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MATHEMATICAL MODELLING OF HYSTERESIS LOOPS FOR REINFORCED CONCRETE COLUMNS

by

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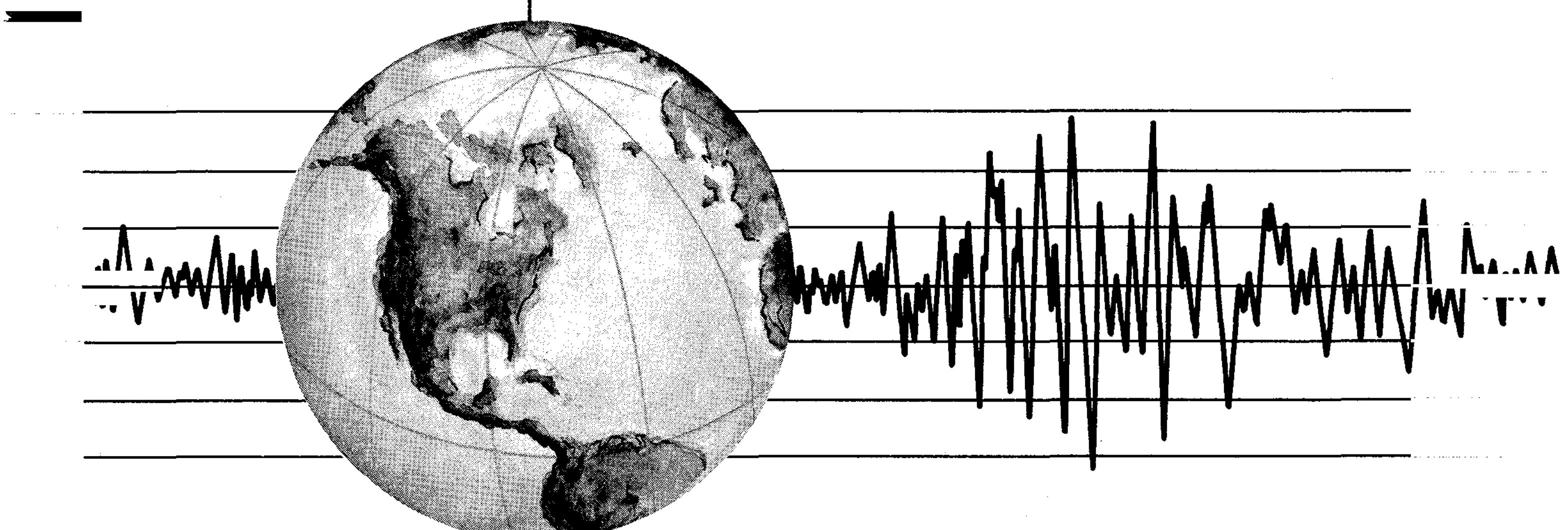
Report to the National Science Foundation



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The objective of this research is to estimate lateral force-deflection curves for reinforced concrete columns subjected to cyclic transverse loads and constant axial loads. These curves are determined in relation to particular column parameters such as shear-span ratio, longitudinal and horizontal reinforcement, and axial force.

The data for this project were obtained from a series of tests reported by Atalay and Penzien and a series of tests made in Japan. 104 specimens are selected from the latter test series, with shear span ratios ranging from 1.0 to 3.0.

Summary equations are developed by statistical methods. This new model takes into account more parameters than previous models. The hysteresis loops generated from these equations are in better agreement with the test data than has been the case with previous models. In particular the new model is compared with one developed previously by Atalay and Penzien.

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ABSTRACT

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1. INTRODUCTION

The objective of the research presented in this report was to establish lateral force-deflection curves for reinforced concrete columns subjected to cyclic transverse loads and constant axial loads, for particular column parameters such as shear span ratio, ratio of longitudinal and horizontal reinforcement, and axial force.

Several researchers, including Penzien and Atalay, have previously developed mathematical models of the restoring force characteristics of reinforced concrete members.[1-14] These models do not apply, however, for all cases involving different modes of failure. To develop a more general model by statistical methods, it is necessary to increase the number of structural parameters included in the model. Up to now empirical expressions for only a few types of strength[15-17] and the stiffness at bending yield for uni-directional loading have been developed as mathematical models based on member parameters.

Recently, digital test data became available for lateral load-deflection relationships for short columns. These had been developed systematically in Japan. This digital information is used in the following to predict the shape of hysteresis loops by statistical procedures.

Finally, the predicted hysteresis loops are used to discuss the adaptability of the Penzien-Atalay model for different combinations of parameters.

2. TEST DATA

2.1 The Test Project

Many structures with short columns have suffered serious damage in recent earthquakes in many parts of the world.[18] In 1972 a large five-year test project was started in Japan to establish new earthquake resistant design methods for such structures. In that project, test data were gathered from about 300 columns subjected to cyclic transverse loads under constant axial loads.

Short columns have been adopted in this program with shear span ratios of 1.0, 1.5, 2.0, 2.5, and 3.0 taken as standard. A satisfactory method for calculating horizontal reinforcement for ductile short columns has not yet been established. In this program, the shear reinforcement ratio, p_w, was obtained from Arakawa's formula[19], in which the mean shear stress at flexural yield strength is used. Tentatively, some test specimens with a shear reinforcement ratio equal to half that described above were also adopted. The shape of the hoops is mainly square with 135° hooks.

Figure 2.1 shows the typical specimen details for all the tests, the scale of the cross section, and the covering and anchoring of the main reinforcement. Figure 2.2 shows the loading apparatus. With this system the test specimen is subjected to antisymmetric moment and constant axial load without the top and bottom of the column rotating. Figure 2.3 shows the system of cyclic loading controlled by the deflection of the top relative to the bottom of the column. Each amplitude is based on the deflection, δ_y, at flexural yield, which is obtained from a loading test for each specimen. Figure 2.4 shows crack patterns developing during the test procedure.

One characteristic of the results is that some specimens showed bond failure prior to or after flexural yielding. This is rare among simple supported systems. The typical failure modes that were observed are as follows:

1) Shear failure prior to flexural yielding
2) Bond failure prior to flexural yielding
3) Shear failure after flexural yielding
4) Bond failure after flexural yielding
5) Steel buckling after flexural yielding
6) Compressive failure of concrete after flexural yielding.

Most specimens failed in cases 2, 3, 4, and 5, and the latter included 24 percent of the specimens.

2.2 Selection of Test Specimens

The test specimens were selected from more than 250 specimens that had already been published. Specimens that had failed in shear or bond at small amplitudes during the loading procedure were excluded. Among the remaining specimens there were many whose graphs are not clear enough to be digitized to computer cards. The number of specimens suitable for the statistical procedure was 104, and the parametric distributions of these are shown in Figs. 2.5a, b, and c. The shear span ratio, a/d, was either 1.0, 1.5, 2.0, 2.5, or 3.0, and the majority of the specimens had a/d = 2.0.

The columns were subjected to constant axial stress, P/bd, (ranging from 21 kg/cm^2 to 70 kg/cm^2) during the loading. Figure 2.5a shows the dimensionless ratio P/bdf'_c , axial stress divided by the concrete compressive strength, f'_c. The compressive strength of the concrete used in these specimens ranges from 153 kg/cm^2 to 453 kg/cm^2.

The longitudinal tensile reinforcement ratio, p_t, is the same as the compressive reinforcement ratio in the cross-section of each specimen, and their values are mainly 0.4 percent, 0.6 percent, and 0.95 percent as shown in Fig. 2.5b. The value of the shear reinforcement ratio is distributed between 0.09 percent and 2.44 percent (see Fig. 2.5c). None of the specimens failed in shear before flexural yield.

2.3 Data Digitization from Graphs

Figure 2.6 shows the outline of the data digitization. After the selection of specimens had been made, the graphs of the force-deflection relationships were enlarged to approximately four times their original size. Then from the enlarged graphs the first, third, and tenth cycles at $1\delta_y$, $2\delta_y$, $3\delta_y$ and $4\delta_y$ were reduced to digitized form. The accuracy of the digitizer is 0.001 inches and that of the operator is a minimum of 0.005 inches. Hence the error should be less than 0.01 percent for the enlarged graphs.

The digitized data were stored on computer cards; 104 specimens occupying approximately 16,000 cards. (These cards are now stored on one 1,200 ft reel of tape.)

2.4 Data Reduction

The lateral force-deflection data of each hysteresis loop (more than 20 points in one loop) were replaced by slopes, deflections, and shear forces at special points of the loop for use in the statistical procedure.

The reduced data set consists of 20 points for each specimen in each cycle as shown in Fig. 2.7. Points 1 to 10 are in the region of positive loading, and points 11 to 20 are in the region of negative loading. Points 1 to 5 and 11 to 15 are the slopes of the curve (in ton/mm). Slopes 1, 5, 11, and 15 are calculated from the original data by taking pairs of points nearest to the δ axis. Slopes 2 and 12 are the stiffness when the deflection is zero; they are obtained from the two points nearest the P axis. Slopes 3, 4, 13, and 14 are, respectively, the stiffnesses at loading and unloading for maximum deflection in each cycle. Deflections 6 and 16 are the maximum deflections, and deflections 9 and 19 are the remaining deflections when the load is zero. Shear forces 8 and 18 are the loads when the loop crosses the load axis; shear forces 7 and 17 are the loads at maximum deflection.

Point 10 is the area of the loop on the positive load side, and point 20 is the corresponding area on the negative side. After checking data at loading and unloading in each of the regions defined above, the set 21 to 30 was computed as shown in Fig. 2.7. Points 21 to 25 are average dimensionless stiffness ratios based on the "peak to peak" stiffness, 27/26. In this way about eighty digital figures (40 points) in one hysteresis loop were reduced to ten digital data.

3. EMPIRICAL EQUATIONS OF HYSTERESIS LOOPS

3.1 Outline of Estimated Hysteresis Loops

In this section, the authors are searching for empirical equations D1, D2, D3, ... D9 which are developed from the test data 21, 22, 23, ... 29 by statistical processes.[20] The skeleton curve is defined as shown in Fig. 3.1. The shear force Q_y, the deflection δ_y (D6) at flexural yield and the envelope curve after flexural yielding are obtained experimentally as estimated equations. The curve from the origin to the yield point is assumed to be parabolic.

This curve opens downwards and the maximum value is Q_y. As a second step, a hysteresis loop is defined in terms of six elements as shown in Fig. 3.2. The six empirical equations are D1, D2, D3, D5, D8, and D9, and cubic equations based on the test data are used between each adjacent pair of elements. The peaks of one loop are defined by the skeleton curve D7, based on the effect of cyclic loads with fixed amplitudes. The first cycle at a given amplitude is defined by D1 (amp) to D9 (amp). All subsequent cycles at that amplitude are defined by D1 (cycle) to D9 (cycle) where "cycle" is the current number of repetitions. It should be noted that the first cycle at a given amplitude should be treated as the last cycle of the previous amplitude until the deflection exceeds the previous amplitude. The location of D1 is the start of any given cycle (loop).

3.2 Skeleton Curve

The calculated shear force, Q_{yc}, at flexural yielding, which is based on plastic reinforced concrete theory(16), does not always agree with the test value, Q_{yt}, especially for short columns. Figure 3.3a shows the average values of Q_{yt}/Q_{yc} for each combination of parameters. The notation for this figure is shown in Fig. 3.5. These kinds of graphs, shown many times in the next section, are always for the same combination of parameters. In the top diagram, the test specimens are separated into domains according to their shear span ratio 1.0 and 1.5; 2.0; 2.5 and 3.0. In the second diagram the three groups are each divided into two domains determined by a shear reinforcement ratio $<$ 1.2 percent or $\geq$ 1.2 percent. Similarly, the third diagram is the distribution of longitudinal reinforcement, and the fourth one is the distribution of axial stress divided by concrete strength.

Figure 3.3b shows the comparison between the experimental values Q_{yt} and calculated values Q_{yc} used so far. In the next curve, Fig. 3.3c, the calculated value has been corrected to $\alpha\, Q_{yc}$, where α is obtained by assuming a linear relation between the four test parameters and the method of least squares is applied to obtain the coefficients.

$$\alpha = 1.418 - 0.105\ a/d - 12.49\ p_t - 7.37\ p_w - 0.464\ P/bdf_c' .$$

Equation 3.1, represented as D7, is obtained from an analysis of the data distributions in Fig. 3.4a.

$$D7(\text{yield}) = 0.801 + (0.623 - 29.07\ p_t - 5.623\ p_w - 1.11\ P/bdf_c')/(a/d) \quad \text{.....(3.1)}$$

Then the ordinate of Fig. 3.3d has been corrected to D7(yield)$\cdot\, Q_{yc}$. A comparison of the three diagrams, Figs. 3.3b, c, and d, indicates that Fig. 3.3d gives the best estimate for shear force at flexural yielding.

Figure 3.4a shows the average rotational angle, δ_y/h, at flexural yielding for each parameter combination, where δ_y is the deflection at flexural yielding, and h is the clear span of the column. An analysis of the significance of the parameters in this diagram indicates that δ_y/h is a linear combination of the parameters, a/d, p_w, and p_t. From the method of least squares,

$$D6 \equiv \delta_y/h = 0.005 - 0.00124\ a/d + 0.63\ p_t - 0.056\ p_w. \qquad (3.2)$$

Figure 3.4b shows the comparison of the experimental results with Eq. (3.2). Although the accuracy is not satisfactory in this diagram, the error is less than in Fig. 3.4c in which a comparison is made between the test results and an empirical equation developed by Sugano[16]. Hence Eq. (3.2) is adopted to estimate δ_y/h.

Next, the envelope curves after flexural yielding are defined. Figure 3.6a is the distribution of average ratios of the shear force at first cycle in each amplitude to the shear force at flexural yield, Q_{yt}. The following estimated equation, D7,of the envelope curve is obtained by the method of least squares:

$$D7(\text{envelope}) = 1.0577 + (a/d - 3.0)(3.777\ p_t - 0.0221\ P/bdf_c^{'})\ \text{amp} \qquad \ldots\ldots(3.3)$$

where amp is the dimensionless amplitude, δ/δ_y; δ_y is calculated for each specimen from Eq. 3.2.

Figures 3.6b and 3.6c are the shear force reduction ratios of the third cycle to the first cycle and the tenth cycle to the first cycle for each amplitude. From these diagrams, Eq. 3.4 is obtained as an estimate of the effect of cyclic loads on shear force reduction:

$$\begin{aligned} D7(\text{cycle}) = {} & 1.046 - 0.00554\ a/d - 0.0345\ \text{cycle}/(a/d) \\ & + (p_t - 0.004)(-0.013 + 2.569\ P/bdf_c^{'} - 5.98\ \text{amp}) \end{aligned} \qquad \ldots\ldots(3.4)$$

These two equations demonstrate the dependence of some parameters in D7(cycle) on other parameters.

Table 3.1 summarizes the process by which the equations used to estimate skeleton curves are obtained from the effect of cyclic loads with fixed amplitude. If an arbitary shear force is needed, it is obtained as follows:

$$Q = D7(\text{amp}) \cdot D7(\text{cycle}) \cdot Q_{yc}$$

TABLE 3.1

ESTIMATED EQUATIONS FOR SKELETON CURVE

Element	Inclination of Effective Parameter	Remarks
D7(yield)	As a/d increases, D7(yield) decreases	
Q_y	p_t increases, decreases	Restrained by a/d
	p_w increases, decreases	Restrained by a/d
	P/bdf'_c increases, decreases	Restrained by a/d
	$D7(yield) = 0.801 + (0.623 - 29.07p_t - 5.623p_w - 1.11P/bdf'_c)/(a/d)$	
D6	As a/d increases, D6(yield) decreases	
	p_t increases, increases	
δ_y/h	p_w increases, decreases	
	$D6(yield) = 0.005 - 0.00124a/d + 0.63p_t - 0.056p_w$	
D7(envelope)	As p_t increases, D7(envelope) decreases	Restrained by a/d, amp
= D7 (amp)	P/bdf'_c increases, increases	Restrained by amp
	$D7(envelope) = 1.0577 + (a/d-3)(3.777p_t - 0.0221P/bdf'_c)amp$	

TABLE 3.1 (continued)

Element	Inclination of Effective Parameter	Remarks
D7(cycle)	As a/d increases, D7(cycle) decreases	
	p_t increases, decreases	
	P/bdf'_c increases, increases	Restrained by p_t
	amp increases, decreases	Restrained by p_t
	cycle increases, decreases	Restrained by a/d
	$D7(cycle) = 1.0455 - 0.0055a/d + (p_t - 0.004)(-0.0132 + 2.569P/bdf'_c - 5.98amp) - 0.0345cycle/(a/d)$	

3.3 Definition of the Hysteresis Loop

Using the test data, the elements D1 to D9 (shown in Fig. 3.2) used to characterize the shape of the hysteresis loop, are now defined. A hysteresis loop is defined by pairs of equations. Each pair consists of one equation for amplitude, and the other for cyclic loading with fixed amplitude. The exception is the element D3. Half of the test data on D3 were negative or zero in the first cycle for each amplitude and positive in the third and tenth cycles. Because of this distribution of data, the estimated equation for D3 was separated with regard to amplitude and the loading cycles.

Applying the same techniques used in Section 3.2, these estimated equations D1, D2, ... D9 are summarized in Table 3.2, which also shows the trend of the parameters with the elements, (e.g., D1(amp) increases as a/d increases). In each case a pair of equations is used as follows: Using D1 as an example, the first cycle at a given amplitude would be described by D1(amp). All subsequent cycles at that deflection would be described by D1(amp) • D1(cycle).

4. ESTIMATED HYSTERESIS LOOPS

4.1 Method for Drawing Hysteresis Loops

The hysteresis loops are drawn using cubic equations. First, as shown in Fig. 4.1a, the initial curve OA is a parabolic equation whose maximum value is at δ_y. In the cyclic hysteresis loop, as shown in Fig. 4.1b, the half cycle consists of three sections -- RANGE 1, RANGE 2, and RANGE 3; the first two are cubic polynomials and the third is a parabola. The boundary conditions for these have already been calculated in Section 3. Some examples of estimated hysteresis loops

TABLE 3.2

ESTIMATED EQUATIONS

	Inclination of Effective Parameter				Remarks
D1	As a/d	increases,	D1(amp)	increases	
	p_w	increases,		decreases	Restrained by a/d
	p_t	increases,		decreases	Restrained by a/d
	P/bdf'_c	increases,		increases	Restrained by a/d
	amp	increases,		decreases	Restrained by a/d
	D1(amp) = 1.354 + (3.5 - a/d)(0.542 - 5.126 p_w - 49.9 p_t + 0.51 P/bdf'_c - 0.153 amp)				
	As amp	increases,	D1(cycle)	increases	Restrained by p_t
	cycle	increases		increases	Logarithm
	D1(cycle) = 0.667 + 8.93 amp (p_t + 0.005)				
D2	As p_t	increases,	D2(amp)	decreases	Restrained by a/d
	p_w	increases,		decreases	Restrained by a/d
	amp	increases,		decreases	Restrained by a/d
	D2(amp) = 1.481 + (a/d - 3.0)(41.08 p_t - 10.09 p_w + 0.07 amp)				
	As cycle	increases,	D2(cycle)	decreases	
	amp	increases,		increases	
	D2(cycle) = 0.844 - 0.031 cycle + 0.031 amp				

TABLE 3.2 (continued)

	Inclination of Effective Parameter				Remarks
D3	As cycle	increases,	D3(amp, cycle)	increases	Logarithm
	p_t	increases,		increases	Restrained by a/d
	P/bdf'_c	increases,		decreases	Restrained by a/d
	amp	increases,		increases	Restrained by a/d
D5	As a/d	increases,	D5(amp)	increases	
	p_t	increases,		decreases	Restrained by a/d
	amp	increases,		increases	Restrained by a/d
	$D5(amp) = 1.054 + (a/d - 3)(0.021 + 12.128\ p_t + 0.039\ amp)$				
	As cycle	increases,	D5(cycle)	increases	Restrained by a/d
	amp	increases,		increases	Restrained by a/d
	$D5(cycle) = 0.972 + (3.5 - a/d)(- 0.114 + 0.014\ cycle + 0.05\ amp)$				
D8	As p_t	increases,	D8(amp)	decreases	Restrained by a/d
	amp	increases,		changes	Restrained by a/d
	$D8(amp) = 0.239 + 5.88\ (a/d - 3)\ p_t + 0.0144\ amp\ (a/d - 2.3)$				
	As cycle	increases,	D8(cycle)	decreases	
	amp	decreases,		increases	Restrained by p_t
	$D8(cycle) = 0.842 + 0.0045\ cycle + 13.559\ (p_t - 0.002)\ amp$				

TABLE 3.2 (continued)

	Inclination of Effective Parameter	Remarks
D9	As p_t increases, D9(amp) increases a/d increases, increases	Restrained by amp Restrained by amp
	$D9(amp) = 0.1656 + \{6.78\ (p_t - 0.002) + 0.0184\ a/d\}\ amp$	
	As cycle increases, D9(cycle) decreases amp increases, increases	

(CASE 1, CASE 2,...CASE 10) are shown in Figs. 4.2 to Fig. 4.11. These are compared with the test results and also with a mathematical model developed by Penzien and Atalay[14] for long columns. The graphs show that the "estimated model" agrees reasonably well with the test results.

In these figures, the three loops correspond to the first, third, and tenth cycles of each amplitude. CASE 1: small shear span ratio (a/d = 1.0), small shear reinforcement (p_w = 0.21); the shape of hysteresis loops obtained from test data is that of the hard spring type even for the initial amplitude. For such a combination of parameters, there is a rapid reduction of shear force. The predicted hysteresis loops demonstrate these results reasonably well. CASES 3 and 4: a/d = 1.5 (Figs. 4.4 and 4.5). The different longitudinal reinforcements of these two cases changes the shapes of the loops. The estimated hysteresis loops also demonstrate this delicate difference.

Again for CASE 5 and CASE 6, with different longitudinal reinforcements, the test results show some differences; such as in the shear reduction by cyclic loads and in the residual deflections when shear force is zero.

These figures show that the estimated hysteresis loops agree reasonably well with the test data. However, the mathematical model obtained from the test data for long columns (a/d = 5.5) does not agree as well as for columns whose shear span ratio is less than 3.0.

4.2 Comparison with a Mathematical Model

It is of some interest at this stage to compare the preceding results with the Penzien-Atalay model[14] of which Fig. 4.12 shows a typical half cycle. Both ends of the half cycle are restrained by an empirical skeleton curve which includes the effect of cyclic loads.

Figures 4.13, 4.14, and 4.15 show comparisons of the estimated stiffness and the stiffness from the mathematical model for the stiffnesses D1, D2, and D3, respectively, (for the case that the amplitude is 1.0 δ_y). The stiffnesses are divided by K_j and shown as dimensionless values.

These graphs indicate that the differences between the mathematical model and the estimated equation (which agrees well with the behavior of the test data) reduce as the shear span becomes large.

5. CONCLUSIONS AND RECOMMENDATIONS

The proposed method of predicting hysteresis loops for reinforced concrete columns involves using test data statistically. The estimated hysteresis loops are obtained by a series of simple, statistical procedures and agree reasonably well with the test data for the following:

1) Change in shear force for a given amplitude and number of cyclic loads.
2) Shape of the hysteresis loops.
3) Shear force and deflection at bending yield for short columns.

It is important to note, however, that this evaluation is based upon test data for columns which <u>never failed in shear or bond</u> before flexural failure. There are no test data for loops in these cases.

The comparison of the Penzien-Atalay mathematical model based on test data for long columns and this estimated model obtained from shorter column data shows emphatically that short columns (shear span ratio less than 3.0) are not adequately described by the mathematical model.

For a complete estimation of the load deflection relationship, we recommend that cyclic loading tests of longer columns (a/d = 3.5, 4.0 and 5.0) be developed systematically.

It should be noted that the estimated equations presented herein are developed only for this particular set of test data. Further work is needed in order that these equations may be applied to the more general case of nonrepetitive cyclic loading.

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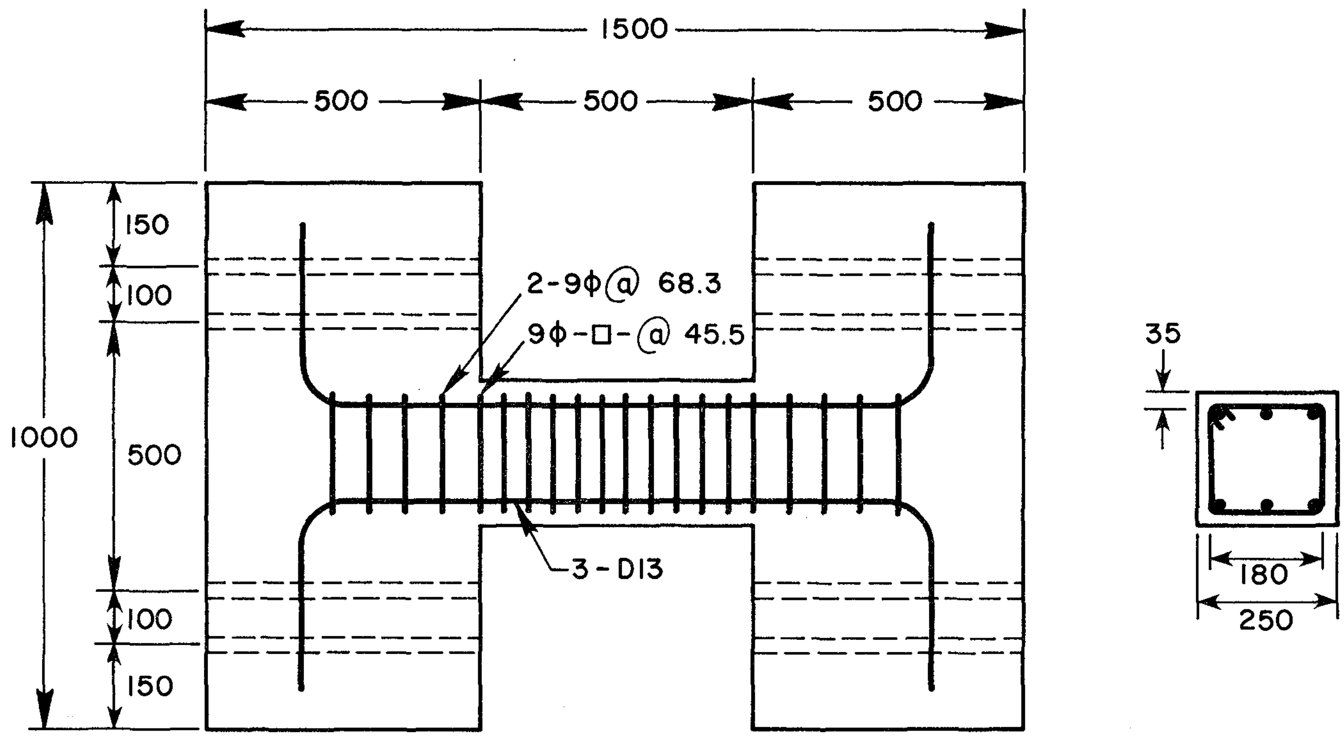


Fig. 2.1 Specimen Details (in mm)

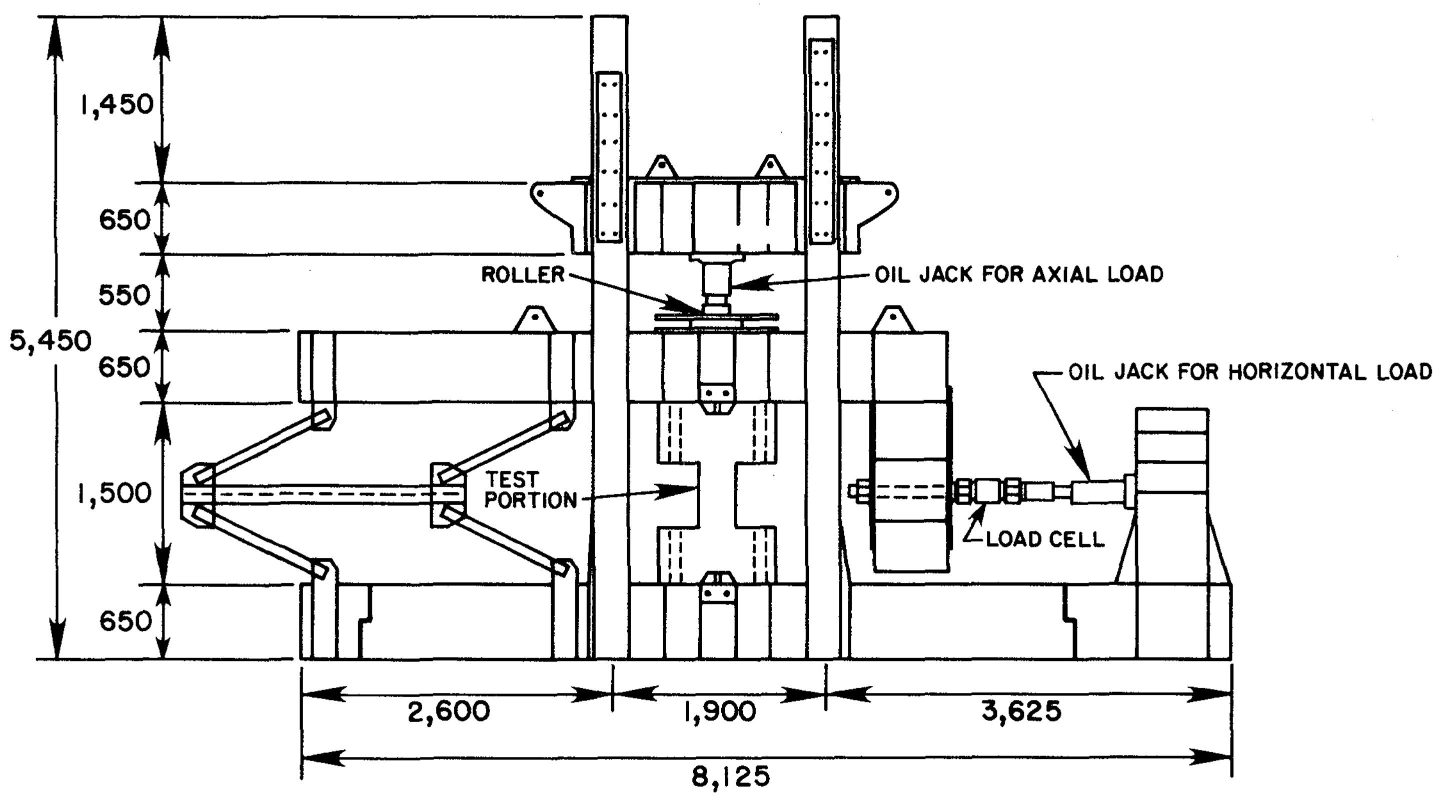


Fig. 2.2 Loading Apparatus (in mm)

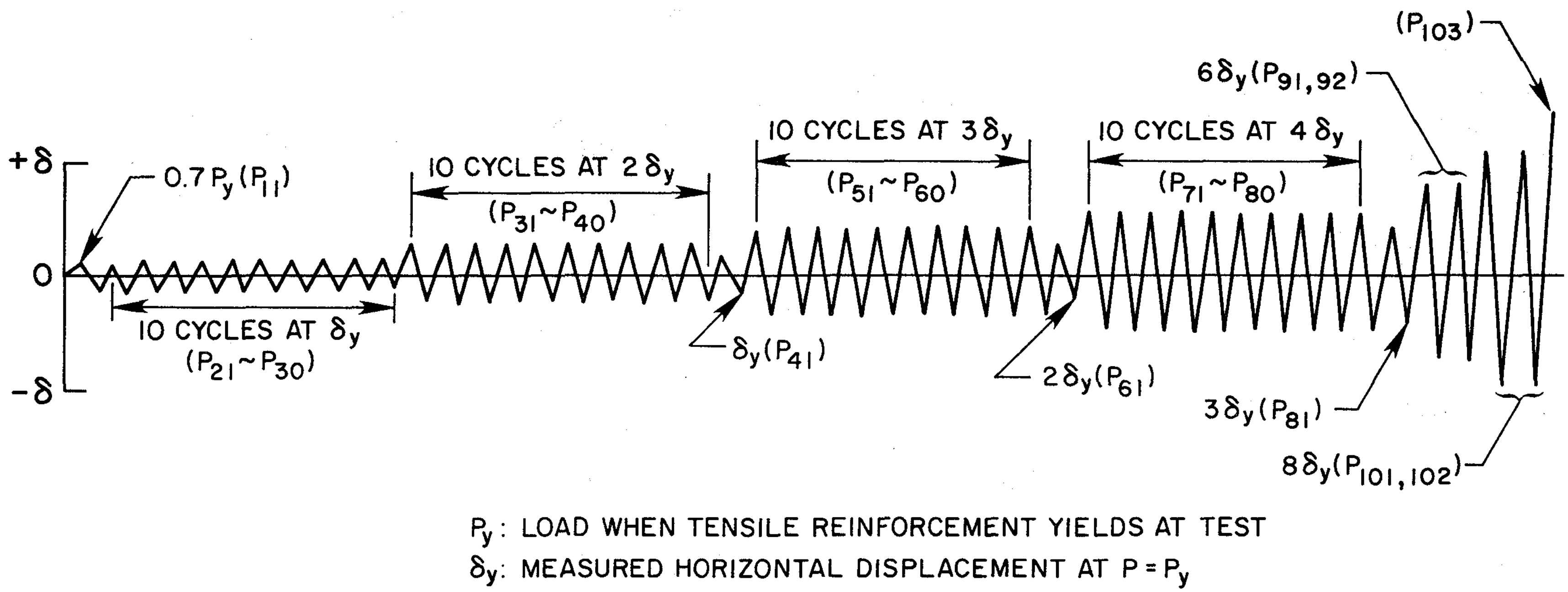


Fig. 2.3 Cyclic Loading System

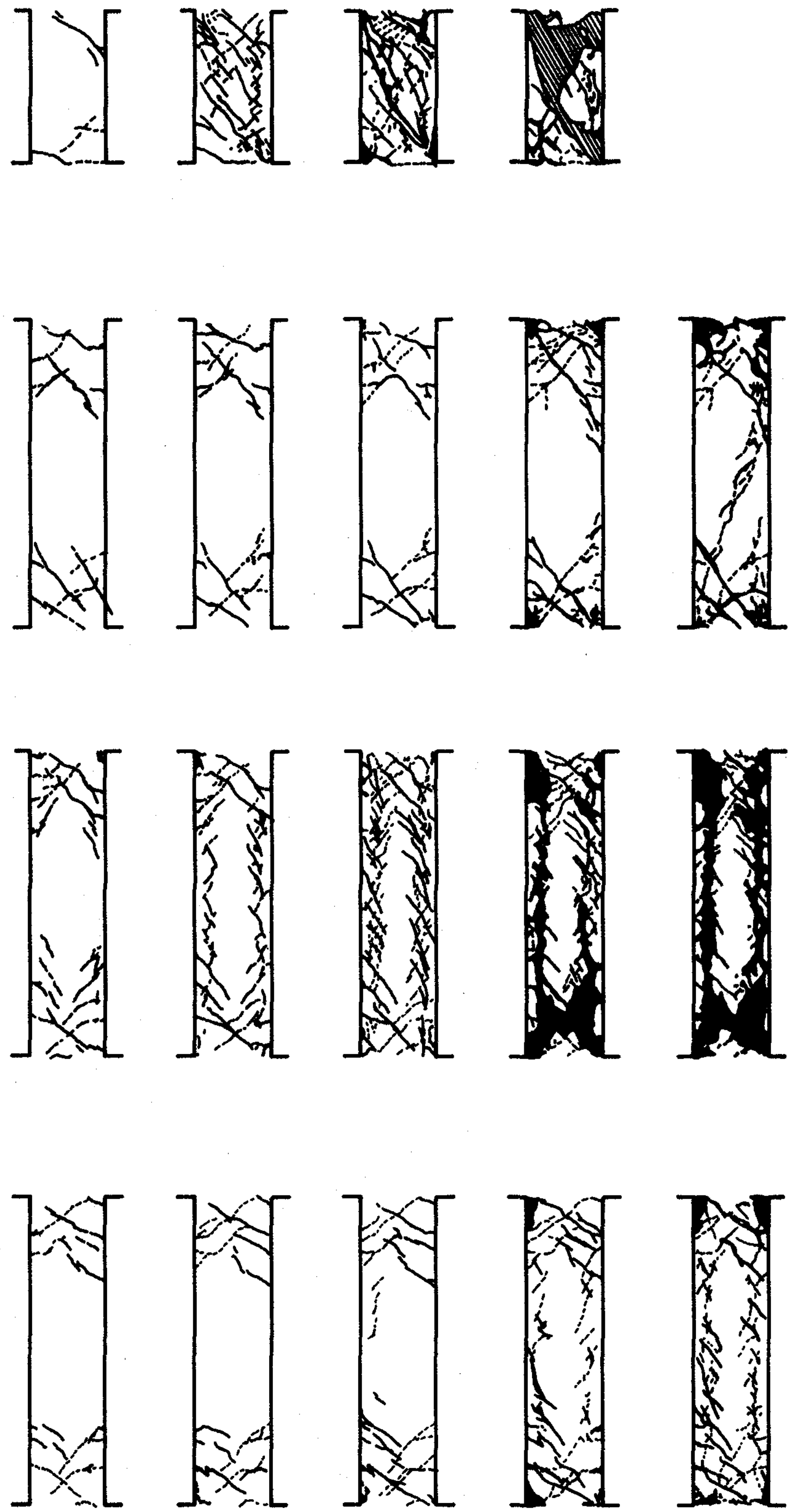


Fig. 2.4 Examples of Crack Patterns

INDICATES FREQUENCY EQUALS 1

INDICATES FREQUENCY EQUALS 2

INDICATES FREQUENCY EQUALS 3

INDICATES FREQUENCY EQUALS 4

INDICATES FREQUENCY EQUALS 5

INDICATES FREQUENCY EQUALS 6

INDICATES FREQUENCY EQUALS 7

INDICATES FREQUENCY EQUALS 8

INDICATES FREQUENCY EQUALS 9

INDICATES FREQUENCY EQUALS 10

INDICATES FREQUENCY EQUALS 11

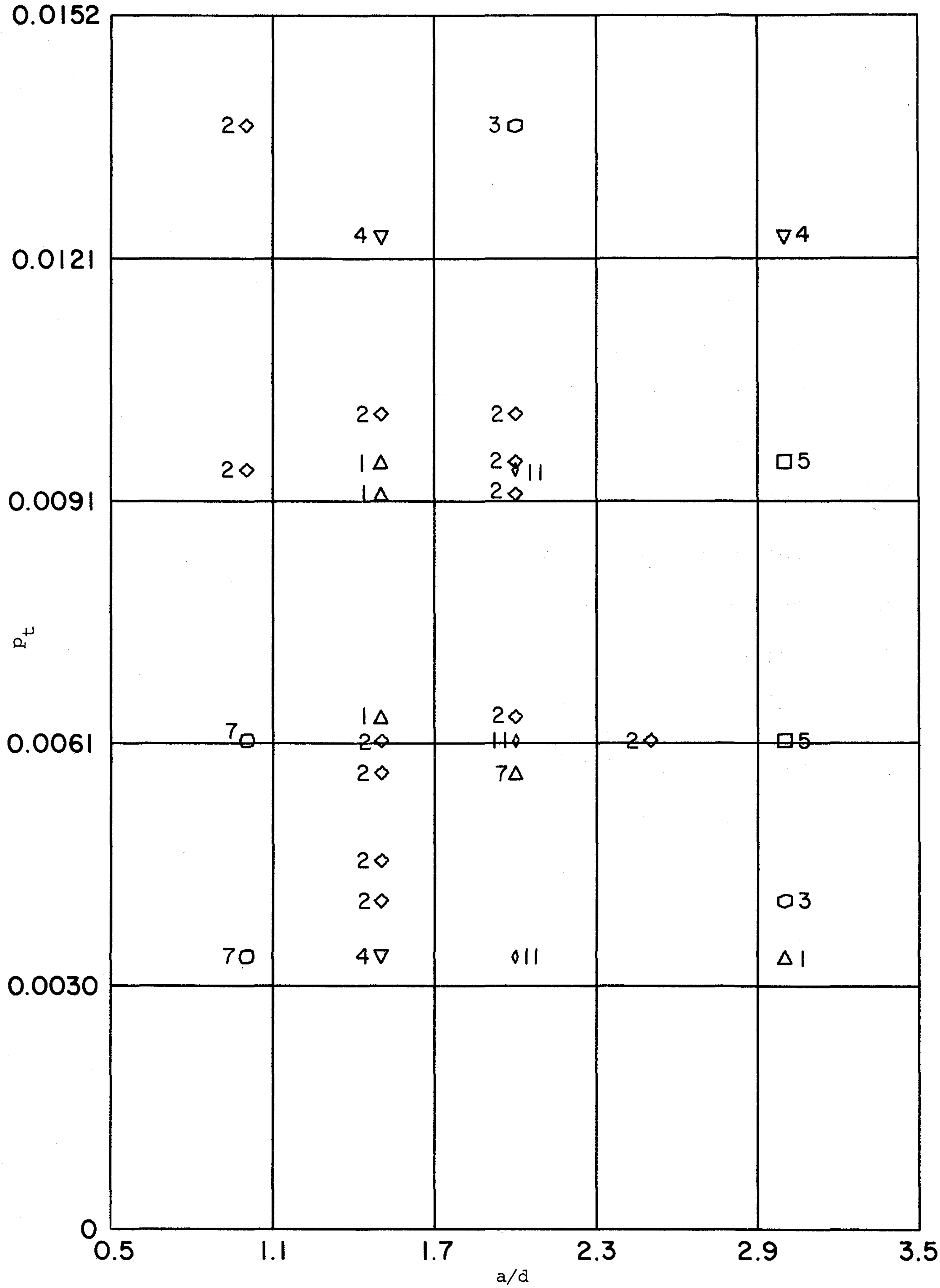


Fig. 2.5a Parameter Distribution: a/d vs p_t

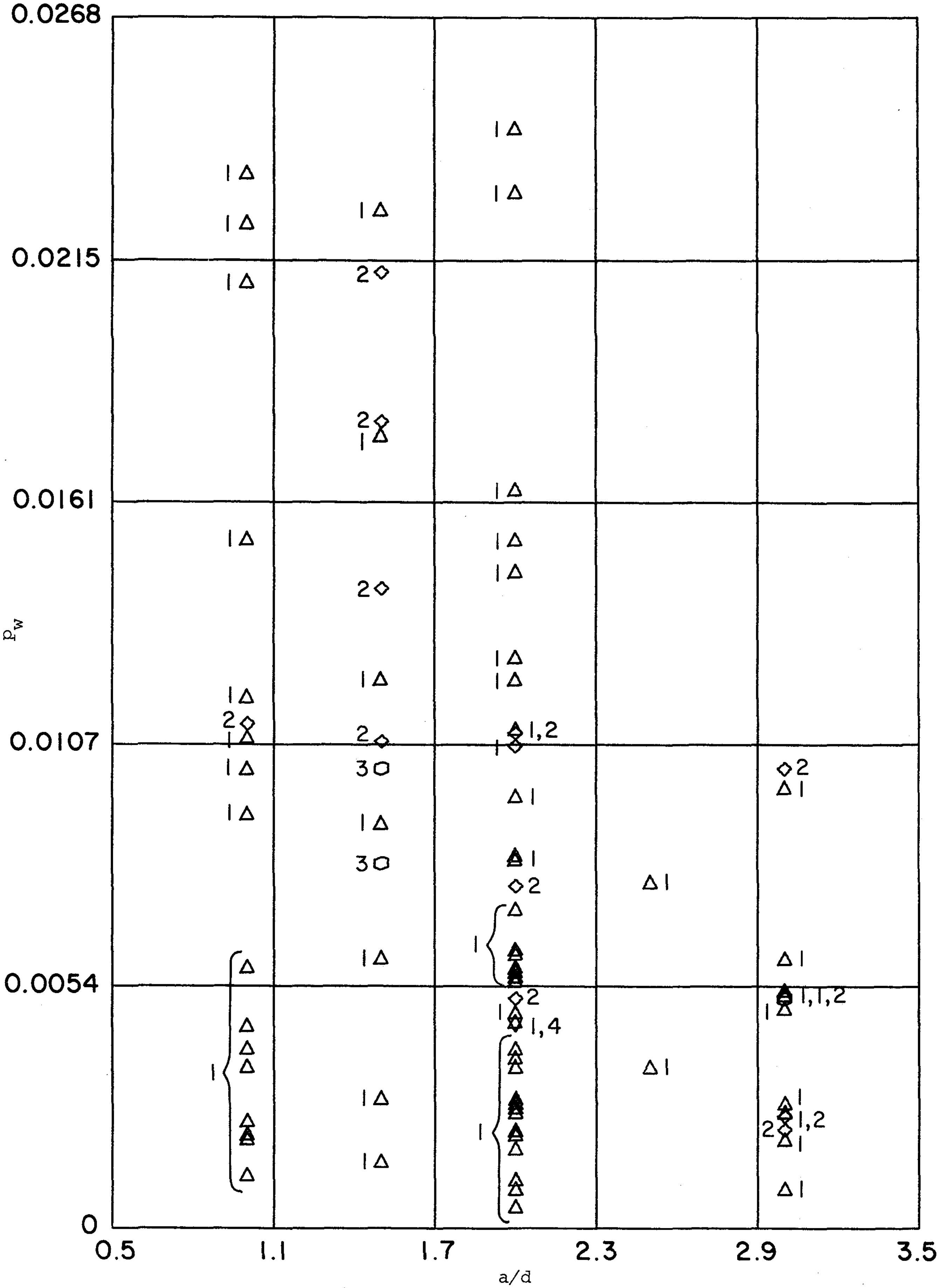


Fig. 2.5b Parameter Distribution: a/d vs p_w

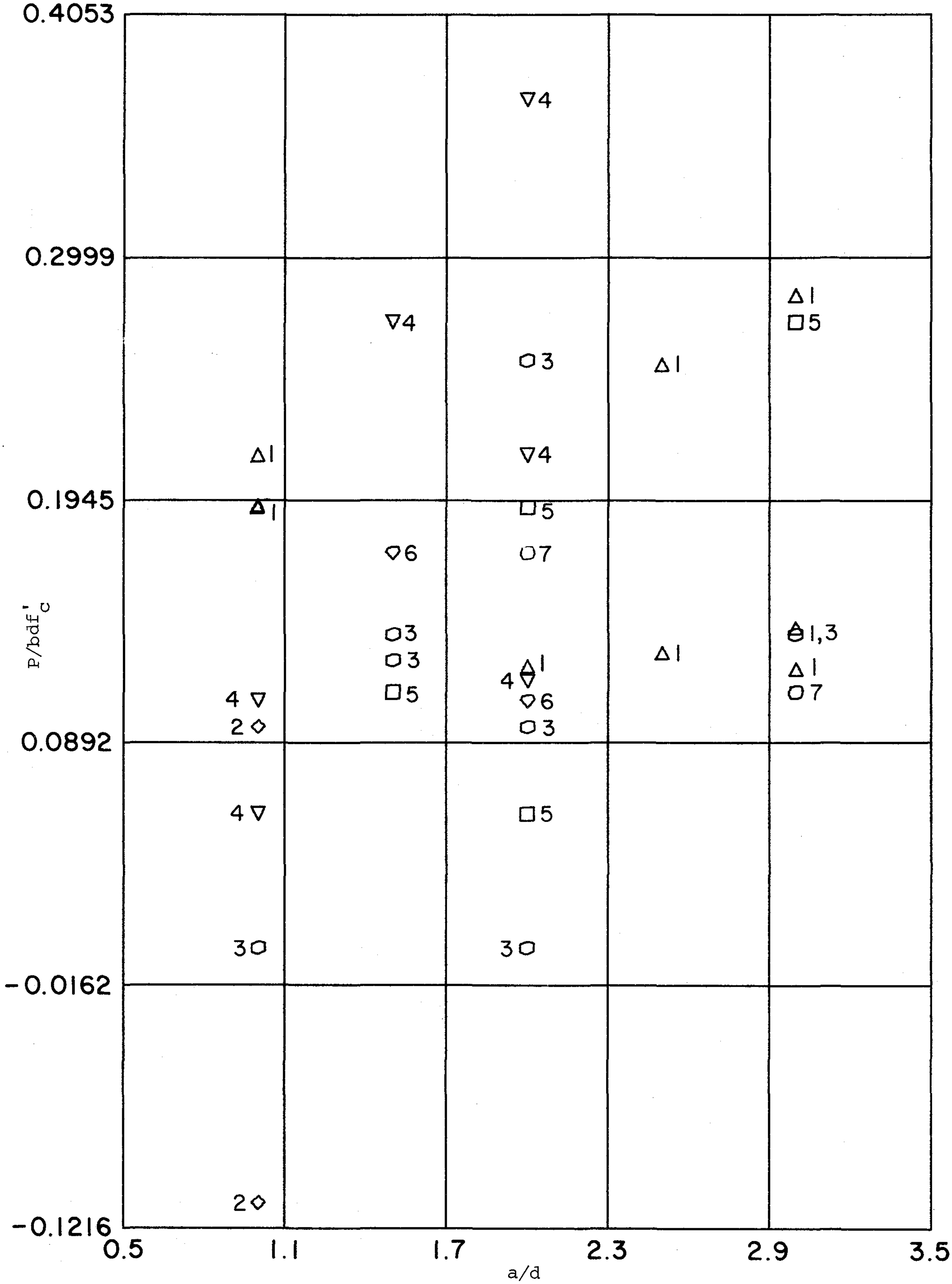


Fig. 2.5c Parameter Distribution: a/d vs P/bdf'_c

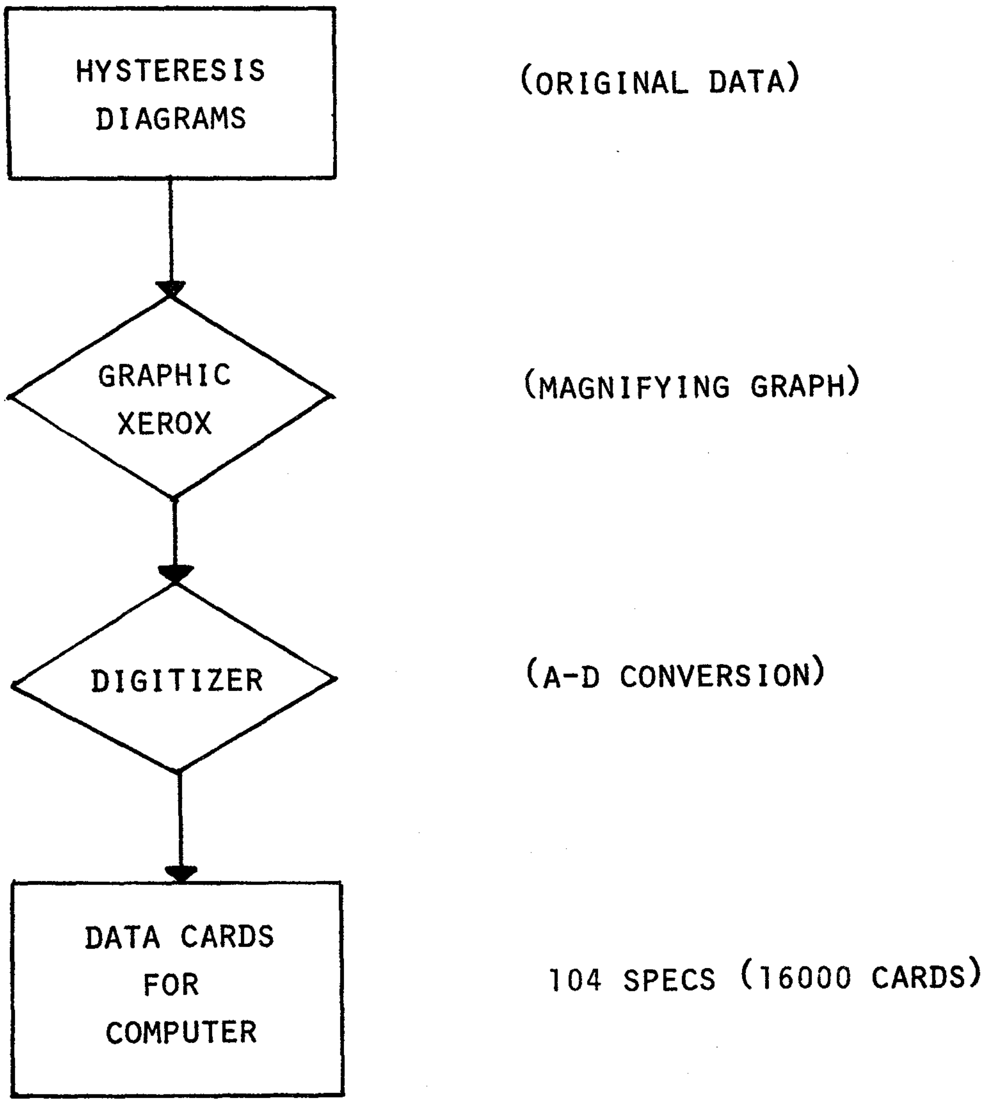
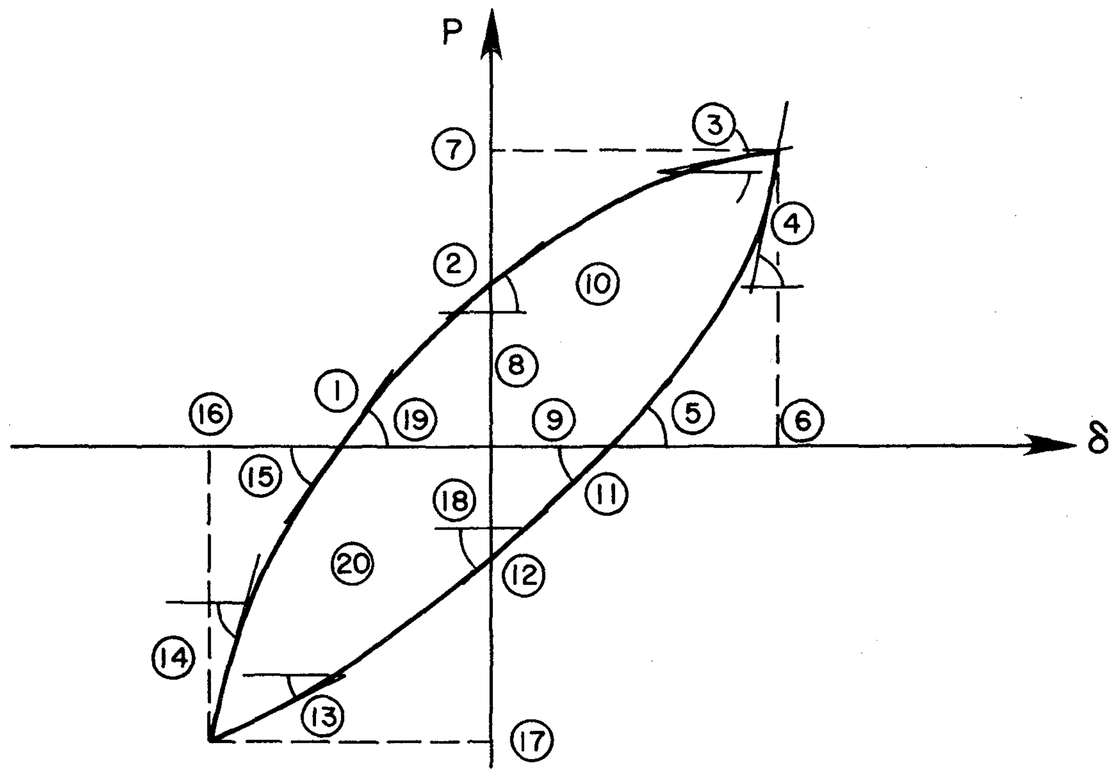


Fig. 2.6 Procedure of A-D Conversion



(a) STEP 1

(21) = [(1) + (11)]/2 / [(27) / (26)]
(22) = [(2) + (12)]/2 / [(27) / (26)]
(23) = [(3) + (13)]/2 / [(27) / (26)]
(24) = [(4) + (14)]/2 / [(27) / (26)]
(25) = [(5) + (15)]/2 / [(27) / (26)]
(26) = (6) + (16)
(27) = (7) + (17)
(28) = [(8) + (18)]/ (27)
(29) = [(9) + (19)]/ (26)
(30) = (10) + (20)

(b) STEP 2

Fig. 2.7 Data Reduction

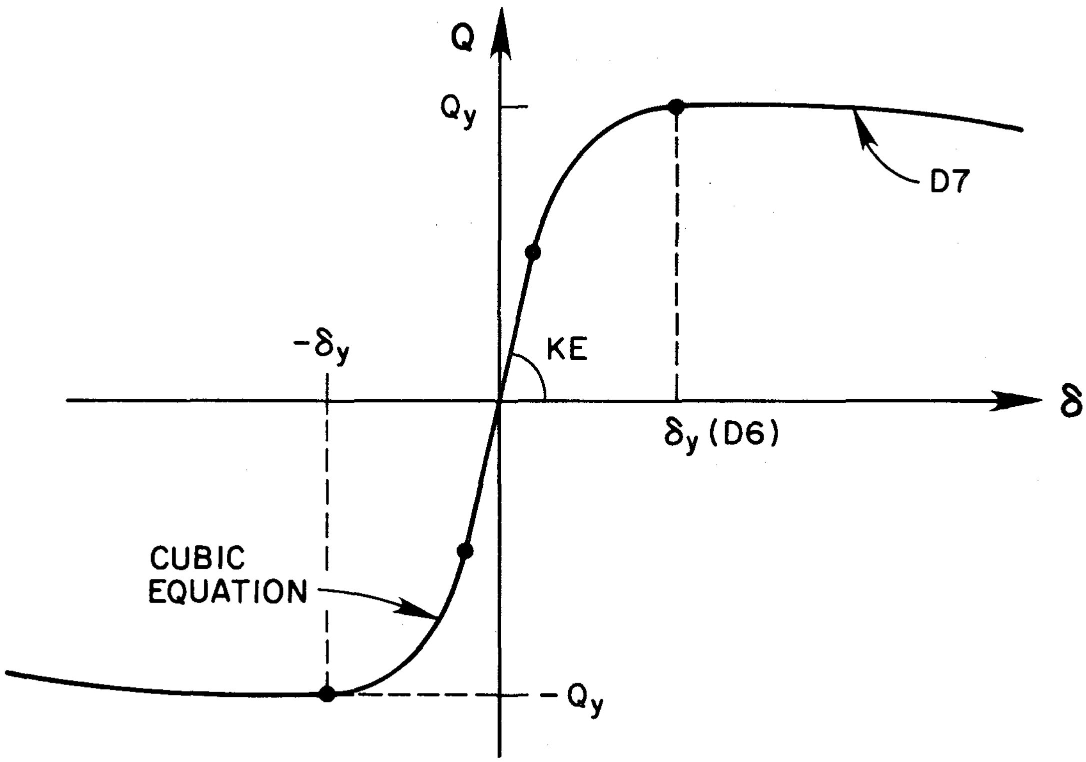


Fig. 3.1 Empirical Skeleton Curve

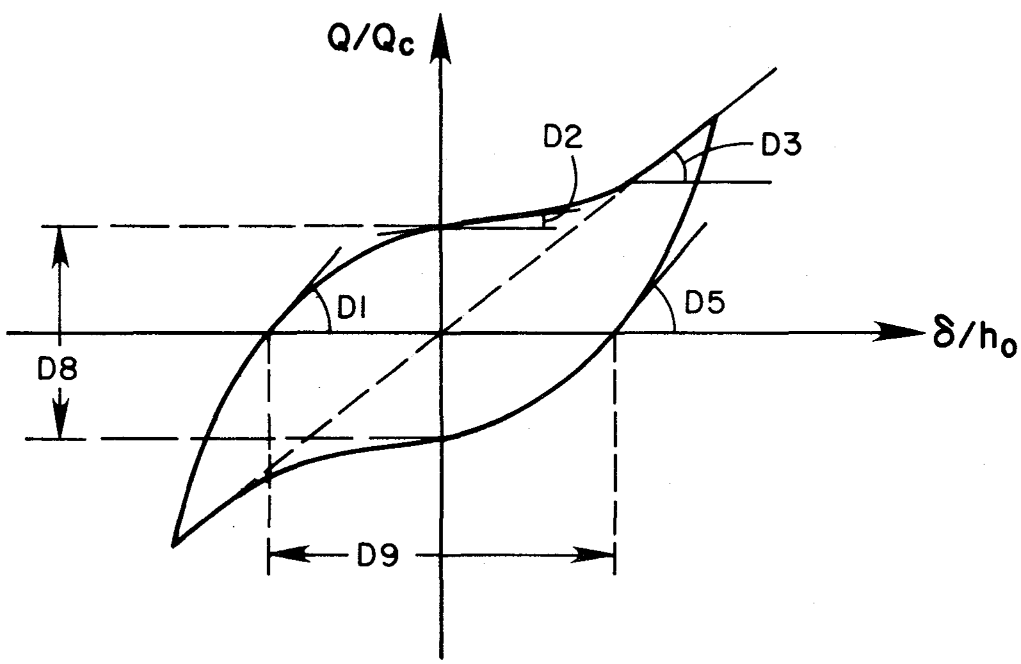


Fig. 3.2 Empirical Hysteresis Loop

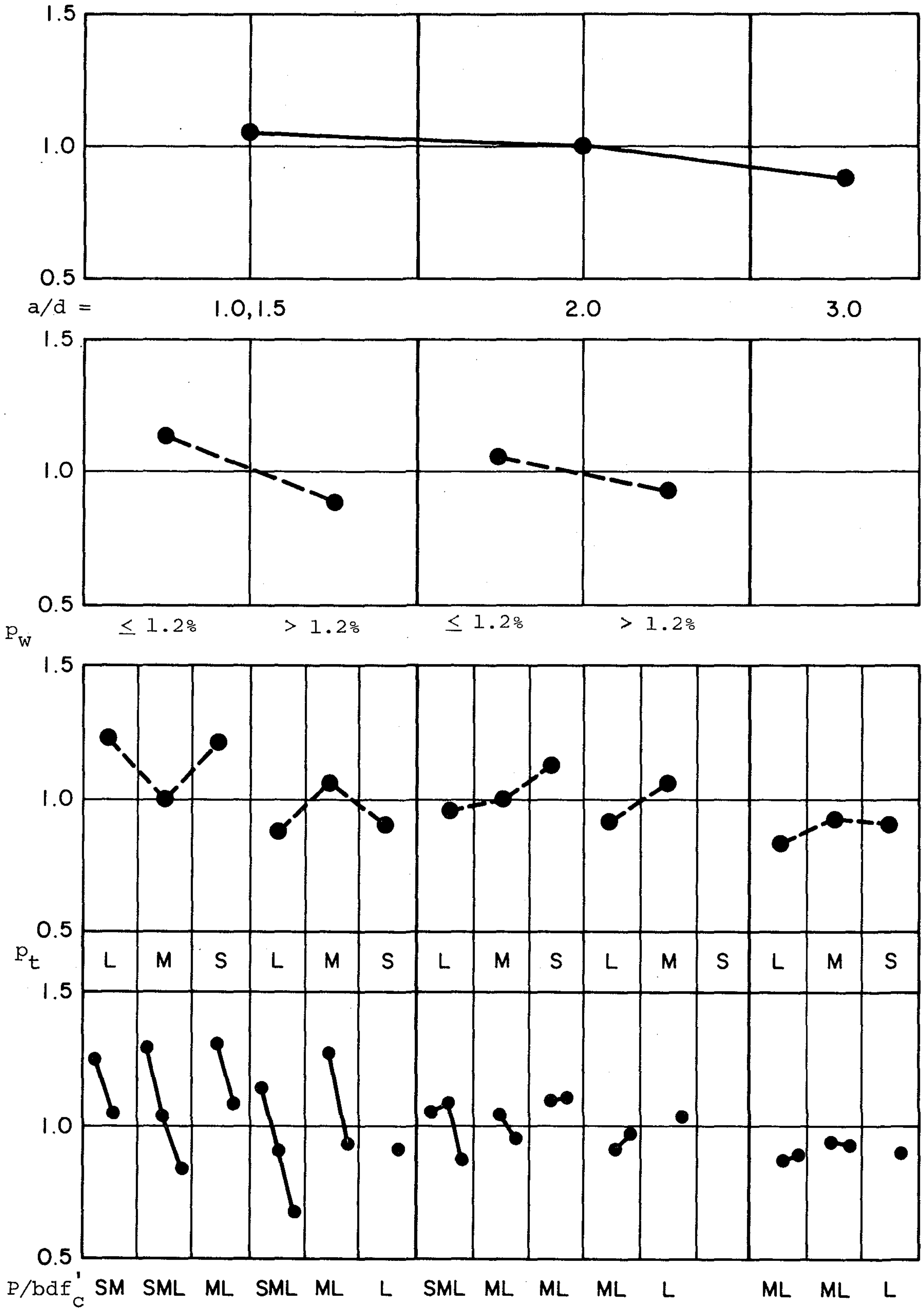


Fig. 3.3a Average Value in each Parameter Domain of Q_{yt}/Q_{yc}

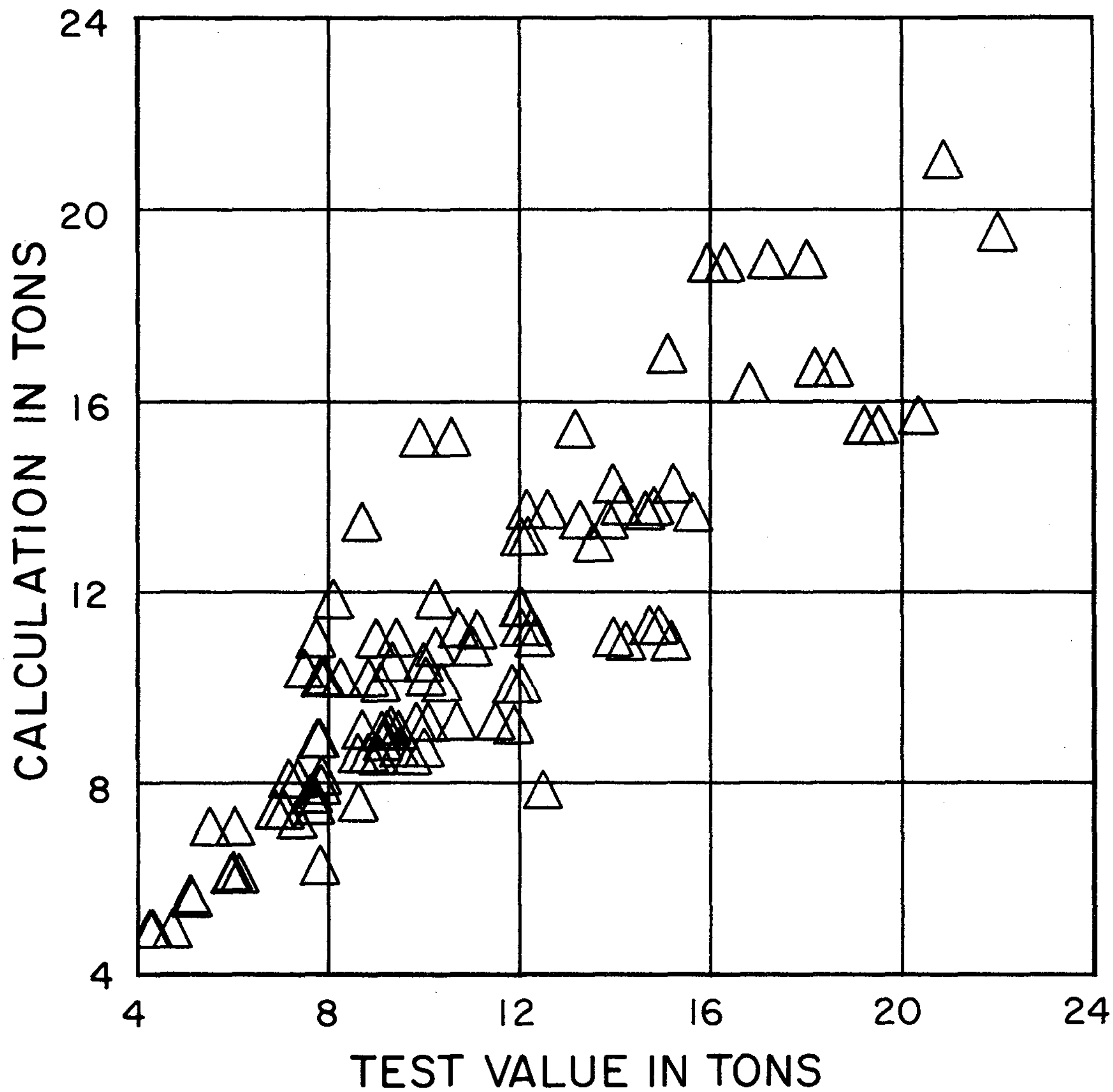


Fig. 3.3b Comparison between Calculated Value and Test Value of Bending Yield Shear Force Q_y

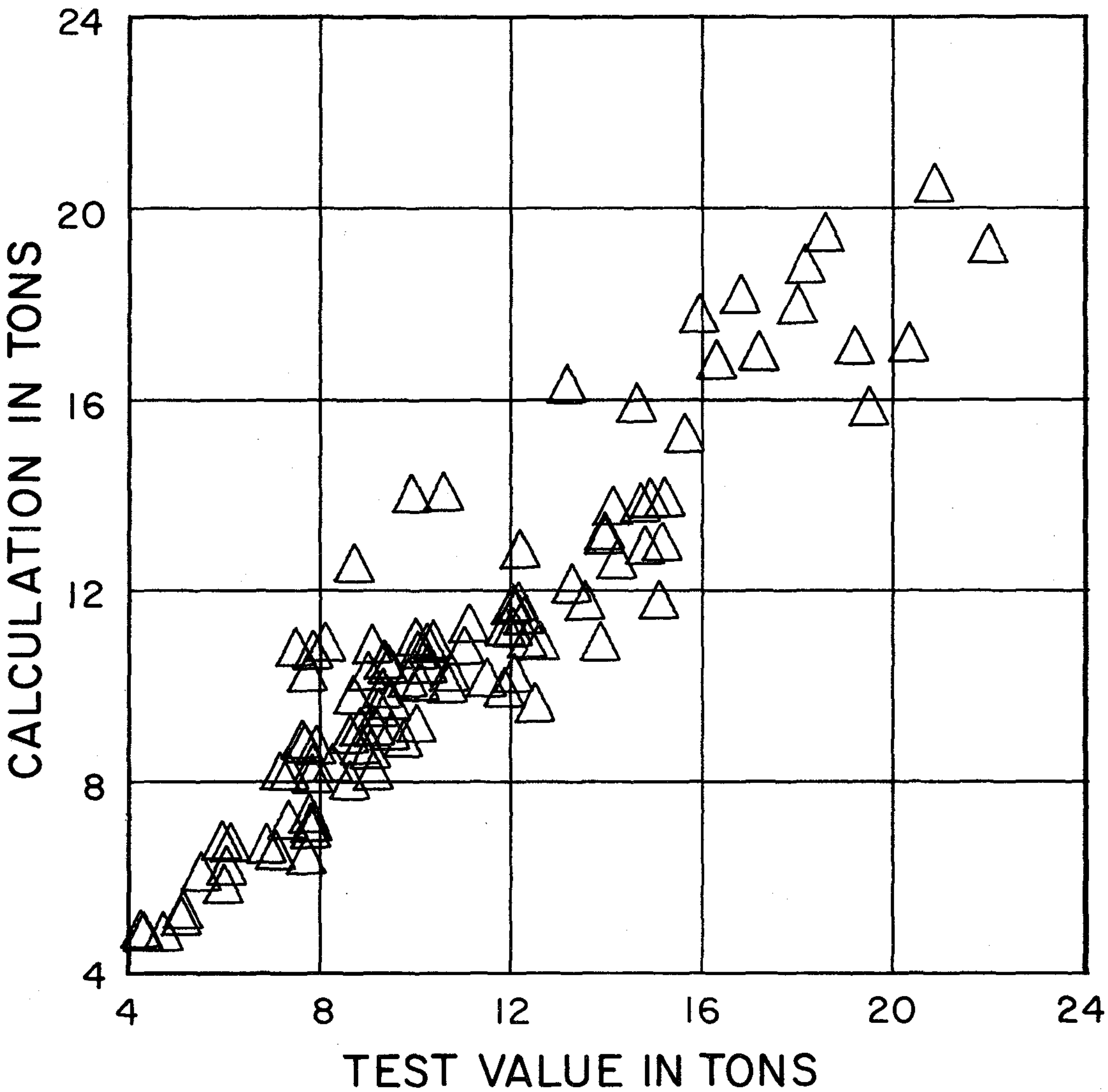


Fig. 3.3c Comparison between Calculated Value and Test Value of Bending Yield Shear Force αQ_y

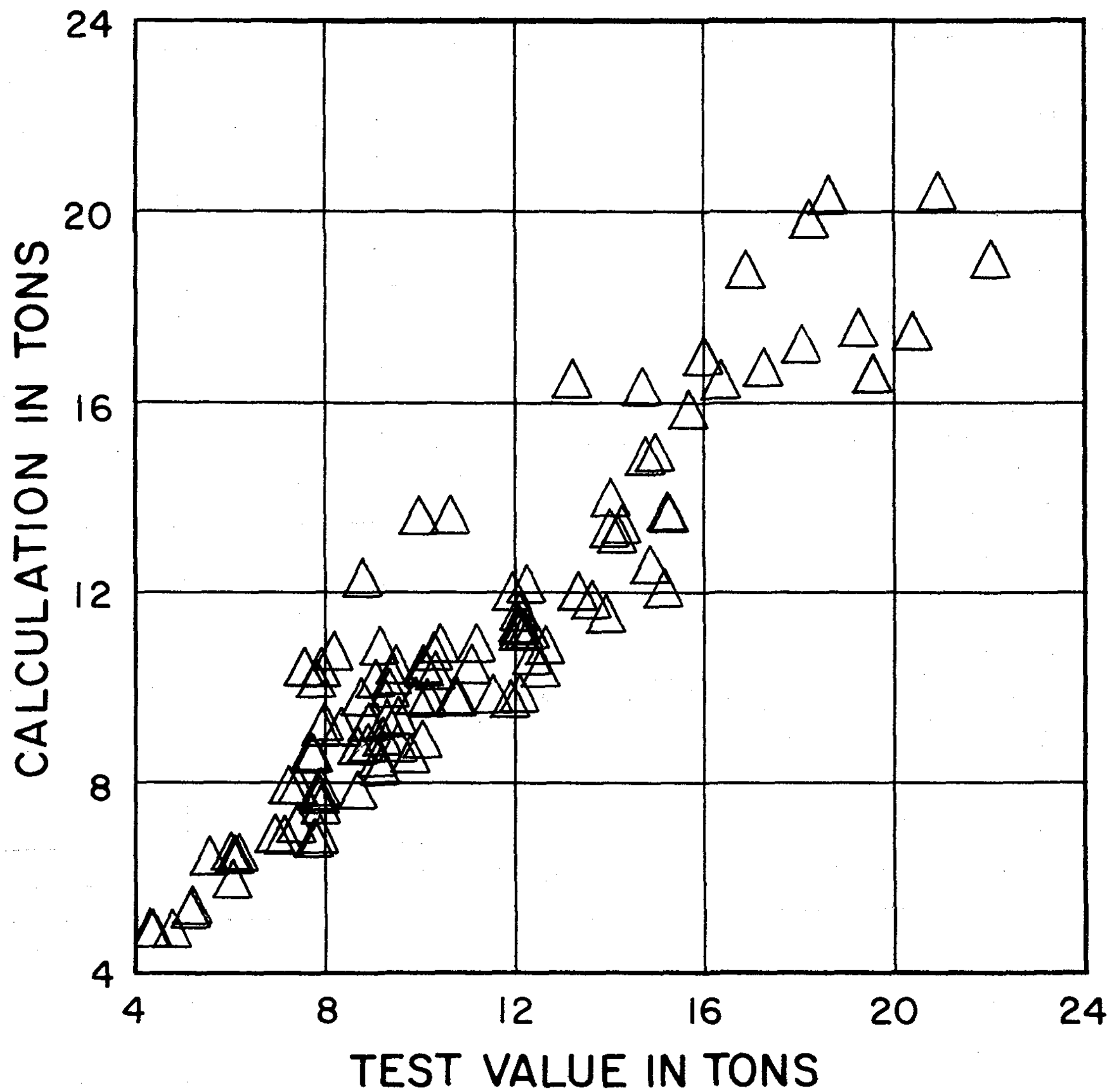


Fig. 3.3d Comparison between Calculated Value and Test Value of Bending Yield Shear Force D7 • Q_y

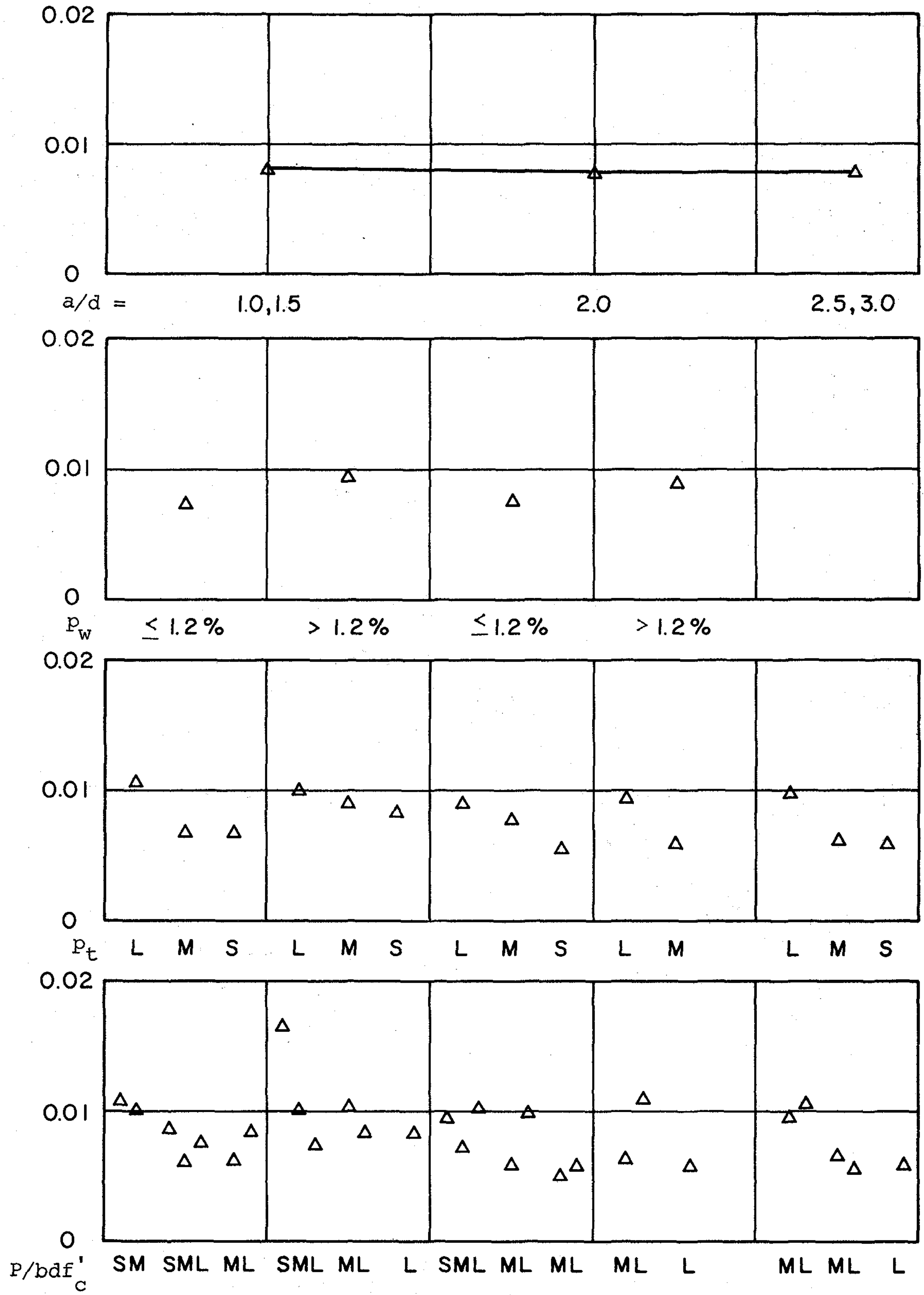


Fig. 3.4a Average Value of D6 in each Parameter Domain

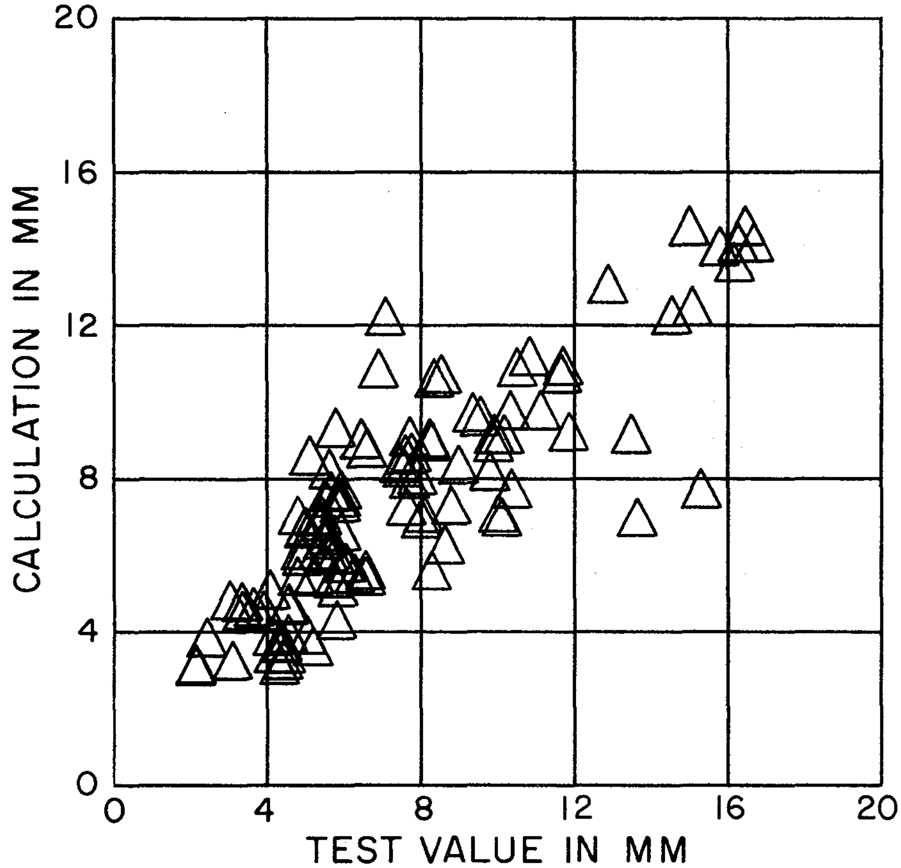


Fig. 3.4b Comparison between Calculated Value and Test Value of Yield Deflection D6

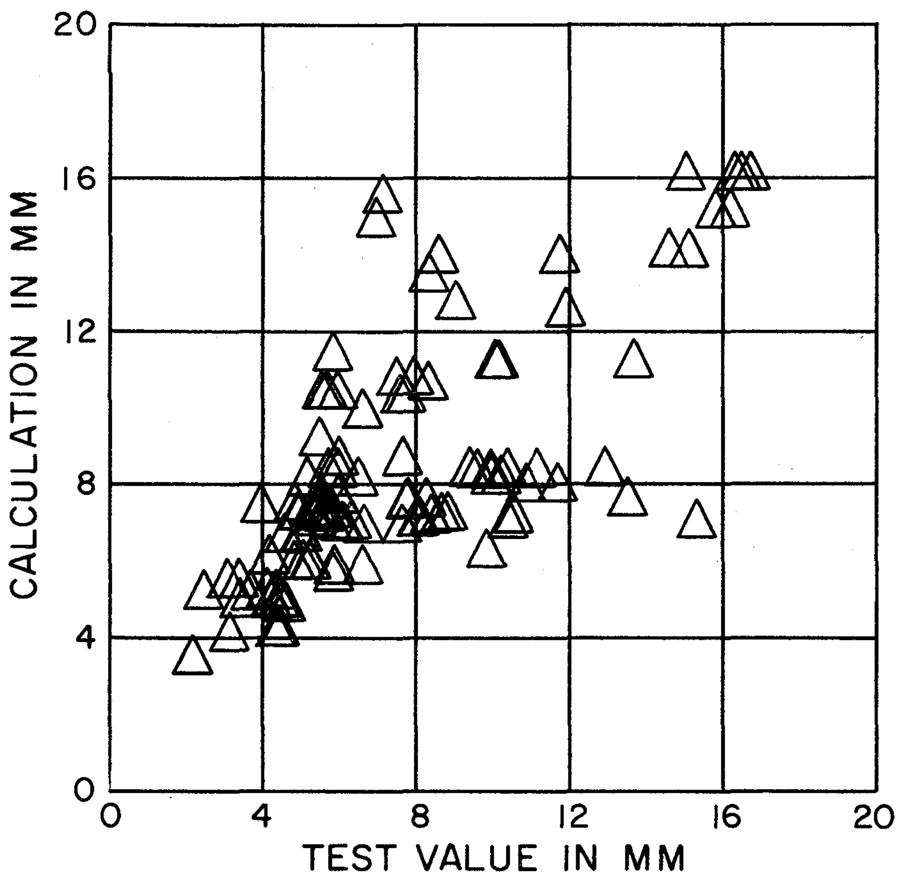


Fig. 3.4c Comparison between Sugano's Calculated Value and Test Value of Yield Deflection

Y: 21 to 29 ; Test Data/(27 / 26)

X: Shear Span Ratio (a/d)

Y: Same as above

X: Shear Reinforcement Ratio (p_w)

Y: Same as above

X: Longitudinal Reinforcement Ratio (p_t)

S: $p_t \leq 0.4\%$

M: $0.4\% < p_t \leq 0.8\%$

L: $0.8\% < p_t$

Y: Same as above

X: Axial Force/Concrete Strength;

S: $-0.11 < P/bdf'_c \leq 0.02$

M: $0 < P/bdf'_c < 0.15$

L: $0.15 < P/bdf'_c < 0.40$

△: 1 δ_y amp = 1.0

◇: 2 δ_y amp = 2.0

⬡: 3 δ_y amp = 3.0

▽: 4 δ_y amp = 4.0

Fig. 3.5 Guide for the Data Distribution Diagrams

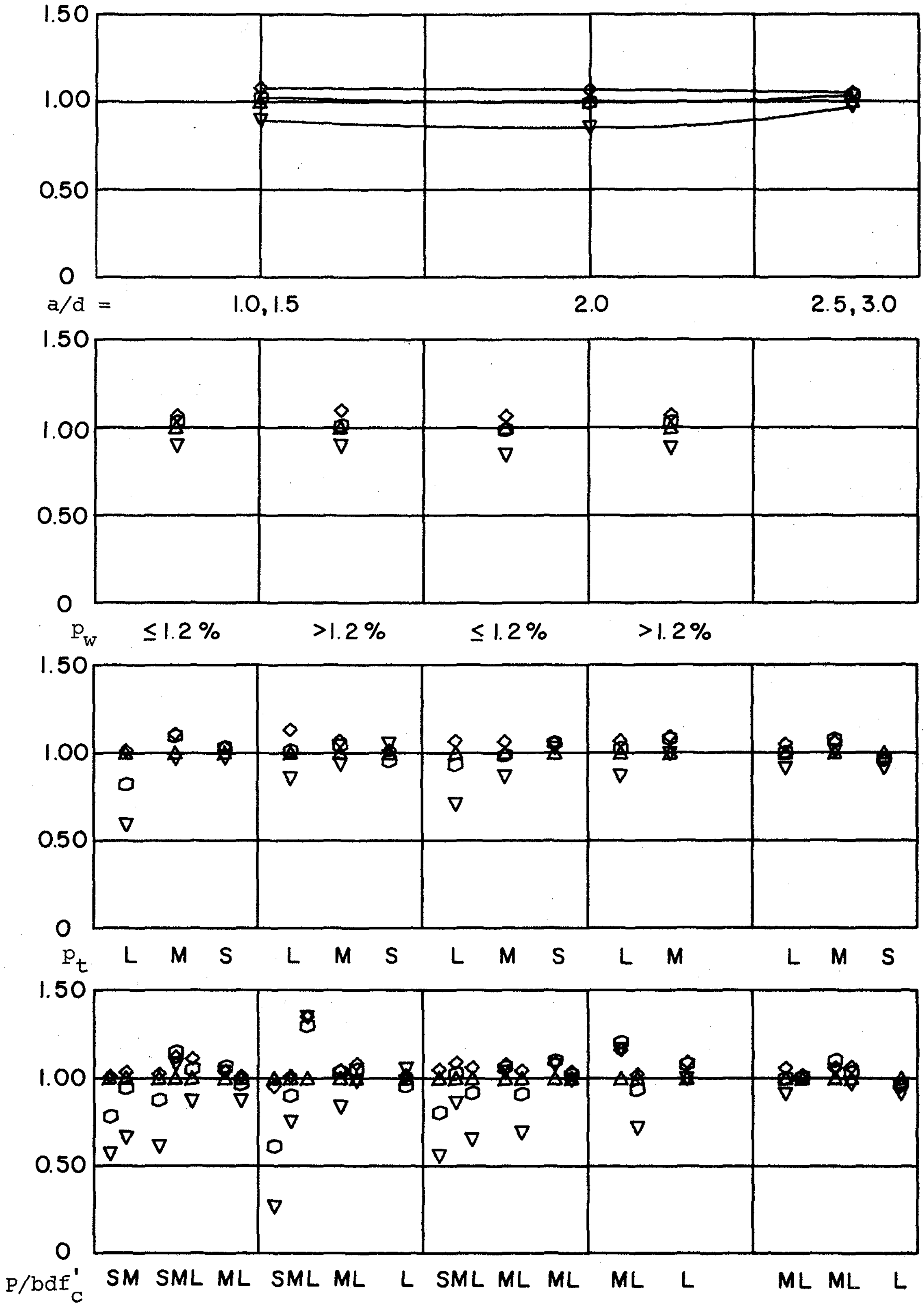


Fig. 3.6a Average Value in each Parameter Domain for D7
(Envelope Curve)

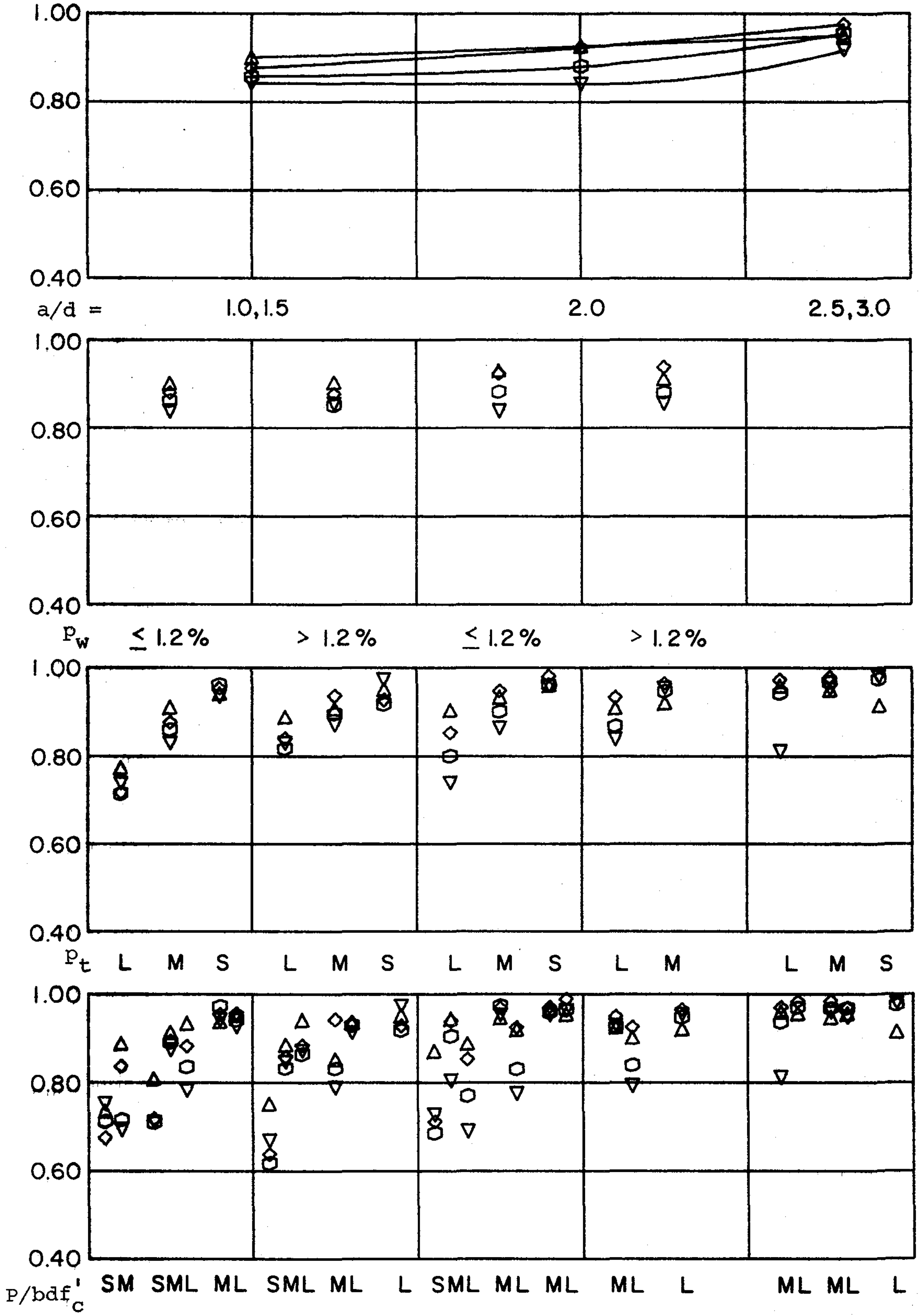


Fig. 3.6b Average Value in each Parameter Domain for D7
(3 cycle/1 cycle)

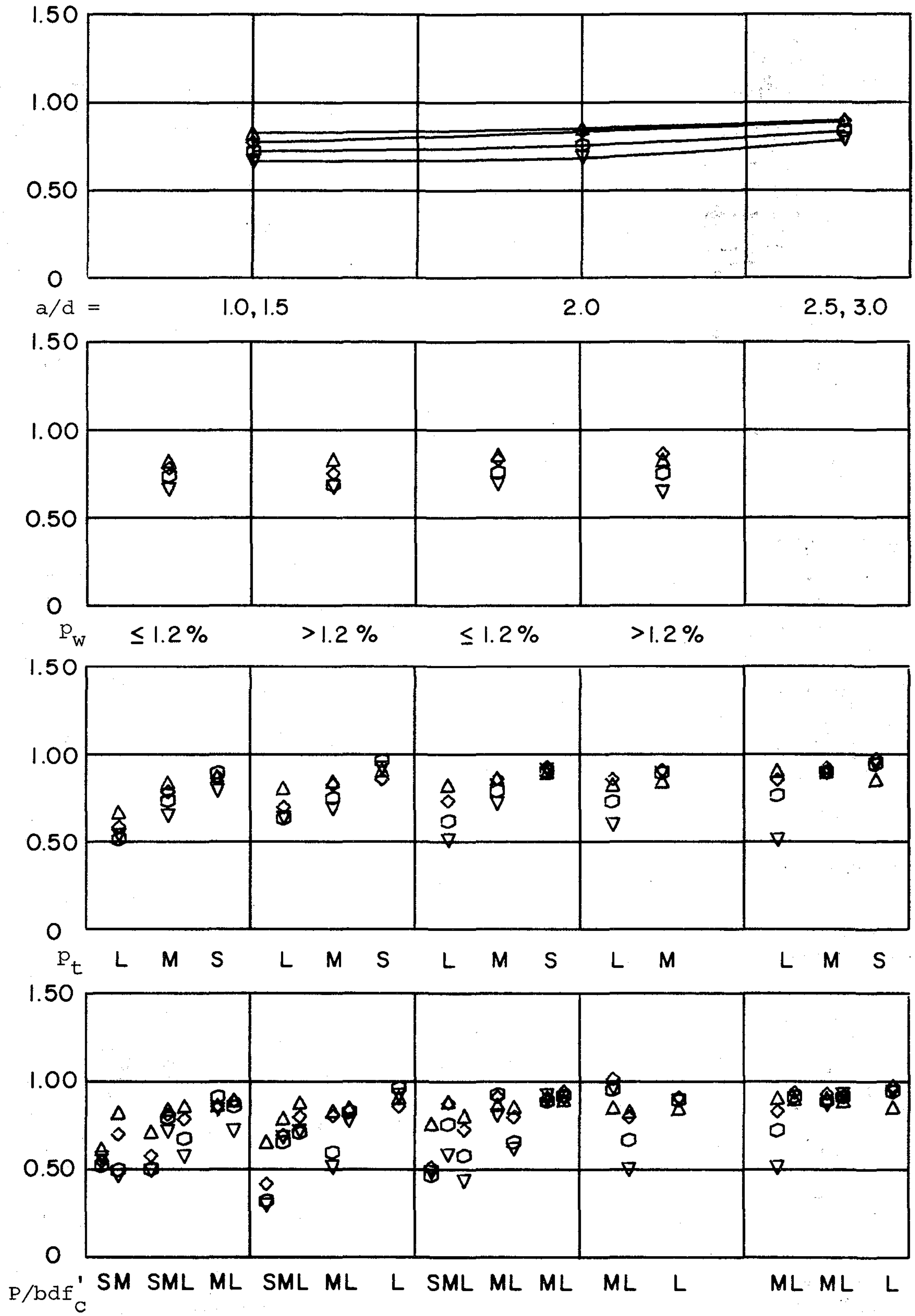


Fig. 3.6c Average Value in each Parameter Domain for D7
(10 cycle/1 cycle)

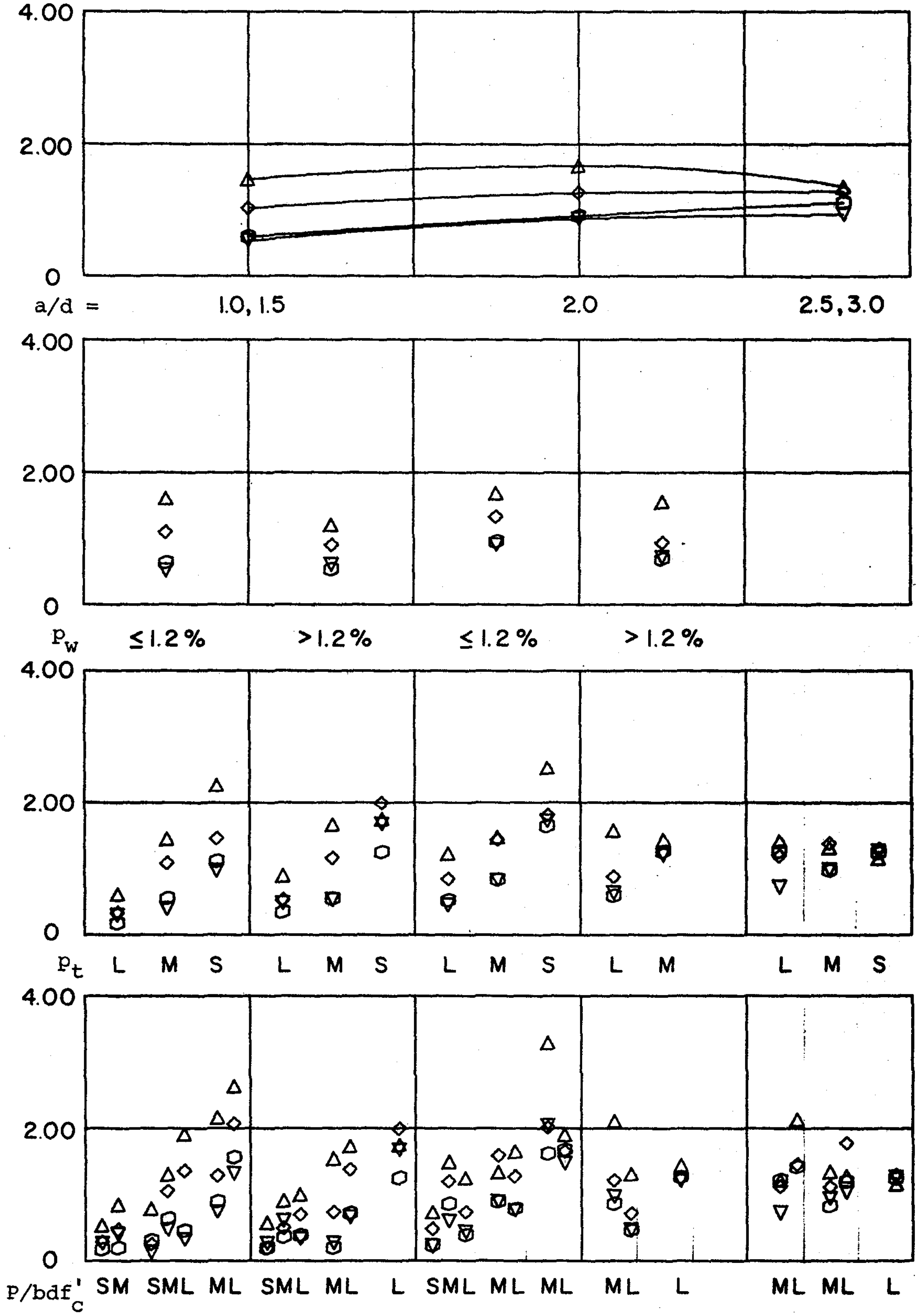


Fig. 3.7a Average Value in each Parameter Domain for Dl (Amplitude)

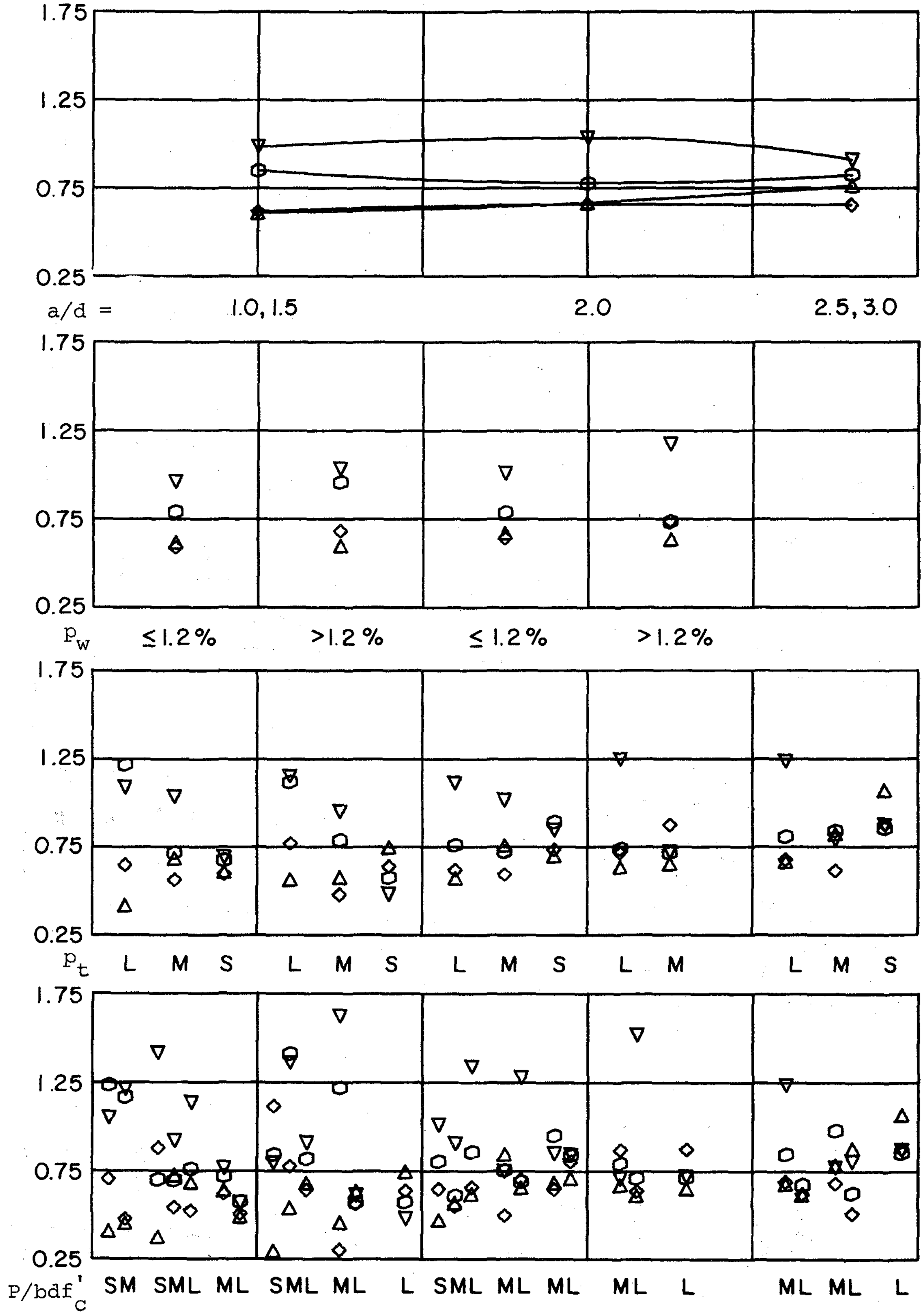


Fig. 3.7b Average Value in each Parameter Domain for D1
(3 cycle/1 cycle)

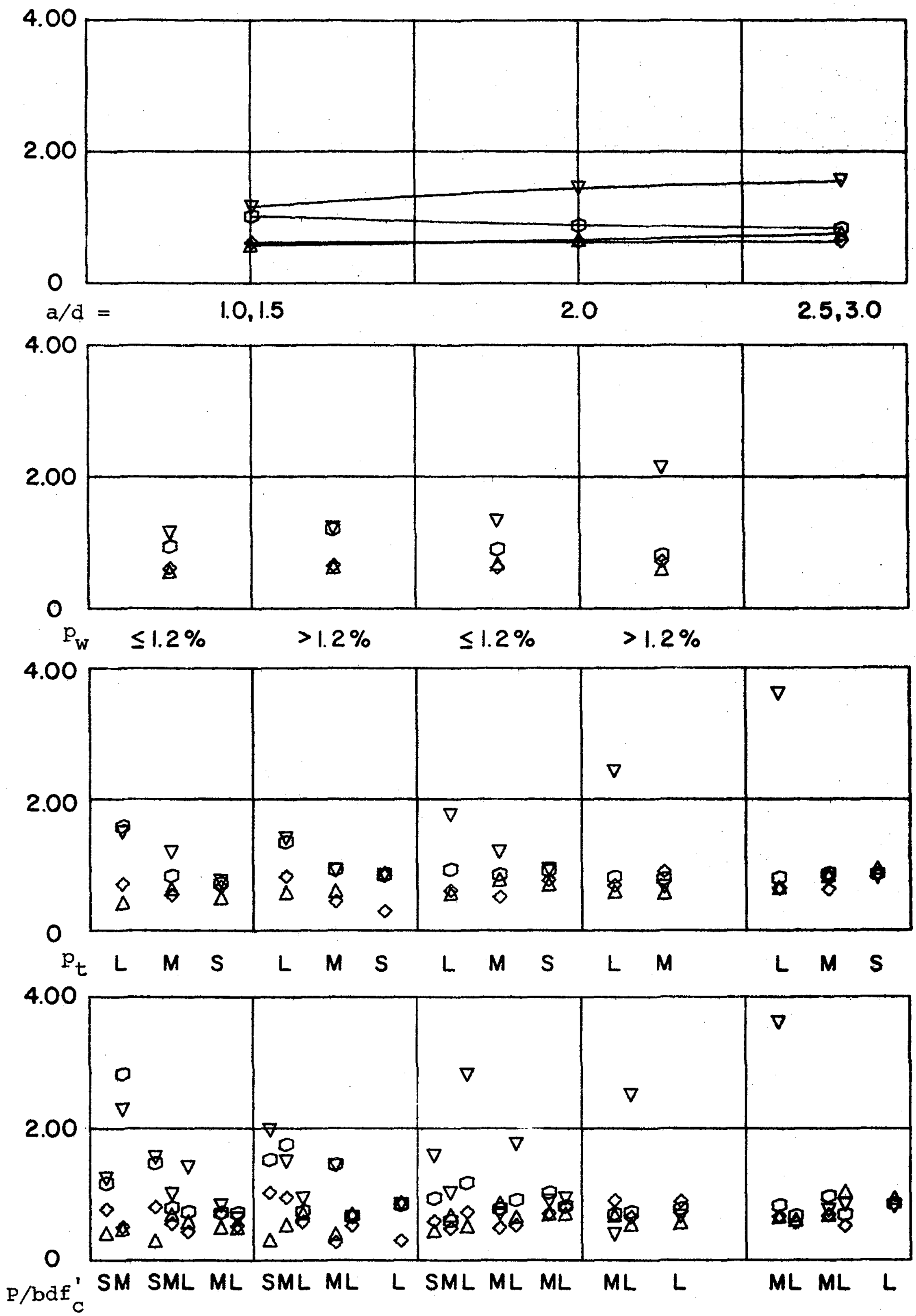


Fig. 3.7c Average Value in each Parameter Domain for D1
(10 cycle/1 cycle)

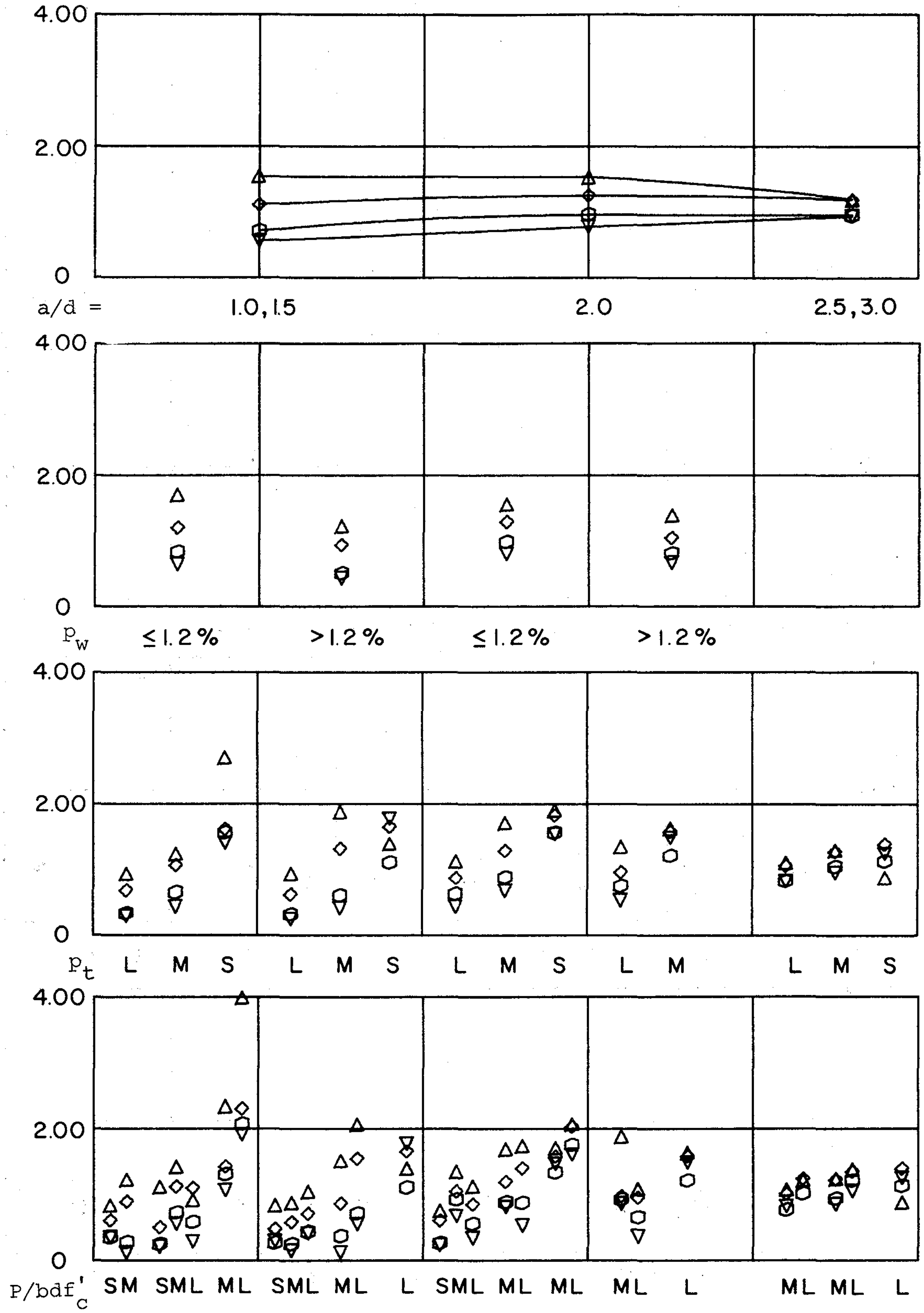


Fig. 3.8a Average Value in each Parameter Domain for D2 (Amplitude)

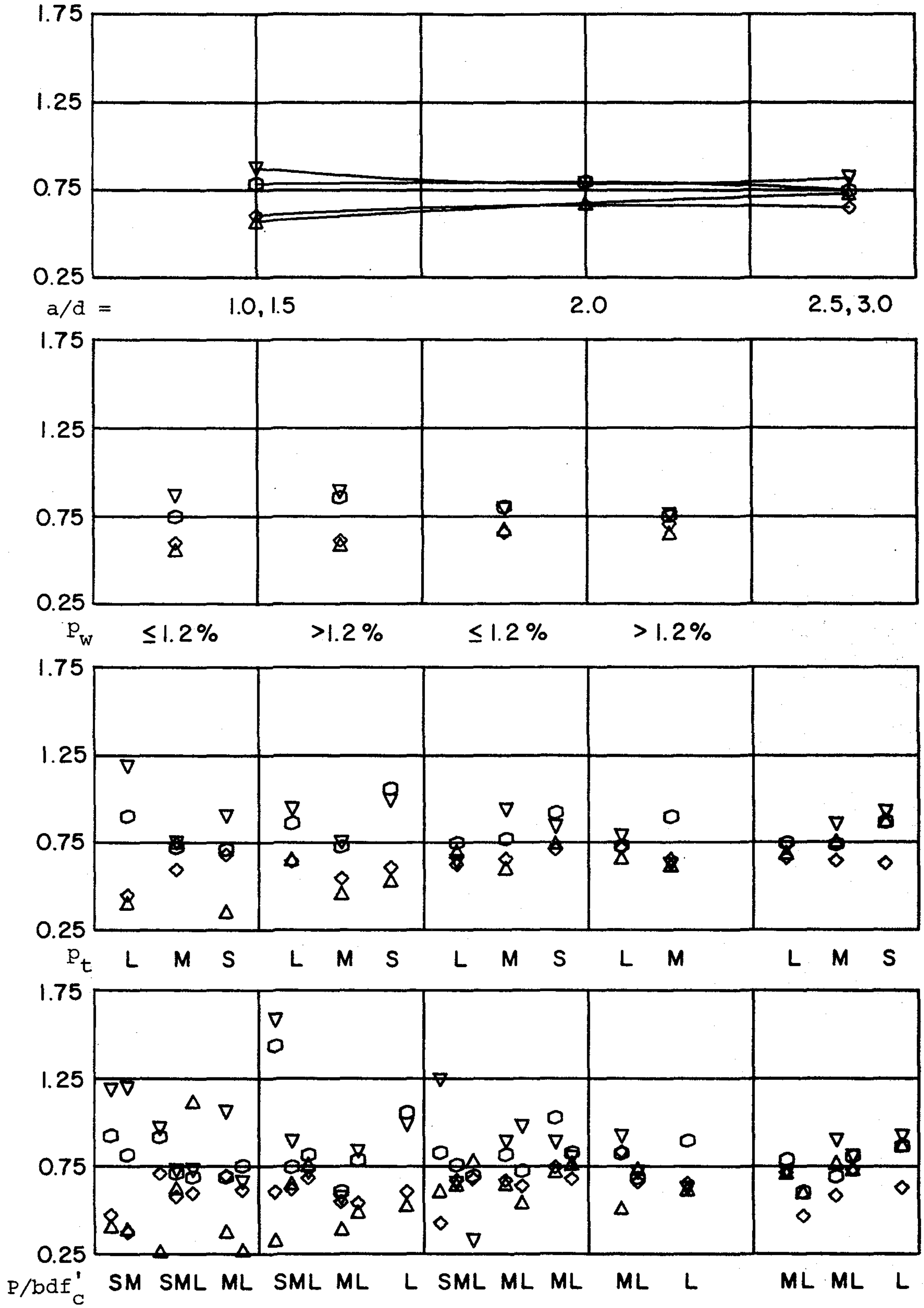


Fig. 3.8b Average Value in each Parameter Domain for D2
(3 cycle/1 cycle)

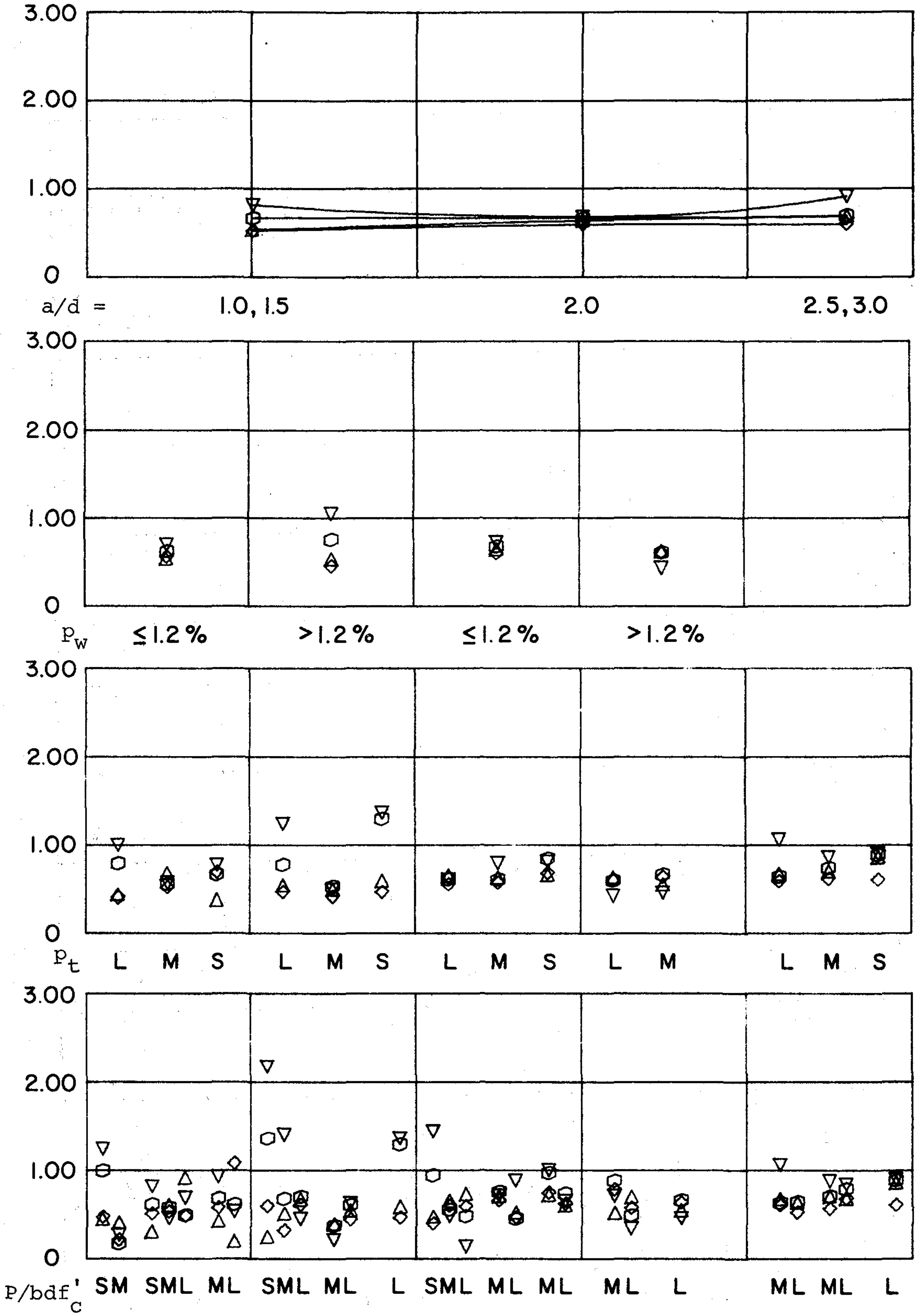


Fig. 3.8c Average Value in each Parameter Domain for D2
(10 cycle/1 cycle)

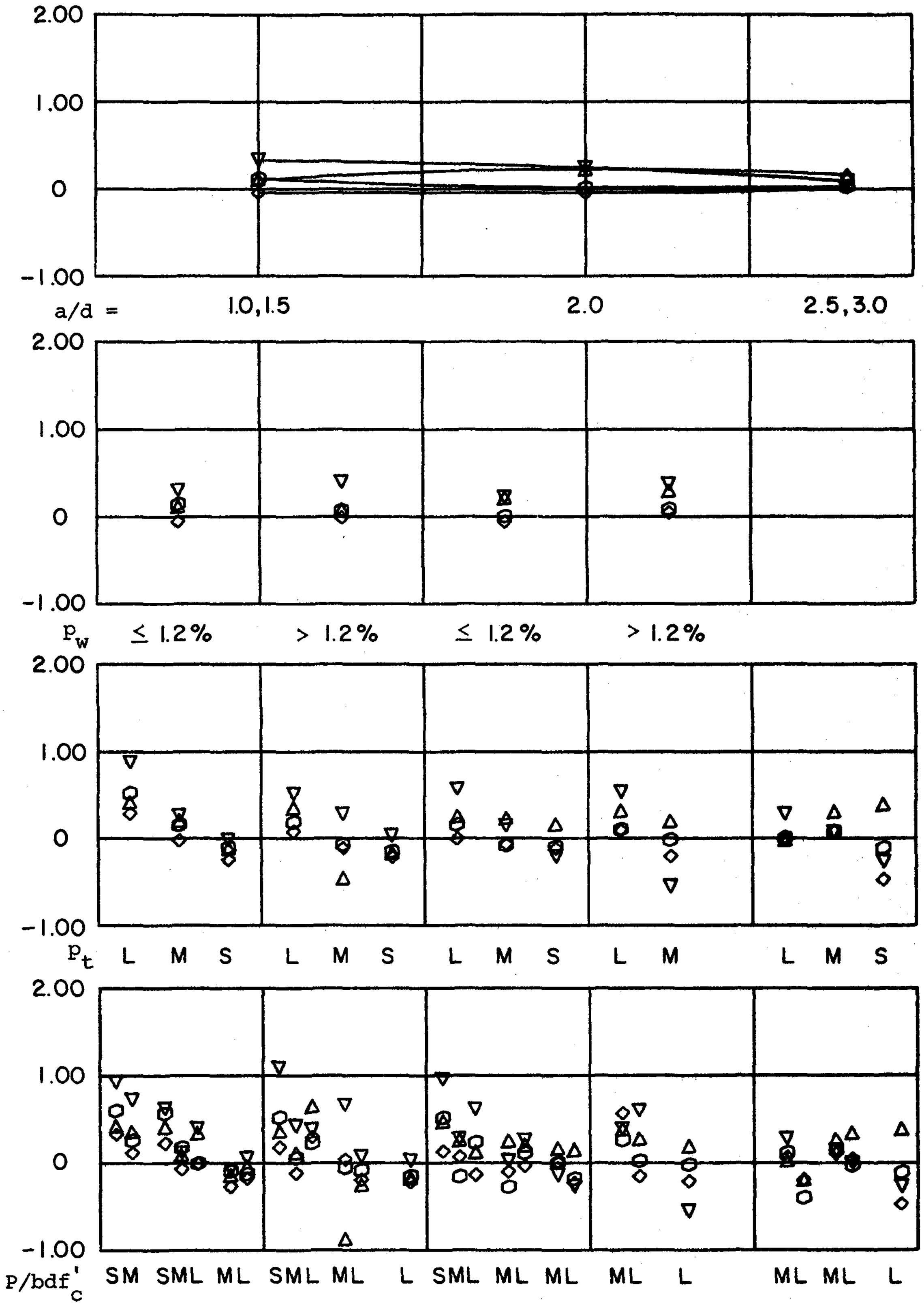


Fig. 3.9a Average Value in each Parameter Domain for D3 (Amplitude)

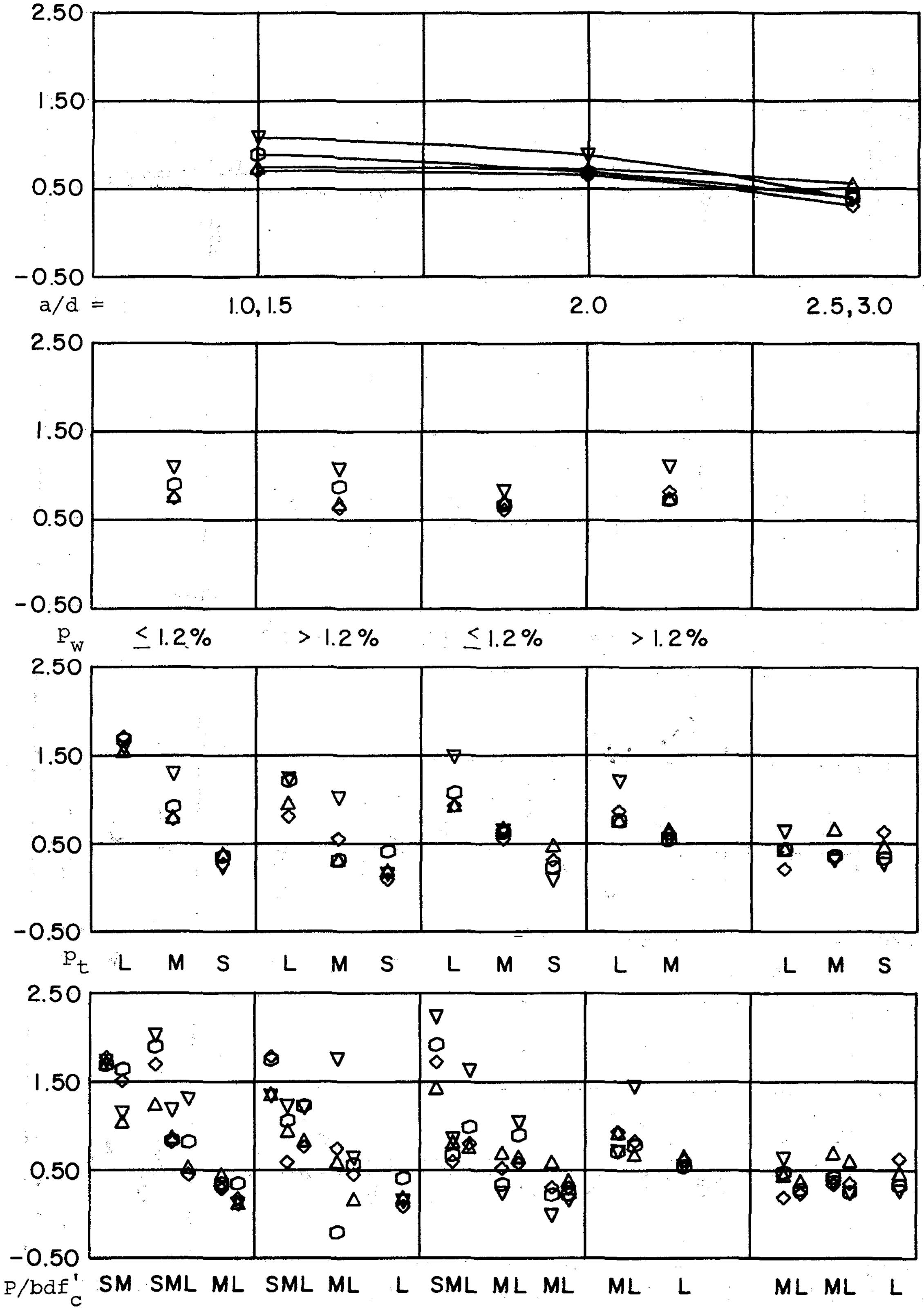


Fig. 3.9b Average Value in each Parameter Domain for D3
(3 cycle/1 cycle)

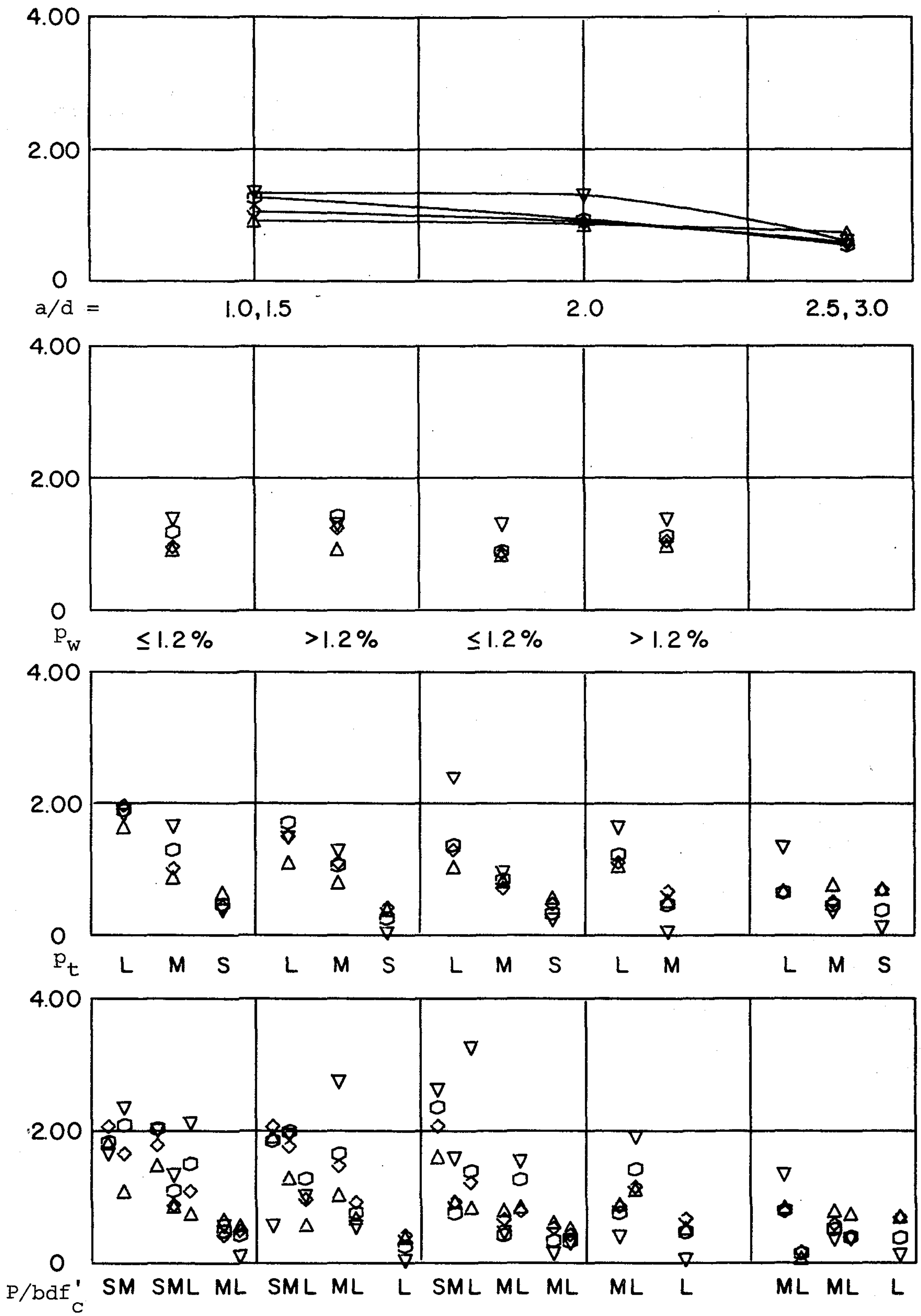


Fig. 3.9c Average Value in each Parameter Domain for D3
(10 cycle/1 cycle)

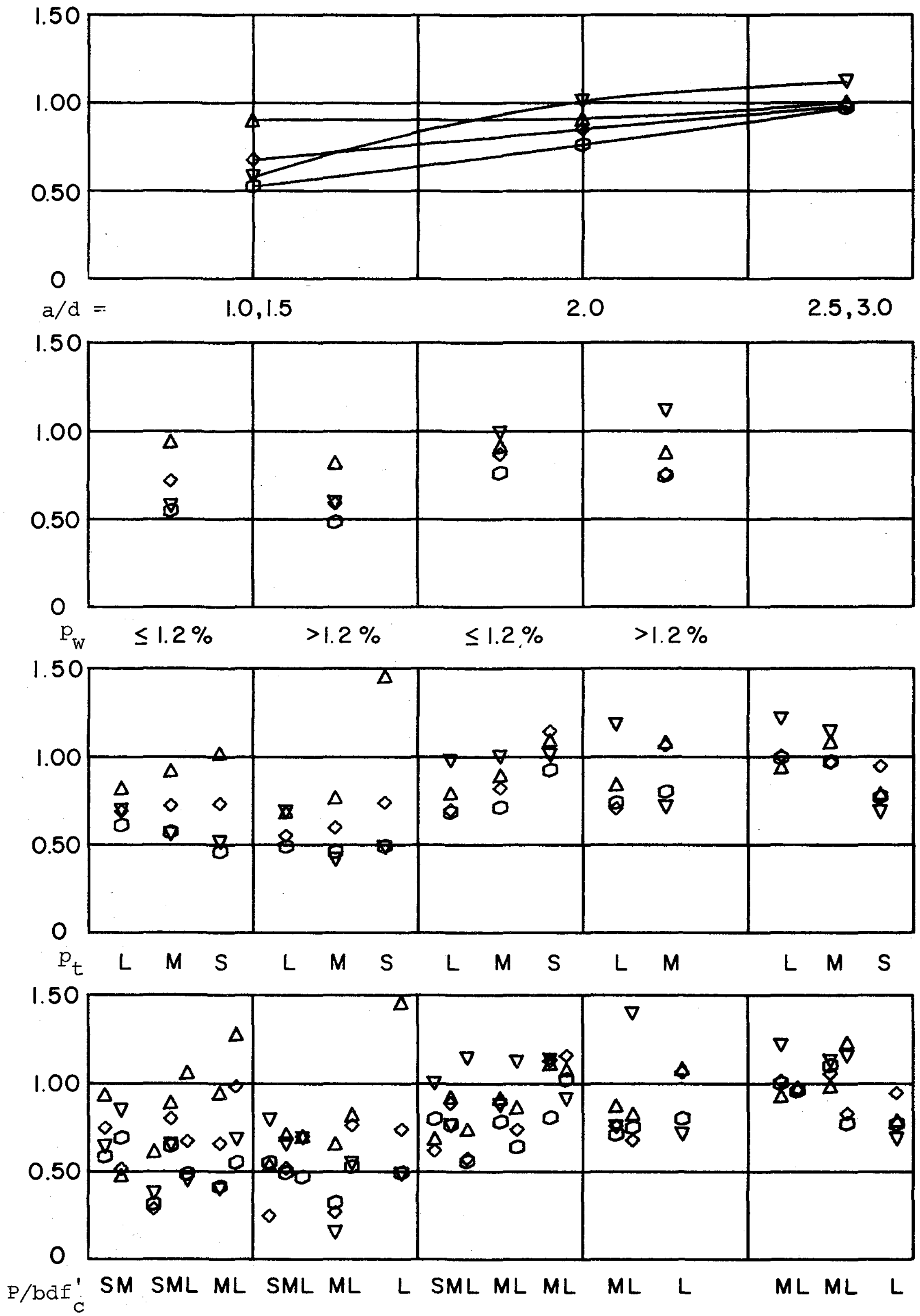


Fig. 3.10a Average Value in each Parameter Domain for D5 (Amplitude)

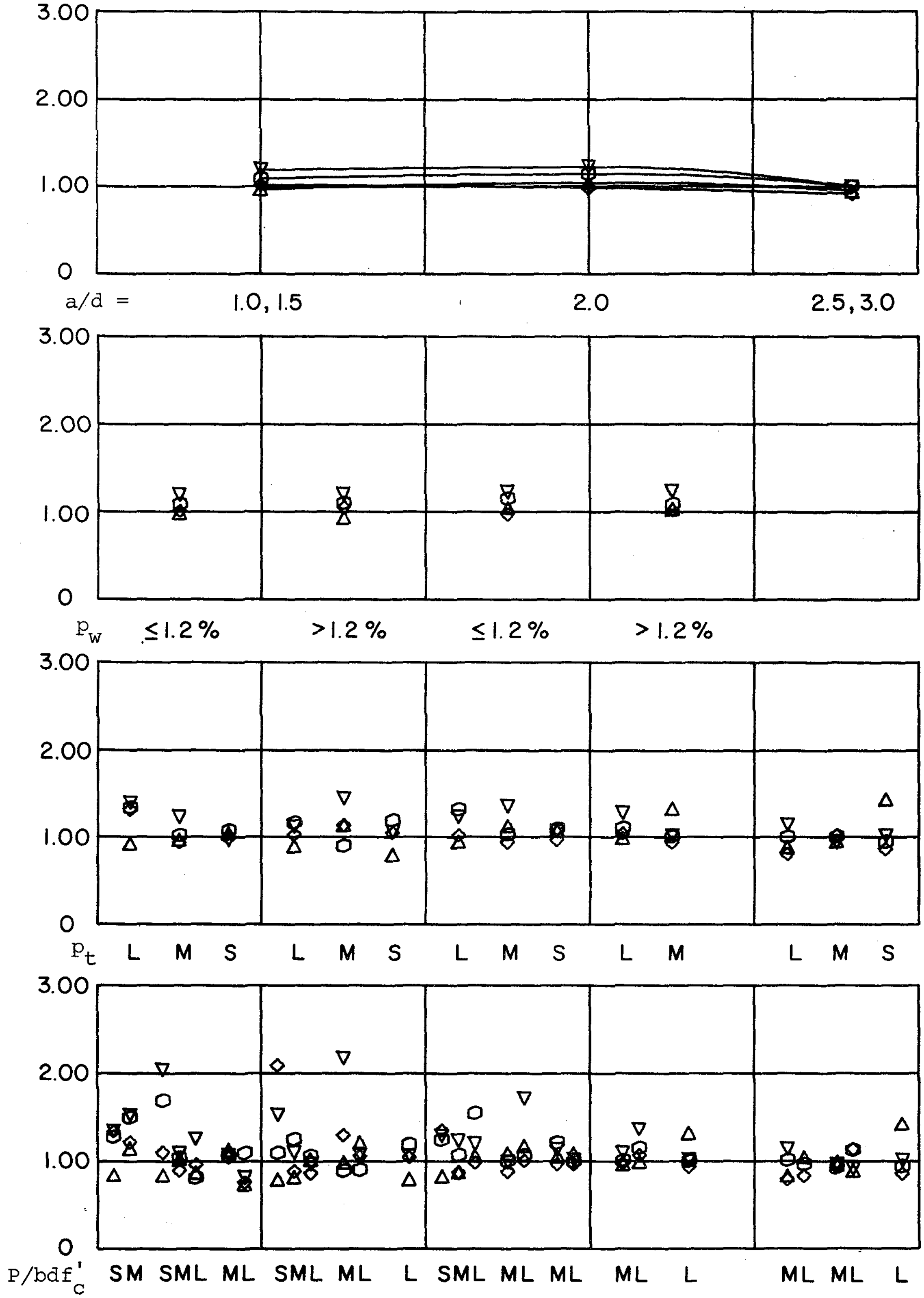


Fig. 3.10b Average Value in each Parameter Domain for D5 (3 cycle/1 cycle)

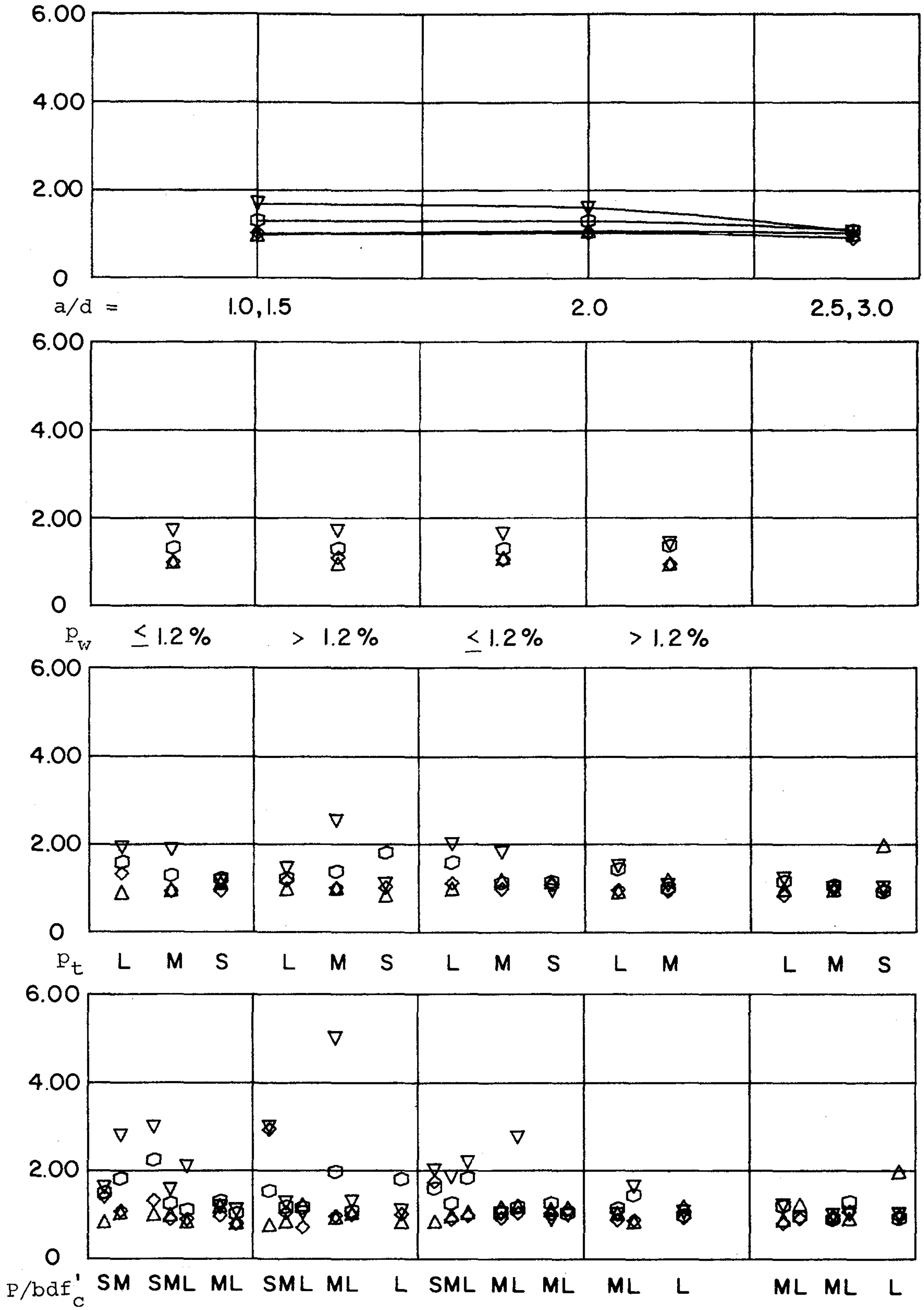


Fig. 3.10c Average Value in each Parameter Domain for D5 (10 cycle/1 cycle)

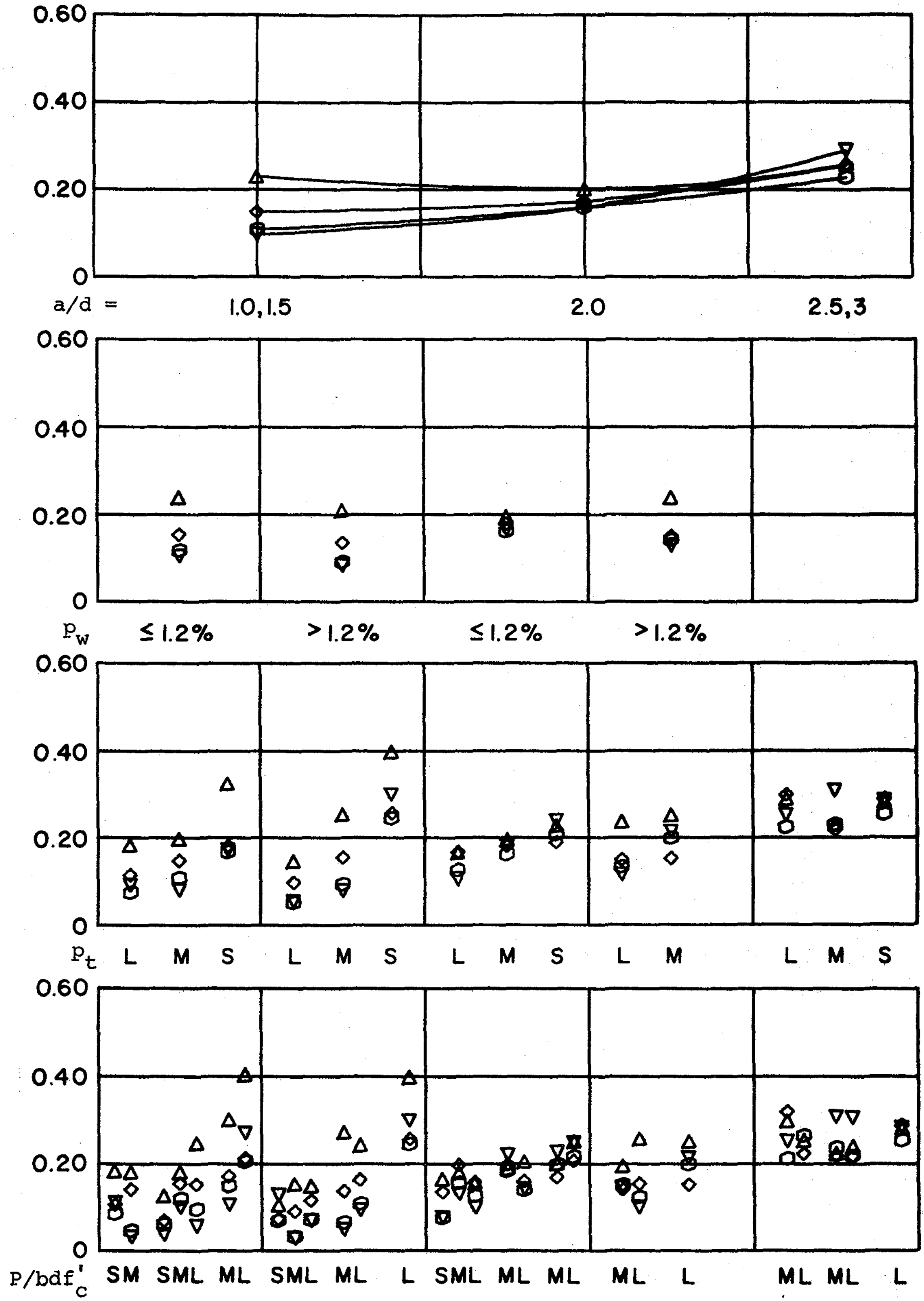


Fig. 3.11a Average Value in each Parameter Domain for D8
(Amplitude)

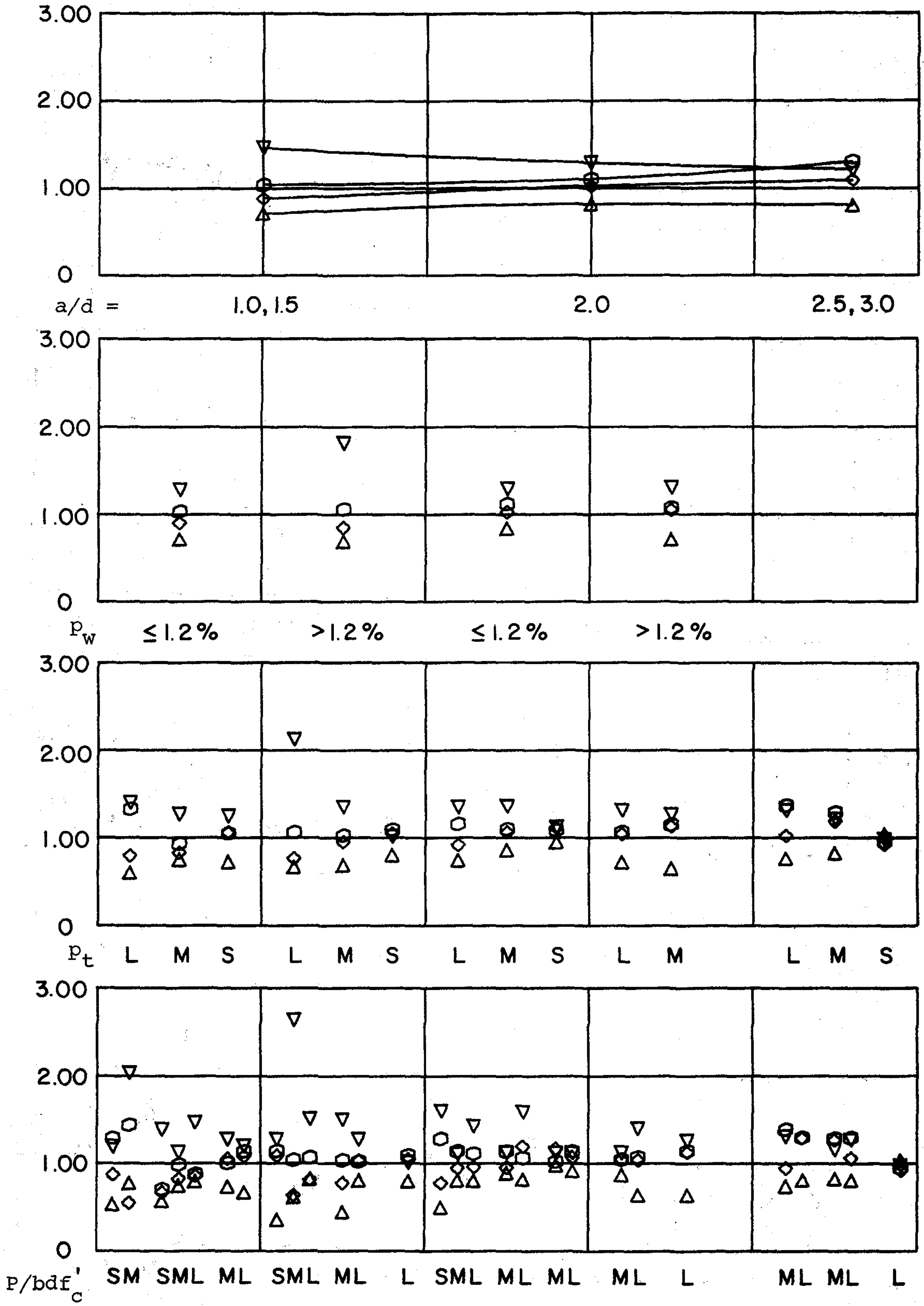


Fig. 3.11b Average Value in each Parameter Domain for D8
(3 cycle/1 cycle)

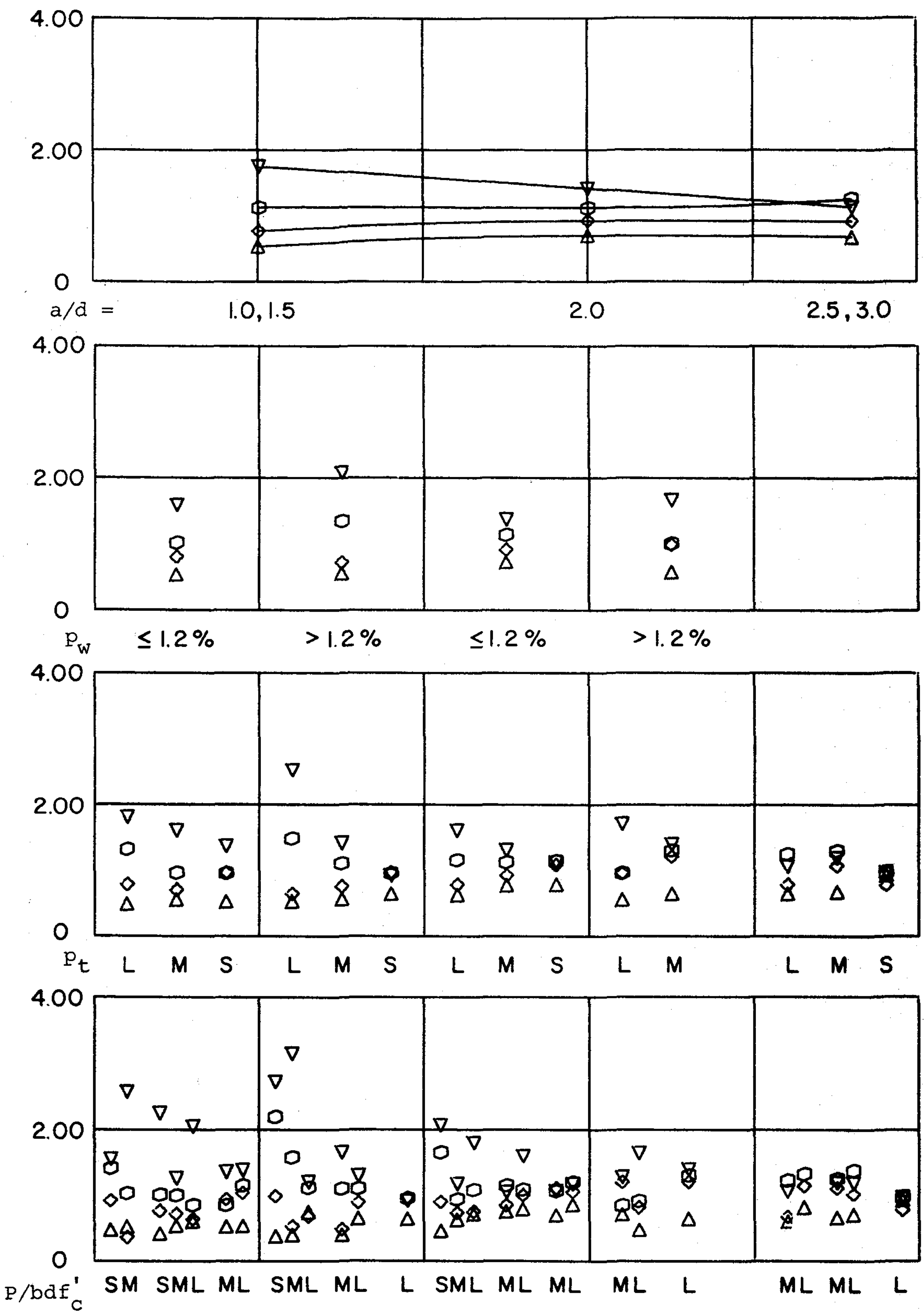


Fig. 3.11c Average Value in each Parameter Domain for D8
(10 cycle/1 cycle)

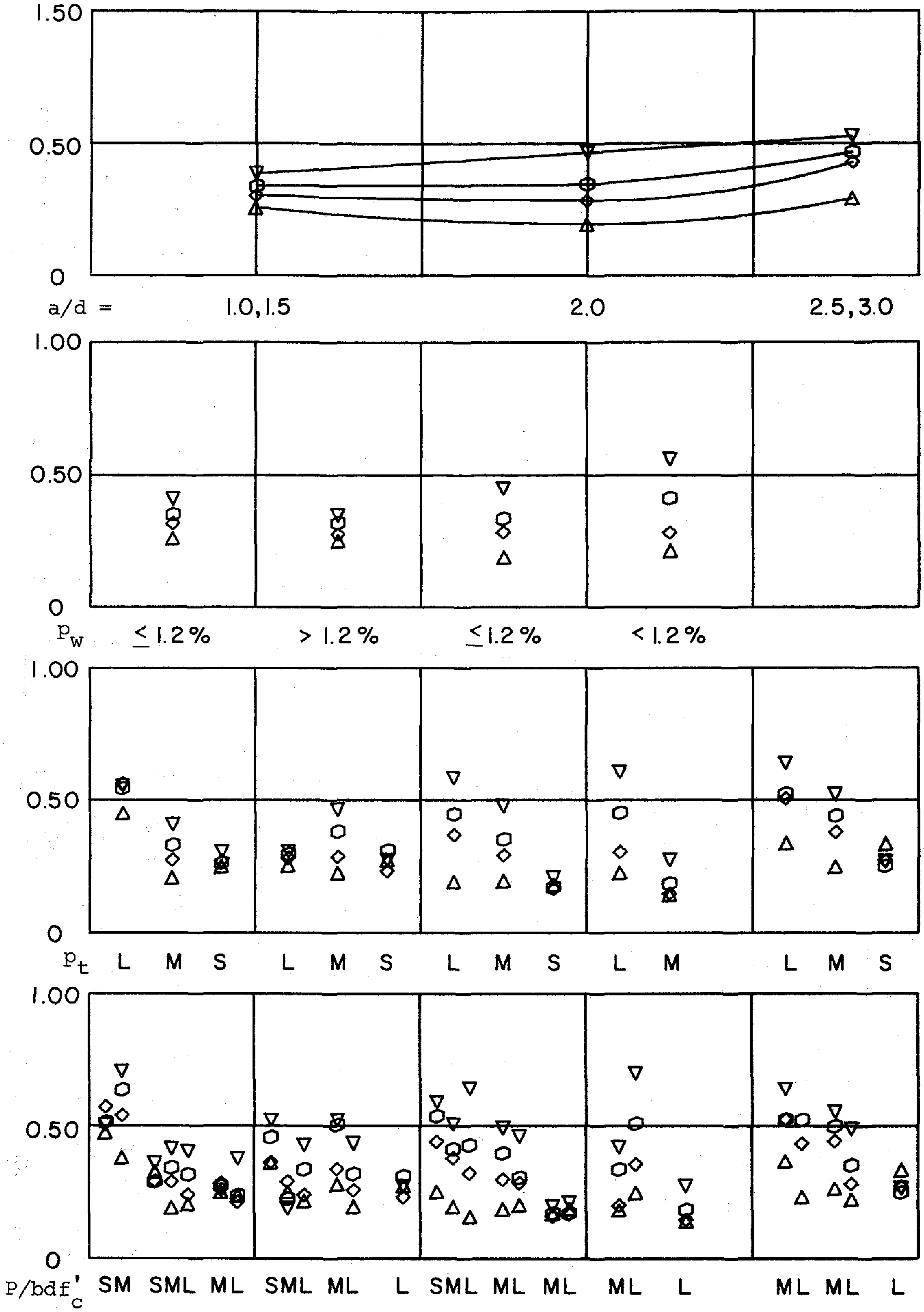


Fig. 3.12a Average Value in each Parameter Domain for D9 (Amplitude)

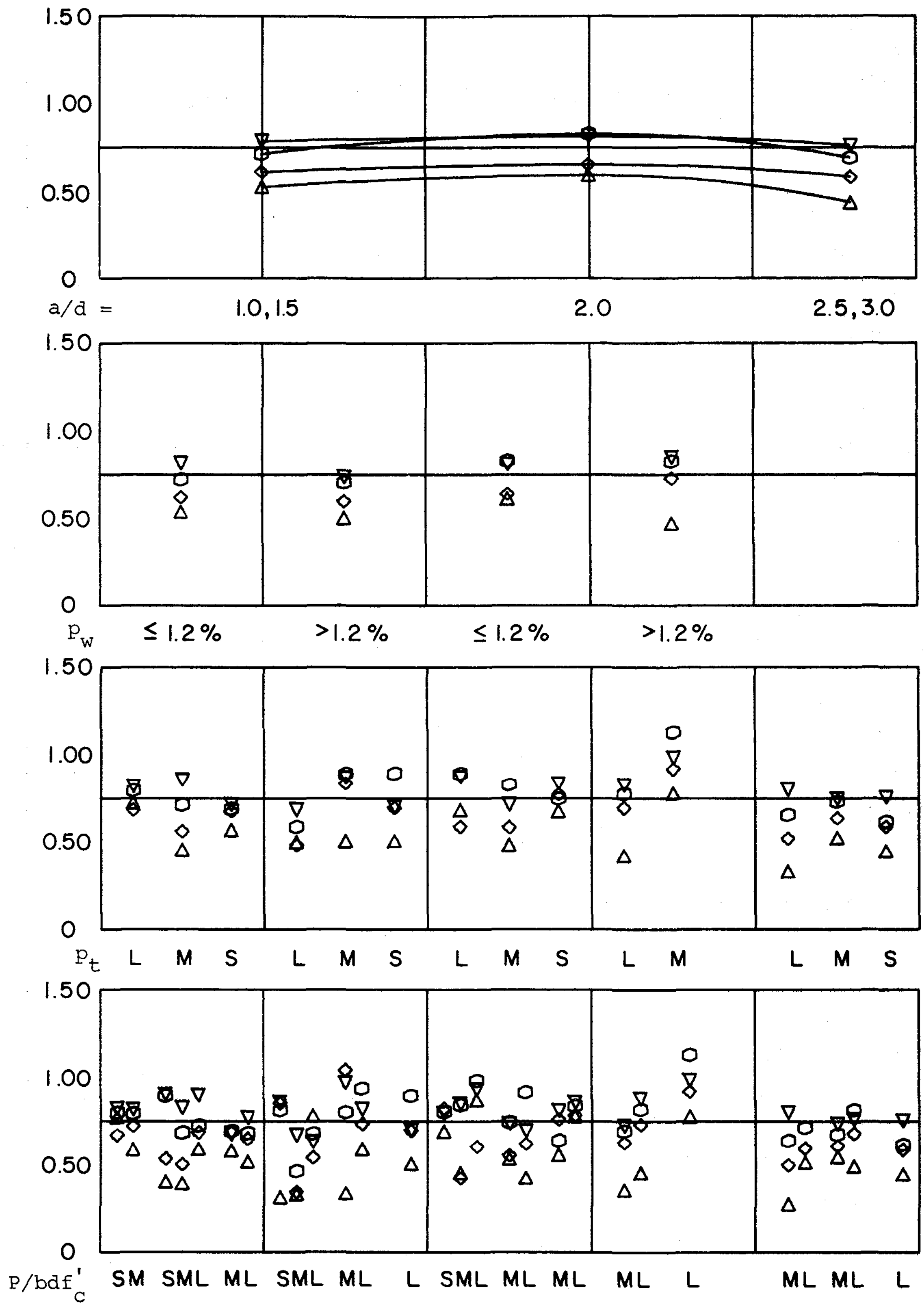


Fig. 3.12b Average Value in each Parameter Domain for D9
(3 cycle/1 cycle)

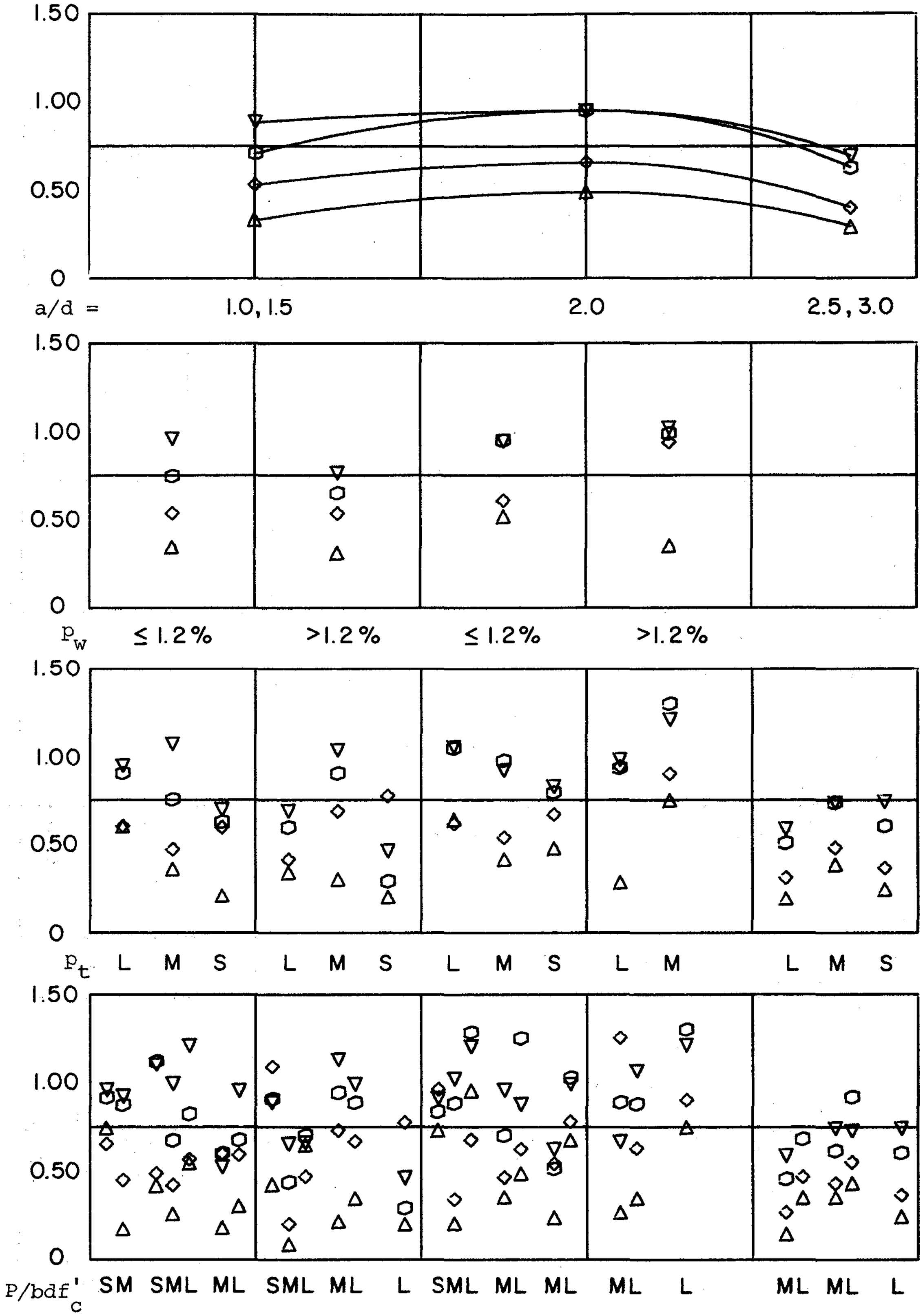


Fig. 3.12c Average Value in each Parameter Domain for D9 (10 cycle/1 cycle)

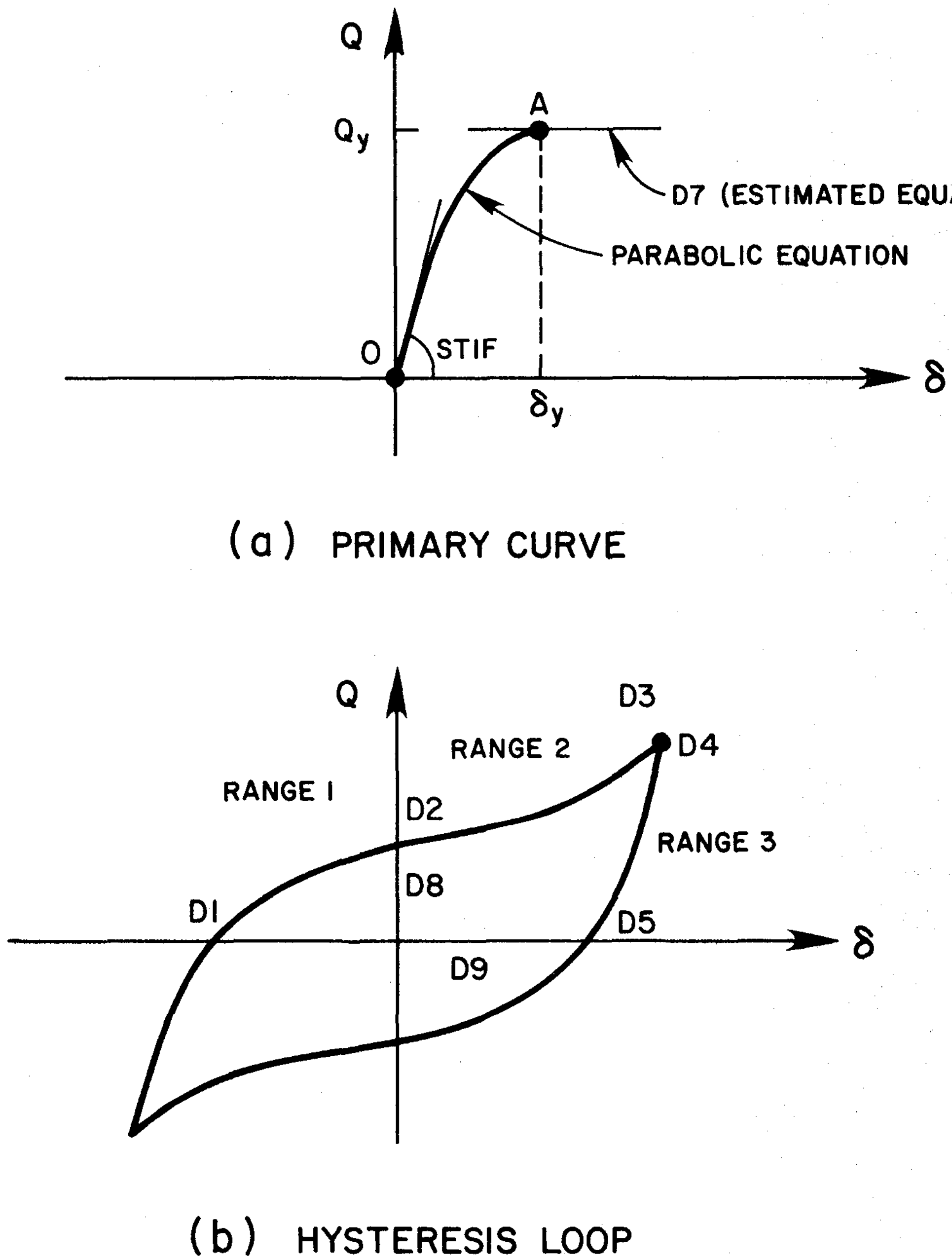
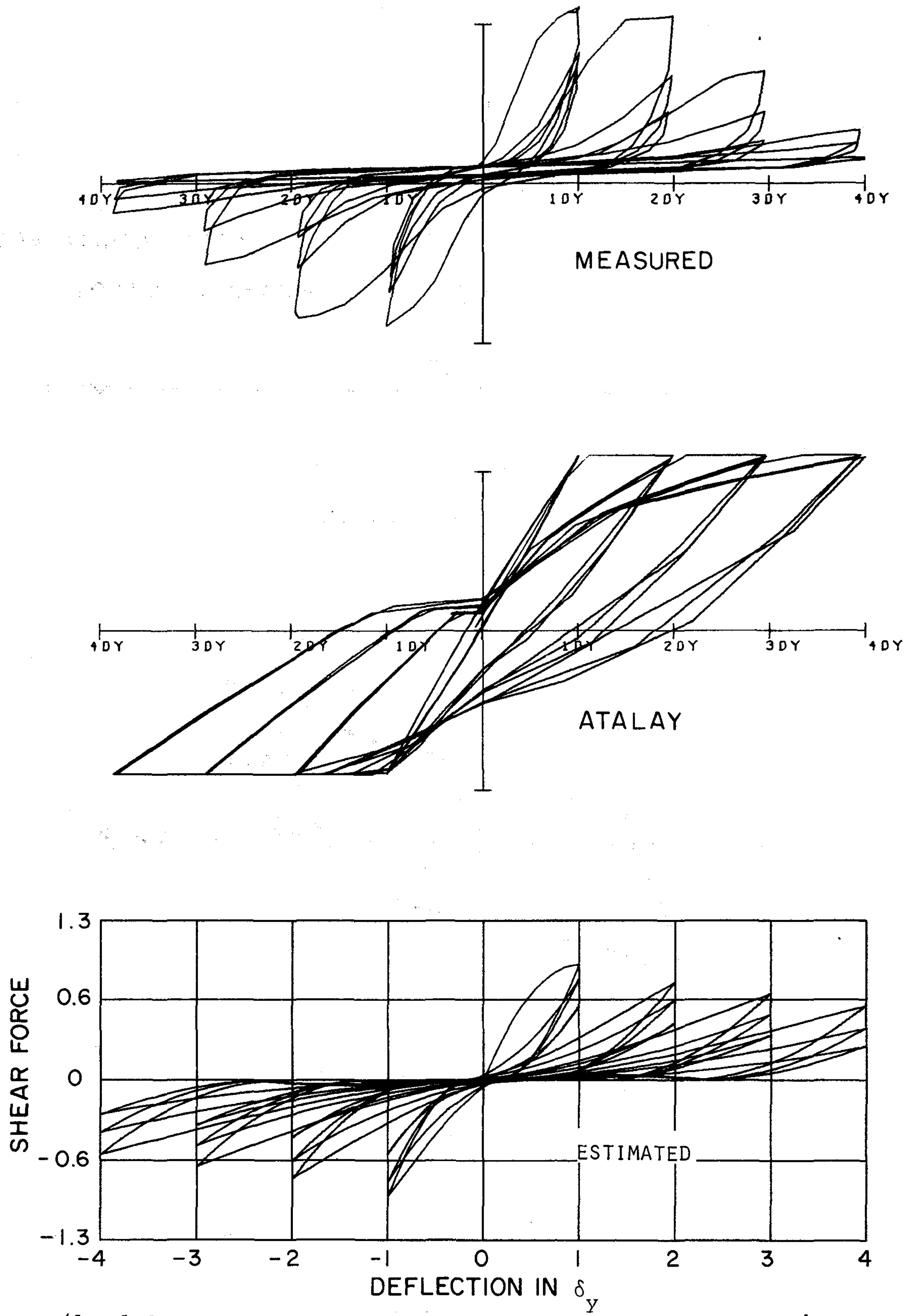
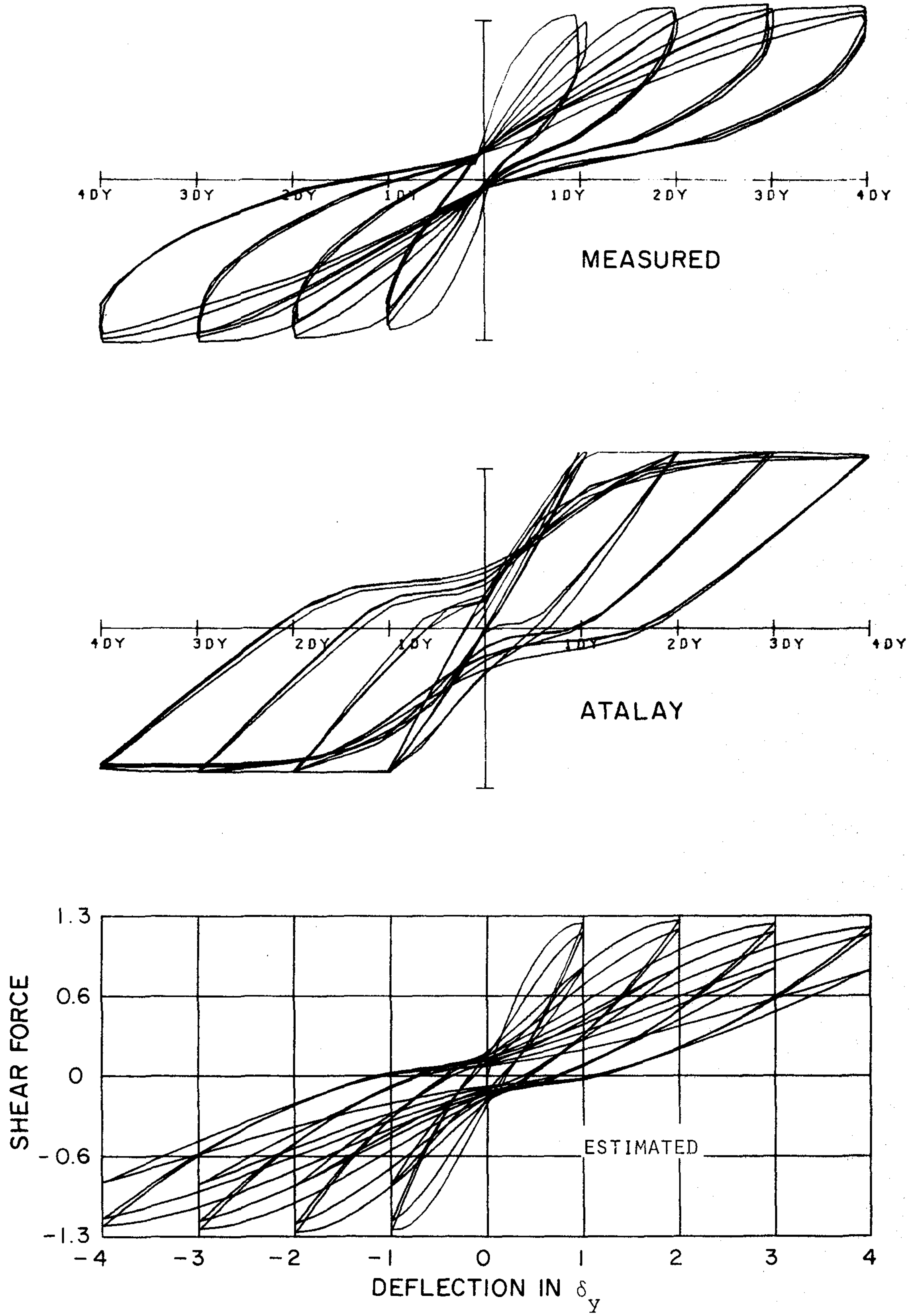


Fig. 4.1 Estimated Hysteresis Loop



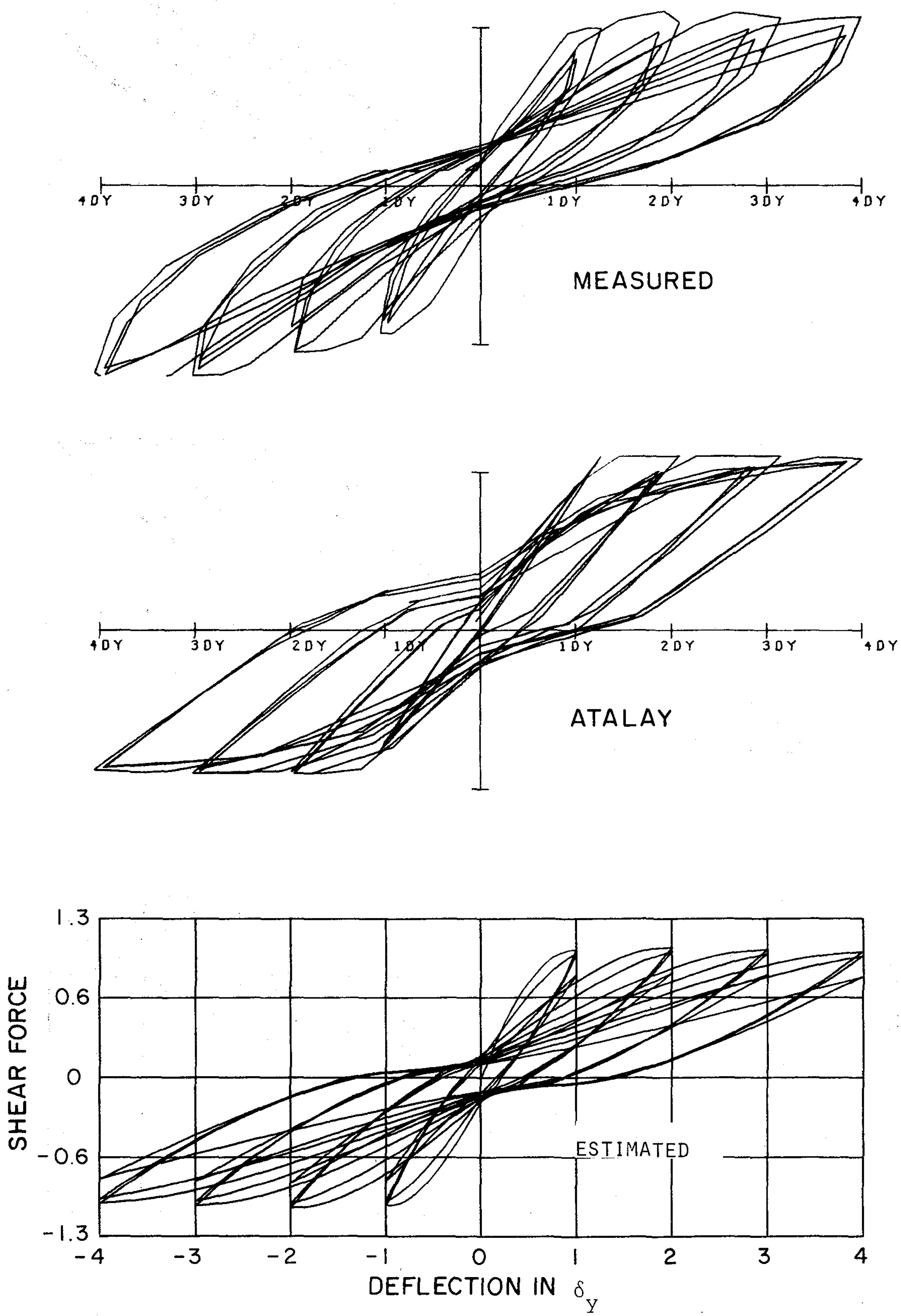
a/d = 1.0 p_t = 0.38 p_w = 0.21 P/bd = 0 f'_c = 190

Fig. 4.2 Comparison of Hysteresis Loops: Case 1



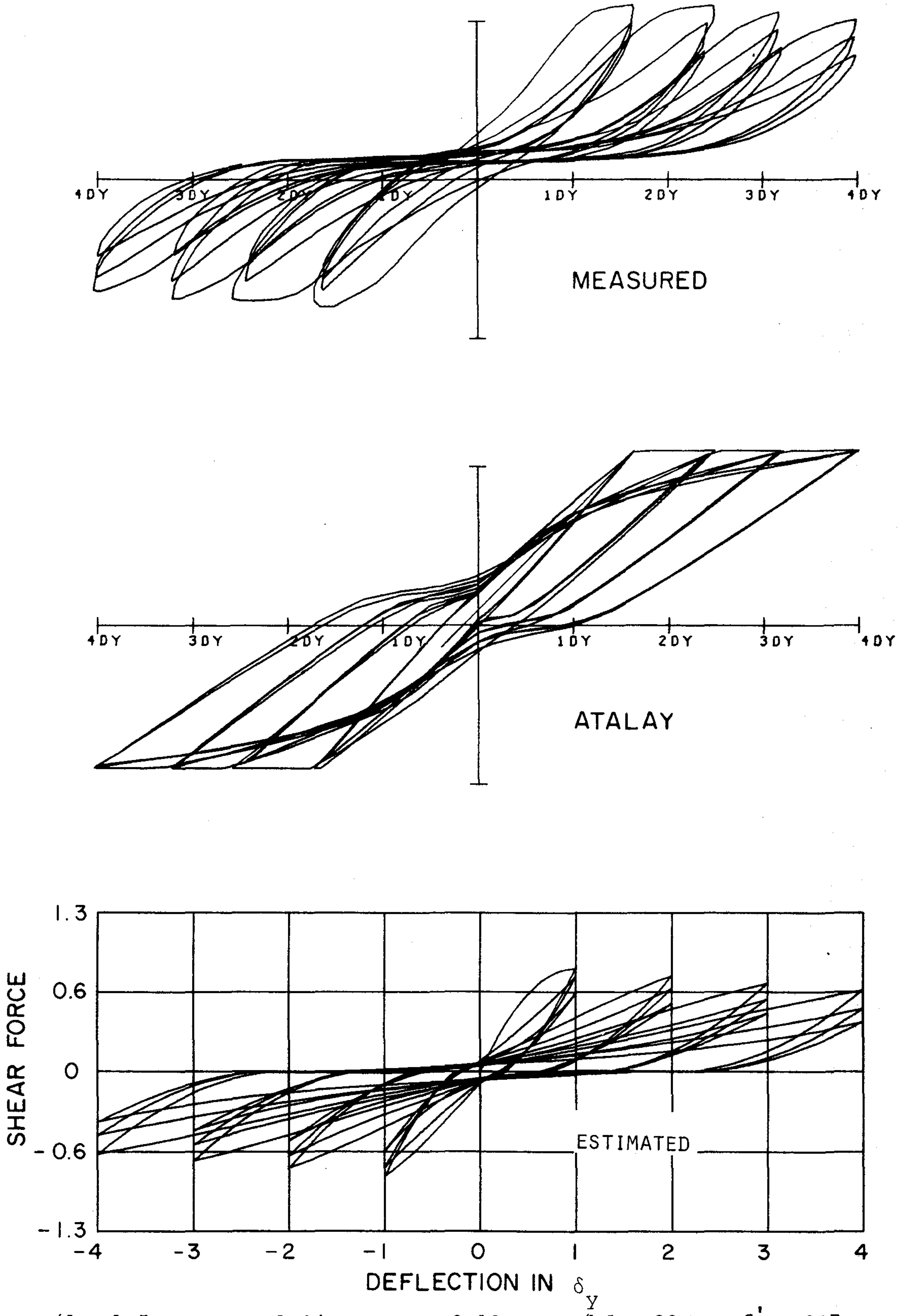
a/d = 1.0 p_t = 0.34 p_w = 0.36 P/bd = 26.3 f'_c = 274

Fig. 4.3 Comparison of Hysteresis Loops: Case 2



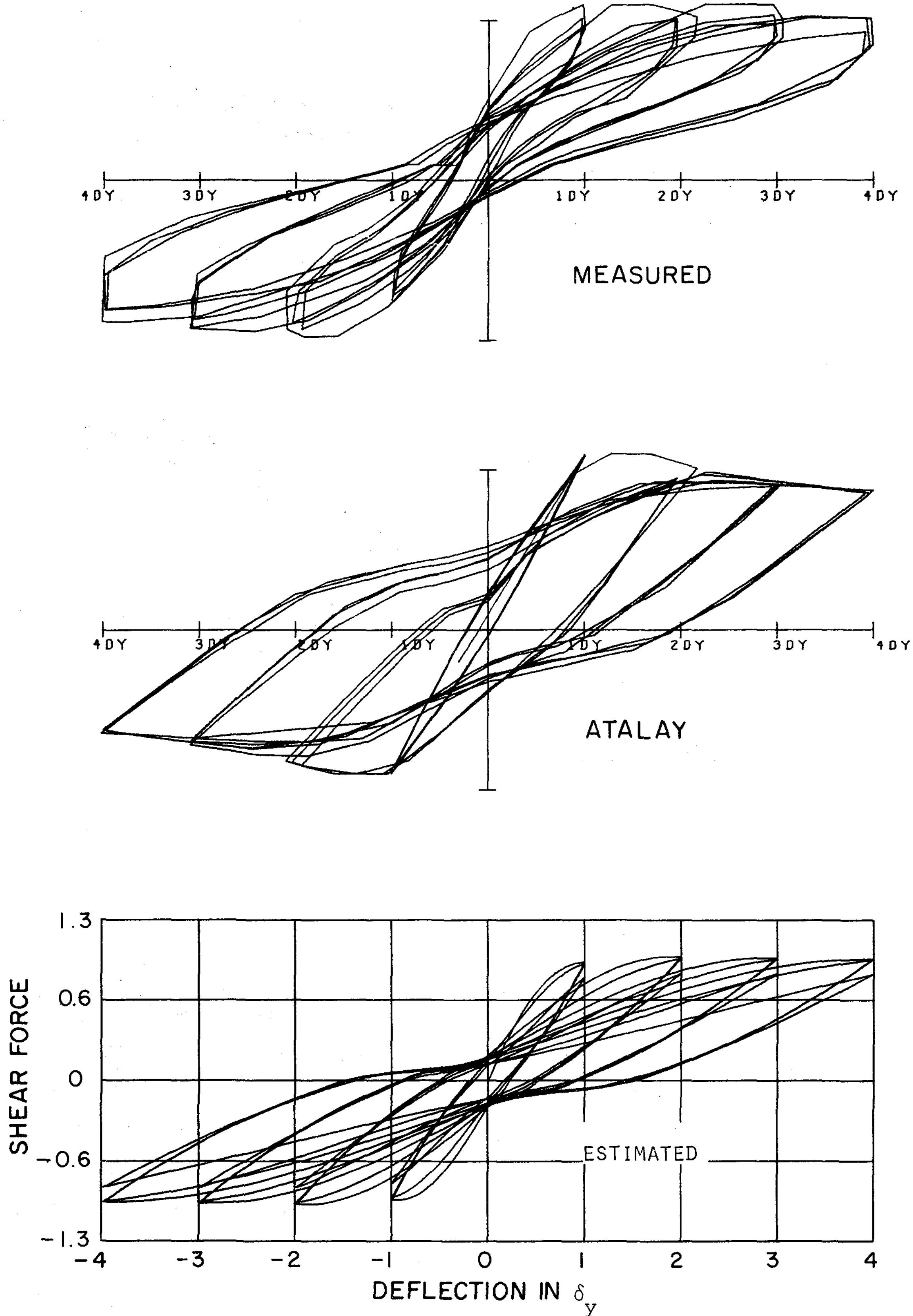
a/d = 1.5 p_t = 0.41 p_w = 1.02 P/bd = 30 f'_c = 240

Fig. 4.4 Comparison of Hysteresis Loops: Case 3



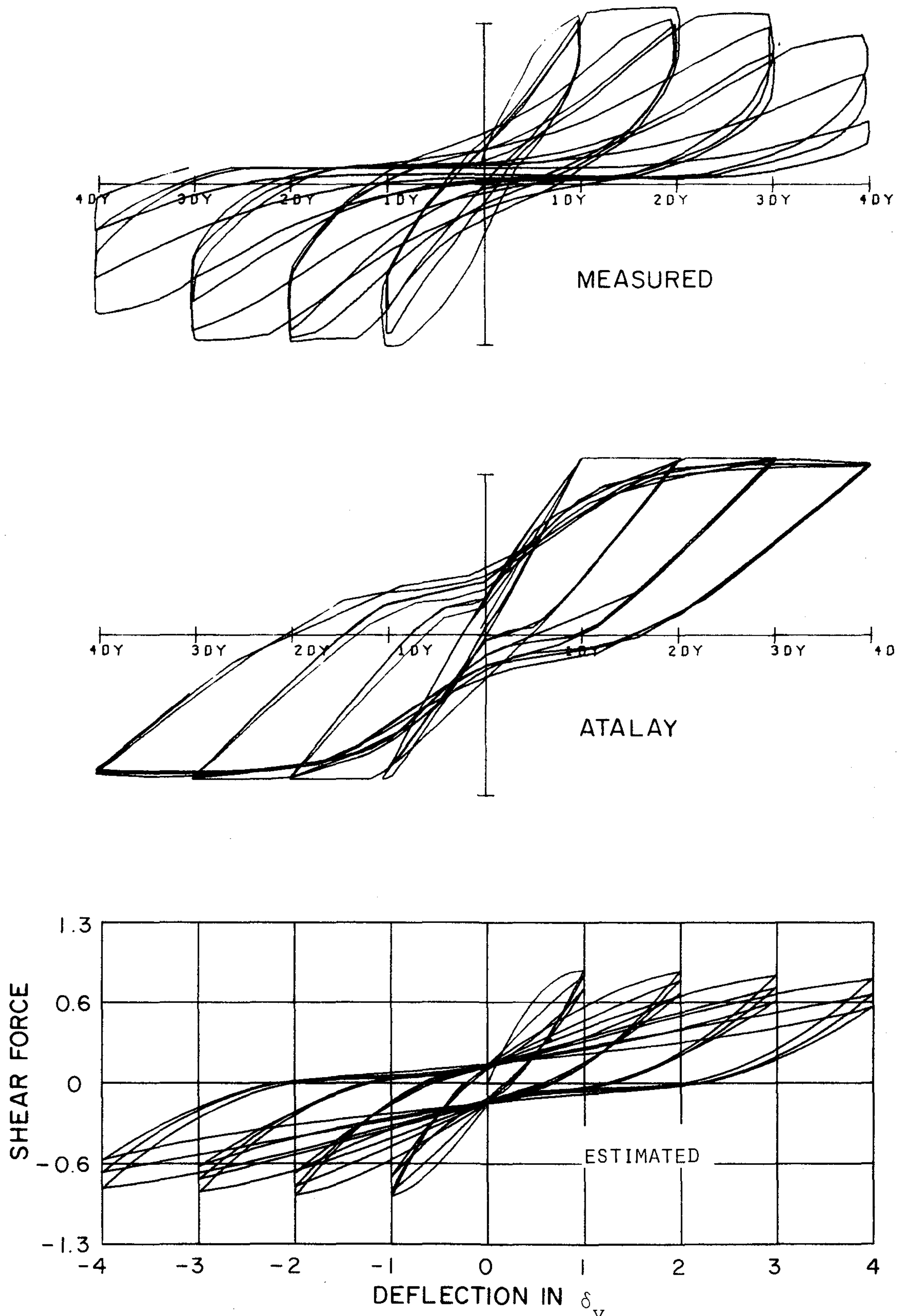
a/d = 1.5 p_t = 1.24 p_w = 2.12 P/bd = 30 f'_c = 207

Fig. 4.5 Comparison of Hysteresis Loops: Case 4



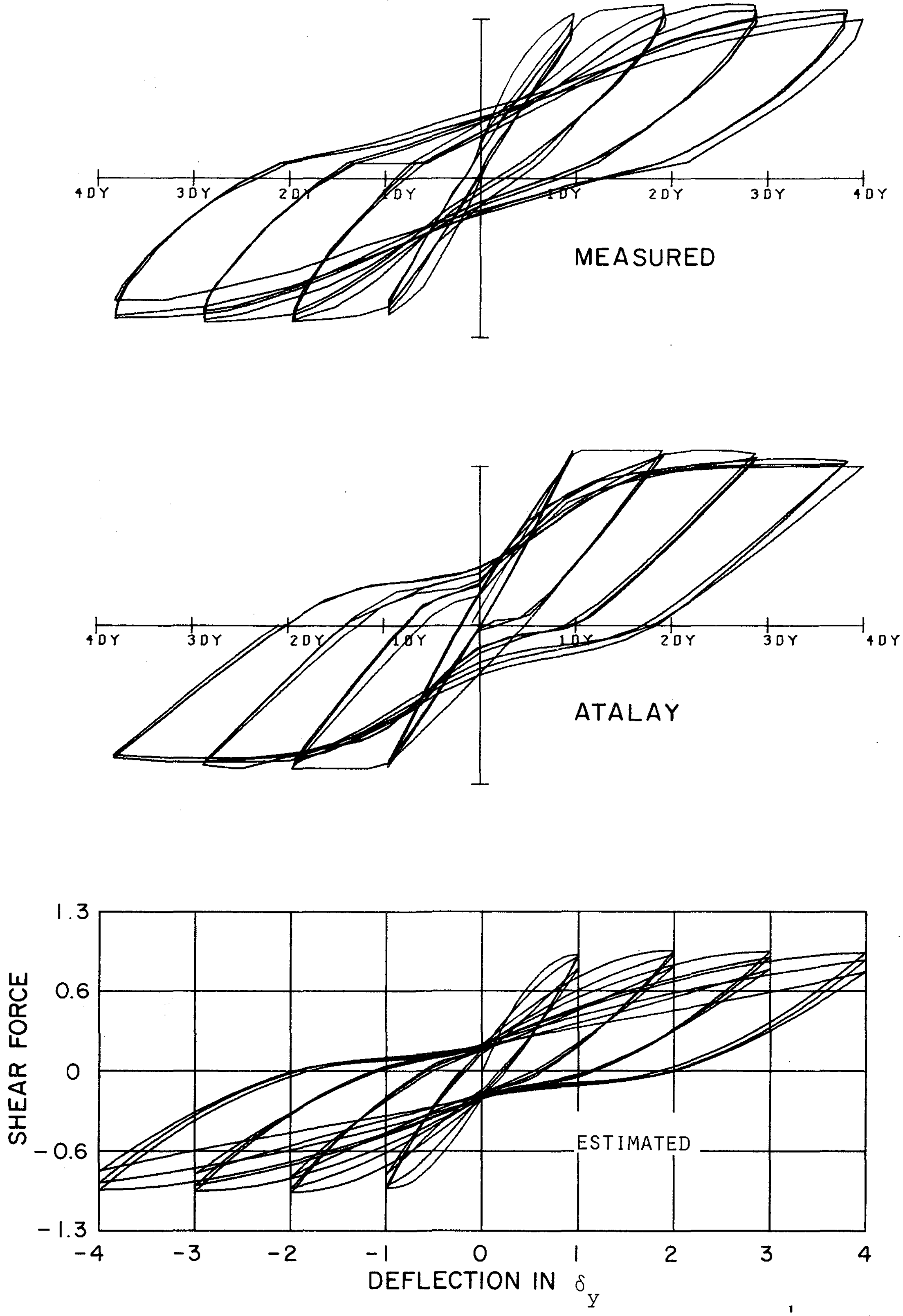
a/d = 2.0 p_t = 0.34 p_w = 0.71 P/bd = 52.5 f_c' = 245

Fig. 4.6 Comparison of Hysteresis Loops: Case 5



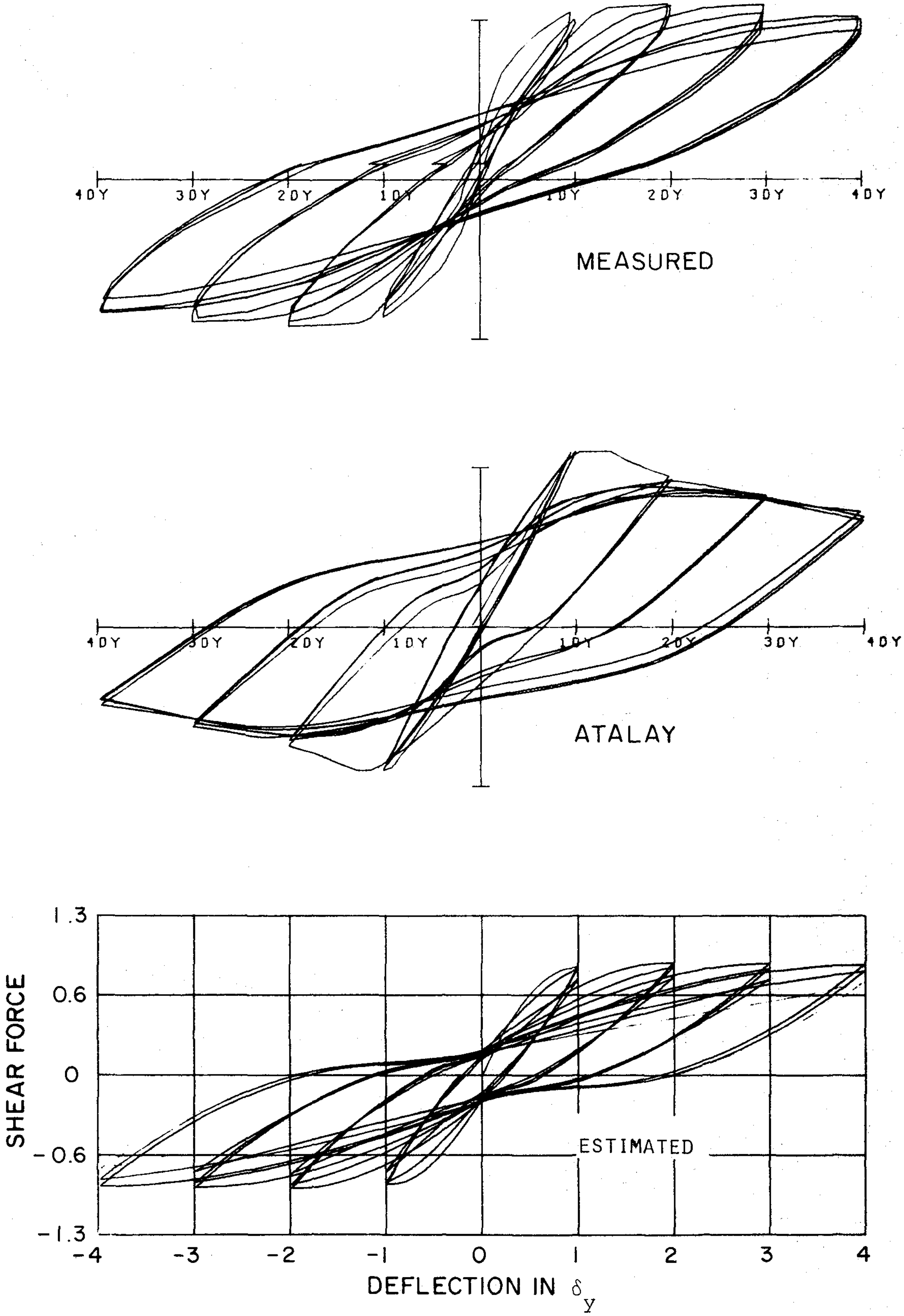
a/d = 2.0 p_t = 0.95 p_w = 1.27 P/bd = 26.3 f'_c = 245

Fig. 4.7 Comparison of Hysteresis Loops: Case 6



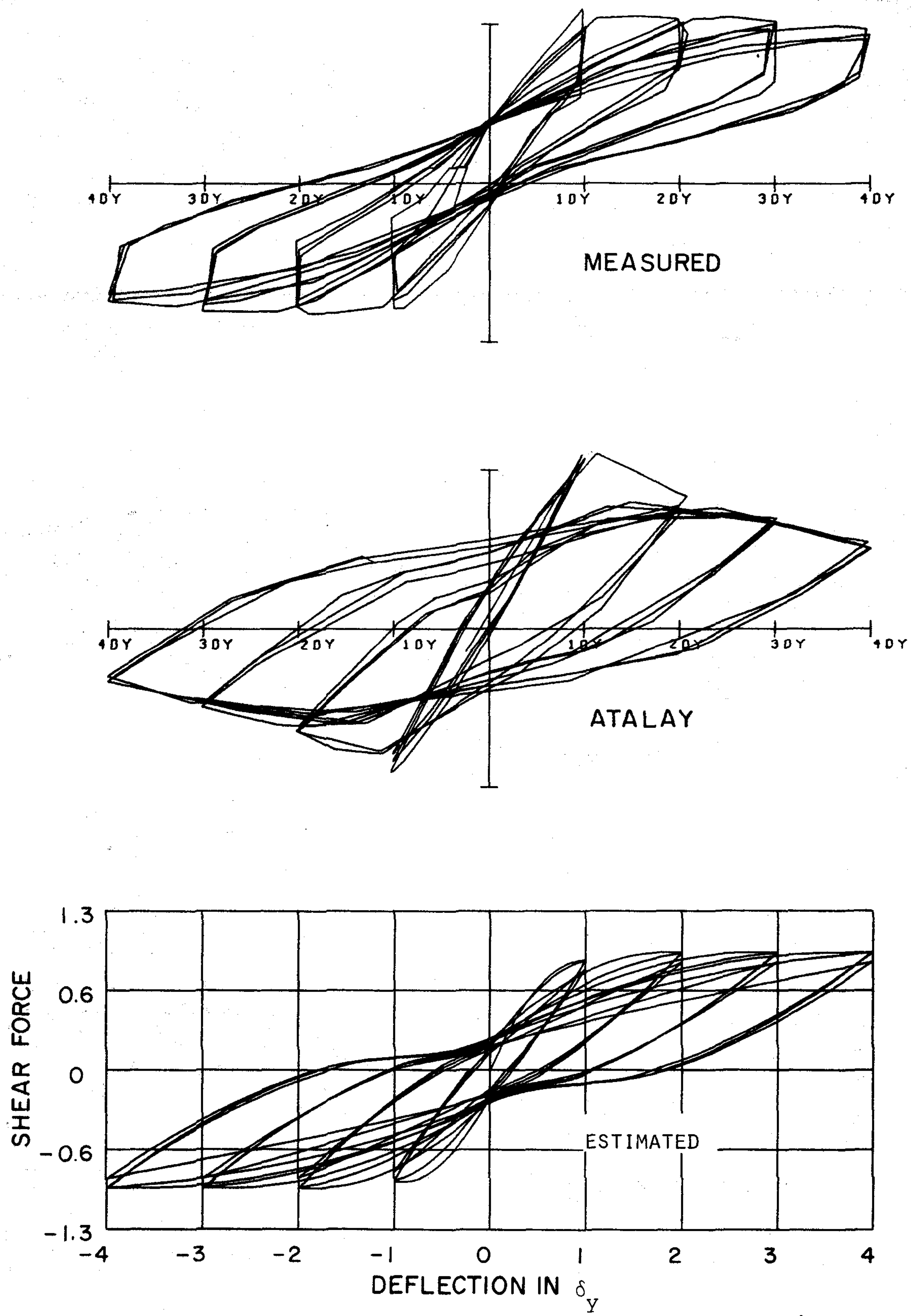
a/d = 2.5 p_t = 0.61 p_w = 0.36 P/bd = 26.3 f'_c = 205

Fig. 4.8 Comparison of Hysteresis Loops: Case 7



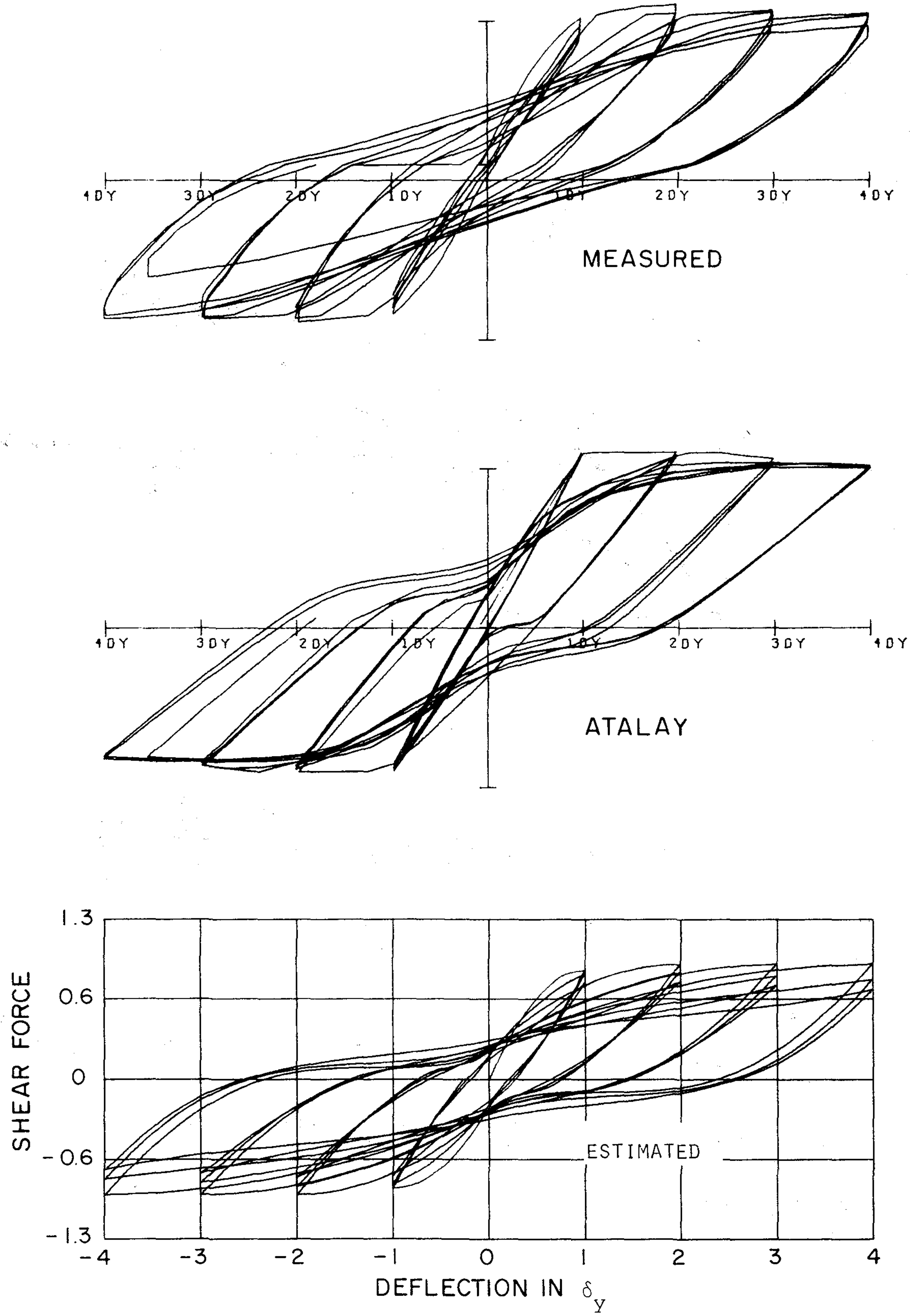
$a/d = 2.5$ $p_t = 0.61$ $p_w = 0.77$ $P/bd = 52.5$ $f'_c = 207$

Fig. 4.9 Comparison of Hysteresis Loops: Case 8



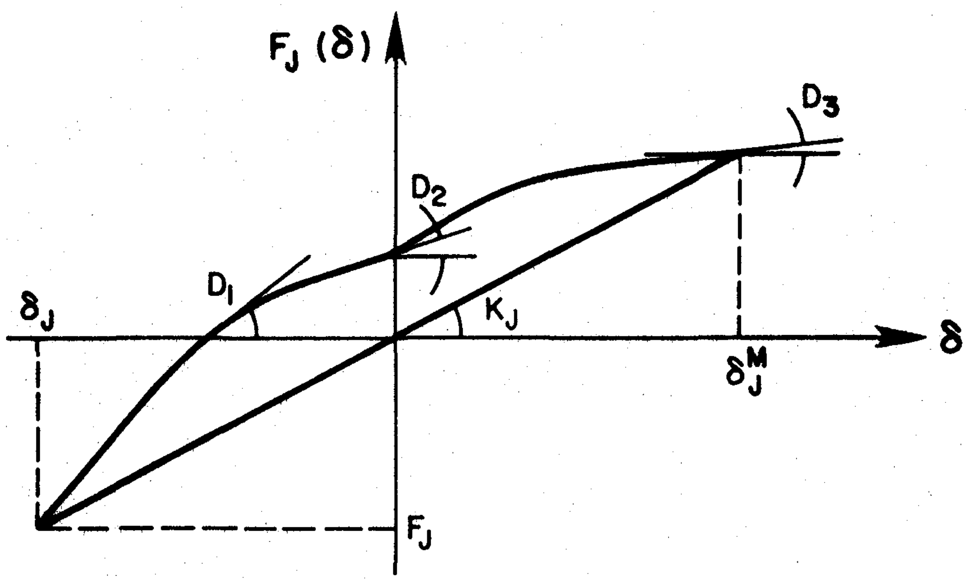
a/d = 3.0 p_t = 0.34 p_w = 0.28 P/bd = 52.5 f'_c = 193

Fig. 4.10 Comparison of Hysteresis Loops: Case 9



a/d = 3.0 p_t = 0.96 p_w = 0.60 P/bd = 26.3 f'_c = 189

Fig. 4.11 Comparison of Hysteresis Loops: Case 10



$$F_J(\delta) = F_J + K_J(\delta-\delta_J) + A_J \cos \frac{\pi}{2}\left(\frac{2\delta - \delta_J^M - \delta_J}{\delta_J^M - \delta_J}\right)$$
$$- B_J\left(\frac{1}{2} + \frac{1}{2}\cos\frac{\pi\delta}{\delta_{PJ}}\right)$$

where

$$A_J = \{- 0.17 + (0.27 + 0.3\ P/bdf_c') \text{ amp} - (0.02 + 0.04\ P/bdf_c') \text{ amp}^2\}\ D7$$

$$B_J = (0.245 - 0.284\ P/bdf_c' - 1.712\ p_w)\ \sqrt{\text{amp} - 1} \cdot D7$$

and δ_{PJ} is the value of δ that yields a zero value of $F_J(\delta)$.

Fig. 4.12 Penzien-Atalay Model

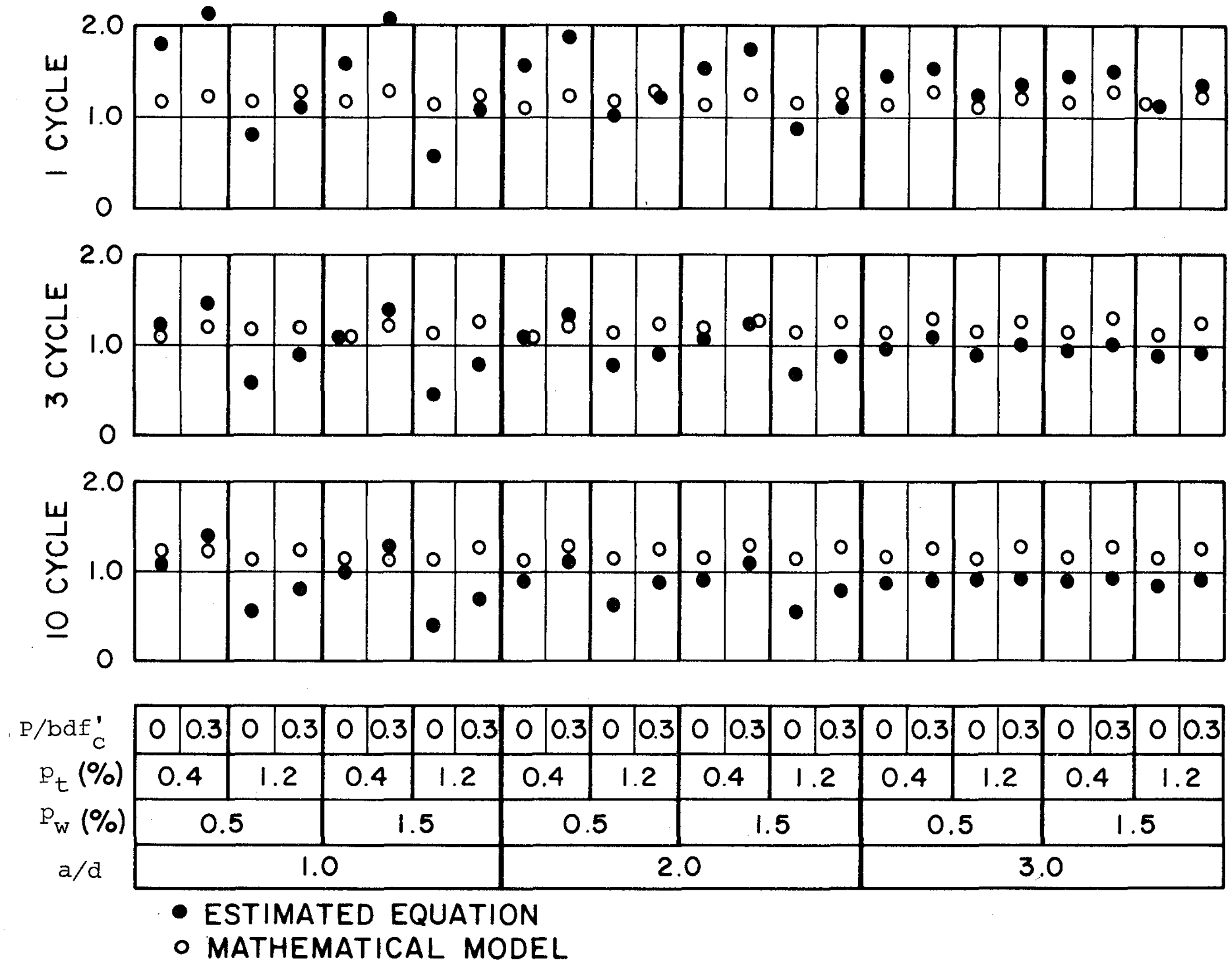


Fig. 4.13 Comparison of Stiffness (D1)

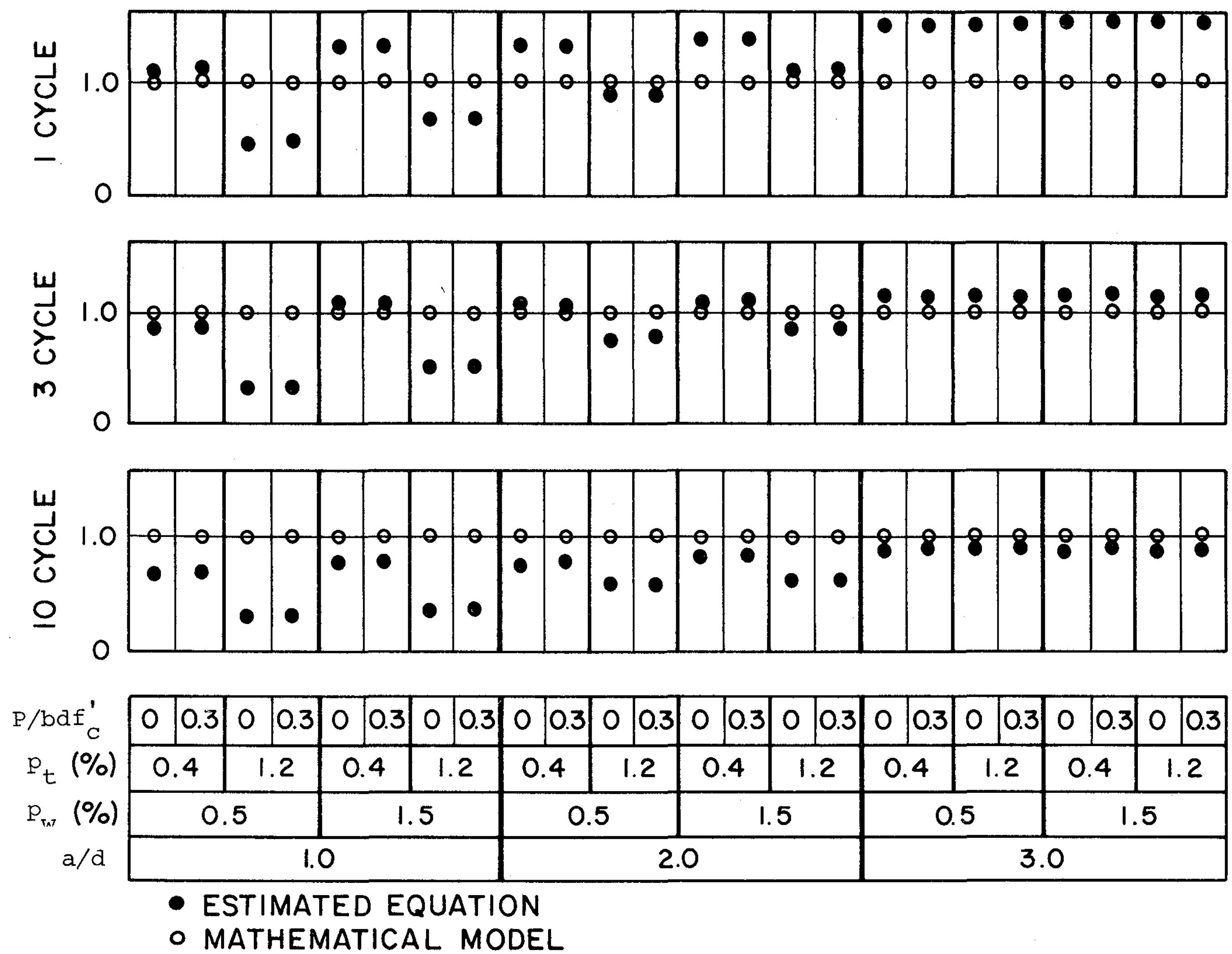


Fig. 4.14 Comparison of Stiffness (D2)

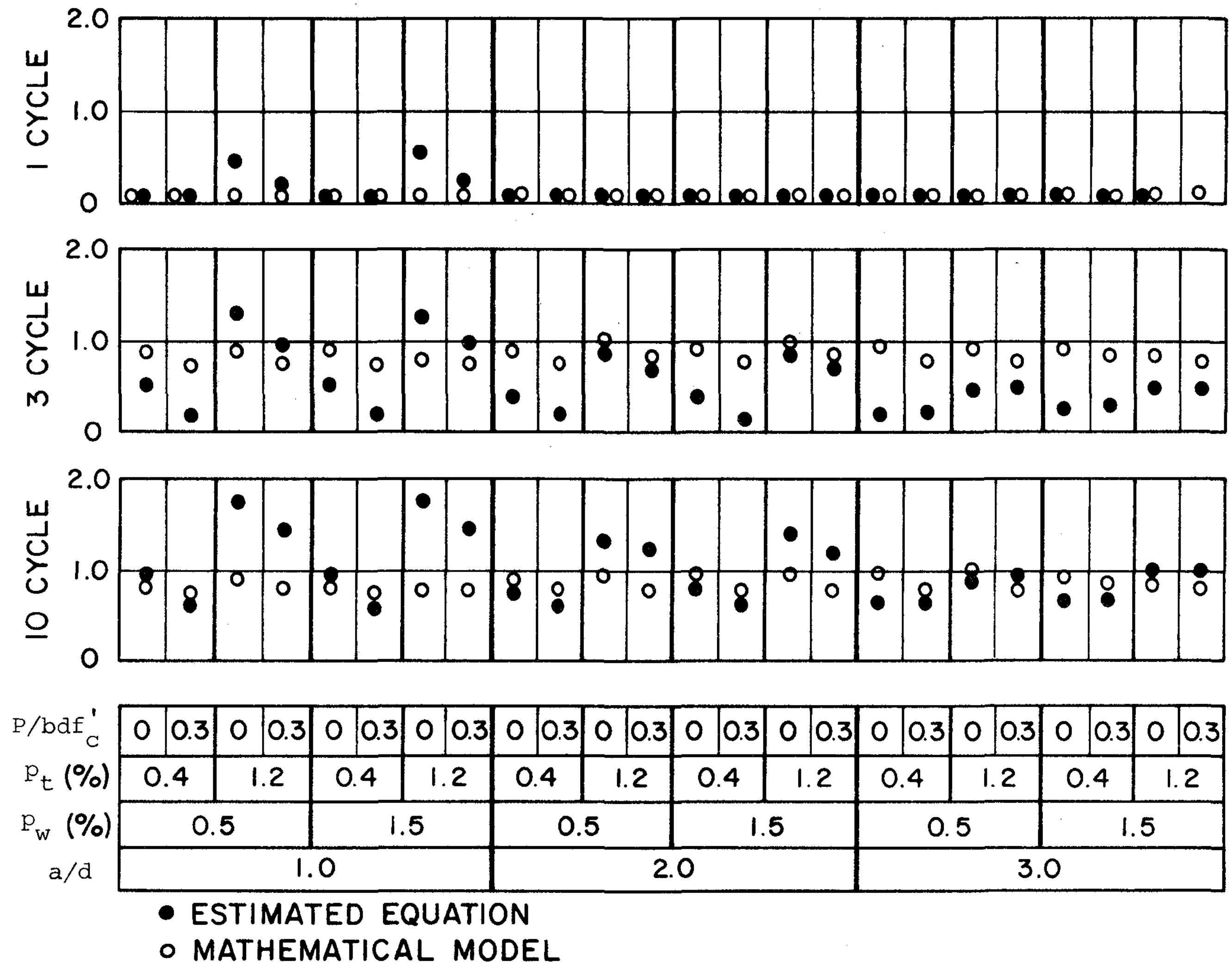


Fig. 4.15 Comparison of Stiffness (D3)

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EERC 68-1 Unassigned

EERC 68-2 "Inelastic Behavior of Beam-to-Column Subassemblages Under Repeated Loading," by V.V. Bertero - 1968 (PB 184 888)A05

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