AN EXPERIMENTAL INVESTIGATION OF THE STATIC

COEFFICIENT OF FRICTION FOR SHEETPILE INTERLOCKS

by

William B. Oliver, Jr.

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Civil Engineering

APPROVED:

R.M. Barker, Chairman

G.W. Clough

A.E. Somers, Jr.

January, 1985

Blacksburg, Virginia

AN EXPERIMENTAL INVESTIGATION OF THE STATIC COEFFICIENT OF FRICTION FOR SHEETPILE INTERLOCKS

by

William B. Oliver, Jr.

(ABSTRACT)

The classical use of 0.3 for the static coefficient of friction for sheetpile interlocks was investigated in this study. The effects of cyclic displacements on the coefficient of friction of the interlocks was also examined.

A broad range of values for the coefficient of friction was observed for over 2000 observations of the shear force required to initiate interlock displacement,. The mean observed value of the coefficient of friction was greater than 0.3 for low interlock stress. The mean coefficient of friction decreased with increased interlock stress. At interlock loads of five kips per inch the mean coefficient of friction was approximately equal to 0.3.

The relationship between interlock stress and the coefficient of friction was found to be nonlinear. An exponential model to predict the coefficient of friction for interlock loads between 1 and 5 kips per inch was developed.

To study the effects of cyclic displacements on interlock friction the specimen interlocks were displaced approximately one hundred times. No significant effect on interlock friction was observed.

To My Parents

William Bruce Oliver
Frances Beaman Oliver

and my grandfather

George K. Beaman

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

1.1 Background

The use of sheetpile sections for cofferdams and bulkheads has increased dramatically over the years since the first installation of a prismatic cell cofferdam at Black Rock Harbor, Connecticut in 1908 [3]. The early design of sheetpile cofferdams evolved empirically. Design techniques were developed from the observed behavior of cellular structures. Over the years several theories to explain cofferdam behavior were presented by engineers such as Terzaghi, Cummings, Hansen and others [2,3,4,9]. Although Terzaghi′s theory of cofferdam behavior was most widely accepted and utilized, it was not until 1979 that experimental research utilizing model tests of cellular sheetpile structures, conducted by Maitland and Schroeder [5], verified the accuracy of Terzaghi′s theory.

By Terzaghi′s design method for a cellular sheetpile cofferdam, the resistance of the cellular structure to an externally applied force such as hydrostatic pressure, is generated by the shear resistance of the cell fill material and by the frictional resistance to movement within the sheetpile interlocks.

Figure 1 shows a simple conceptual form of the Terzaghi Method. A plan view of a single cell is shown in Figure 1(a). To simplify design calculations it is customary to replace the circular area with straight lines enclosing an equivalent rectangular area. Dimension L

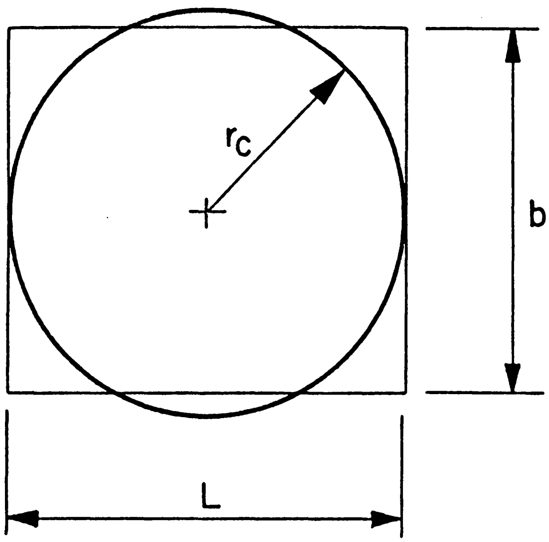

Figure 1(a). Plan view of single cell.

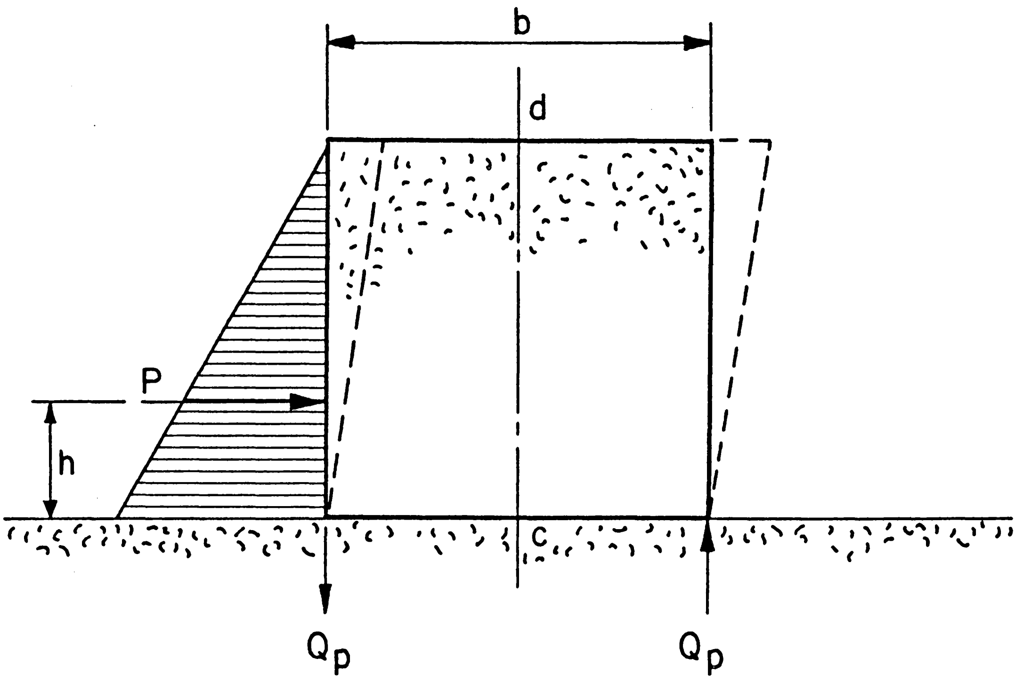

Figure 1(b). Vertical section through single cell.

Figure 1. Terzaghi concept of cellular resistance to lateral forces.

represents a unit length, which for a single cell is the cell diameter. Dimension b is the equivalent width which when multiplied by L will yield the original circular area.

In Figure 1(b) is shown a vertical section passed through a mass of soil confined between two straight walls of sheet piles driven into supporting soil or bearing on rock foundation. As soon as a resultant overturning force P is applied at elevation h, the near side row of sheet piles is subject to pull by a force Q_p and the far side is subject to pushing down by the same Q_p. The horizontal force P produces a change in the shape of the cell as it increases in magnitude. The vertical cross section changes from a rectangle to a parallelogram with equal area. The change in shape is caused by shearing failure along an infinite number of vertical planes. Total failure occurs as soon as the total shearing force on a plane such as c-d becomes equal to the available shearing resistance of that plane.

Figure 2 depicts the analysis of a cell with complete drainage founded on rock. Area a-b-c-d represents the average unit pressure caused by the cell fill material before the application of the horizontal load. Upon the application of a horizontal load resulting in moment, M, the distribution of vertical pressure may be represented by line m-n. If Q represents the total vertical shear force of each triangle acting at its center of gravity, the resisting moment per unit of length is:

$$M = 2/3 \times b \times Q \qquad (1)$$

and

$$Q = 3M/2b \qquad (2)$$

The vertical shearing force on the plane g-h must be equal to Q. Shearing resistance of the cell fill material, S' on the plane g-h is derived from the total lateral pressure P_A on that plane as shown in Figure 3. This gives

$$S' = P_A \tan\phi \tag{3}$$

Where ϕ is the angle of internal friction of the cell fill material and

$$P_A = 1/2\,\gamma H^2 K_a \tag{4}$$

where γ is unit weight of the cell fill material, H is the free-standing cell height and K_a is the ratio of horizontal to vertical stress in the cell fill. Putting Eq. (4) into Eq. (3) results in

$$S' = 1/2\,\gamma H^2 K_a \tan\phi \tag{5}$$

To the available shear in the fill, is added the resistance due to friction in the sheetpile interlocks at both ends of the diameter through which the neutral plane g-h passes. Hoop tension, T, in the interlocks at an elevation where the radial pressure is P_A will be:

$$T = P_A r_c \tag{6}$$

where r_c is the radius of the cell. The vertical friction force in the interlock is:

$$S_1 = P_A r_c f \tag{7}$$

where f is coefficient of friction of the interlocks.

Since there are two interlocks in a unit length 2L of cell, the total available interlock friction on the neutral plane g-h is:

$$S_2 = 2P_A r_c f \tag{8}$$

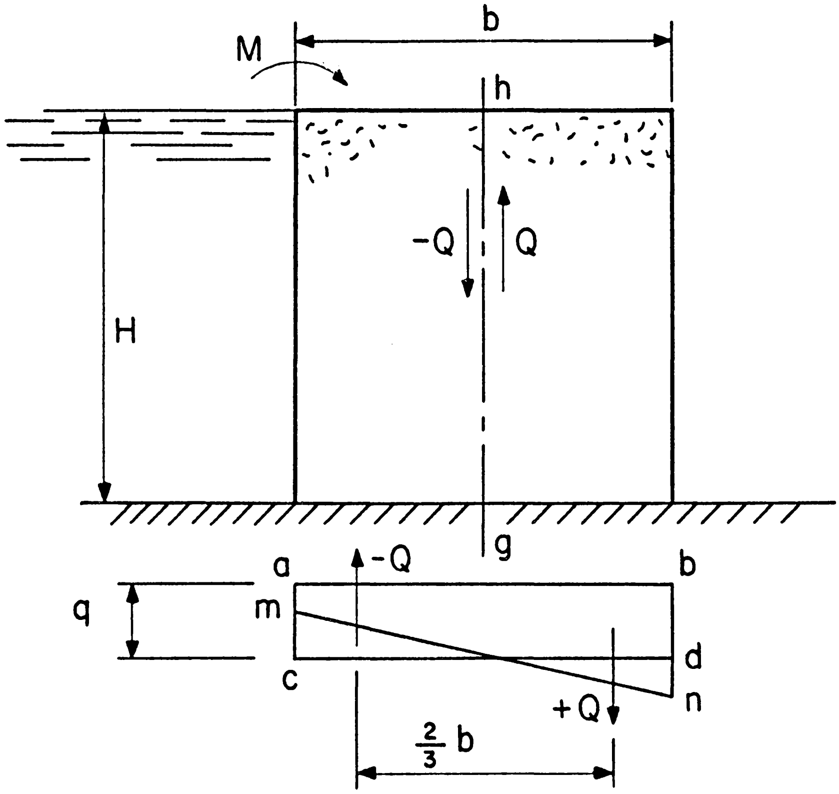

Figure 2. Analysis of stability of cell on rock foundation.

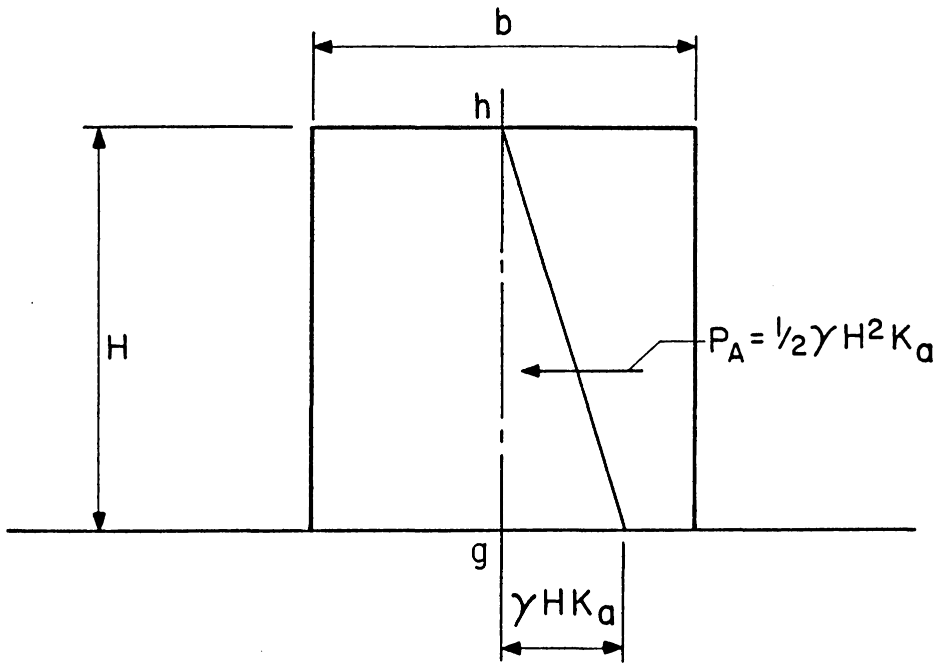

Figure 3. Total lateral pressure on centerline of cell.

and per lineal foot of cofferdam:

$$S'' = 2 \times 1/2\gamma H^2 K_a r_c f/2L$$

$$= 1/2\gamma H^2 K_a r_c f/L \qquad (9)$$

The total available shear per foot of length therefore, will be:

$$S = S' + S'' \qquad (10)$$

Substituting Eqs. (5) and (9) into Eq. (10) results in:

$$S = 1/2\gamma H^2 K_a \tan\phi + 1/2\gamma H^2 K_a r_c f/L$$

$$S = 1/2\gamma H^2 K_a (\tan\phi + r_c f/L) \qquad (11)$$

The factor of safety, S.F., against failure by shear on the centerline plane g-h can be defined as the ratio of the available shear resistance to the applied shear force, that is,

$$S.F. = S/Q \qquad (12)$$

Substituting Eqs. (2) and (11) into Eq. (12), and simplifying, gives:

$$S.F. = 1/3\gamma bH^2 K_a (\tan\phi + r_c f/L)/M \qquad (13)$$

Traditionally the coefficient of interlock friction, f in Eq. (13), has been taken as that of steel on steel which is approximately equal to 0.3 [1].

1.2 Objective

If an accurate determination of the factor of safety against shear failure for a cofferdam structure is to be made, the coefficient of interlock friction used in Eq. (13) should be known.

Therefore, it is the purpose of this study to determine in the laboratory a coefficient of interlock friction for sheetpile sections, specifically those used in the construction of Lock and Dam 26(R) located on the Mississippi River at Alton, Illinois. An experimental determination of the shear force required to initiate interlock displacement for a given constant hoop tension is made. Variation of the shear force due to cyclic displacement of the sheetpile interlocks is also examined. Data collected for six sets each of regular and high strength sheetpile specimens is used to determine the coefficient of friction for the sheetpile interlocks under variable hoop tension.

This determination in the laboratory of the coefficient of interlock friction for the sheetpiles used in the Lock and Dam 26(R) project assesses the accuracy of the traditional use of f as equal to 0.3. An accurate value of f will improve predictions of cofferdam behavior in the field as well as in computer models currently under development at Virginia Tech.

1.3 Outline

A brief outline of the contents of the chapters in this report is given to provide a frame of reference and to define the scope of the project. Chapter two serves a dual purpose. It describes the testing procedure used during the tests and the equipment utilized in the tests so that duplication of test results by others may be possible.

Chapter three describes the results obtained by the tests. The chapter documents the statistical reduction of data to yield a coefficient of friction for the sheetpile interlocks and provides a discussion of various aspects of the results.

Chapter four presents a summary of the report and conclusions drawn from the results of the research task.

II. EXPERIMENTAL METHOD

2.1 Procedure

In order to determine the coefficient of interlock friction for sheetpile sections the rectangular steel test frame shown in Figures 4 and 5 was first designed, then fabricated, and finally erected at the Prices Fork Research Laboratory near the Virginia Tech campus. The design of the test frame included specimen fixtures for holding an assemblage of three test specimens, joined at their interlocks, in horizontal alignment A constant normal load was applied horizontally to simulate hoop tension in the assemblage of specimens followed by the application of a shear load to the central specimen until vertical displacement along the interlocks occurred. The direction of the vertical shear load was then reversed and monitored until vertical displacement in the opposite direction occurred. This procedure was repeated for approximately 20 cycles. The normal load was then incrementally increased and the process repeated.

Six tests each were made for both regular and high strength sheetpile sections. A detailed description of materials and equipment follows.

2.2 Sheetpile Specimens

United States Steel sheetpile sections, PS32 and PSX32, were obtained directly from the construction site by the United States Army Corps of Engineers and delivered to the Prices Fork Lab. The sections were precut to a length of four inches. These sections had

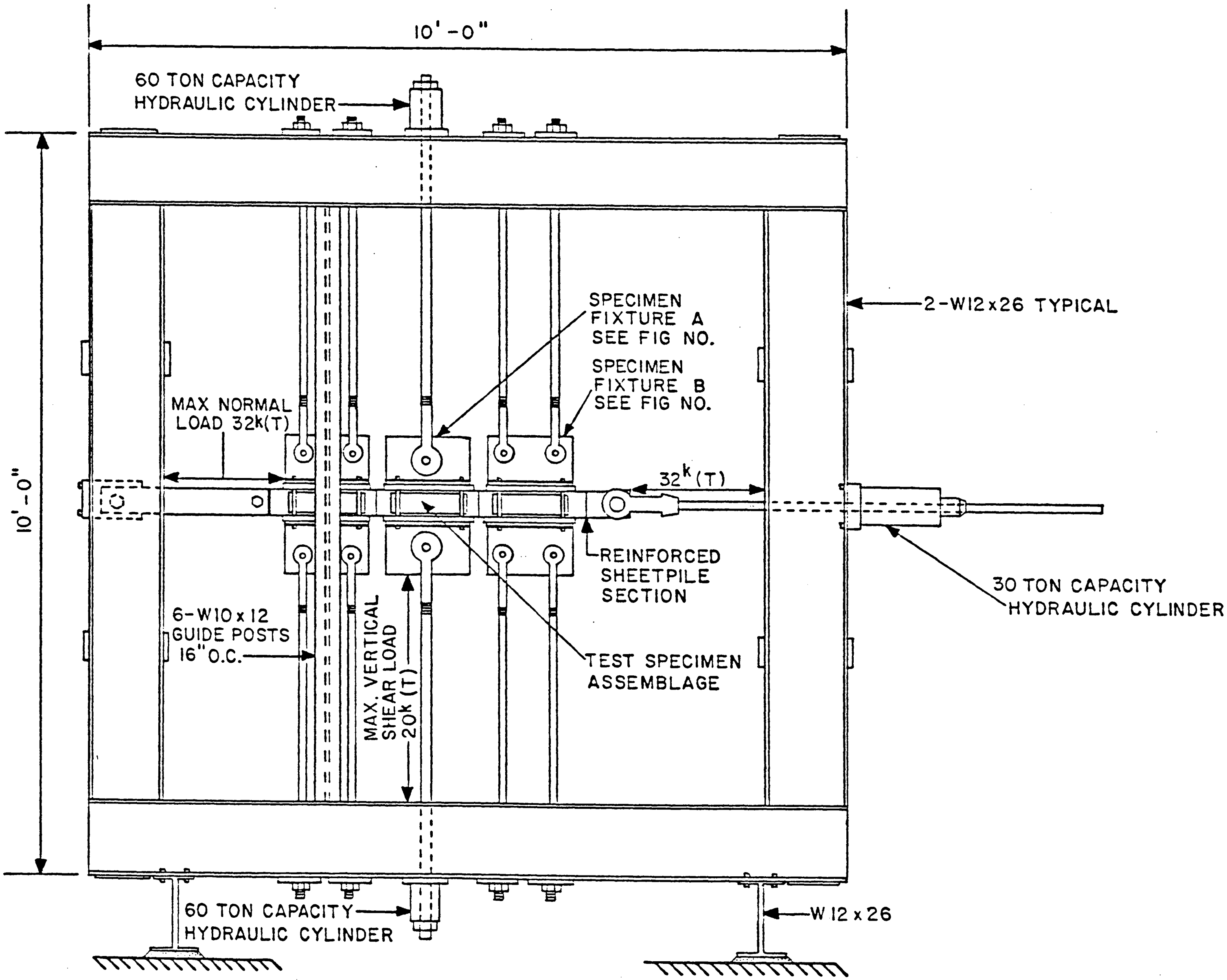

Figure 4. Rectangular steel test frame.

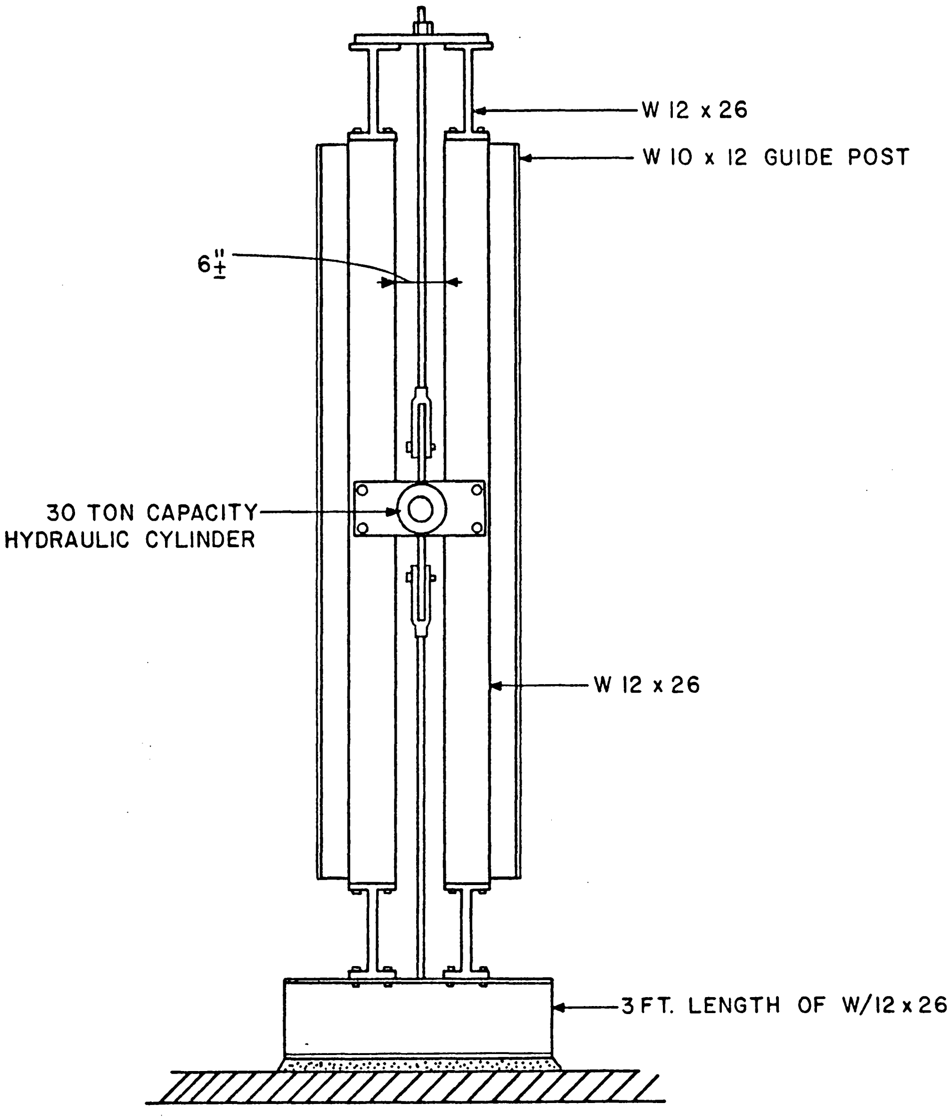

Figure 5. Rectangular steel test frame, end view.

been stored outdoors at the construction site and as a result their surface was pitted and scaled. The specimens were prepared for strain gage application by disc grinding with grit numbers 24 through 80. Grinding was confined to the center of the sheetpile webs on both sides of the specimens.

The web thickness at the point of strain gage application was recorded by measurement with a micrometer to one thousandth of an inch accuracy. Uni-directional, 120 ohm, Micro-Measurements brand electrical resistance foil strain gages, (M-M designation CEA-XX-250UW-120) were applied along the major axis on both sides of each specimen according to the manufacturers instructions [6,7,8]. Lead wires were soldered to terminal strips and the entire installation was covered with a water proofing compound, M-COAT A.

Tensile test coupons were cut from the webs of the sheetpile specimens. Three coupons from each of the two grades of sheetpiles were loaded until failure in a Tinius Olsen universal testing machine located on the Virginia Tech campus. The average yield stress, average ultimate stress and average modulus of elasticity for the PS32 piles were respectively 45 ksi, 76 ksi and 28470 ksi. The respective values for the PSX32 piles were 49 ksi, 71 ksi and 28460 ksi. The average modulus of elasticity for both the PS32 and PSX32 piles was 28400 ksi with a standard deviation of 1500 ksi. The percent deviation was 5.3%. Table 1 shows the results of these tests. The modulus of elasticity as determined by these tests was used to calculate the stress within the test specimens during loading of the sheetpile assemblage.

TABLE 1. Properties of sheetpile specimens tested at Virginia Tech

Sheetpile Type	Average Yield Stress	Average Ultimate Stress	Number of Specimens Tested	Average Elastic Modulus
PS32	45 ksi	76 ksi	3	28470 ksi
PSX32	49 ksi	71 ksi	3	28460 ksi

For PS32 and PSX32 Tensile Tests

Average Modulus = 28400 ksi
Standard Deviation = 1500 ksi
Percent Deviation = 5.3%

2.3 Test Frame

A rectangular test frame consisting of W 12 x 26 steel sections bolted together at the corners and separated 6 inches by adjustable lacing plates to form two rectangular frames was constructed (Figures 4 and 5). Bolted connections were used to simplify disassembly for storage. Design moments and shear loads for the frame were generated from the maximum hoop tension or normal load anticipated during the testing operations. This load was 32 kips or 8 kips/inch of interlock. A primary objective in designing the test frame and specimen fixtures was to limit total deflection and elongation along a line of transmitted force to one tenth of the combined sheetpile interlock displacement. Interlock displacements were anticipated to be approximately fifteen one-hundreths of an inch per interlock. This resulted in the selection of the W12 x 26 wide flange sections.

Six W10 x 12 sections were mounted vertically within the test frame on sixteen inch centers. These sections were used to restrict any rotations about the principal axis of the specimen assemblage that might occur due to eccentric loading conditions.

Specimen fixtures as shown in Figures 6, 7 and 8 were utilized to hold the test specimens during the application of loads. Type A specimen fixture was used to transmit the shear load generated by the hydraulic cylinders shown in Figure 4. Type A specimen fixture was designed to transmit loads up to 20 kips. Type B specimen fixtures were held within the test frame by 7/8" diameter threaded rods with a nut and bearing plate on one end and a clevis with pin on the other

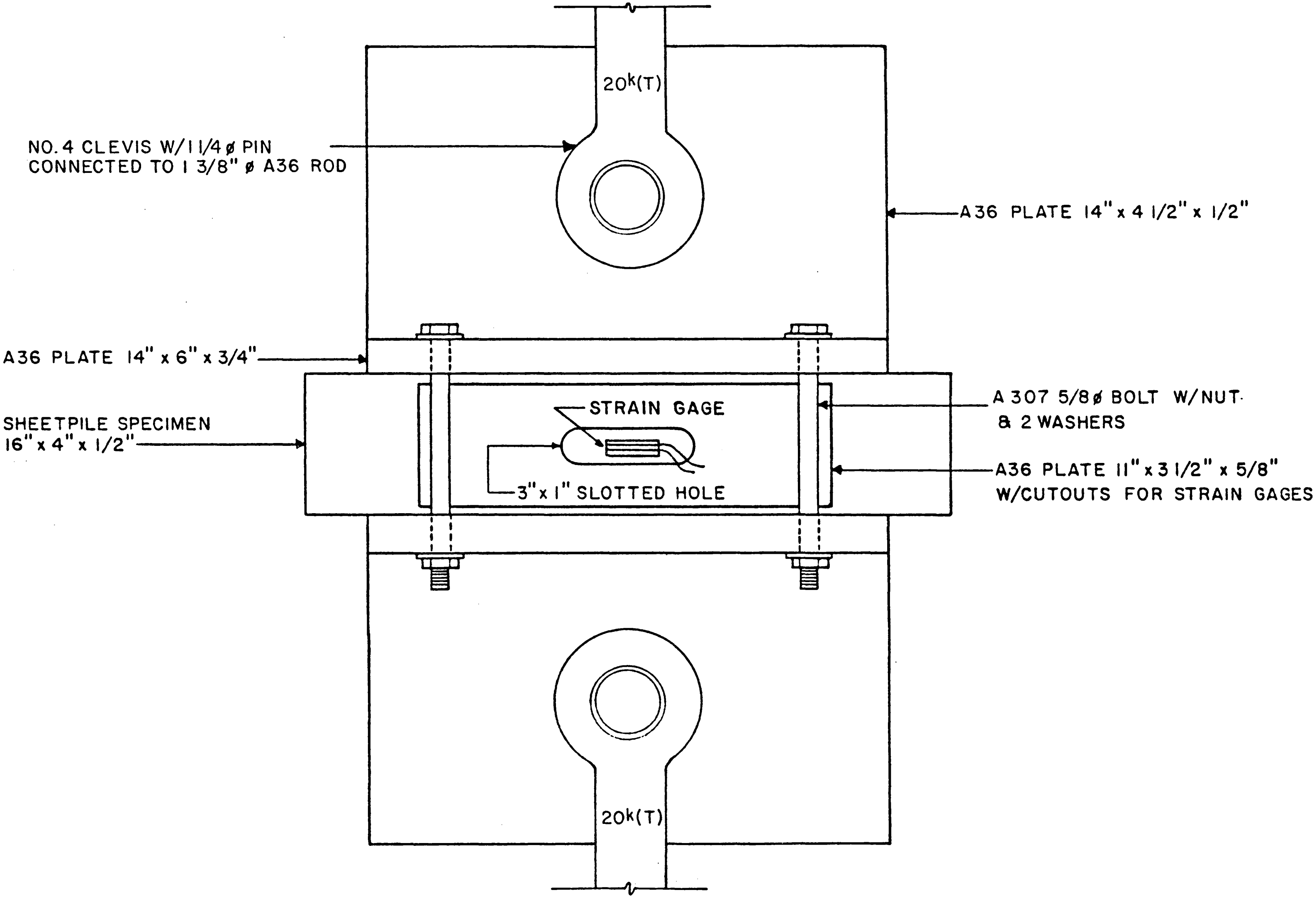

Figure 6. Type A specimen fixture.

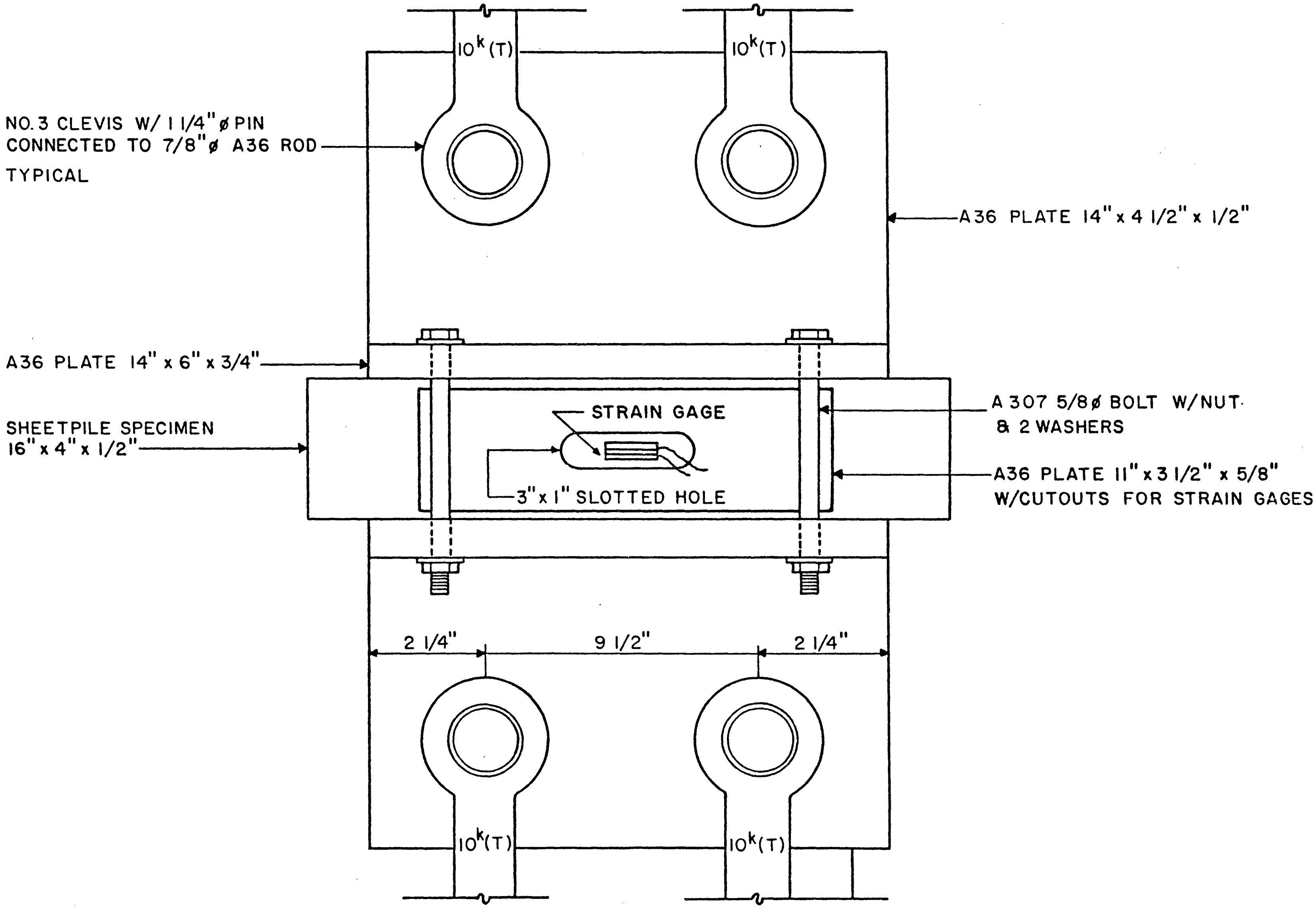

Figure 7. Type B specimen fixture.

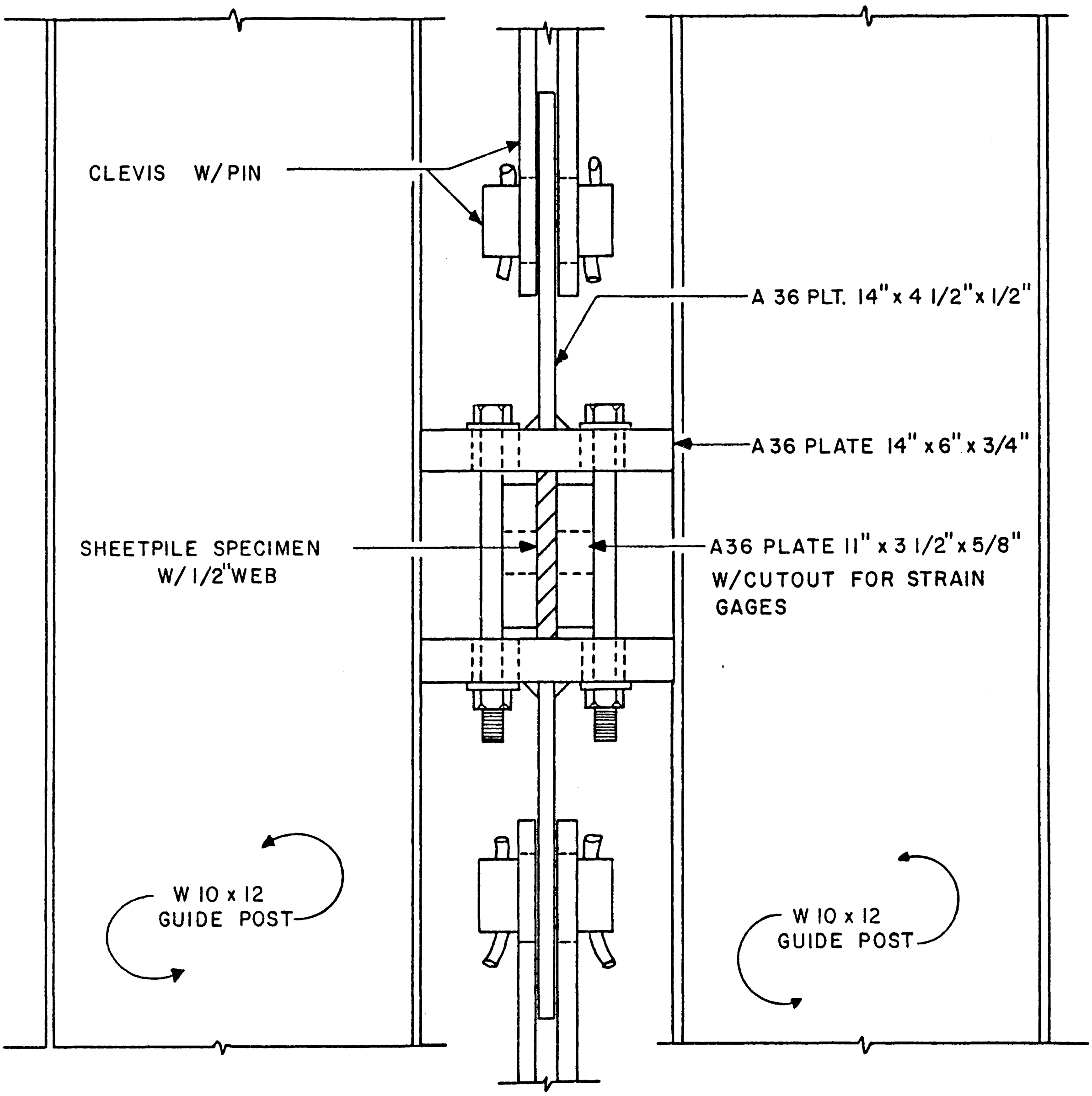

Figure 8. Type A and B specimen fixtures, end view.

end. Type B specimen fixtures were used to restrict vertical displacement of the two outer specimens and were designed for loads up to 10 kips.

Applied loads were monitored by mounting 120 ohm three element, rectangular rosette strain gages (M-M designation CEA-XX-250UR-120) on the load applying rods. Two gages were mounted opposite each other along the principal axis of the rods. The signals from the normal load applying rod was read via a Baldwin SR-4 strain indicator. Signals from the two vertical shear load applying rods were amplified by two Vishay bridge amplification and meter units. The amplified signals were recorded on an HP x-y-y plotter. All of the load applying rods were calibrated to within five percent accuracy on a Tinius Olsen testing machine.

The distribution of the vertical shear load to the two Type B specimen fixtures was also monitored by instrumenting the eight 7/8" diameter rods with 120 ohm uni-directional strain gages. This instrumentation was used to check load conditions across the specimen assemblage.

The installation and wiring techniques for the uni-directional and rossette gages applied to the rods was the same as described in the previous paragraphs with the addition of a butyl-rubber compound for impact protection.

2,4 Hydraulics

For the application of the horizontal or normal load a 30 ton capacity hydraulic cylinder with hollow plunger design was utilized. This cylinder was powered by a 10,000 psi capacity handpump. A locking valve and pressure gage were mounted in the pressure hose between the pump and cylinder. The locking valve was used to hold the normal load at a static value during the application of the vertical shear load to the central specimen.

The vertical shear load was applied to the central specimen by a 60 ton capacity hydraulic cylinder powered by a 2000 psi capacity electric pump. Two hydraulic cylinders of this type were mounted opposite one another within the test frame. This allowed the reversal of the applied vertical shear load during the evaluation of the effects of cyclic displacements on interlock friction.

III. RESULTS

3.1 Shakedown Tests

The first assemblage of specimens tested were type PS32. For this set the normal load was applied in increments of 2 kips over a range of 2 to 12 kips and by 4 kip increments from 12 to 24 kips. Prior to applying the vertical shear load the normal load within each of the three test specimens was checked and compared to the load in the normal load applying rod. The load in each test specimen was found to agree within approximately five percent of the known load in the normal direction.

During the application of the vertical shear load the distribution of forces across the specimen fixtures was periodically checked. The distribution of forces for the lower range of normal loads, i.e. 2 to 8 kips, was found to be fairly uniform. Interlock displacement in this lower range was fairly even with both interlocks displacing an equal amount, approximately 1/4 inch. In the higher ranges of normal load, interlock displacement became uneven. Usually only one interlock would displace. Thus the load distribution across the specimen fixtures was also somewhat uneven.

Video taping of the test showed some vertical displacement of the Type B specimen fixtures. This vertical movement was attributed to play in the clevis and pin connections.

During this shakedown test a broad range of vertical shear loads required to initiate interlock displacement was recorded. For reasons of safety and to avoid potential damage to the vertical load applying rods which would be required to execute additional tests it was decided that an upper normal load limit of 20 kips would be prudent.

3.2 Test Procedure

The test procedure used for all but two of the remaining sets of specimens consisted of incrementally increasing the normal load from four kips to twenty kips at four kip increments. For each normal load the vertical shear load required to initiate interlock displacement was recorded on the HP x-y-y plotter. Two time base sweep rates were used. For the first and last interlock displacements a time base sweep rate of 0.25 s/cm was used. For approximately twenty displacements a time base sweep rate of 2.5 s/cm was used.

3.3 Test Results

Figure shows a typical plot of the vertical shear force required to initiate interlock displacement. Due to hydraulic back pressure and cylinder friction in the idling hydraulic cylinder the net force is the algebraic sum of the upper and lower plots for any given cycle.

At the moment of interlock displacement, the forces acting on the test specimen are those shown in Figure 10 where V is the vertical shear force, N is the normal load or hoop tension, and F is the total interlock friction force. For equilibrium the resisting frictional force, F, must be equal to the shear force V. The total frictional force, F, acting along both interlocks is given by

$$F = 2f \times N = V \tag{14}$$

where f is the static coefficient of friction.

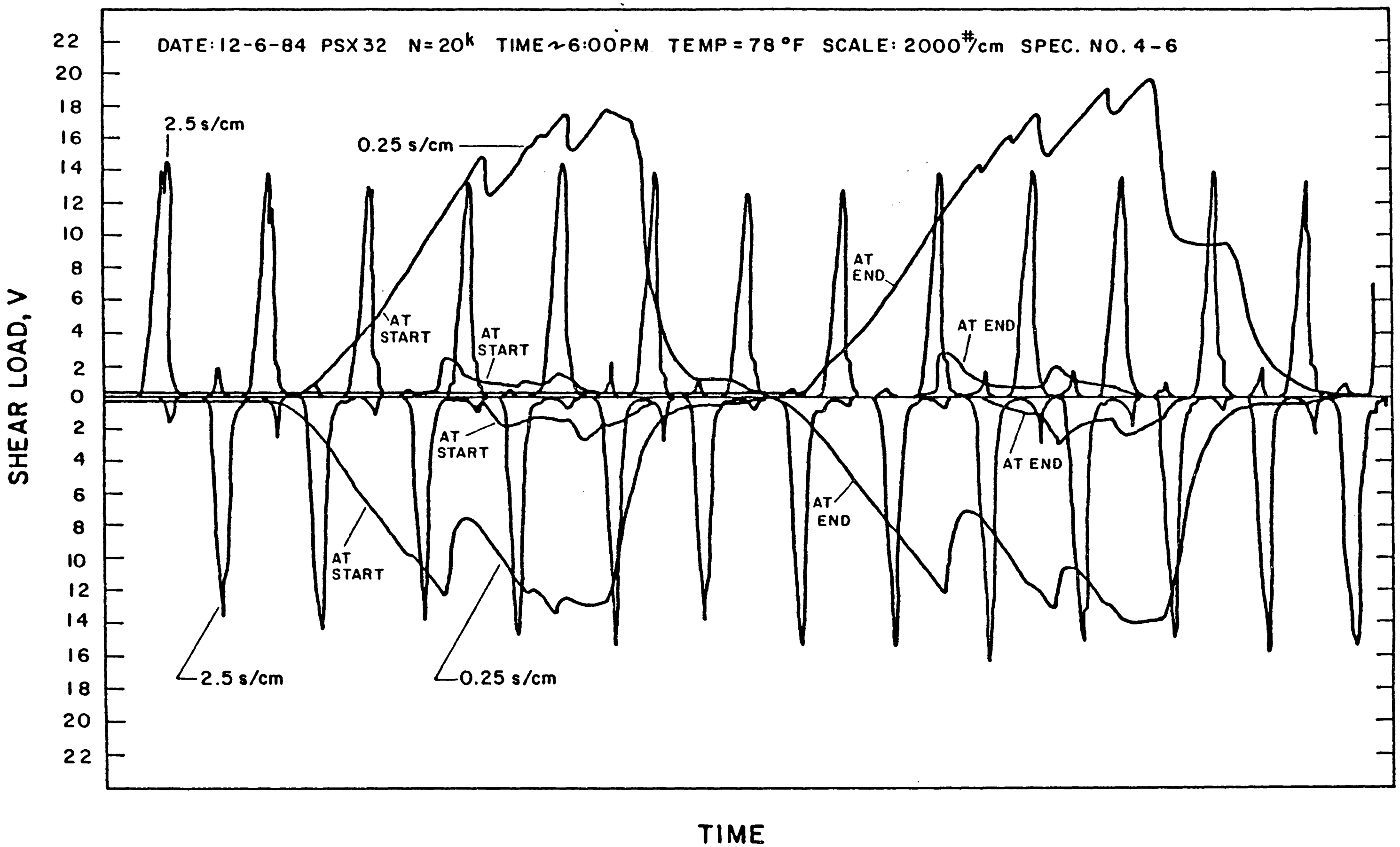

Figure 9. Typical plot of vertical shear force required to initiate interlock displacement.

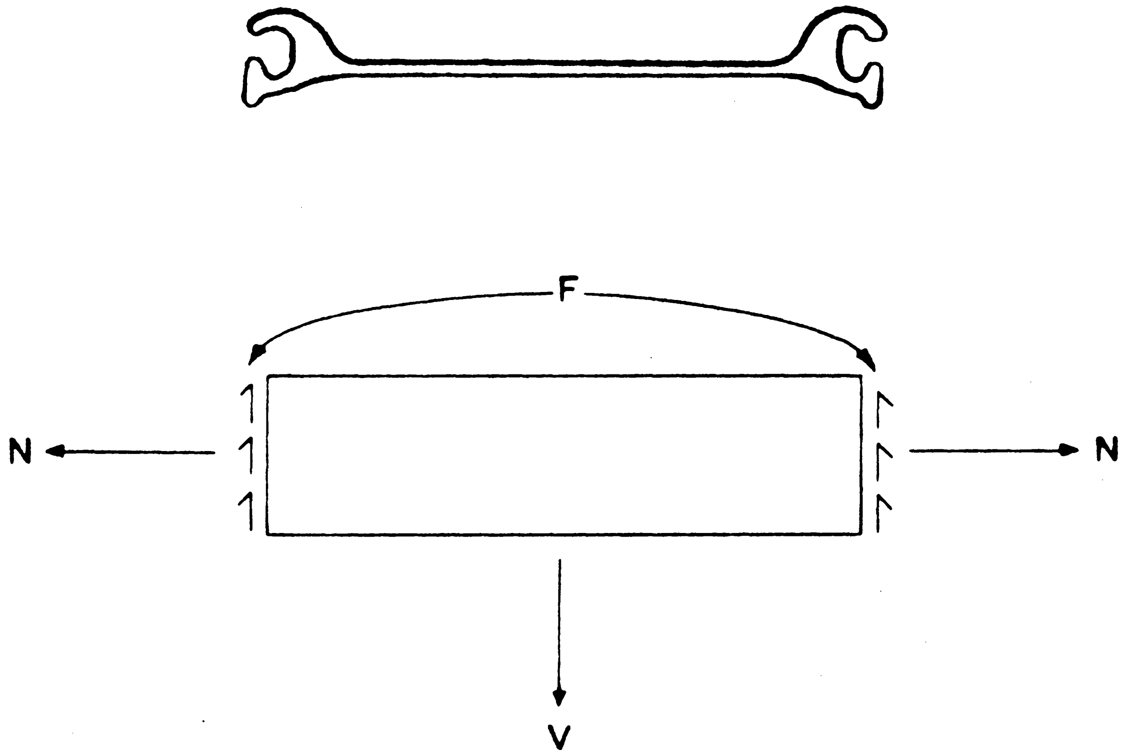

Figure 10. Forces acting on test specimen at moment of interlock displacement.

The coefficient of friction is thus:

$$f = V/2N \tag{15}$$

As the normal load was increased a reduction in the static coefficient of friction, f, was observed. All specimens tested consistently behaved in this manner. This result eliminated concern over the vertical displacement of the Type B specimen fixtures. If extreme misalignment of the interlocks was present due to the vertical displacement of the Type B specimen fixtures, one would expect an increase in the static coefficient of friction with increased normal load.

Tables 2 through 7 show the results of the tests. Tables 2 through 4 break the results down into two columns, one column for each of the two time base sweep rates. Table 5 and 6 show the result for each pile type with combined sweep rates. Table 7 shows the results for combined sweep rates and combined pile types. For all the tables the variables are as follows:

f = the static coefficient of friction

N = the normal load in kips

n = the number of displacement cycles

MEAN = the mean for the given number, n, of displacement cycles

STD = the standard deviation

MIN = the minimum observed value

MAX = the maximum observed value

RANGE = the difference between MAX and MIN

VAR = the variance

CV = the coefficient of variation multiplied by 100

TABLE 2. Results for PS32 piles, 2.5 s/cm and 0.25 s/cm sweep rates.

VARIABLE = f

	N=4		N=8		N=12		N=16		N=20	
	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25
n	108	49	162	38	136	35	138	46	143	40
MEAN	0.465	0.452	0.406	0.439	0.384	0.411	0.337	0.347	0.308	0.321
STD	0.098	0.108	0.098	0.100	0.081	0.085	0.063	0.043	0.075	0.052
MIN	0.238	0.250	0.206	0.244	0.192	0.267	0.169	0.256	0.145	0.180
MAX	0.662	0.738	0.650	0.600	0.592	0.567	0.512	0.425	0.688	0.412
RANGE	0.425	0.488	0.444	0.356	0.400	0.300	0.344	0.169	0.542	0.232
VAR	0.010	0.012	0.010	0.001	0.006	0.007	0.004	0.002	0.006	0.003
CV	21.11	23.81	24.02	22.50	21.13	20.62	18.60	12.47	24.36	16.17

TABLE 3. Results for PSX32 Piles, 2.5 s/cm and 0.25 s/cm sweep rates.

VARIABLE = f

	N=4		N=8		N=12		N=16		N=20	
	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25
n	156	98	171	70	163	89	154	83	151	75
MEAN	0.529	0.551	0.398	0.430	0.356	0.376	0.322	0.340	0.327	0.334
STD	0.069	0.116	0.070	0.115	0.065	0.094	0.051	0.074	0.056	0.070
MIN	0.338	0.225	0.206	0.162	0.117	0.125	0.212	0.188	0.150	0.200
MAX	0.725	0.812	0.550	0.719	0.550	0.533	0.450	0.525	0.445	0.475
RANGE	0.388	0.588	0.344	0.556	0.433	0.408	0.238	0.338	0.295	0.275
VAR	0.005	0.013	0.005	0.013	0.004	0.009	0.002	0.005	0.003	0.005
CV	13.11	21.03	17.53	26.80	18.34	25.06	15.84	21.69	17.14	20.96

TABLE 4. Results for combined PS32 and PSX32 Piles, 2.5 s/cm and 0.25 s/cm sweep rates.

VARIABLE = f

	N=4		N=8		N=12		N=16		N=20	
	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25	2.5 (s/cm)	0.25
n	264	147	333	108	299	124	292	129	294	115
MEAN	0.503	0.518	0.402	0.433	0.368	0.388	0.329	0.342	0.318	0.329
STD	0.088	0.122	0.084	0.109	0.074	0.093	0.057	0.064	0.066	0.064
MIN	0.238	0.225	0.206	0.162	0.117	0.125	0.169	0.188	0.145	0.180
MAX	0.725	0.812	0.650	0.719	0.592	0.567	0.512	0.525	0.688	0.475
RANGE	0.488	0.588	0.444	0.556	0.475	0.442	0.344	0.338	0.542	0.295
VAR	0.008	0.015	0.007	0.012	0.005	0.008	0.003	0.004	0.004	0.004
CV	17.51	23.59	21.00	25.26	20.11	24.02	17.39	18.82	20.94	19.52

TABLE 5. Results for PS32 piles, combined time bases

	N=4	N=8	N=12	N=16	N=20
n	157	200	171	184	183
MEAN	0.461	0.413	0.389	0.340	0.311
STD	0.101	0.098	0.082	0.058	0.707
MIN	0.238	0.206	0.192	0.169	0.145
MAX	0.738	0.650	0.592	0.512	0.688
RANGE	0.500	0.444	0.400	0.344	0.542
VAR	0.010	0.010	0.007	0.003	0.005
CV	21.92	23.85	21.15	17.22	22.75

TABLE 6. Results for PSX32 piles, combined time bases

	N=4	N=8	N=12	N=16	N=20
n	254	241	252	237	226
MEAN	0.538	0.408	0.363	0.328	0.329
STD	0.090	0.086	0.077	0.060	0.061
MIN	0.225	0.162	0.117	0.188	0.150
MAX	0.812	0.719	0.550	0.525	0.475
RANGE	0.588	0.556	0.433	0.338	0.325
VAR	0.008	0.007	0.006	0.004	0.004
CV	16.86	21.23	21.26	18.40	18.52

TABLE 7. Results for combined pile types and both sweep rates.

Variable = f

	N=4	N=8	N=12	N=16	N=20
n	411	441	423	421	409
MEAN	0.508	0.410	0.374	0.333	0.321
STD	0.102	0.092	0.080	0.060	0.066
MIN	0.225	0.162	0.117	0.169	0.145
MAX	0.812	0.719	0.592	0.525	0.688
RANGE	0.588	0.556	0.475	0.356	0.542
VAR	0.010	0.008	0.006	0.004	0.004
CV	20.01	22.46	21.49	17.94	20.58

For the determination of the statistical values all observed data was used. See Appendix for a discussion of the procedures used to calculate the mean, variance, standard deviation and coefficient of variation.

Figure 11 shows a plot of the mean coefficent of friction, f, for the 2.5 s/cm and 0.25 s/cm sweep rates for combined pile types. It can be seen from this plot that the mean coefficient of friction for the various normal loads are nearly the same for each of the two time bases.

Figure 12 shows a schematic plot of N vs. f for the data presented in Table 5. The schematic plot was developed by J.W. Tukey of reference [10] and is used to present statistical values in a graphical form.

The boxed in area covers the values of f which were observed 50% of the time. The upper limit of the box represents the value of f that 75% of the data did not exceed. The lower limit of the box represents the value of f that 25% of the data was less than. The horizontal line dividing the box represents the median value of f. The cross within the box represents the mean value of f. The extreme ends of the vertical lines extending above and below the box represent the maximum and minimum observed values of f. Similarly Figures 13 and 14 are schematic plots of the data reported in Tables 6 and 7.

The broad range of the coefficients of friction observed in the test results may be due to the condition of the sheetpile interlocks and to variations in manufacturing tolerances. The surface of the

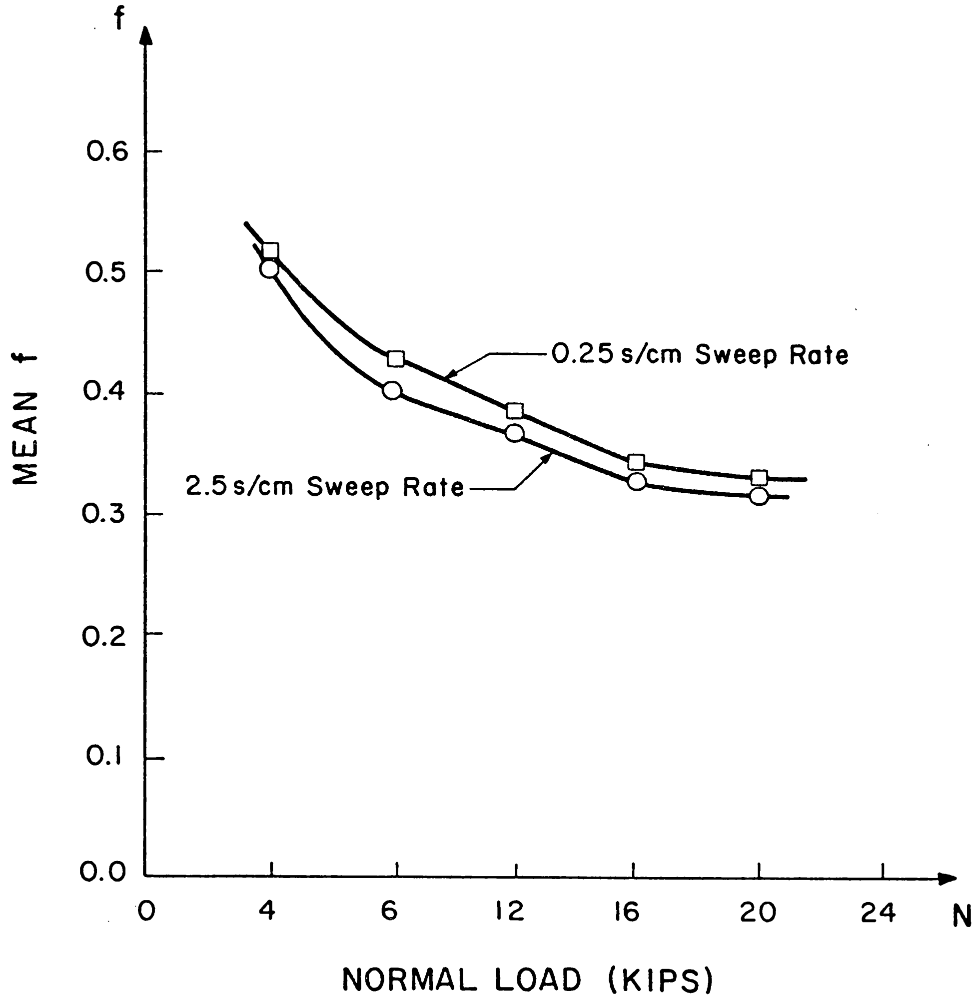

Figure 11. Plot of mean coefficient of friction for combined pile types, 2.5 s/cm vs. 0.25 s/cm.

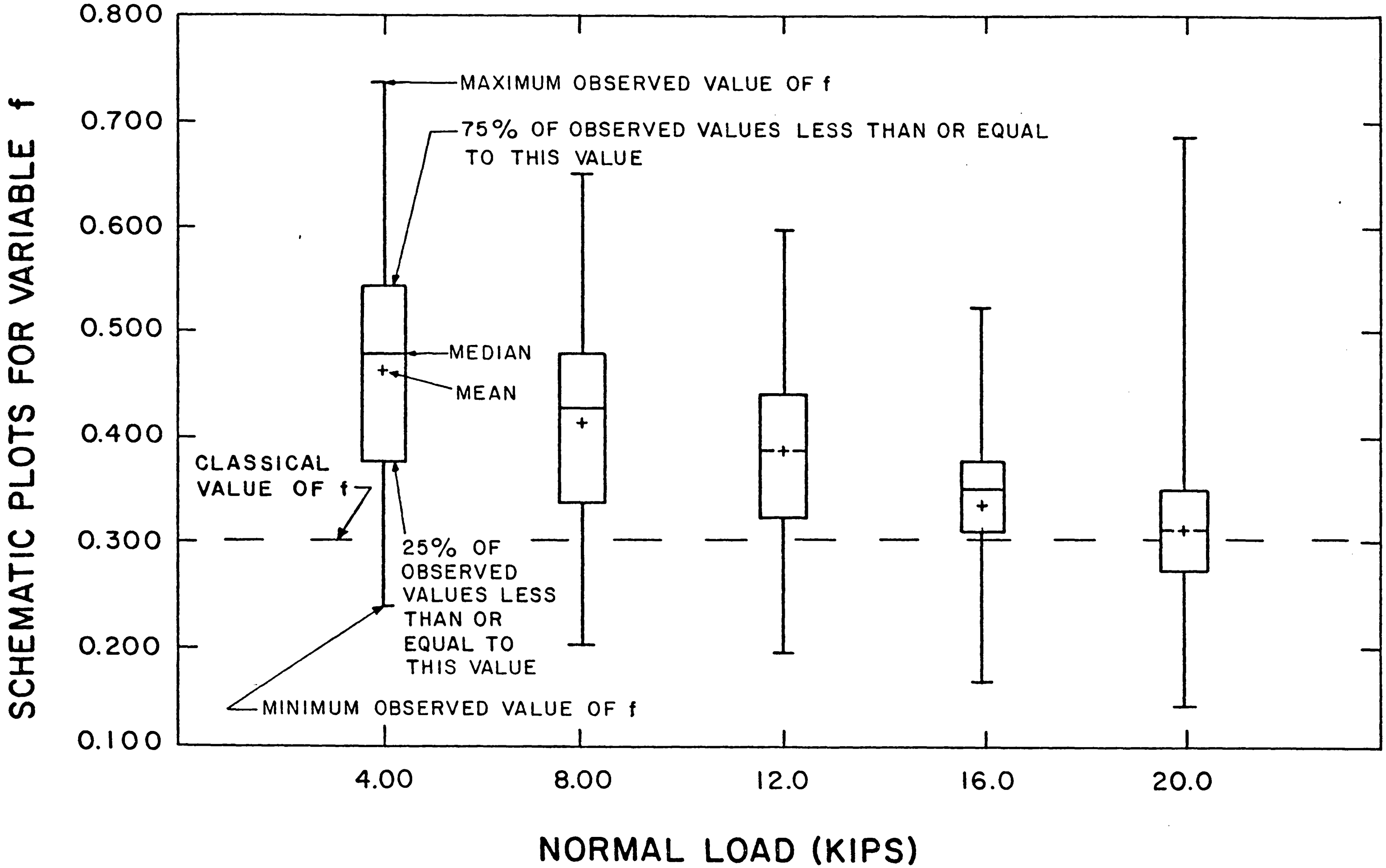

Figure 12. Schematic plot of N vs. f for PS32 piles.

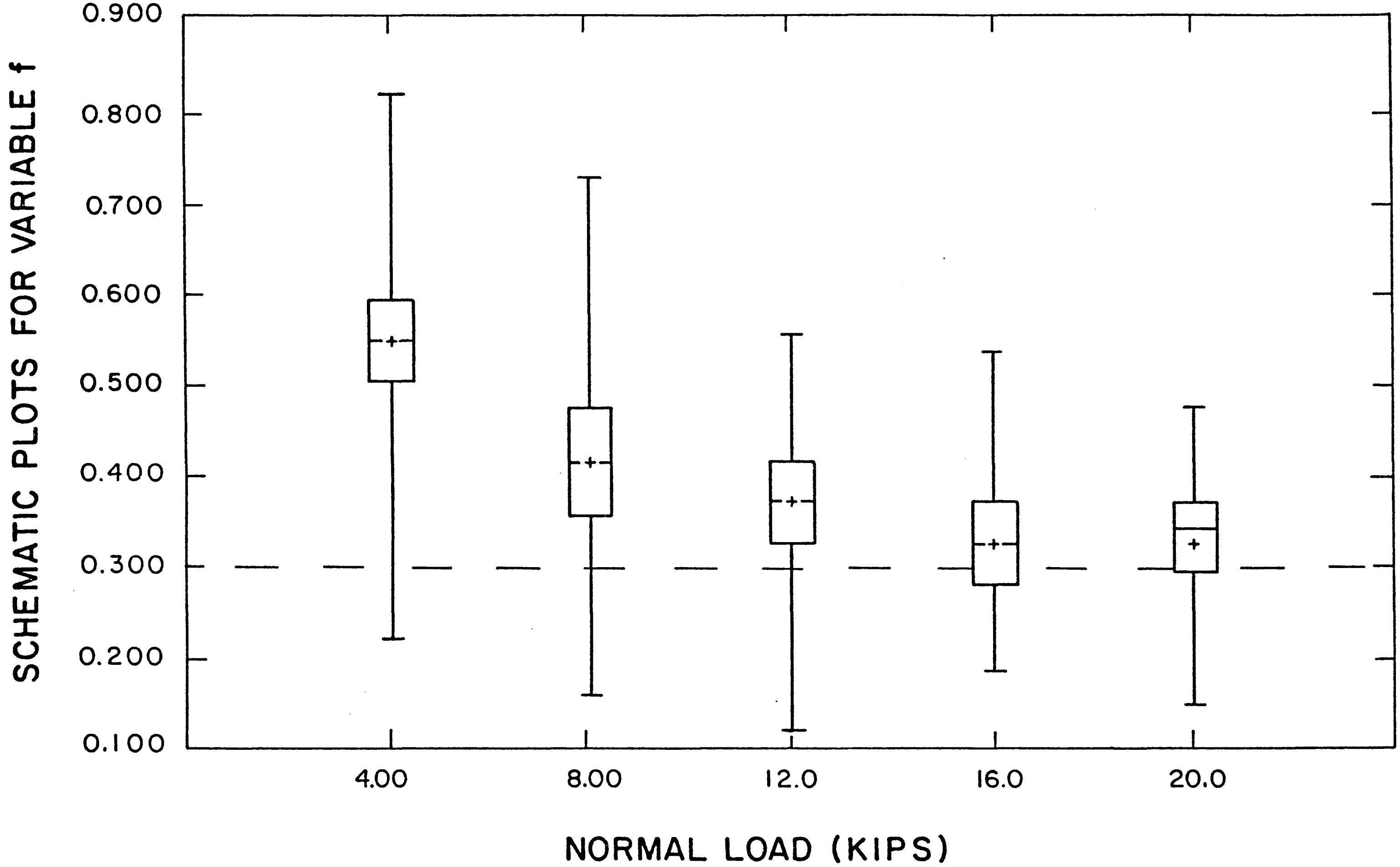

Figure 13. Schematic plot of N vs. f for PSX32 piles.

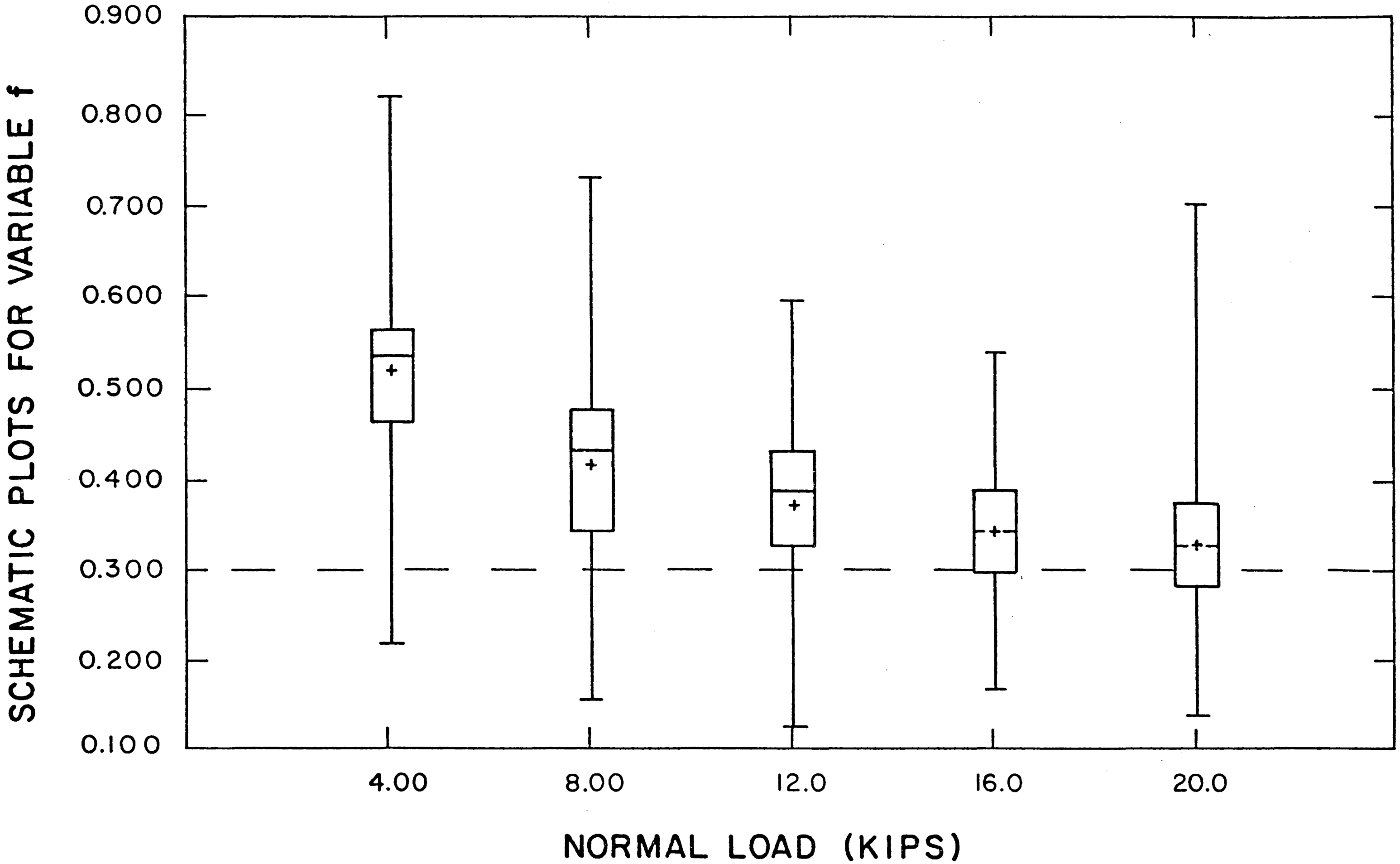

Figure 14. Schematic plot of N vs. f for combined pile types.

interlocks was scaled and pitted from storage outdoors. The scaling and pitting was not necessarily uniform for all specimens tested, thereby causing a variation in interlock friction. Manufacturing tolerances allowed for the interlocks may result in a slightly different alignment of the thumb and finger of each specimen. This may also have contributed to the variation in interlock friction observed during the tests.

3.4 Effects Of Cyclic Displacements On Interlock Behavior

To determine if cyclic displacement was the cause of the reduction in the coefficient of friction with increased normal load, two assemblages of PS32 piles were tested by starting with a normal load of 20 kips and decreasing it incrementally to 4 kips. For each normal load increment of 4 kips, the central pile was displaced approximately 20 times. The results from these tests are presented in Table 8(a). Table 8(b) is provided as a comparison: it shows the results for the PS32 piles which were tested in a bottom up sequence. Figure 15 shows a plot of the mean coefficient of friction for the two test sequences. Although there is some difference in the coefficient of friction for the lower normal load range there is no conclusive evidence of any effect due to cyclic displacements for the number of cycles used in these tests.

3.5 Prediction Equation For Coefficient Of Friction

An exponential decay model appears to be suitable for predicting the coefficient of friction; that is,

$$f = a_o e^{-a_1 N} \tag{16}$$

TABLE 8. Comparison of test results for PS32 piles top down test procedure vs. bottom up test procedure.

8(a) Top down test sequence (Specimen No. 10-15)

	N=4	N=8	N=12	N=16	N=20
n	54	82	69	77	76
MEAN	0.516	0.454	0.411	0.362	0.328
STD	0.091	0.102	0.068	0.036	0.079
MIN	0.275	0.244	0.267	0.256	0.180
MAX	0.738	0.650	0.525	0.425	0.688
RANGE	0.462	0.406	0.258	0.169	0.508
VAR	0.008	0.010	0.004	0.001	0.006
CV	17.70	22.37	16.50	9.84	24.09

8(b) Bottom up test sequence (Specimen No. 1-9 and 16-18).

	N=4	N=8	N=12	N=16	N=20
n	128	124	104	109	103
MEAN	0.433	0.388	0.376	0.323	0.301
STD	0.091	0.085	0.088	0.656	0.064
MIN	0.225	0.206	0.192	0.169	0.145
MAX	0.662	0.594	0.592	0.512	0.488
RANGE	0.438	0.388	0.400	0.344	0.342
VAR	0.008	0.007	0.008	0.004	0.004
CV	21.09	22.03	23.53	20.31	21.40

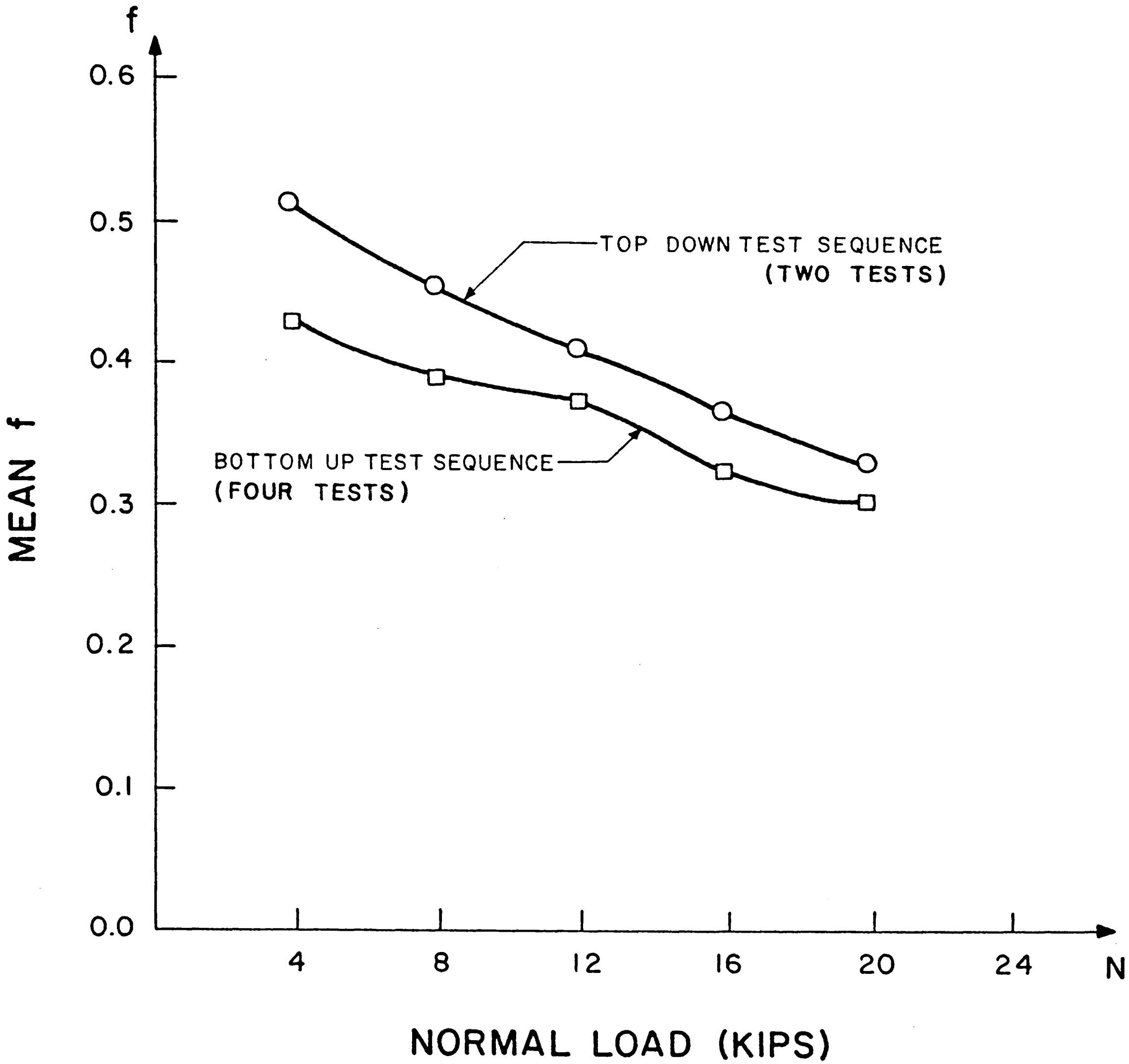

Figure 15. Plot of N vs. f for top down test sequence vs. bottom up test sequence.

where f is the static coefficient of friction, a_o, a_1 are constants, and N is the normal load in kips.

Taking the logarithm on both sides of Equation (16) we have

$$\ln f = \ln a_o - a_1 N \qquad (17)$$

Introducing the variable,

$$Y = \ln f \qquad (18)$$

into Eq. (17) converts the exponential model of Eq. (16) into a linear model.

$$Y = \ln a_o - a_1 N \qquad (19)$$

A least squares linear regression analysis of the test data was performed for the PS32, PSX32 and combined PS32 and PSX32 test results. On this basis the constants for the PS32 piles are estimated to be

$$a_o = 0.4940$$

$$a_1 = 0.0242$$

and the prediction equation for the PS32 piles is

$$f = 0.4940e^{-0.0242N}, \quad 4 \leq N \leq 20 \qquad (20)$$

For the PSX32 piles the constants are

$$a_o = 0.5451$$

$$a_1 = 0.0305$$

and the prediction equation is

$$f = 0.5451e^{-0.0305N}, \quad 4 \leq N \leq 20 \qquad (21)$$

The constants for the combined PS32 and PSX32 piles are

$$a_o = 0.5236$$

$$a_1 = 0.0279$$

and the prediction equation is

$$f = 0.5236e^{-0.0279N}, \; 4 \leq N \leq 20 \qquad (22)$$

In obtaining these prediction equations all data points were retained: none were discarded or ignored. The prediction equations presented in this report are only valid for normal loads between four and twenty kips. Table 9 shows the predicted values for normal loads of 4, 8, 12, 16, and 20 kips, the upper and lower 95% confidence limits and the observed mean coefficient of friction for each normal load.

Figures 16 through 18 show a semi-log plot of the prediction equations for each pile type and combined pile types with the associated 95% confidence intervals. Figure 19 shows an arithmetic plot of the prediction equation for combined pile types, Equation (22), with the observed mean coefficients of friction for both pile types and the classical design value of f.

TABLE 9. Prediction equations, predicted values, and confidence limits.

PS32 $f = 0.4940e^{-0.0242N}$

N	Predicted f	Observed Mean f	Upper 95% Limit	Lower 95% Limit
4	0.448	0.461	0.699	0.288
8	0.407	0.413	0.635	0.261
12	0.370	0.389	0.576	0.237
16	0.336	0.340	0.523	0.215
20	0.304	0.311	0.475	0.195

PSX32 $f = 0.5451e^{-0.0305N}$

N	Predicted f	Observed Mean f	Upper 95% Limit	Lower 95% Limit
4	0.482	0.538	0.747	0.312
8	0.427	0.408	0.661	0.276
12	0.378	0.363	0.585	0.244
16	0.334	0.328	0.518	0.216
20	0.296	0.329	0.459	0.191

PS32 and PSX32 $f = 0.5236e^{-0.0279N}$

N	Predicted f	Observed Mean f	Upper 95% Limit	Lower 95% Limit
4	0.468	0.508	0.728	0.301
8	0.419	0.410	0.651	0.270
12	0.375	0.374	0.582	0.241
16	0.335	0.333	0.521	0.215
20	0.300	0.321	0.466	0.193

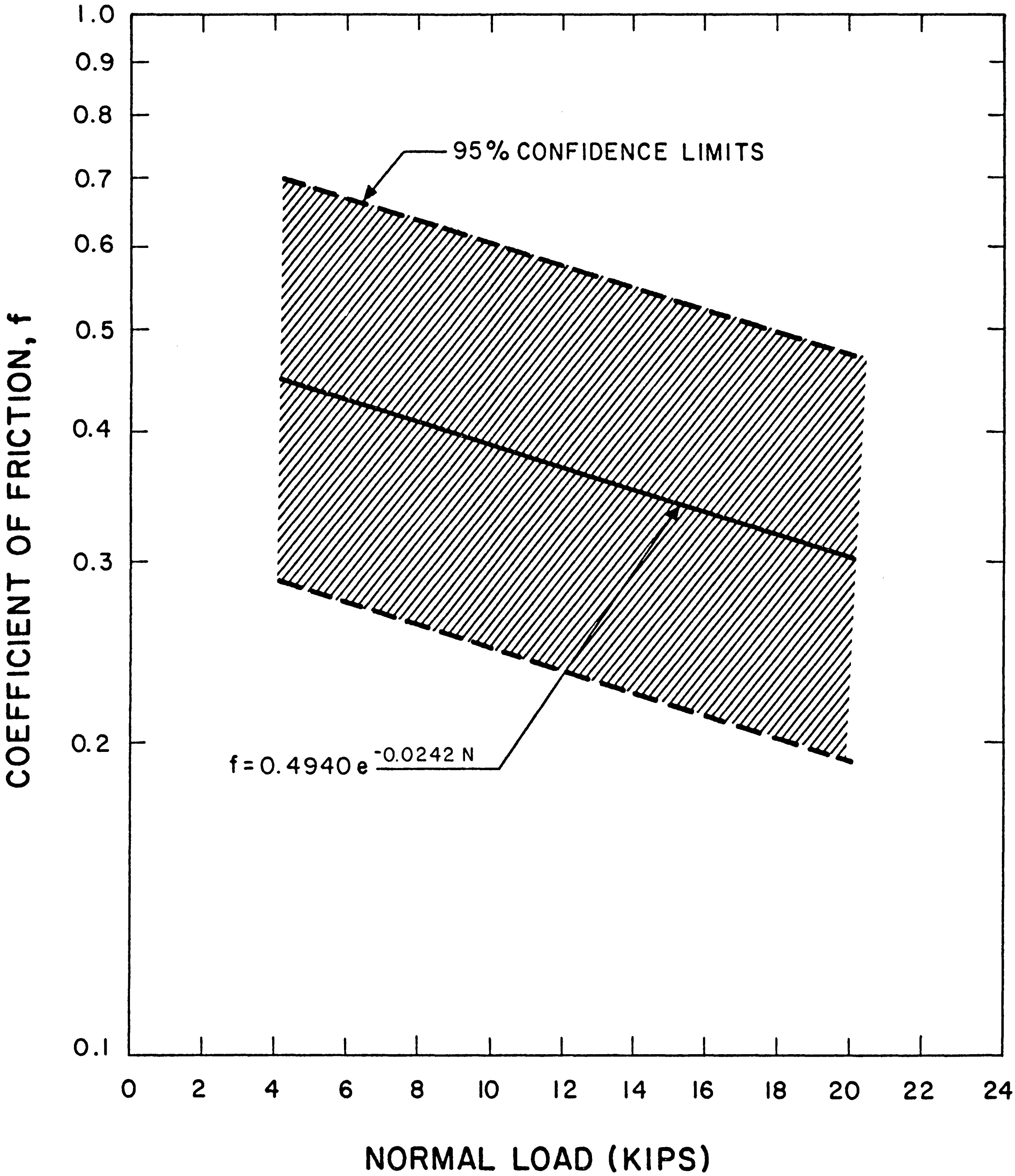

Figure 16. Semi-log plot of PS32 prediction equation with confidence limits.

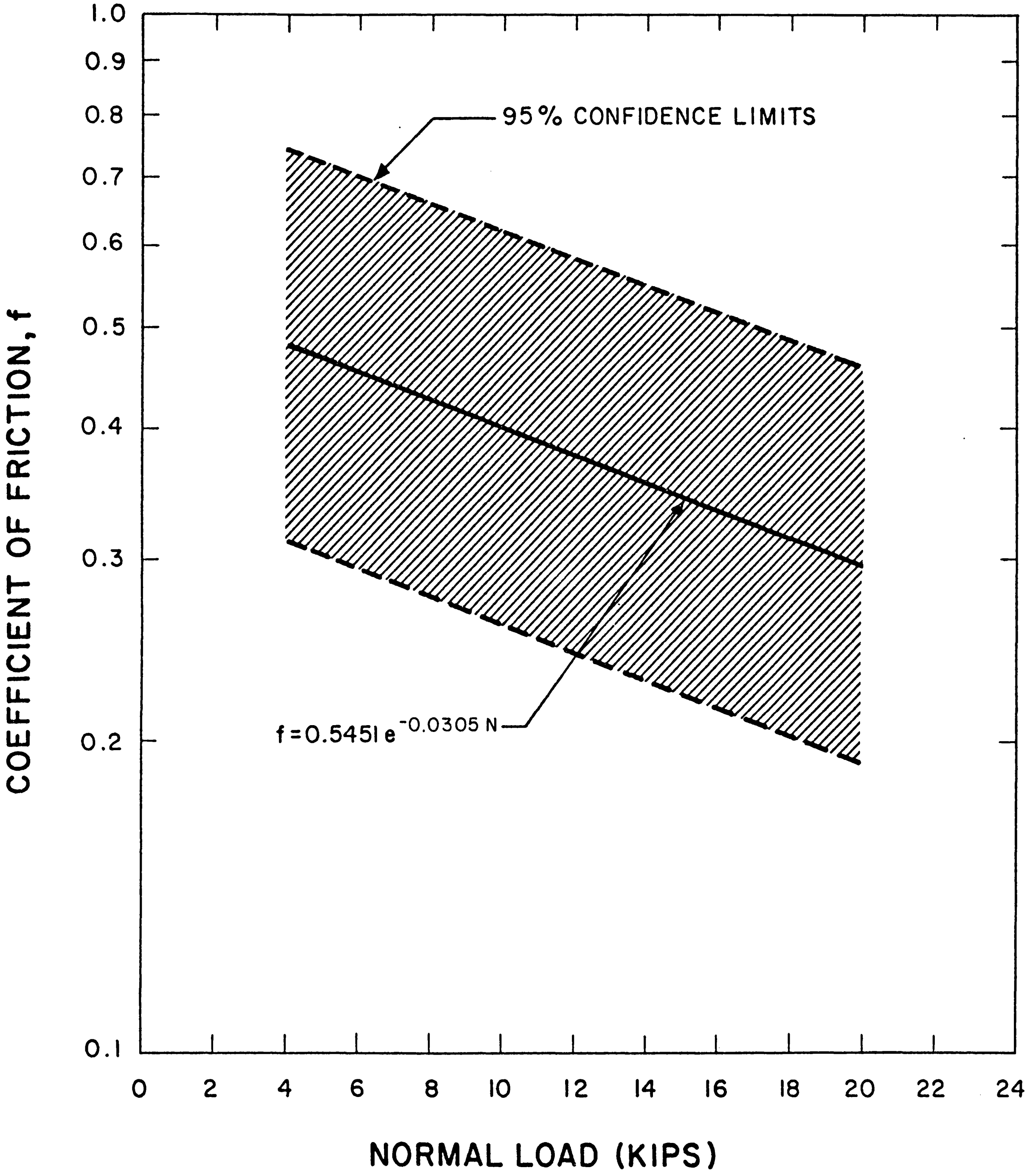

Figure 17. Semi-log plot of PSX32 prediction equation with confidence limits.

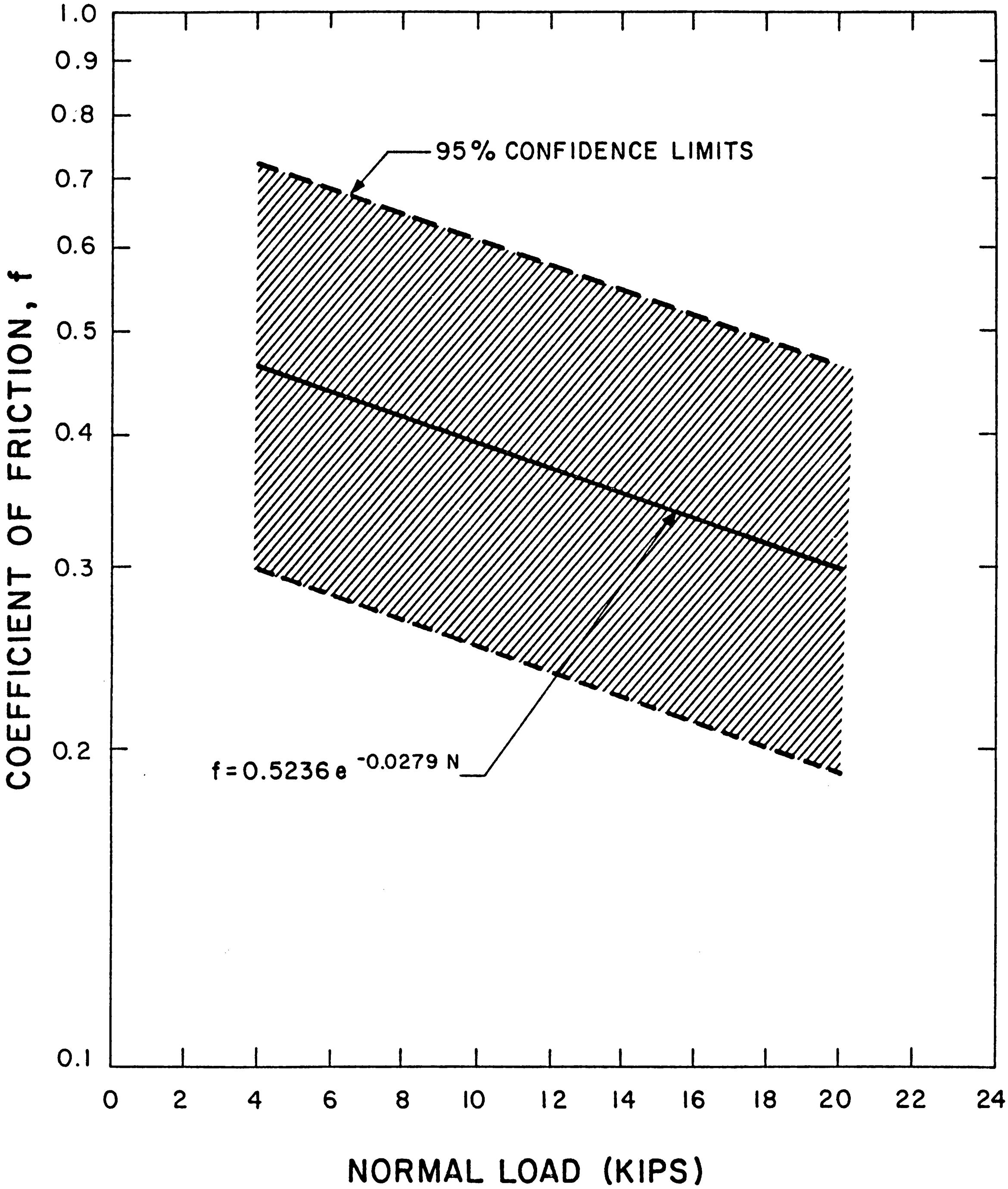

Figure 18. Semi-log plot of prediction equation for combined pile types with confidence limits.

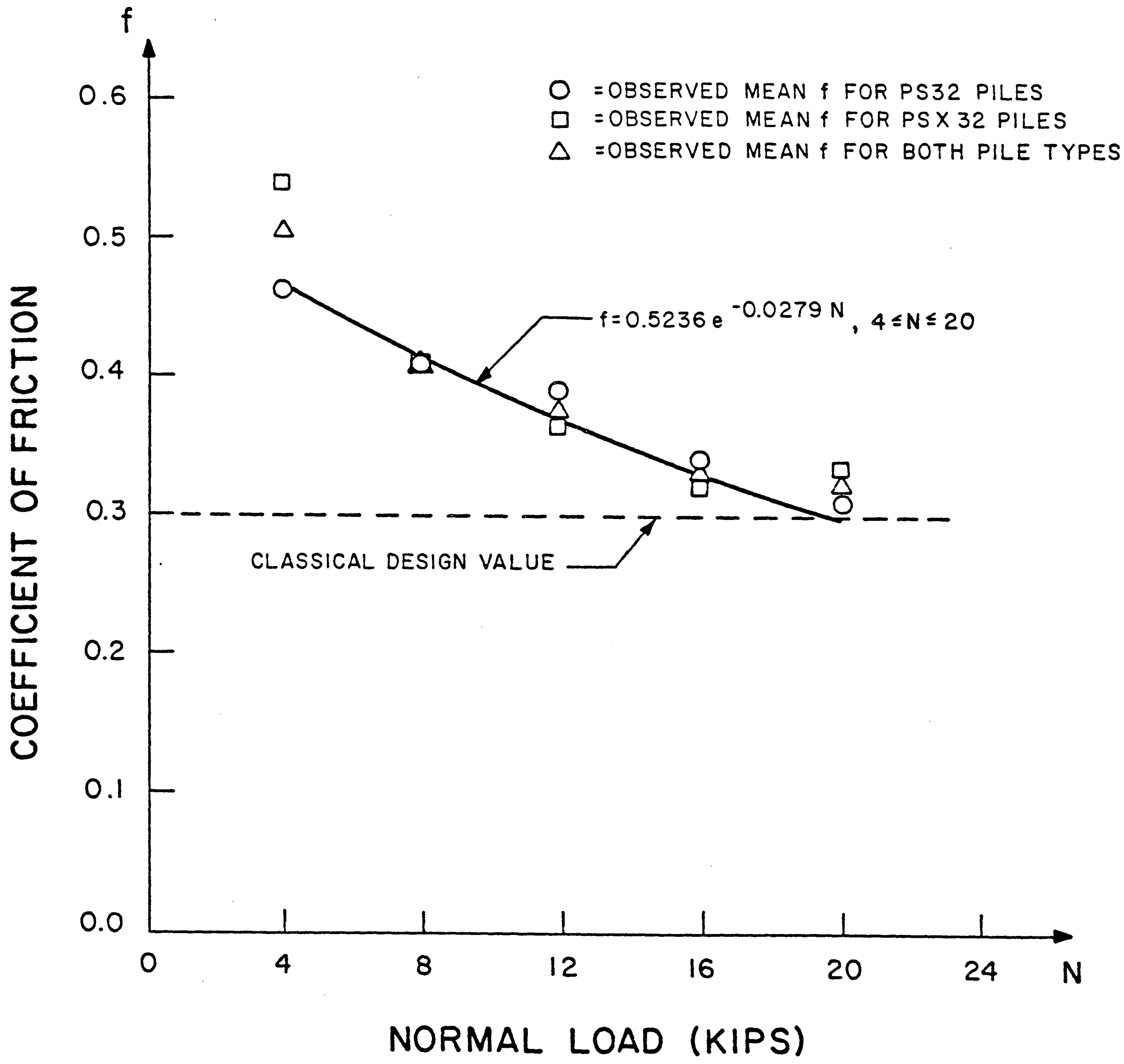

Figure 19. Arithmetic plot of prediction equation for combined pile types.

IV. SUMMARY AND CONCLUSIONS

4.1 Summary

In this study, an original testing procedure was devised to determine the static coefficient of friction for sheetpile interlocks. Six sets of three specimens for two different types of sheetpiles were tested. A total of 2105 observations were made.

Three four inch wide sheetpile specimens were joined at the interlocks and held within a test frame where a hoop tensile load was applied across the specimen assemblage. A vertical shear load was applied to the central specimen until vertical displacement occured. The direction of the vertical load was reversed and applied until displacement in the opposite direction occured. The hoop tensile load was incrementally increased and the process repeated.

The range of hoop tensile load was 4 to 20 kips at four kip increments. Loads were generated by hydraulic cylinders and applied via strain gage instrumented, calibrated steel rods. The static hoop tensile load was monitored on a strain indicator. The dynamic vertical loads were monitored via a strain gage bridge amplifier and recorded on an x-y-y plotter.

With the hoop tensile or normal load and the vertical load known a coefficient of friction for the interlocks may be calculated as

$$f = V/2N \qquad (15)$$

where f is the static coefficient of friction of the sheetpile interlocks, V is the vertical shear load, and N is the normal or hoop tensile load.

The effect of cyclic displacement on interlock shear strength was also examined by cyclical displacement of the central sheetpile specimen approximately 20 times for each normal load. For the number of cycles tested the effect of cyclic displacements had no noticeable effect on interlock shear strength.

The results from these tests revealed a broad range of values for the static coefficient of friction, f. For the lower normal load range, i.e. one and two kips per inch, a higher mean coefficient of friction was observed. With increased normal load a decrease in f was observed. At the maximum normal load tested, five kips per inch, the mean value of f was approximately equal to 0.3.

The relationship between normal load and the static coefficient of friction was found to be nonlinear. An exponential model to predict the coefficent of friction for the combined pile types was developed. The prediction equation for f is

$$f = 0.5236e^{-0.0279N} \tag{22}$$

where the variables are as previously defined for Equation (15).

For the range of normal load tested, these tests verified that the classical use of 0.3 for the static coefficient of friction provides a reasonable estimate of the sheetpile interlock shear strength.

4.2 Conclusions

The most notable feature of the test data is the broad range of f. This range is especially evident at lower normal loads with an mean f notably higher than the classical value of 0.3. With increased normal load a decrease in f is evident. For the normal load range tested the coefficient of friction seems to be asymptotically approaching 0.3.

From the observed experimental data several conclusions may be made.

1. Based on these observations the use of 0.3 for the static coefficient of friction for the sheetpile interlocks seems to be reasonable.

2. The designer of sheetpile structures should be aware that the use of this value will only provide an estimate of the resisting shear generated by the interlocks.

3. The designer may keep in mind that the coefficient of friction will be slightly higher under lower normal loads and decrease moderately under higher normal loads.

4. The ultimate shear strength of the interlocks should not be considered to be greater than 0.3 times the hoop tension in the interlock.

5. For a moderate number of cyclic displacements the shear strength of the interlock is not affected.

4.3 Recommendations

Several recommendations for further study in the area of sheetpile interlock behavior may be made.

1. The specimens tested for this research task had been stored outdoors resulting in a scaled and pitted surface. New sheetpile

specimens delivered directly from the manufacturer should be tested. These test would provide valuable data on the behavior of new specimens whose interlock surface condition would be dramatically different from that of the specimens heretofore tested.

2. Further study of the effect of cyclic displacement on interlock friction for a larger number of displacement cycles than was used in these tests might reveal an effect on interlock friction.

3. Further studies should be conducted to verify the traditional use of f as equal to 0.3 for higher interlock loads, i.e. greater than 5 k/in.

REFERENCES

1. Belz, C.A., 1970. Cellular Structure Design Methods. Design and Installation of Pile Foundations and Cellular Structures. Envo Publishing Co. Inc., Lehigh Valley Pennsylvania.

2. Cummings, Edward M., 1960. Cellular Cofferdams and Docks. Transactions, American Society of Civil Engineers, No. 125.

3. Dismuke, Thomas D., 1970. Stress Analysis of Sheet Piling in Cellular Structures. Design and Installation of Pile Foundations and Cellular Structures, Envo Publishing Co. Inc., Lehigh Valley Pennsylvania.

4. Hansen, Jurgens Brinch, 1953. Earth Pressure Calculations. The Danish Technical Press, The Institution of Danish Civil Engineers, Copenhagen.

5. Maitland, J.K. and W.L. Schroeder, 1979. Model Studies of Circular Sheetpile Cells. Journal of Geotechnical Engineering Division, American Society of Civil Engineers, Vol. 105, no. 7, July, pp. 823-827.

6. Micro-Measurements Division, 1979. Instruction Bulletin B-127-8. Measurements Group, Inc., P.O. Box 27777, Raleigh, N.C. 272611.

7. Micro-Measurements Division, 1983. TT-G04, Leadwire Attachment. Measurements Group, Inc., P.O. Box 27777, Raleigh, N.C., 272611.

8. Micro-Measurements Division, 1983. TT-G06, Soldering Techniques. Measurements Group, Inc., P.O. Box 27777, Raleigh, N.C., 272611.

9. Terzaghi, Karl, 1945. Stability and Stiffness of Cellular Cofferdams. American Society of Civil Engineers, No. 110.

10. Tukey, J.W., 1977. Exploratory Data Analysis, Addison Wesley Publishing Company, Reading, Mass.

APPENDIX

For the calculation of the mean, variance, standard deviation and coefficient of variation all observed data was used.

The arithmetic mean coefficient of friction, f, is

$$f = \frac{\sum fi}{n}$$

where f is the mean coefficient of friction

fi is an individual observed coefficient of friction

n is the number of observations

The variance of the coefficient of friction is

$$VAR(f) = \frac{\sum (f - fi)^2}{n}$$

The standard deviation of the coefficient of friction is

$$STD(f) = \sqrt{VAR(f)}$$

As a measure of dispersion about the mean, the coefficient of variation is calculated as

$$CV(f) = [STD(f)/f] \times 100$$

The vita has been removed from the scanned document