CONCRETE FORMWORK PRESSURE EVALUATION FOR SRS TEST WALL

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1. OBJECTIVE

The purpose of this study was to determine formwork pressures during concrete placement for three prototype wall segments of 28 ft height at the US Department of Energy Savannah River Site near Aiken, South Carolina. The formwork pressures were obtained from measured tensile loads in the form ties which were converted to equivalent concrete pressures based upon tributary area. The form ties were instrumented with strain gages to convert the ties to load cells. Tie force and pour rate data were recorded at intervals during the time of the concrete placements. Lateral pressures were determined and compared with pressures predicted by empirical formulas recommended by the American Concrete Institute (U.S.) and the Construction Industry Research Information Association (U.K.)

2. EXPERIMENTAL PROGRAM

a) General

Field studies were performed on three adjacent test wall segments which were poured on separate dates, the first (Segment 1) on December 19, 1990 and the second (Segment 2A) and third (Segment 2B) on January 10, 1991. Segments of the wall poured on the latter date were placed simultaneously, by use of a subdividing bulkhead, and referred to as Segments 2A and 2B. The test wall was subdivided with the intent of evaluating three different concrete mixes. The wall had a nominal height of 28 ft and a thickness of 2 ft.

b) Formwork Description

Figures 1 and 2 depict the layout of the formwork and the locations of the instrumented form ties for wall Segments 1, 2A, and 2B. Form faces were 3/4-in. plywood panels stiffened with vertical Burke Aluma beams at 8 in. on center. The verticals were supported by wales made from double 8 in. steel channels which were in turn supported by the form ties. The form ties consisted of 1.5 in. diameter she-bolts with a 1 in. diameter coil threaded inner rod. Figure 3 shows the formwork and tie arrangement and the location of the strain gage instrumented area. All sections of the test wall were reinforced on each face with No. 6 rebar placed 12 inches on center both horizontally and vertically. No. 5 rebar ties were spaced at 5 ft on center vertically and horizontally.

c) Form Tie Instrumentation and Calibration

A total of 40 she-bolts were each instrumented with a full bridge of temperature compensated electrical resistance strain gages so that each tie acted as a load cell. A full bridge load cell arrangement was used to assure that neither temperature variations (either ambient or concrete induced), nor unexpected bending in the ties, would affect the axial force measurements. The instrumented ties were installed in the formwork at the numbered locations shown in Figures 1 and 2. The 20 she-bolts used in the first pour were recovered for use in the second test pour.

Calibration of the she-bolts was accomplished by loading each she-bolt in a universal testing machine. Each load cell was calibrated for load versus strain at 10-kip intervals up to a load of at least 30 kips. This procedure resulted in the development of a linear relationship for determining the load corresponding to any strain level within the elastic load range. Testing machine calibration within 0.5% and reproducibility during tie calibration suggested that error should be less than 1% within the expected load range.

d) Concrete Mix Proportions

Three basic concrete mixes were designed for the test wall, but variations in admixtures resulted in a total of five mixes (Table 1). The basic mixes were designated as 5-B for wall Segment 1, 5-C for wall Segment 2A, and J-2 for wall Segment 2B. All three concrete mixtures contained Type II portland cement. The 5-B and 5-C mixes were distinguished by a considerable content of blast furnace slag and fly ash. During the pouring of wall Segments 2A and 2B, there was some experimentation with the admixture brands that resulted in additional versions of Mix J-2. In addition, problems with pumping Mix 5-C, containing a large irregular aggregate, forced abandonment of that mix during placement and completion of Segment 2A with Mix J-2. The distribution of the various mixes to the segments is given in Table 1.

e) Placement and Consolidation of Concrete

Placement of concrete for each wall segment was accomplished by the use of concrete pumps which conveyed the concrete mix from transit mix trucks. Concrete for each wall was placed in 2 ft lifts and vibrated internally with 2 in. diameter air vibrators for the full depth of each lift plus a few inches into the previous lift.

3. PRESENTATION AND ANALYSIS OF DATA

a) Rate of Concrete Placement

The increase in concrete height versus time for each pour is shown in Figure 4 for Segment 1 and in Figure 5 for Segments 2A and 2B. Interruptions in the concrete placement are indicated by plateaus in the pour rate curves. The interruptions were due to occasional delays in the arrival of concrete delivery trucks, switching to successive trucks, or in one case a blockage in the pump used for Segment 2A. These factors contributed to much slower average placement rates for Segments 2A and 2B. The overall rates of placement were approximately 11.0 ft/hr for Segment 1, 5.5 ft/hr for Segment 2A, and 5.7 ft/hr for Segment 2B. The final placement heights were 28 ft for Segment 1, 27 ft for 2A and 27.8 ft for 2B.

b) Pressure Determinations

Tie forces were typically recorded at 5 to 10 minute intervals during the placement of the concrete. The shorter interval was maintained during active placement but extended to the longer interval during placement delays. All 20 of the instrumented ties used in the first pour continued to function for the duration of the pour. However, during the second pour, tie number 10 could not be balanced, and tie number 17 did not respond, in each case, apparently due to instrumentation damage during installation. Both of these ties were located in wall Segment 2B.

Each form tie force reading, recorded to the nearest 10 lbs, was converted to lateral pressures for comparison with results from pressure theories. Tie loads were divided by their associated tributary areas. Tributary areas were assumed to be defined by lines located at one-half the distance between both laterally and vertically adjacent form ties. The lower boundary for ties located at the bottom was the base of the wall, and the upper boundary for ties located at the top was the top of the concrete pour. During the concrete placement, tie forces were determined to gradually increase to a maximum and then to slightly decrease. The maximum tie forces recorded were 25,330 lbs for tie #13 in Segment 1, 20,510 lbs for tie #33 in Segment 2A, and 23,620 lbs for tie #13 in Segment 2B.

For determination of a maximum pressure envelope, a conservative approach was utilized. The maximum force which occurred in each individual tie was selected for determination of the pressure, even if, at a given tie/wale level, the maximums were reached at somewhat different times. The forces were divided by their associated tributary areas. At a given respective level, these maximum lateral pressures were then averaged and displayed in plots of tributary pressures versus depth to the ties in Figures 6 thru 9. Thus, these plots represent the maximum lateral pressure envelope for each wall segment and for Segment 2A and Segment 2B combined.

c) Analysis of Measured Pressures

Figures 6 thru 8 show both the average and the individual tie area maximum lateral formwork pressures for each wall segment versus the depth to the ties. The maximum pressure in Segment 1 was 1,395 psf, and it occurred at a depth of 19 ft from the top of the pour. The maximum pressure at an individual tie was 1,850 psf, occurring at the same level. The maximum pressure for Segment 2A was 1,130 psf while the maximum individual tie pressure was 1,270 psf, both at a depth of 18 ft from the top of the pour. For Segment 2B, the maximum pressure and the maximum individual tie pressure occurred at different levels. A maximum pressure of 1,270 psf occurred at a depth of 11.8 ft from the top of the pour, and the maximum individual tie pressure of 1,630 psf occurred at a depth of 18.8 ft from the top of the pour.

Because several changes were made in the concrete mixes that were placed in Segments 2A and 2B, a plot averaging the lateral pressure results of the two segments was also constructed and is shown in Figure 9. The result was a maximum pressure of 1,200 psf.

There is a strong consistency in the profiles of the maximum pressure plots. In each case, the readings from the top of the pour tend to fall along the linear hydrostatic head shown on each graph. After reaching a maximum or near maximum value, the lateral pressures then tend to decrease slightly toward the bottom of the wall.

There is some scatter in the individual tie forces and apparent tributary pressures at a given vertical elevation. However, this is not considered unusual since the tightness of individual ties varies initially, some may loosen initially with vibration and continous beam deformations of the vertical studs, and seating at wing nuts is not perfect initially due to tie alignment variations. The individual tie-associated tributary pressures reflect the varying amount of force collected at each tie due to these tie installation differences. However, the average of the maximum calculated pressures from ties at a given level better represents the actual concrete pressure occurring at that level. Due to these possible tie installation variables, formwork accessories such as ties are rated with a higher factor of safety, i.e. 2.0, by manufacturers than is typical of other structures. The variations versus the maximum average pressure were relatively small compared to the tolerance provided by the high factor of safety.

A summary envelope of maximum pressures for all three segments is provided in Figure 10. Note that in all three cases, the tributary pressures are somewhat higher at tie levels 3 and 5 down from the top and somewhat lower at tie level 4. It is believed that this anomaly is due to effects of the nonuniform span of the continuous verticals. Such effects would alter the actual tributary areas, possibly enlarging the areas tributable to levels 3 and 5 and reducing the area tributable to level 4. In such a case, the actual pressures would be less at levels 3 and 5 and more at level 4 than calculated by simple tributary areas. This would have the effect of smoothing the measured distribution. The distribution of measured pressures agrees with the general pattern of pressures measured in other investigations (see Figure 11).

4. COMPARISON WITH THEORETICAL FORMULAS

Two approaches for estimating concrete formwork pressures have been developed and recommended by professional associations. Both are empirical, that is the formulas were partly developed by fitting equations to test data.

a) ACI Recommendations

American Concrete Institute Committee 347 (Ref. 1) recommends that the lateral pressure of newly placed concrete is given by

$$P = wh \quad \text{. . . . . (1)}$$

where P = lateral pressure (psf), w = unit weight of concrete (pcf) and h = depth of fluid or plastic concrete (ft). For wall concrete made with Type I cement, weighing 150 pcf, containing no pozzolans or admixtures, having a slump of 4 in. or less and normal internal vibration to a depth 4 ft or less, the maximum pressure is given as follows:

i. For rates of placement less than 7 ft/hr

$$P(\max) = 150 + \frac{9{,}000*R}{T} \quad \text{. . . . .(2)}$$

with a maximum of 2,000 psf, a minimum of 600 psf, but in no case greater than 150 h.

ii. For rates of placement from 7 to 10 ft/hr

$$P(max) = 150 + \frac{43{,}400}{T} + \frac{2{,}800*R}{T} \quad \ldots \ldots \quad (3)$$

with a maximum of 2,000 psf, a minimum of 600 psf, but in no case greater than 150 h.

where

$P(max)$ = maximum lateral pressure, psf
R = rate of placement of concrete, ft/hr
T = temperature of concrete in forms, degrees fahrenheit
h = maximum height of fresh concrete in the forms, ft.

Although the ACI provisions are severely limited by restrictions on Equations 2 and 3, the ACI recommendations also provide that experimental methods may be used to determine an appropriate design pressure.

b) CIRIA Recommendations

The procedures developed by the Construction Industry Research Information Association (Ref. 2) for estimating lateral formwork pressures are more complex than the ACI recommendations, cover a wider variety of cement types, and allow for the influence of pozzolans and chemical admixtures. The maximum lateral concrete pressure on formwork is expressed as follows:

$$P(max) = D\,[C_1\sqrt{R} + C_2K(H - C_1\sqrt{R})^{0.5}] \quad \ldots \ldots \quad (4)$$

$$\text{or } P(max) = Dh, \text{ whichever is smaller} \quad \ldots \ldots \quad (5)$$

where

C_1 = coefficient (1.0 for walls, 1.5 for columns) dependent on the size and shape of formwork, $\sqrt{mh}$
C_2 = coefficient (0.3, 0.45, or 0.6) dependent on the constituent materials of the concrete, $\sqrt{m}$
D = weight density of concrete, kN/m^3
H = vertical form height, m
h = vertical pour height, m
K = temperature coefficient determined by $[36/(T+16)]^2$
R = rate of vertical rise of concrete, m/hour
T = concrete temperature at placement, degrees Celsius.

When $C_1\sqrt{R} > H$, the fluid pressure (Dh) is to be taken as the design pressure. The first term within the brackets of Equation 4 incorporates the effects of vibration and workability, and the second term incorporates the effects of the height of discharge, cement type, admixtures, and concrete temperature at placement.

The coefficient C_2 is determined as follows:

Cement Type and Admixtures	Value of C_2
OPC, RHPC or SRPC without admixtures	0.3
OPC, RHPC or SRPC with any admixture, except a retarder	0.3
OPC, RHPC or SRPC with a retarder	0.45
LHPBFC, PBFC, PPFAC or blends containing less than 70% ggbfs or 40% pfa without admixtures	0.45
LHPBFC, PBFC, PPFAC or blends containing less than 70% ggbfs or 40% pfa with any admixtures, except a retarder	0.45
LHPBFC, PBFC, PPFAC or blends containing less than 70% ggbfs or 40% pfa with a retarder*	0.6
Blends containing more than 70% ggbfs or 40% pfa*	0.6

*These combinations of materials are rare, and the values indicated are derived by CIRIA from extrapolation of data, together with a consideration of the theoretical effects.

where

OPC = ordinary Portland cement
LHPBFC = low heat Portland-blastfurnace cement
PBFC = Portland-blastfurnace cement
PPFAC = Portland pulverised-fuel ash cement
RHPC = rapid-hardening Portland cement
SRPC = sulphate-resisting Portland cement
ggbfs = ground granulated blastfurnace slag
pfa = pulverised-fuel ash.

c) Comparison with Theories

Both ACI and CIRIA assume the lateral pressure envelope to be a full liquid head from the top of the pour to the maximum calculated pressure and to be constant at that maximum value at greater depths. As mentioned above, the envelopes bounded by the maximum pressures in Figures 6 thru 9 come close to matching the full hydrostatic head proposed by the procedures. After the measured pressures depart from the hydrostatic line and reach a maximum, they tend to decrease instead of remaining constant as the ACI and CIRIA procedures suggest. The CIRIA report (Ref. 2), however, notes that in field measurements the actual pressure typically decreases in this manner (see Figure 11). Table 2 compares the measured lateral concrete pressures to those estimated with the ACI and CIRIA procedures.

Due to use of admixtures and pozzolans, Type II cement, and target slumps greater than 4 in. which exceed limitations imposed on Equations 2 and 3 of the ACI procedure, only Equation 1 technically applies. As can be seen in Table 2, Equation 1 significantly overestimated the pressure since it is based upon a hydrostatic head. If the limitations on admixtures are ignored, Equation 3 provided a good estimate of the maximum pressure in Segment 1 when extrapolated to the actual rate of pour. Similarly, Equation 3 was reasonably close, although unconservative, in estimating the pressures for Segments 2A and 2B when the limitations were ignored. On a similar basis, Equation 2 produced a poor estimate for all three segments.

Estimates of the lateral pressure based upon the CIRIA formula are dependent in part on the selection of the C_2 coefficient. For Segment 1 (Mix 5-B) with a sulphate-resisting cement and retarders, C_2 would be at least 0.45 and possibly as high as 0.60 with the high content of slag and fly ash. For Segments 2A and 2B, the preponderance of concrete was variations of Mix J-2 with sulphate-resisting cement and retarding admixtures for which C_2 would be 0.45. The CIRIA estimates of lateral pressures reasonably correlate to the measured pressures and offer a conservative prediction as would be desirable. Considering that Mix 5-B contains a rare combination of materials and that CIRIA data was extrapolated to this range, the degree of agreement is reasonable. It is also worth noting that the CIRIA calculated depths to the maximum pressure seem quite reasonable when superimposed upon Figures 6 thru 9.

5. SUMMARY

The results of this study as cited in this report can be summarized as follows:

1. The maximum lateral concrete pressures for wall Segments 1, 2A and 2B were 1,395 psf, 1,130 psf, and 1,270 psf, respectively. The rate of placement for Segment 1 was 11 ft per hour which was approximately twice that of Segments 2A and 2B. The upper portion of the measured pressure envelopes tend to agree with the general assumption of a hydrostatic head.

2. The ACI formula which applies, based upon a hydrostatic head, greatly overestimates the measured actual pressures. If certain limitations are ignored, the ACI formula corresponding to medium rates of pour estimates pressures which reasonably correlated to the measured actual pressures.

3. The CIRIA formula reasonably and conservatively predicts the measured values for lateral concrete pressures. Also, the depth at which the maximum pressure is predicted seems to be close to that indicated by the profiles of the measured pressures.

4. Pressures measured in wall Segment 1 with Mix 5-B were made under severe placement conditions for formwork pressure with a high rate of pour and low concrete and ambient temperatures. Lower rates of pour and higher temperatures would generally decrease the expected pressures.

5. A possible design pressure envelope is shown in Figure 10.

6. REFERENCES

1) ACI Committee 347, "Guide to Formwork for Concrete," ACI 347R-88, American Concrete Institute, Detroit, 1988.

2) Clear, C. A., and Harrison, T. A., "Concrete Pressure on Formwork," Report 108, Construction Industry Research and Information Association, London, 1985.

7. APPENDIX

Conversions to SI Units

To convert	To	Multiply by
pcf	N/m^3	157.1
ft	m	0.3048
psf	N/m^2	47.856
°F	°C	(°F-32)/1.8

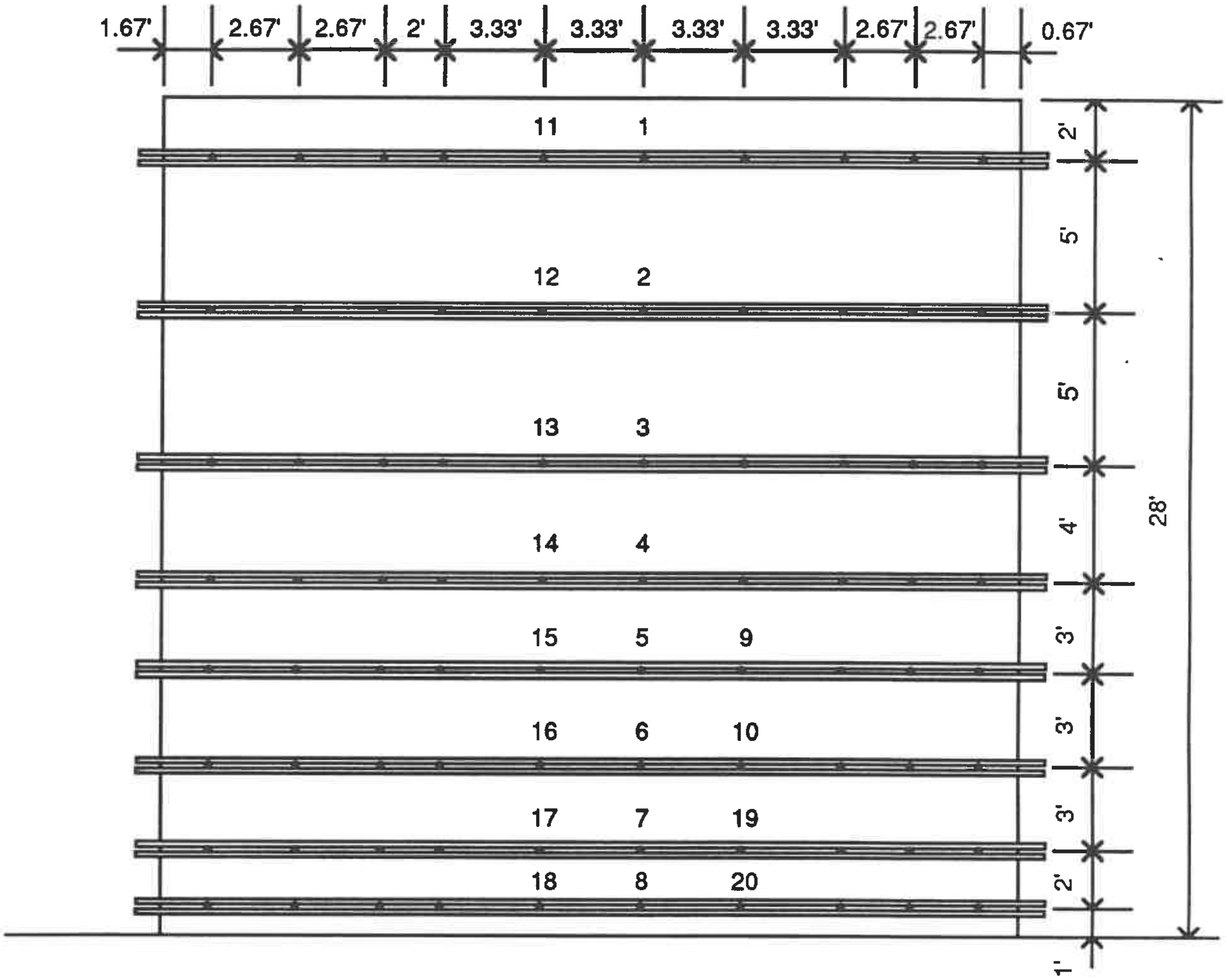

Figure 1. Elevation of Wall Segment 1

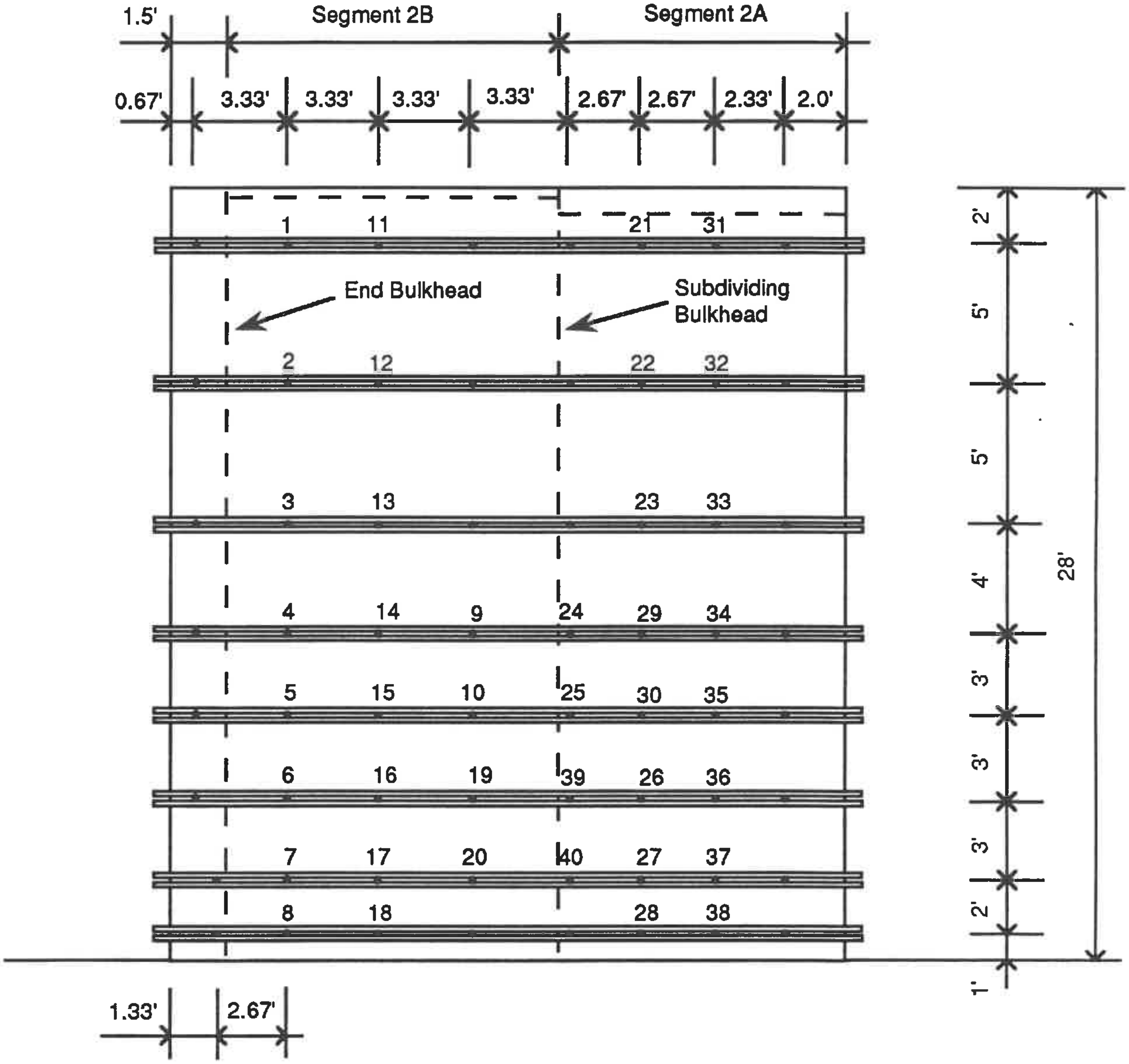

Figure 2. Elevation of Wall Segments 2A and 2B

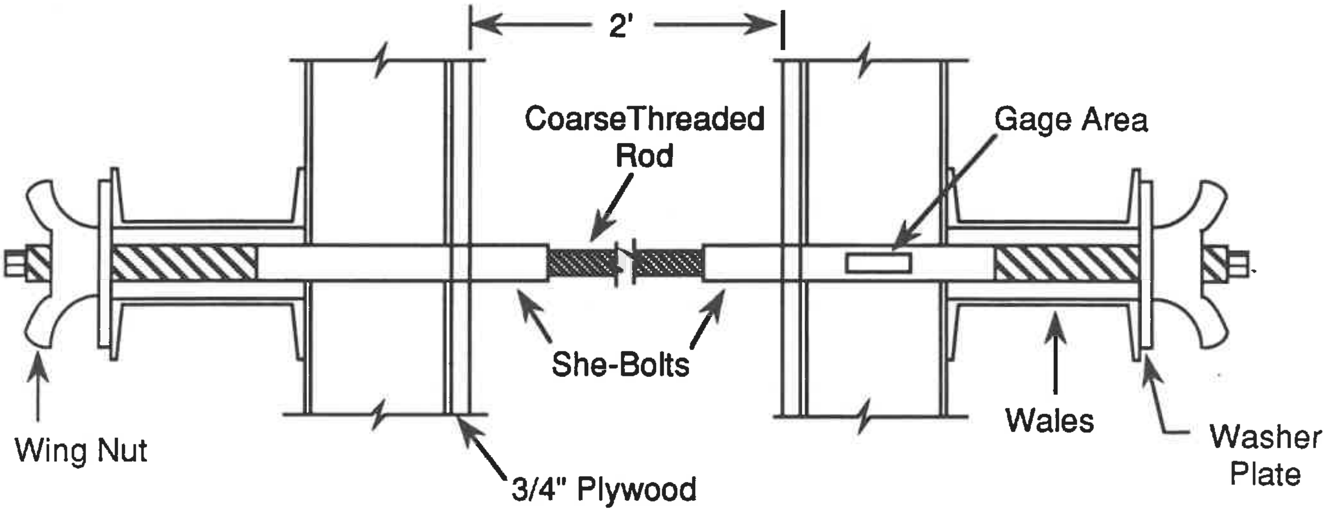

Figure 3. She-Bolt and Form Assembly

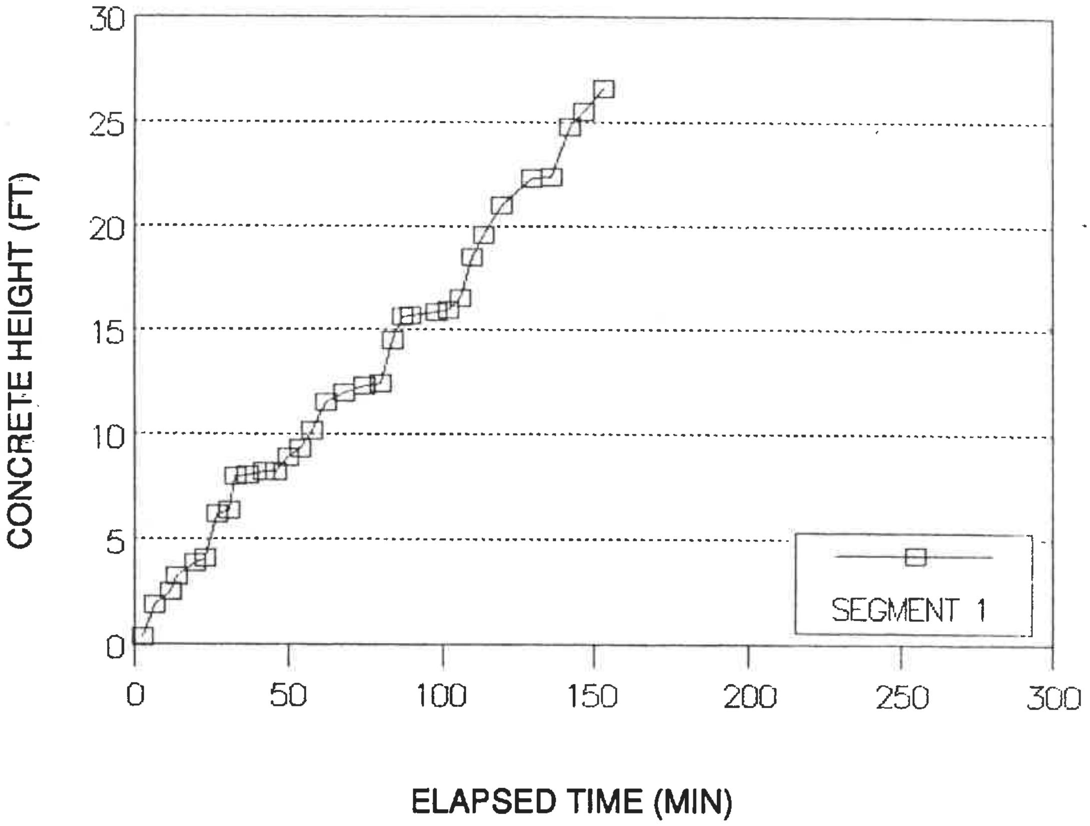

Figure 4. Concrete Height Versus Time for Wall Segment 1

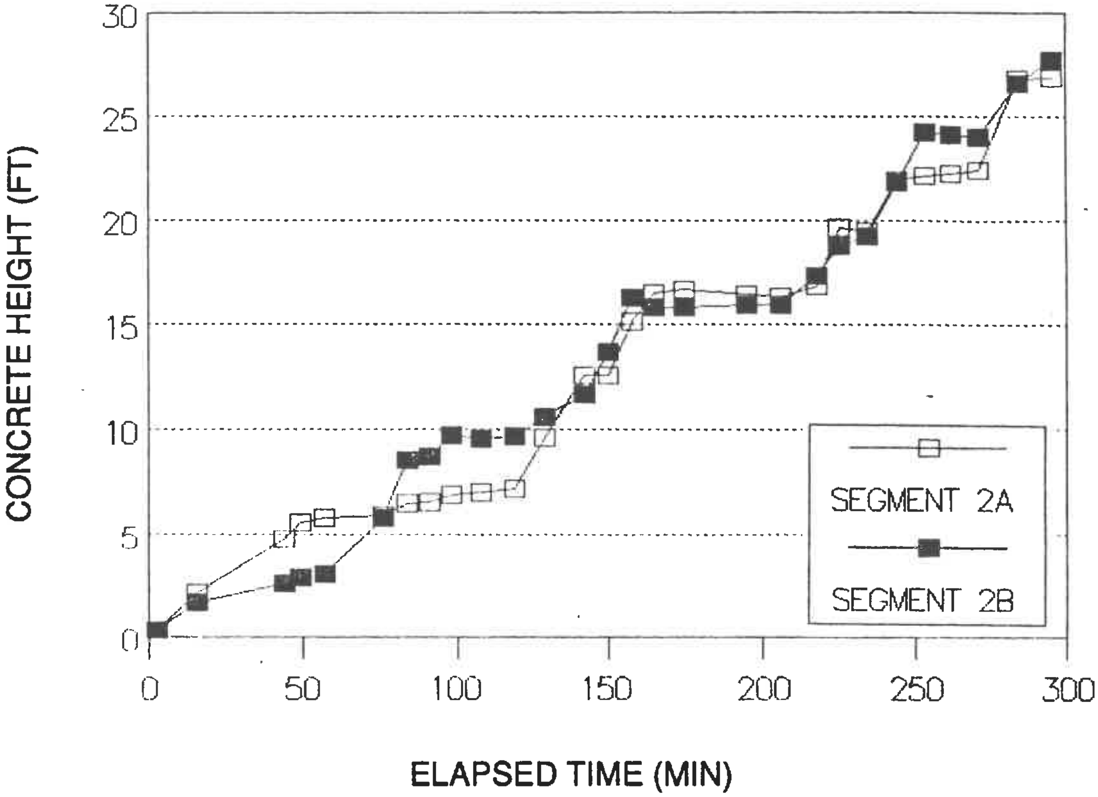

Figure 5. Concrete Height Versus Time for Wall Segments 2A and 2B

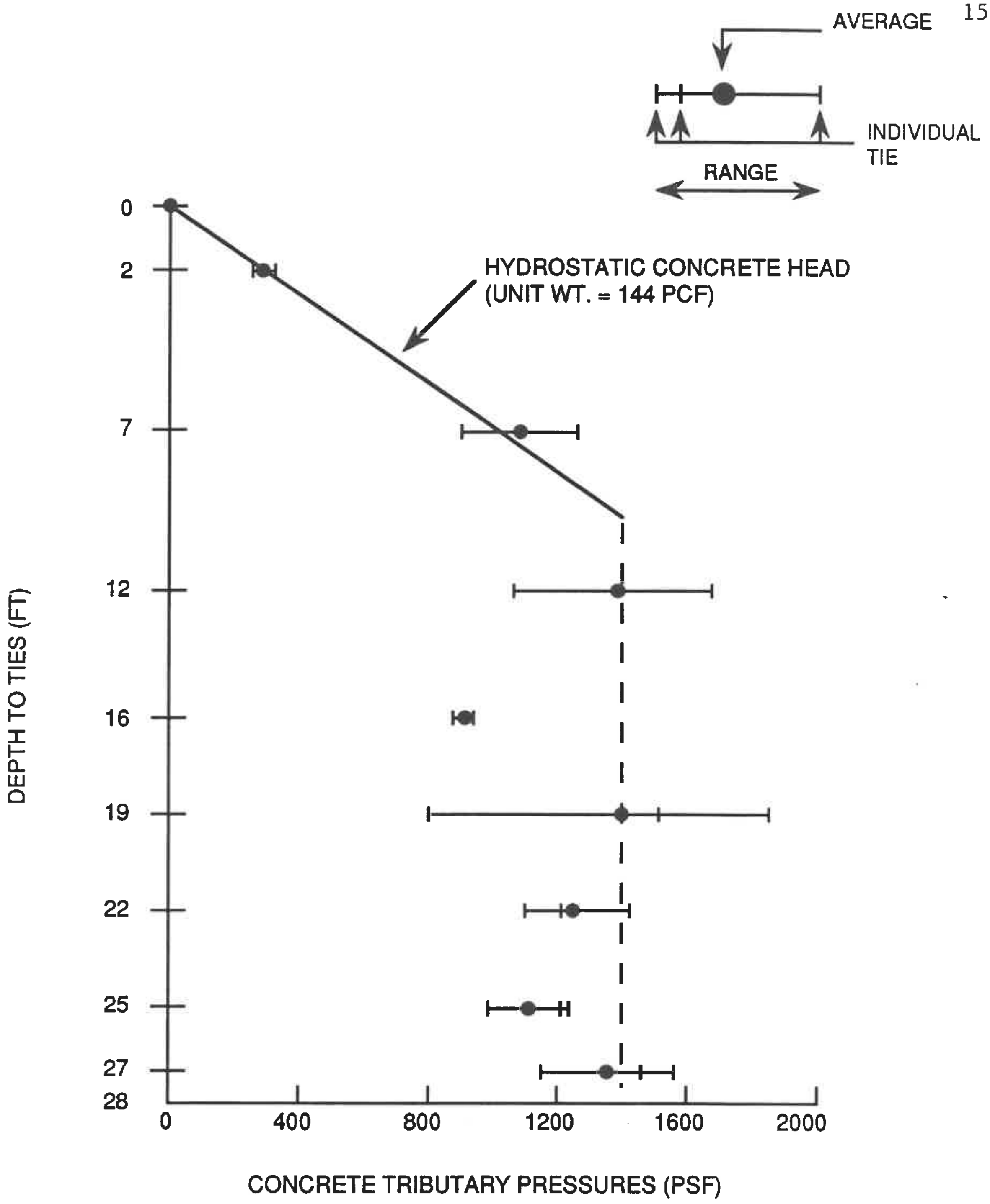

Figure 6. Concrete Tributary Pressures for Wall Segment 1

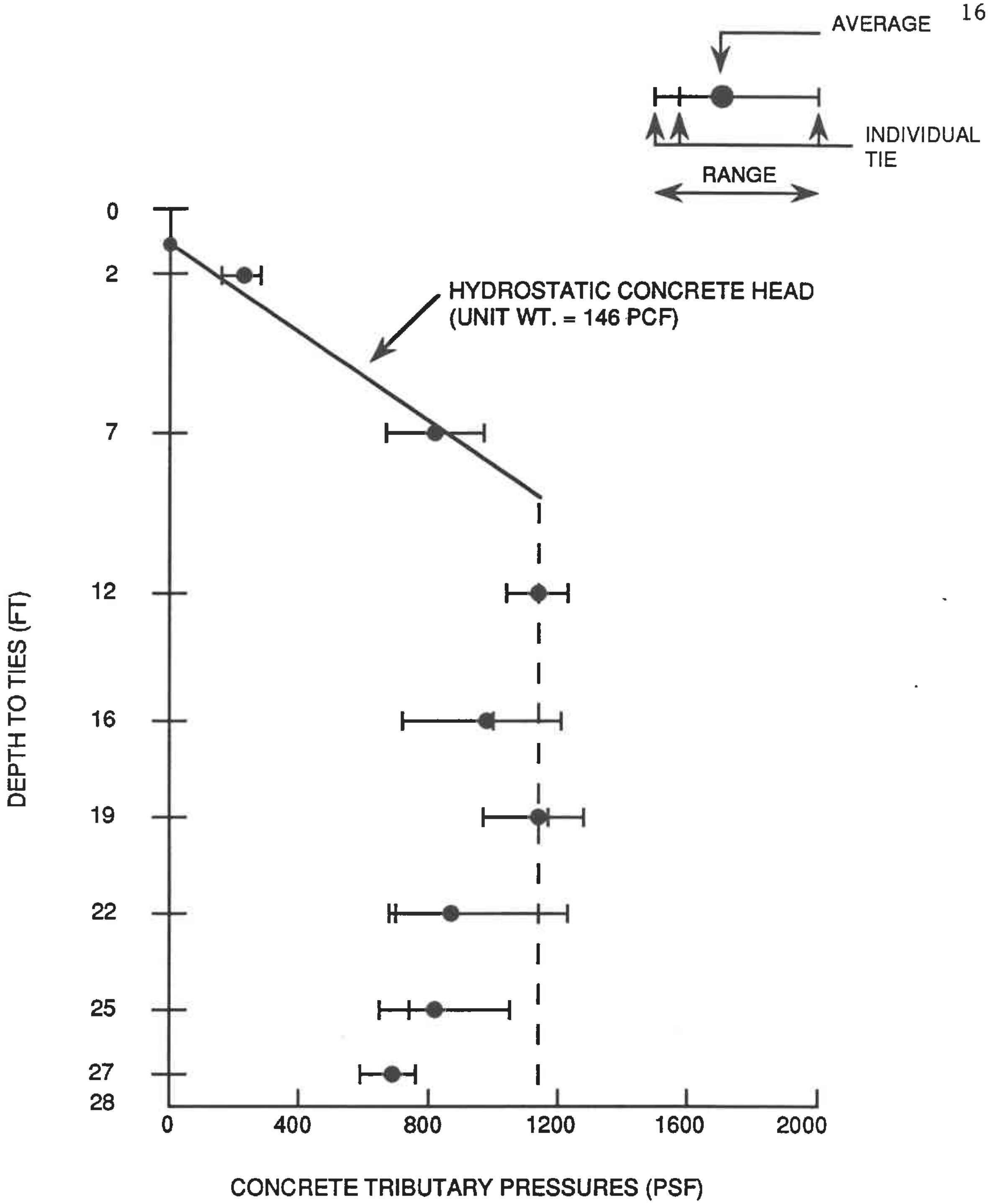

Figure 7. Concrete Tributary Pressures for Wall Segment 2A

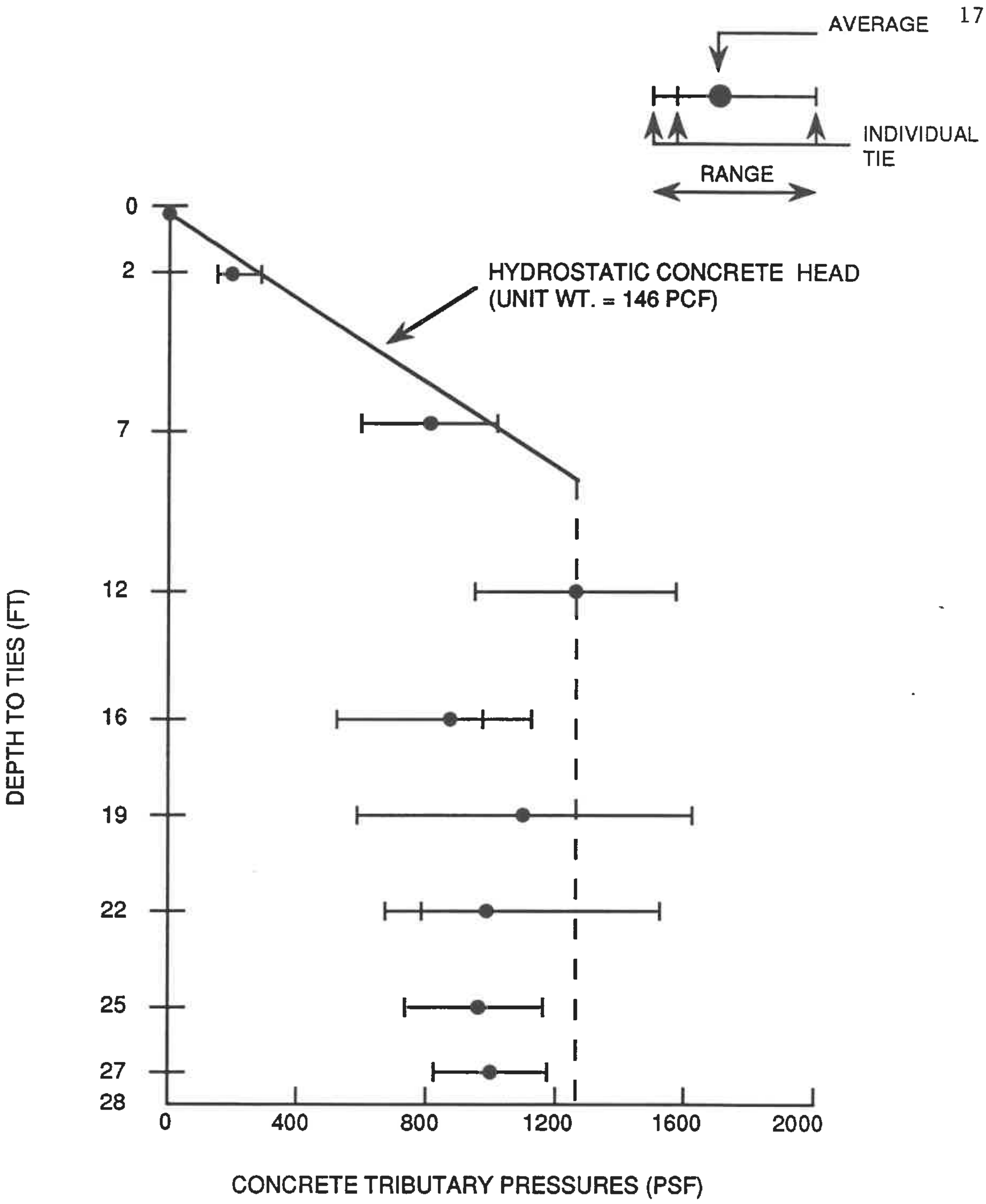

Figure 8. Concrete Tributary Pressures for Wall Segment 2B

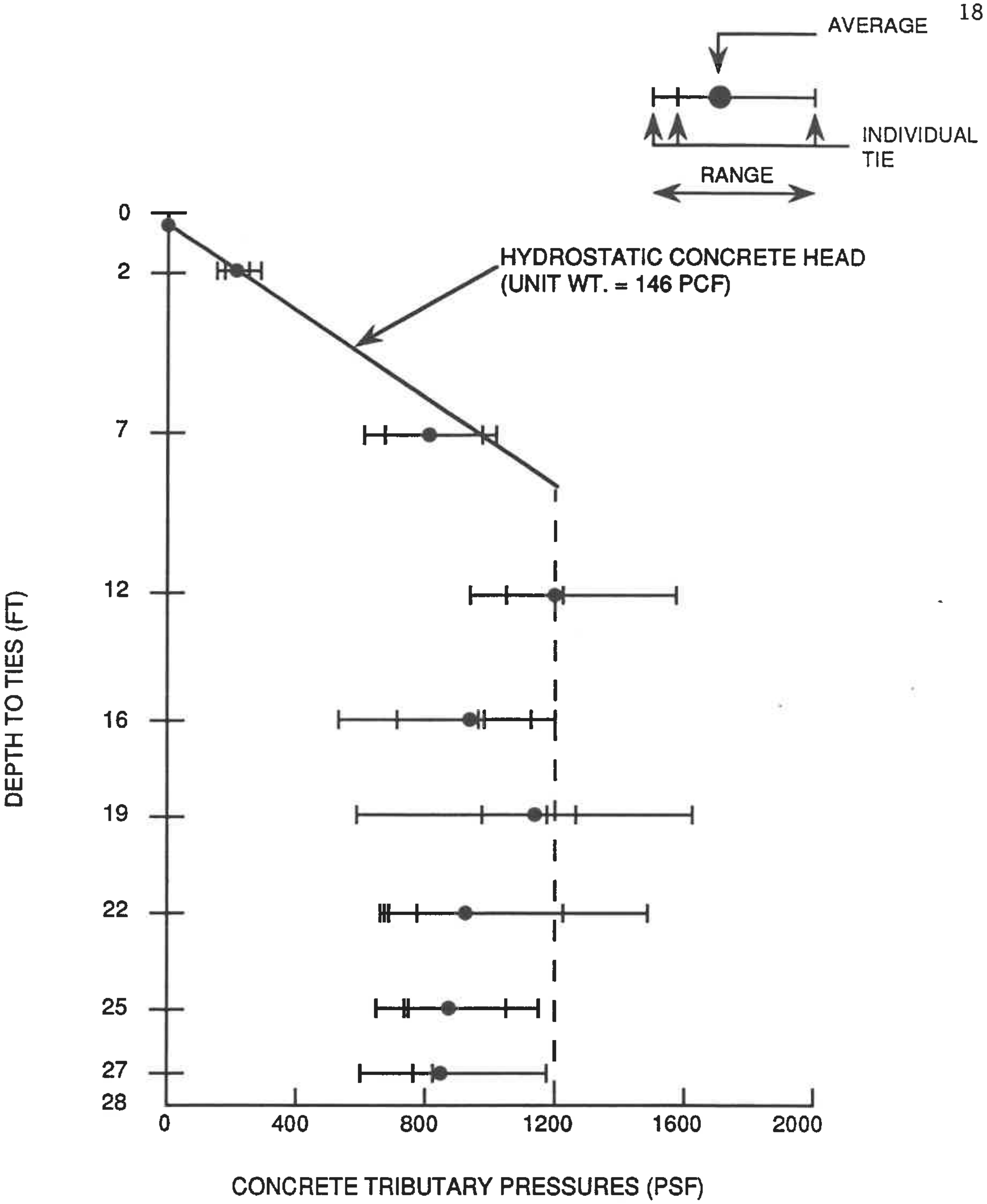

Figure 9. Average Concrete Tributary Pressures for Wall Segments 2A and 2B

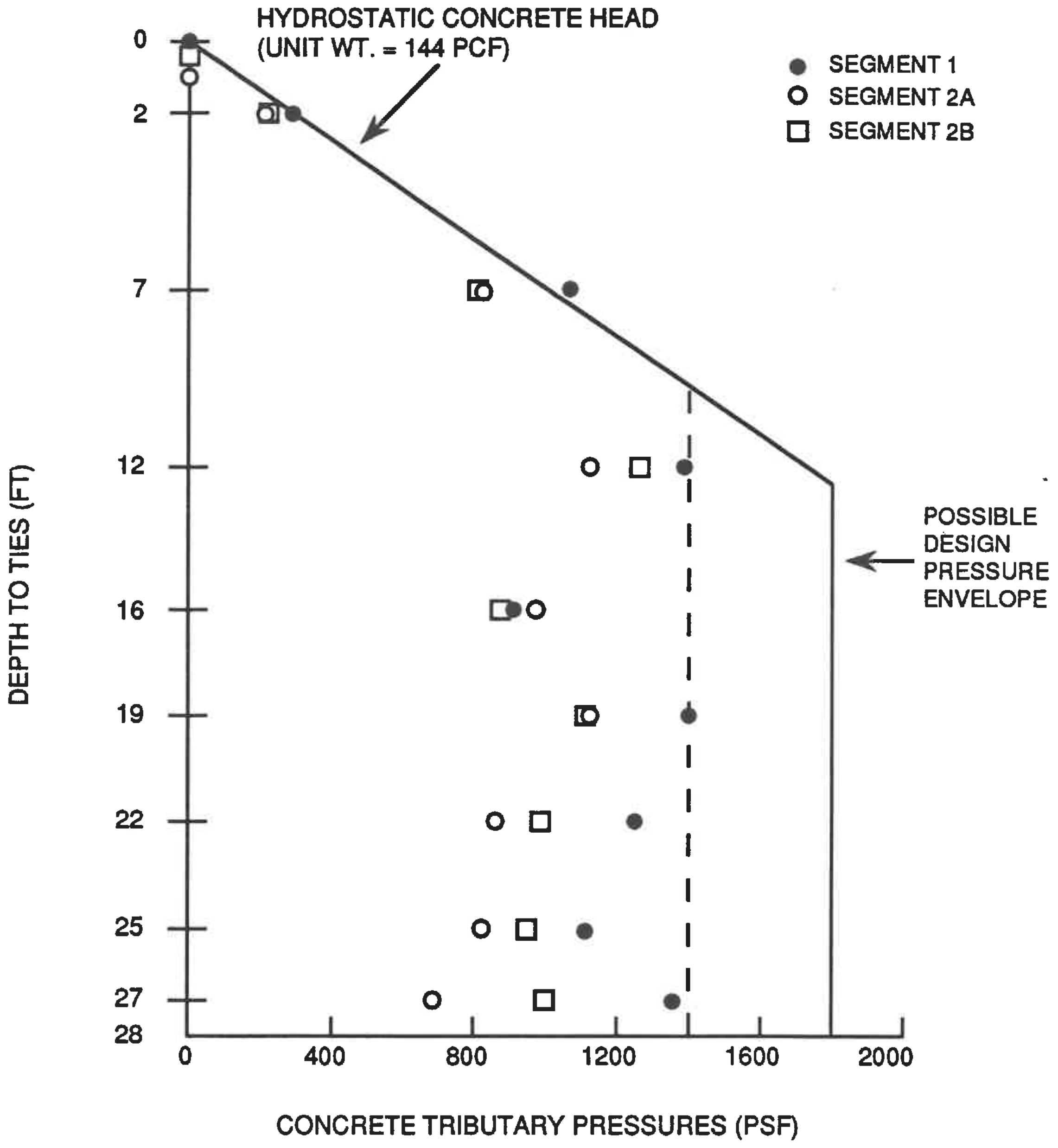

Figure 10. Concrete Tributary Pressures for Wall Segments 1, 2A, and 2B

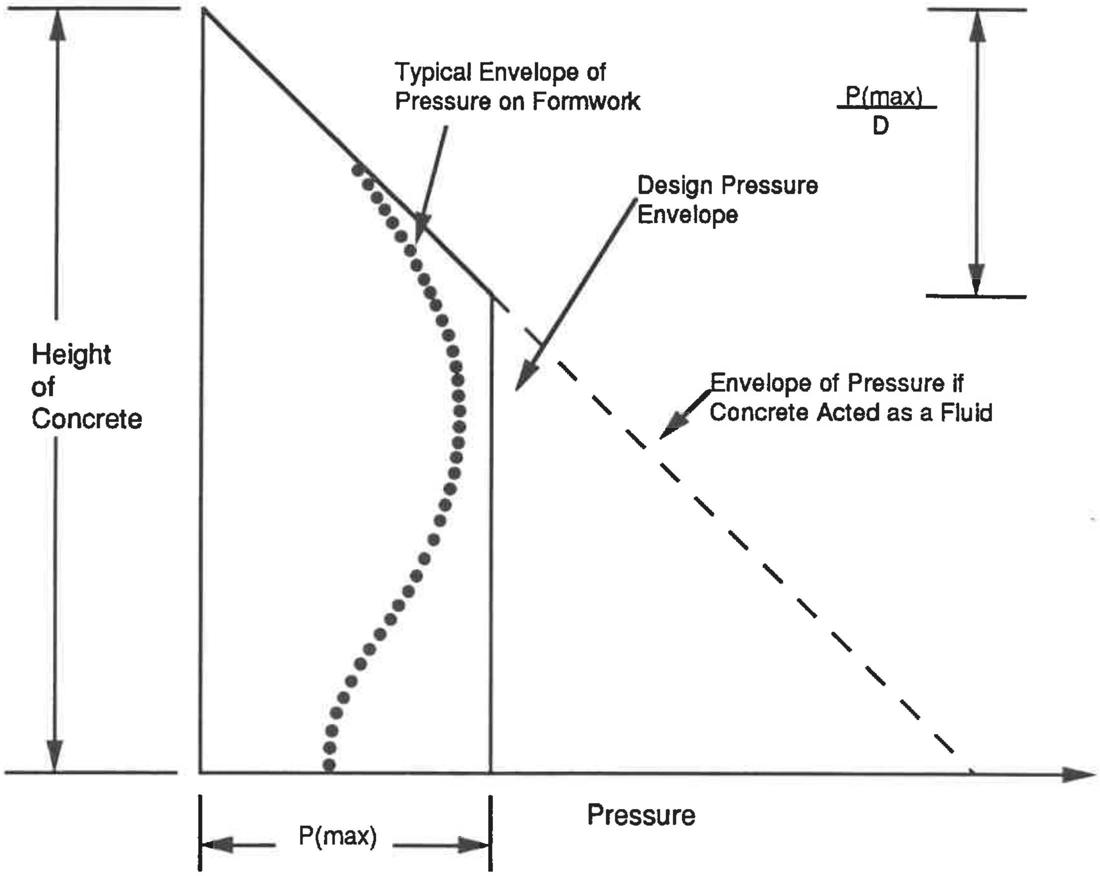

Figure 11. Design Pressure Envelope *(from Reference 2, Figure 3)*

Table 1. **Concrete Mix Proportions per Cubic Yard**

Mix	5-B	5-C	J-2	J-2 RHEO	J-2 50G
Cement (Type II)	120 lbs	115 lbs	598 lbs	598 lbs	598 lbs
Slag	274 lbs	260 lbs			
Fly Ash	135 lbs	125 lbs			
Coarse Aggregate					
No. 4 Stone		600 lbs			
No. 67 Stone	1658 lbs	1110 lbs	1845 lbs	1845 lbs	1845 lbs
Sand	1357 lbs	1380 lbs	1210 lbs	1210 lbs	1210 lbs
Water	240 lbs	220 lbs	267 lbs	229 lbs	267 lbs
Admixtures					
WRDA - 79	21.0 ozs/cy	25.0 ozs/cy	30.5 ozs/cy		30.5 ozs/cy
DARAVAIR	8 - 10 ozs/cy	7.0 ozs/cy	4.0 ozs/cy	5.5 ozs/cy	4.0 ozs/cy
HRWR - Melment 50G					
(Plant)	42.3-47.6 ozs/cy	45.0 ozs/cy			72.0 ozs/cy
(Site)	21.2-31.4 ozs/cy	25.0 ozs/cy			24.0 ozs/cy
- Melment 33			64.0 ozs/cy		
Rheobild 1000				120 ozs/cy	
Pozz 300N				30.0 ozs/cy	
Segment Use	1	2A bottom 7 ft		2A middle 9 ft	2A top 11 ft
			2B bottom 10 ft	2B middle 6 ft	2B top 12 ft

Table 2. Comparison of Variables and Theoretical and Measured Pressures

	Segment 1	**Segment 2A**	**Segment 2B**
Measured Pressure	1395 psf	1130 psf	1270 psf
ACI Calculated Pressure			
Equation 1	4032 psf*	3942 psf*	4058 psf*
Equation 2	1908 psf**	911 psf**	938 psf**
Equation 3	1460 psf**	1076 psf**	1085 psf**
CIRIA Calculated Pressure			
$C_2 = 0.45$	1680 psf	1300 psf	1310 psf
$C_2 = 0.60$	1960 psf	NA	NA
Average Concrete Temperature (T)	56.3°F (13.5°C)	63°F (17.2°C)	63°F (17.2°C)
Average Rate of Pour (R)	11 ft/hr (8.53 m/h)	5.5 ft/hr (1.58 m/h)	5.7 ft/hr (1.74 m/h)
Average Unit Weight (D)	144 pcf (22.624 kN/m^3	146 pcf (22.938 kN/m^3	146 pcf (22.938 kN/m^3)
Vertical Height of Form (H)	28 ft (8.53 m)	28 ft (8.53 m)	28 ft (8.53 m)
Vertical Height of Pour (h)	28 ft (8.534 m)	27 ft (8.229 m)	27.8 ft (8.473 m)
Size and Shape of Formwork Coefficient (C_1)	1.0	1.0	1.0
Concrete Constituent Materials Coefficient (C_2)	0.45-0.6	0.45	0.45

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*Maximum hydrostatic pressure calculated at base.

**Calculated but one or more variables exceed range or limitations of the equation indicated.