cables are summarized in Figure 3-2. No data were identified during the survey which cover the Reynolds Number range from 1×10^2 to 8×10^2. *With the exception of the SEACON II cable data,* due to the large scatter of the data shown in Figure 3-2 covering the Reynolds Number range for 8×10^3 to 9×10^4 and since those data were all derived from shallow angle tow tests, it is felt that the data are inadequate for use in computer simulations requiring drag coefficients for non-vibrating jacketed cables. The SEACON II data are adequate for use in the computer simulations and the average value over the Reynolds Number range from 8×10^2 to 8×10^3 is 1.55.

3.3 SYNTHETIC ROPES

The available data for synthetic ropes are summarized in Figure 3-3. It can be seen that the drag coefficients for the braided ropes are slightly higher than for the plaited rope. Although only a single investigator could be identified for synthetic ropes (i.e., Charnews), it is felt that the data covering the range from 6×10^3 to 5.3×10^4 for plaited rope and the range from 3×10^3 to 2.4×10^4 for braided rope are adequate for use in computer simulations requiring drag coefficients of non-vibrating cables.

No data could be found for synthetic ropes having stranded or parallel lay constructions.

3.4 CHAIN

The available drag coefficient data for chain are summarized in Figure 3-4. It is felt that the data shown are adequate over the Reynolds Number ranges shown. Data are lacking for straight link chain in the Reynolds Number range from 10^2 to 1.4×10^4. Data are lacking for stud link chain in the Reynolds Number range from 10^2 to 10^5.

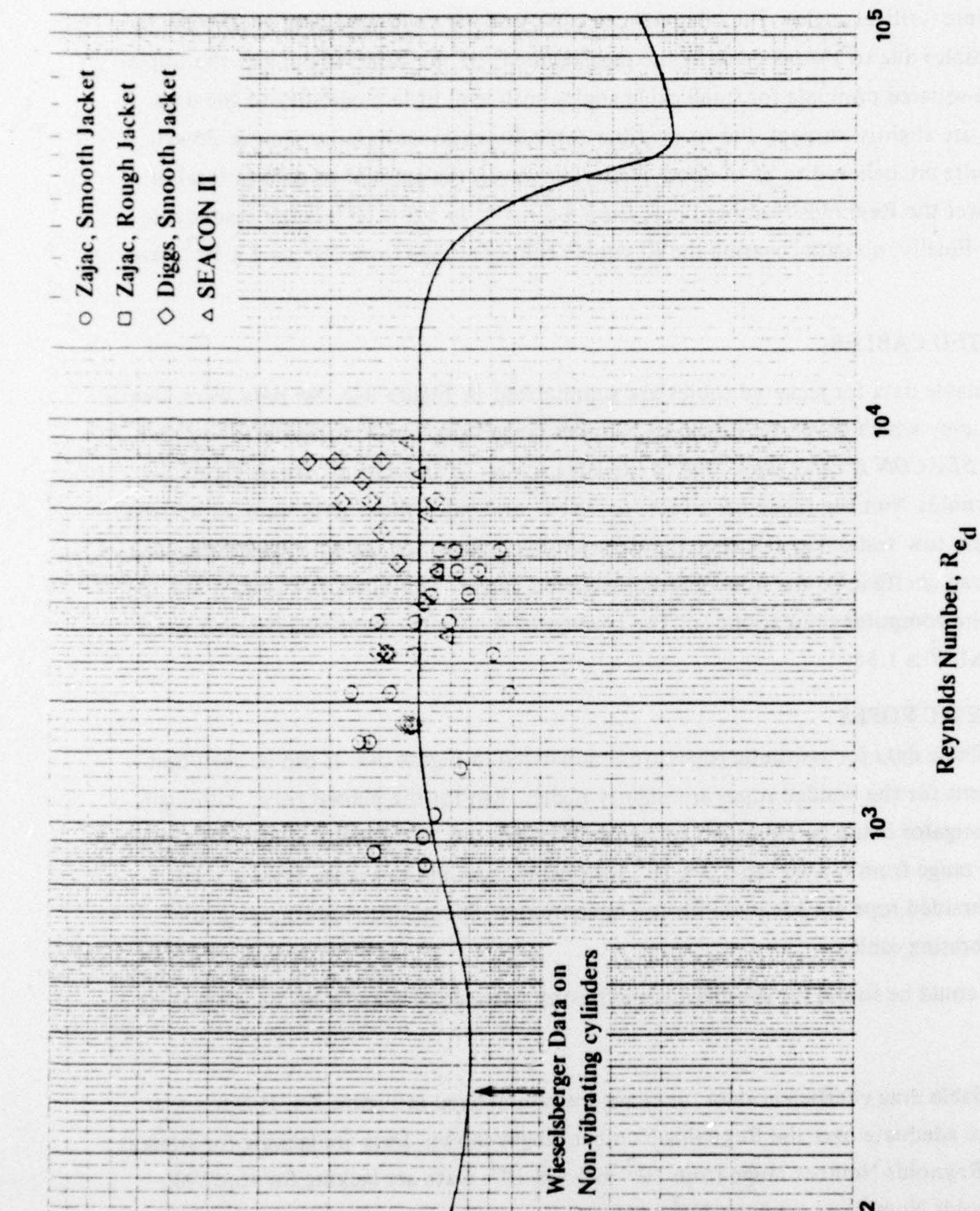

Figure 3-2. Summary of Drag Coefficient Data for Jacketed Steel Cables

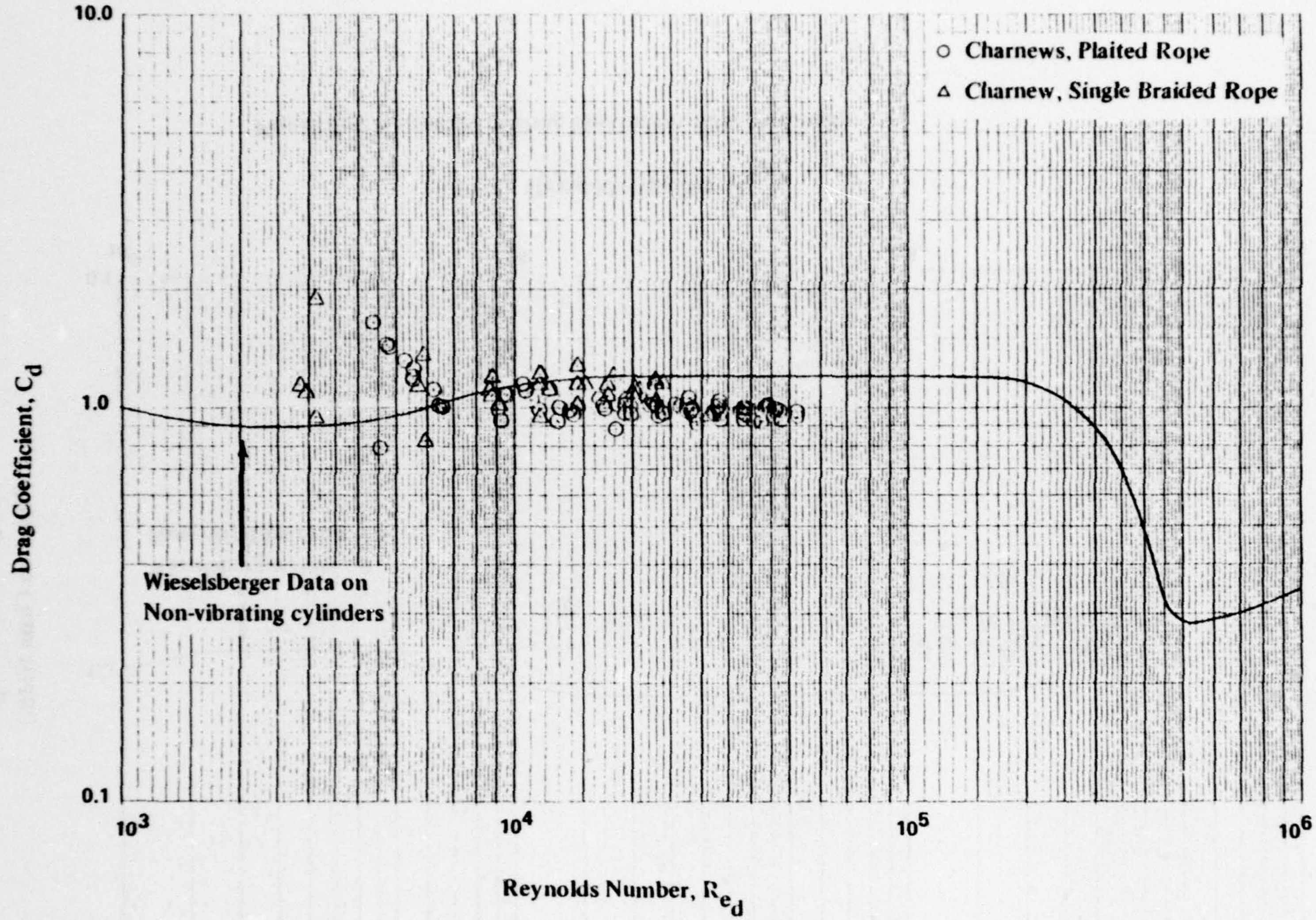

Figure 3-3. Summary of Drag Coefficient Data for Synthetic Ropes

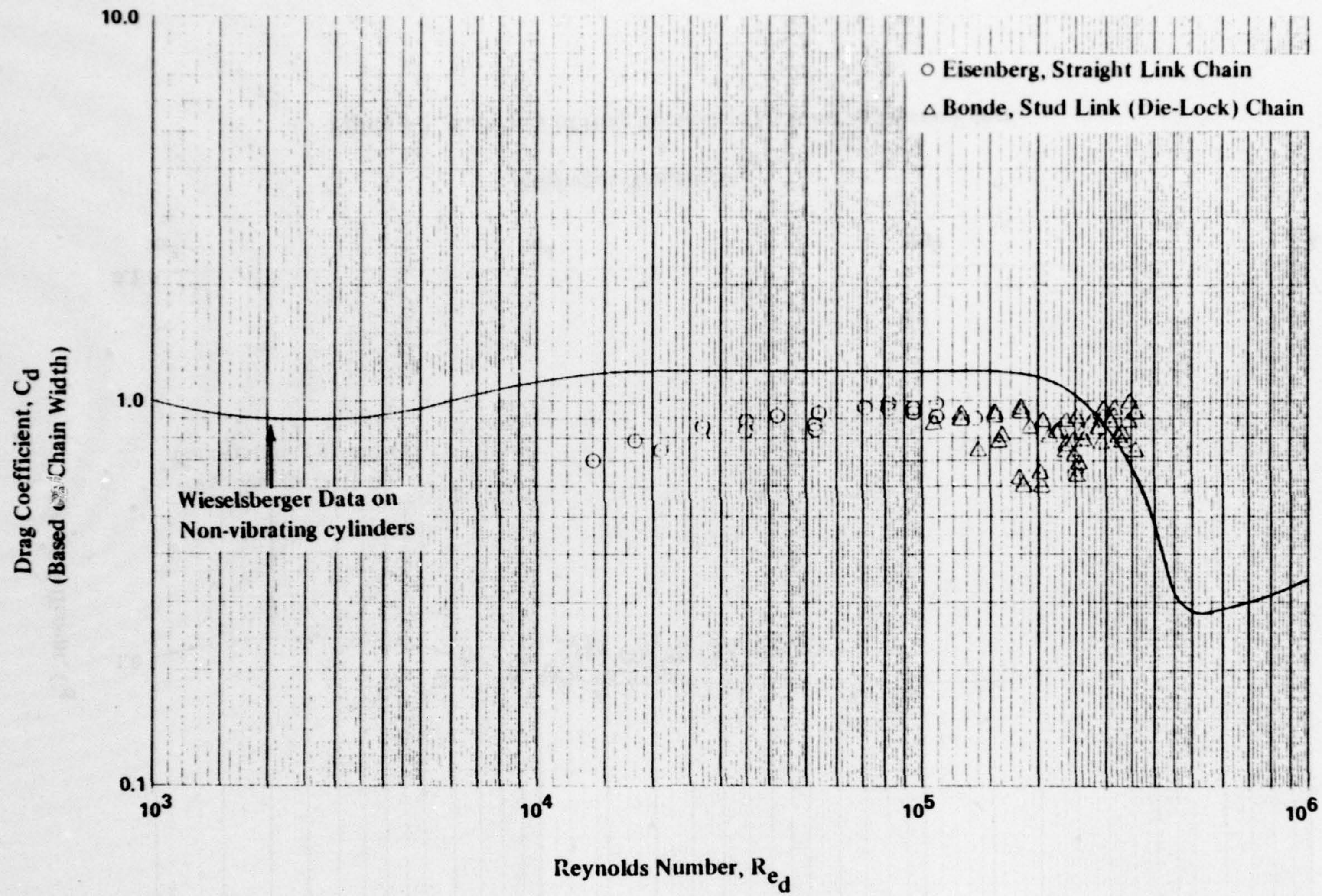

Figure 3-4. Summary of Drag Coefficient Data for Chain

Section 4

BIBLIOGRAPHY OF SOURCES CONSULTED

1. Alberson, N.D., "A Survey of Techniques for the Analysis and Design of Submerged Mooring Systems", Civil Engineering Laboratory, Technical Report R815, August 1974.

2. Barnett, Kenneth M., and Cermak, J.E., "Turbulence Induced Changes in Vortex Shedding From a Circular Cylinder", College of Engineering, Colorado State University, Technical Report No. 26, January 1974.

3. Bearman, P.W., "The Flow Around a Circular Cylinder in the Critical Reynolds Number Regime".

4. Benedict, Richard P., "A Wind Tunnel Determination of the Forces Acting on Stranded Wire Ropes and Cables", Virginia Polytechnic Institute, June 1967.

5. Berteaux, H.O., "Buoy Engineering", John Wiley and Sons, Incorporated, 1976.

6. Bishop, R.E.D., and Hassan, A.Y., "The Lift and Drag Forces on a Circular Cylinder Oscillating in a Flowing Fluid", Proceedings of the Royal Society, A, Volume 277, pp. 51 - 75, 1963.

7. Bloor, M. Susan, "The Transition to Turbulence in the Wake of a Circular Cylinder", Journal of Fluid Mechanics, Volume 19, Part 2, pp. 290 - 304, 1964.

8. Bonde, L., "Determination of Stud Link Anchor Chain (Die-Lock Type) Drag Coefficients from Tow Test Data", Hydrospace Research Corporation, Report 113, November 1965.

9. Casarella, Mario J., and Parsons, Michael, "Cable Systems Under Hydrodynamic Loading", Marine Technology Society Journal, Volume 4, No. 4, July 1970.

10. Charnews, D.P., "Drag Coefficients of Vibrating Synthetic Rope", Massachusetts Institute of Technology/Woods Hole Oceanographic Institute, Masters Thesis, September 1971.

11. Chen, Y.N., "Fluctuating Lift Forces of the Karmen Vortex Streets on Single Circular Cylinders and in Tube Bundles – Part 1. The Vortex Street Geometry of the Single Circular Cylinder", Transactions of the ASME Journal of Engineering for Industry, 1971.

12. Chen, Y.N., "Fluctuating Lift Forces of the Karman Vortex Streets on Single Circular Cylinders and in Tube Bundles – Part 2. Lift Forces of Single Cylinder", Transactions of the ASME Journal of Engineering for Industry, 1971.

13. Chiu, W.S., and Lienhard, J.H., "On Real Fluid Flow Over Yawed Circular Cylinders", ASME Paper No. 67 - WA/FE-11, November 1967.

14. Choo, Young-il, and Casarella, Mario J., "Hydrodynamic Resistance of Towed Cables", Journal of Hydronautics, Volume 5, No. 4, October 1971.

15. Coder, David, W., "Hydrodynamic Forces on Oscillating and Non-Oscillating Smooth Circular Cylinders in Crossflow", Naval Ship Research and Development Center, Report No. 3639, October 1972.

16. Dale, J.R., and Holler, R.A., "Vortex Wakes from Flexible Circular Cylinders at Low Reynolds Numbers", Naval Air Development Center, Report No. NADC-AE-7011, July 1970.

17. Dale, J.R., and McCandless, J., "Determination of Normal Drag Coefficients for Flexible Cables", Naval Air Development Center, Report No. NADC-AE-6719, June 1967.

18. Dale, J.R., McCandless, J., and Holler, R.A., "Water Drag Effects of Flow Induced Cable Vibrations", ASME Publication 68 - WA/FE-47, December 1968.

19. Dale, J.R., Menzel, H., and McCandless, J., "Dynamic Characteristics of Underwater Cables Flow Induced Transverse Vibrations", Naval Air Development Center, Report No. NADC-AE-6620, September 1966.

20. Delaney, Noel K., and Sorensen, Norman E. "Low Speed Drag of Cylinders of Various Shapes", NACA TN-3038, November 1953.

21. Diggs, Jesse S., "A Survey of Vortex Shedding from Circular Cylinders with Applications Toward Towed Arrays", MAR, Incorporated, Technical Report No. 144, May 1975.

22. Diggs, Jesse S., "Hydrodynamic Characterization of Various Towed Array Towcables", MAR, Incorporated, Technical Report No. 128, August 1974.

23. Eames, Michael C., "Optimum Towing at High-Speed", Naval Research Establishment, Technical Note SS/63/3, July 1963.

24. Eisenberg, P., "Characteristics of the NRL MARK 3 Boat-Type Buoy and Determination of Mooring Line Sizes", David Taylor Model Basin, Report No. 550, September 1945.

25. Ferguson, N., and Parkinson, G.V., "Surface and Wake Phenomena of the Vortex-Excited Oscillations of a Circular Cylinder", Transactions of the ASME, Journal of Engineering for Industry, Paper No. 67 - Vibr - 31, March 1967.

26. Fung, Y.C., "Fluctuating Lift and Drag Acting on a Cylinder in a Flow at Supercritical Reynolds Numbers", Space Technology Laboratories Report GM - TR-0165, May 1958.

27. Fung, Y.C., "Fluctuating Lift and Drag Acting on a Cylinder in a Flow at Supercritical Reynolds Numbers", Institute of Aeronautical Science, Paper No. 60-6, January 1960.

28. Gerrard, J.H., "An Experimental Investigation of the Oscillating Lift and Drag of a Circular Cylinder Shedding Turbulent Vortices", Journal of Fluid Mechanics, Volume 11, Part 2, pp. 244-256, March 1961.

29. Gibbons, Thomas, and Walton, Chester O., "Evaluation of Two Methods for Predicting Towline Tensions and Configurations of a Towed Body System Using Bare Cable", David Taylor Model Basin, Report 2313, December 1966.

30. Glass, Robert J., "A Study of the Self-Excited Vibrations of Spring Supported Cylinders in a Steady Fluid Stream", University of Maryland, Ph.D. Thesis, 1966.

31. Glass, Robert J., "A Study of the Hydroelastic Vibrations of Spring Supported Cylinders in a Steady Fluid Stream Due to Vortex Shedding, Ohio Northern University, 1970.

32. Glenny, D.E., "A Review of Flow Around Circular Cylinders, Stranded Cylinders, and Struts Inclined to the Flow Direction", Australian Defense Scientific Service, Aeronautical Research Laboratories, Mechanical Engineering Note No. 284, October 1966.

33. Griffin, O.M., "Flow Near Self-Excited and Forced Vibrating Circular Cylinders", Transactions of the ASME Journal of Engineering for Industry, 1971.

34. Griffin, O.M., "The Unsteady Wake of an Oscillating Cylinder at Low Reynolds Number", Transactions of the ASME, Journal of Applied Mechanics, December 1971.

35. Griffin, O.M., Skop, R.A., and Koopman, G.H., "Measurements of the Response of Bluff Cylinder to Flow Induced Vortex Shedding", Offshore Technology Conference, Paper No. DTC 1814, April 1973.

36. Griffin, O.M., and Votaw, C.W., "The Vortex Street in the Wake of a Vibrating Cylinder", Journal of Fluid Mechanics, Volume 55, Part 1, pp. 31-48, 1972.

37. Halle, H., and Lawrence, W.P., "Crossflow-Induced Vibration of a Circular Cylinder in Water", ASME Publication 73 - DET - 68, September 1973.

38. Hama, Francis R., "Three-Dimensional Vortex Patterns Behind a Circular Cylinder", Journal of Aeronautical Sciences, February 1957.

39. Hatfield, H.M., and Morkovin, M.V., "Effect at an Oscillating Free Stream on the Unsteady Pressure on a Circular Cylinder", Transactions of the ASME, Journal of Fluids Engineering, June 1973.

40. Heinmiller, Robert H., Jr., "The Woods Hole Buoy Project Moorings – 1960 through 1974", Woods Hole Oceanographic Institute, Technical Report WHOI-76-53, June 1976.

41. Heller, S.R., Jr., and Chung, Bong Soo, "On the Transverse Vibration of Wire Rope", ASME Publication 73-WA/OCT-15, November 1973.

42. Hoerner, S.F., "Fluid Dynamic Drag", Published by the Author, 1965.

43. Humphreys, John S., "On a Circular Cylinder in a Steady Wind at Transition Reynolds Numbers", Journal of Fluid Mechanics, Volume 9, Part 4, December 1960.

44. Jones, G.W., Jr., "Unsteady Lift Forces Generated by Vortex Shedding About a Large, Stationary, and Oscillating Cylinder at High Reynolds Numbers", ASME Publications 68-FE-36, May 1968.

45. Jones, G.W., Concotta, J.J., and Walker, R.W., "Aerodynamic Forces on a Stationary and Oscillating Circular Cylinder at High Reynolds Numbers", NASA TR-R-300, February 1969.

46. Kaplan, S., "Low Reynolds Number Flow Past a Circular Cylinder", Journal of Mathematics and Mechanics, Volume 6, pp. 595-603, 1957.

47. Lienhard, John H., "Synopsis of Lift, Drag, and Vortex Frequency Data for Rigid Circular Cylinders", Washington State University, College of Engineering, Research Division Bulletin 300, 1966.

48. Lienhard, J.H., and Liu, L.W., "Locked-In Vortex Shedding Behind Oscillating Circular Cylinders with Application to Transmission Lines", ASME Publication 67-FE-24, May 1967.

49. Kobashi, Yasujiro, "Measurements of Pressure Fluctuation in the Wake of Cylinder", Journal of the Physical Society of Japan, Volume 12, No. 5, May 1957.

50. Koopman, G.H., "The Vortex Waters of Vibrating Cylinders at Low Reynolds Numbers", Journal of Fluid Mechanics, Volume 28, Part 3, pp. 501-512, 1967.

51. Kretschmer, J.R., Edgerton, G.A., and Albertson, N.D., "Seafloor Construction Experiment, SEACON II-An Instrumented Tri-Moor for Evaluating Undersea Cable Structure Technology, " Civil Engineering Laboratory, Naval Construction Battalion Center, Technical Report R-848, December 1976.

52. Mei, V.C., and Currie, I.G., "Flow Separation on a Vibrating Circular Cylinder", Journal of the Physics of Fluids, Volume 12, No. 11, November 1969.

53. Meier-Windhorst, August, "Flutter Vibrations of Cylinders in a Uniform Flow", David Taylor Model Basin, Translation 333, July 1966.

54. Myers, L., "Estimation of the Tangential and Normal Coefficient of Drag for the ONR HDPE Jacketed Cable Used on the 6G1-D Sea Trial", MAR, Incorporated Technical Memo No. 33, June 1976.

55. Nelligan, J.J., "A Survey of the Experimental Methods in Vortex Shedding from Cables and Cylinders", MAR, Incorporated, Technical Report No. 137, December 1974.

56. Nelligan, J.J., Gay, S.M., and Gibbons, T., "Kennecott Towed System Study", MAR, Incorporated Technical Report No. 144, May 1975.

57. Okamoto, Tetsushi, and Yagita, Miki, "The Experimental Investigation on of the Flow Past a Circular Cylinder of Finite Length Placed Normal to the Plane Surface in a Uniform Stream", Bulletin of the ASME, Volume 16, No. 95, May 1973.

58. Paidoussis, M.P., "Stability of Towed, Totally Submerged Flexible Cylinders", Journal of Fluid Mechanics, Volume 34, Part 2, pp. 273-297, 1968.

59. Pattison, J.H., Rispin, P.P., and Tsai, N.T., "Handbook on Hydrodynamic Characteristics of Moored Array Components", David Taylor Naval Ship Research and Development Center, Report No. SPD-745-01, March 1977.

60. Pode, Leonard, "An Experimental Investigation of the Hydrodynamic Forces on Stranded Cables", David Taylor Model Basin, Report 713, May 1950.

61. Pode, Leonard, "Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream", David Taylor Model Basin, Report 687, March 1951.

62. Popov, S.G., "Dependence Between the Strouhal and Reynolds Numbers in Two-Dimensional Flow Past a Circular Cylinder", NASA Technical Translation TT F-11, 763, July 1968.

63. Ramberg, S.E., and Griffin, O.M., "The Effects of Vortex Coherence, Spacing, and Circulation on the Flow-Induced Forces on Vibrating Cables and Bluff Structures", Naval Research Laboratory Report 794, January 1976.

64. Ramsey, J.P., and Davis, L., "Empirical Hydrodynamic Characterization of an 0.802-Inch Diameter Double-Armored Towline", Hydrospace Research Corporation, Report No. 308, December 1970, CONFIDENTIAL.

65. Ramsey, J.P., and Dillon, D.B., "Empirical Hydrodynamic Characterization of Two Bare Double-Armored Towlines", Hydrospace Research Corporation, Report No. 293, November 1970.

66. Reid, Robert O., and Wilson, Basil W., "Boundary Flow Along a Circular Cylinder", National Engineering Science Company Technical Report 204-4, March 1962.

67. Relf, E.F., and Powell, C.H., "Tests on Smooth and Stranded Wires Inclined to the Wind Direction, and a Comparison of Results on Stranded Wires in Air and Water", Advisory Committee for Aeronautics, Great Britain, Reports and Memoranda (New Series) No. 307, January 1917.

68. Roshko, Anatol, "On the Development of Turbulent Wakes from Vortex Streets", NACA Report 1191, 1954.

69. Roshko, A., "On the Drag and Shedding Frequency of Two-Dimensional Bluff Bodies", NACA TN 3169, July 1954.

70. Roshko, Anatol, "Experiments on the Flow Past a Circular Cylinder at Very High Reynolds Number", Journal of Fluid Mechanics, Volume 10, Part 3, 1961.

71. Schmidt, L.V., "Measurements of Fluctuating Air Loads on a Circular Cylinder", Journal of Aircraft, Volume 2, 1965.

72. Schultz, M.P., "Wind Tunnel Determination of the Aerodynamic Characteristics of Several Twisted Wire Ropes", David Taylor Model Basin, Report 1645, Aero Report 1028, June 1962.

73. Skop, R.A., and Griffin, O.M., "A Model for the Vortex-Excited Resonant Response of Bluff Cylinders", Journal of Sound and Vibration, 27(2), pp. 225-233, 1973.

74. Souders, W.G., Coder, D.W., and Nelka, J.J., "Experimental Measurements of Lift and Drag on an Oscillating, Smooth Circular Cylinder in Crossflow", Naval Ship Research and Development Center, Report 302-H-01, November 1968.

75. Springston, G.B., Jr., "Generalized Hydrodynamic Loading Functions for Bare and Faired Cables in Two-Dimensional Steady-State Cable Configurations", Naval Ship Research and Development Center, Report 2424, 1967.

76. Thews, J.G., and Landweber, L., "On the Resistance at a Heavy Flexible Cable for Towing a Surface Float Behind a Ship", United States Experimental Model Basin, Report No. 418, March 1936.

77. Thews, J.G., and Landweber, L., "The Tension in a Loop of Cable Towed Through a Fluid", United States Experimental Model Basin, Report No. 422, June 1936.

78. Thom, A., "The Flow Past Circular Cylinders at Low Speeds", Proceedings Royal Society, London, Series A, Volume 141, pp. 651-669, 1933.

79. Toebes, Gerrit, H., "Fluidelastic Forces on Circular Cylinders", Proceedings ASME, Journal of the Engineering Mechanics Division, Volume 93, No. EM6, December 1967.

80. Toebes, Gerrit, H., "The Unsteady Flow and Wake Near an Oscillating Circular Cylinder", Transactions of the ASME, Journal of Basic Engineering, Paper No. 68-WA/FE-23, December 1968.

81. Votaw, C.W., and Griffin, O.M., "Vortex Shedding from Smooth Cylinders and Stranded Cables", Journal of Basic Engineering, September 1971.

82. Webster, B., Diggs, J., and Rispin, P., "A Summary of the Hydromechanical Characterization of Various Towed Array Towcables", NSRDC, July 1974.

83. Welsh, Clement J., "The Drag of Finite-Length Cylinders Determined from Flight Tests at High Reynolds Numbers for a Mach Number Range from 0.5 to 1.3", NACA TN 2941, June 1953.

84. Wilson, Basil W., "Characteristics of Anchor Cables in Uniform Ocean Currents", the A&M College of Texas, Technical Report No. 204-1, April 1960.

85. Wilson, Basil W., "Characteristics of Deep-Sea Anchor Cables in Strong Ocean Currents", The A&M College of Texas, Technical Report No. 204-3, February 1961.

86. Wootton, L.R., "The Oscillations of Large Circular Stacks in Wind", Proceedings Instructions Civil Engineers, 43, pp. 573-598, August 1968.

87. Zajac, E.E., "Dynamics and Kinematics of the Laying and Recovery of Submarine Cable", Bell System Technical Journal, Volume 36(5), pp. 1129-1207, September 1957.

88. "Drag Measurements of Bare and Faired Cables", Unpublished DTMB letter enclosure, May 1964.

89. "Design Manual – Harbors and Coastal Facilities", Naval Facilities Engineering Command, DM-26, July 1968.

90. "Designer's Guide for Deep-Ocean Ship Moorings", Hydrospace Research Corporation, Technical Report No. 270, March 1970.