Formwork Pressures in Tall and Thick Concrete Walls

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Abstract: Investigations are carried out on two concrete wall placements each 20.5 ft high, with thicknesses of 5 ft and 4 ft, respectively, to determine the loads and pressures exerted by the fresh concrete on the forms. Form tie forces are measured at intervals during the concrete placement, by instrumenting form ties with electrical resistance strain gages. Concrete pressures on the forms are determined from these forces by using the respective tie tributary areas. Maximum pressures of 1,062 psf for Wall I and 891 psf for Wall II are measured. The pressure influencing variables such as concrete density, mix design, admixtures, slump, stiffening time of concrete, concrete temperature, pour rate, consolidation method, and formwork dimensions are determined and used in comparing the measured wall pressures. Comparisons are also made between field results and currently recommended and proposed procedures for estimating wall form pressure.

Introduction

General

Formwork for concrete must support all loads which may be applied until these loads can be carried by the concrete structure itself. Formwork represents a major proportion of the cost of most concrete structures. To design efficient and economical formwork without sacrificing quality and safety, it becomes necessary to predict the magnitude and nature of loads and pressures which the forms will experience. Determining the lateral pressures and influencing variables has been an important issue for form designers, form suppliers, and contractors.

The demand for higher lifts, use of concrete pumps for rapid rates of placing, high speed vibrators, and concrete admixtures has led to a higher range of pressure being exerted on the forms. Determination of significant variables and evaluation of their effect on the lateral pressure of fresh concrete could lead to more representative design values which would help achieve the three objectives in designing formwork, namely: quality, safety, and economy.

Objective and Scope of Research

The objective of this research is to evaluate further the lateral pressures exerted by fresh concrete on wall formwork. The research included two wall placements of considerable height and slow concrete placing rates. The effects of various parameters such as mix design, admixtures, concrete temperatures, rates of pours, and stiffening times for concrete, were considered. The measured pressures were compared to each other and to the values ob-

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Note. Discussion open until February 1, 1990. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on July 9, 1986. This paper is part of the *Journal of Construction Engineering and Management*, Vol. 115, No. 3, September, 1989. ©ASCE, ISSN 0733-9364/89/0003-0444/$1.00 + $.15 per page. Paper No. 23880.

tained from recommended and proposed procedures for predicting lateral pressures.

Significance

Data on pressures exerted by fresh concrete in forms are limited, particularly for tall and thick walls. The results of this study provide additional reference data and indicate situations where pressures may exceed pressures predicted by conventional formulas if such formulas are misused.

Review of Literature

Over the years, investigators (ACI Committee 622 1958; Clear and Harrison 1985; Gardner 1980; Rodin 1952; Douglas et al. 1981) have concluded that many factors affect lateral pressure of fresh concrete in vertical forms to various degrees. These factors have included:

- rate of placement
- consistency of concret
- unit weight of concrete
- maximum aggregate size
- temperature of concrete mix
- ambient temperature
- smoothness and permeability of forms
- cross section of forms
- consolidation methods and amplitude
- depth of vibration
- concrete impact
- placing procedures
- pore water pressure
- type of cement
- depth of placement
- admixtures

As a result of various studies, several recommended and proposed procedures for empirically estimating pressures have been developed. Each method assumes that concrete pressure increases linearly with depth to a maximum value, $P(\text{max})$, and remains constant thereafter. However, the procedure for determining $P(\text{max})$ varies significantly in the methods.

Recommendations of Rodin

Rodin (Rodin 1952; Snow 1965) proposed the following formulas for the lateral pressure of fresh concrete against vertical forms which were based on a concrete mix having proportions of 1:2:4 (by weight) with a slump of 6 in. at a temperature of 70° F:

$$h(\text{max}) = 3.6R^{1/3} \quad (1)$$

$$P(\text{max}) = 150h(\text{max}) \quad (2)$$

where $P(\text{max})$ = maximum lateral pressure (psf); $h(\text{max})$ = head at which maximum pressure occurs (ft); and R = rate of placing (ft/hr).

The concrete density was 150 pcf, and consolidation was done by internal vibration. Where external vibrators are used, Rodin suggested that the formwork should be designed for full liquid pressure, since the full depth would be fluidized.

Recommendations of ACI Committee 347

In 1955, the American Concrete Institute organized Committee 622 (subsequently ACI Committee 347), which developed design recommendations and formulas for estimating the magnitude and distribution of lateral pressure on concrete formwork (ACI Committee 622 1958). Their objective was to keep the determination of pressure straightforward, with a minimum of variables and assumptions. The committee concluded that placement rate, concrete mix temperature, and the effect of vibration are the most important variables to be considered for wall form pressures. The formulas and limitations on their use have evolved somewhat over the years.

For walls and a concrete unit weight of 150 pcf, the maximum pressure for design is currently (ACI Committee 347 1978; Hurd 1979) given as follows:

1. With rates of placement less than 7 ft/hr

$$P(\max) = 150 + \frac{9{,}000R}{T} \quad \text{(3)}$$

where P(max) should not exceed the lesser of 2,000 psf or $150h$.

2. With rates of placement of 7 to 10 ft/hr

$$P(\max) = 150 + \frac{43{,}000}{T} + \frac{2{,}800R}{T} \quad \text{(4)}$$

where P(max) should not exceed the lesser of 2,000 psf or $150h$.

3. With rates of placement greater than 10 ft/hr

$$P(\max) = 150h \quad \text{(5)}$$

where P(max) = maximum lateral pressure (psf); R = rate of placement (ft/hr); T = concrete mix temperature in the forms (degrees F); and h = maximum height of fresh concrete in the forms (ft).

These formulas apply to internally vibrated concrete, made with Type I cement, containing no pozzolans or admixtures, and having a slump of not more than 4 in. Depth of vibration is limited to 4 ft below the top of the concrete.

For concrete weighing other than 150 psf, the resulting pressure from the equations is multipled by the ratio of actual unit weight to 150 pcf.

When a retarding admixture or fly ash or other pozzolan replacement of cement is used in hot weather, an effective value of temperature less than that of the concrete in the form should be used in the pressure formulas.

Recommendations of CIRIA

The Construction Industry Research Information Association in England has conducted studies and developed a method for calculating pressures for design of formwork (Clear and Harrison 1985). Influencing variables considered by this method include: vertical form height, rate of rise, concrete temperature at placing, and the use of admixtures and/or blends or blended cements.

The CIRIA report recommends the following expression for the maximum concrete pressure on formwork:

$$P(\max) = D[C_1\sqrt{R} + C_2K\sqrt{H - C_1\sqrt{R}}] \qquad (\mathrm{kN/m^2}) \qquad (6)$$

or, $P(\max) = Dh$, whichever is the lesser, ... (7)

where C_1 = coefficient (1.0 or 1.5) 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 concrete (m); D = weight density of concrete (kN/m^3); H = vertical form height ($\sqrt{\mathrm{m}}$); h = vertical pour height (m); K = temperature coefficient taken as $[36/(T + 16)]^2$; R = rate of concrete rise (m/h); and T = temperature of concrete at placing (°C). When $C_1R > H$, the fluid pressure (Dh) should be taken as the design pressure.

The term $C_1\sqrt{R}$ is used to consider the effect of vibration and workability. The effects of height of discharge, cement type, admixtures, and concrete temperature are considered in the term $C_2K\sqrt{H - C_1\sqrt{R}}$.

Recommendations of Gardner

Gardner (1980) carried out an investigation by placing concrete under controlled conditions into forms of different widths. He assumed the lateral pressure envelope to be a liquid head up to some limiting value and thereafter constant at the limiting value. The results suggest that the maximum lateral pressure exerted by fresh concrete increased with:

- depth of immersion of the vibrator
- power of the vibrator
- minimum dimension of the form
- rate of placing the concrete
- slump of the concrete, and
- decrease in the concrete temperature.

The following equation was developed:

$$P(\max) = 153h(i) + \frac{2{,}467HP}{d} + 13.26d + \frac{8{,}305R^{1/2}}{T} + 53(\text{slump-3}) \qquad (8)$$

with a limiting value of

$$P(\max) = 153h \qquad (9)$$

where d = minimum form dimension (in.); h = total height of the form (ft); $h(i)$ = immersed depth of the vibrator (ft); HP = power of the vibrator; R = rate of placing the concrete (ft/hr); and T = temperature (°F).

Gardner's study was limited to a form 15.1 ft high and 3 ft wide, and thicknesses (d) of 0.92, 0.95, or 1.7 ft. The concrete was placed in the form in 2.0-ft lifts for the first 14 ft and then the last 1.1 ft. The immersed depth of the vibrator was 3.28 ft and the duration of vibration was 2.5 min.

Gardner suggested that Eq. 8 is moderately accurate at placing rates of 20 ft/hr and conservative for lower placing rates.

Experimental Program

Introduction

In the field studies conducted, form ties for two large wall placements were instrumented to measure the forces during the pour. The formwork details, concrete mix, its properties, and construction procedures were determined by the contractor to meet construction needs of the power plant project. In response to the investigators' request, the owner and the contractor cooperated with and facilitated the investigators' efforts to instrument the forms and collect the data.

Wall and Formwork Description

The field studies were conducted on concrete placements for two walls 20.5 ft high and approximately 44 ft long. Wall I was 5 ft thick and Wall II 4 ft thick. Each face of both walls was reinforced with vertical No. 11 bars spaced 6 in. on center, and horizontal No. 11 bars spaced 12 in. on center.

Figs. 1 and 2 show the layout of the reinforcement, formwork, and instrumented form ties for Walls I and II, respectively. The form faces were 3/4-in. plywood (4 ft × 8 ft) forming panels. The panels were stiffened with C 3 × 4.1 horizontal ribs spaced at 12 in. on center. The horizontal ribs were supported by vertical strongbacks made from double C 5 × 6.7, which were in turn supported at intervals of the vertical span by the ties.

The two forms were held together with a grid of 1-1/8-in. diameter she-bolts (Fig. 3), with a 3/4-in. diameter coarse threaded inside rod. The she-bolt was rated by the manufacturer's literature at a working load of 15,300 lb tension based on a 2.0 to 1 safety factor, as recommended by ACI 347-78 for walls over 8 ft high.

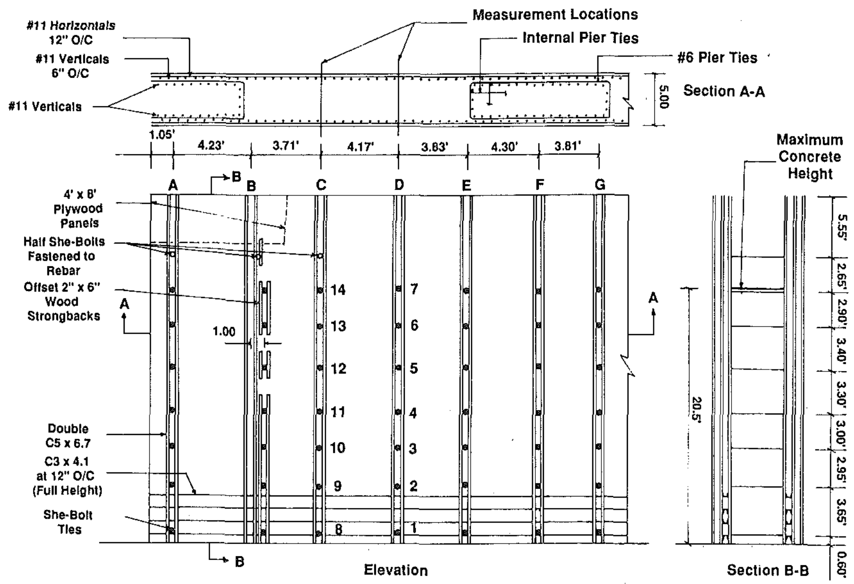

FIG. 1. Wall I Form and Reinforcement Layout

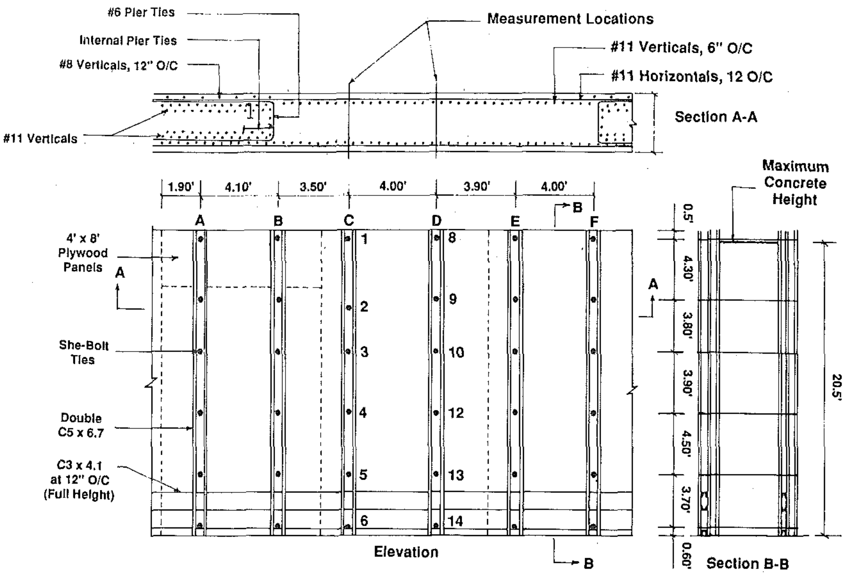

FIG. 2. Wall II Form and Reinforcement Layout

In the first test, the she-bolts at the top of vertical lines A, B, and C were not conventional tie assemblies. Rather, they were half assemblies connected to the outside face rebar to aid in stabilizing the form. Vertical form support was provided by a 2 × 6-in. ledger fastened below the form panels into the previous concrete pour. As shown in Fig. 1, the ties on line B were offset approximately 1 ft from the steel strongbacks due to interference with pier cage reinforcement situated in some sections of the wall. The net effect of the offset was to reduce the tributary area of the ties on line C.

Lateral stability was provided by a series of guy wires. In addition, horizontal channels were connected to the outside of the C 5 × 6.7 channels for form panel alignment.

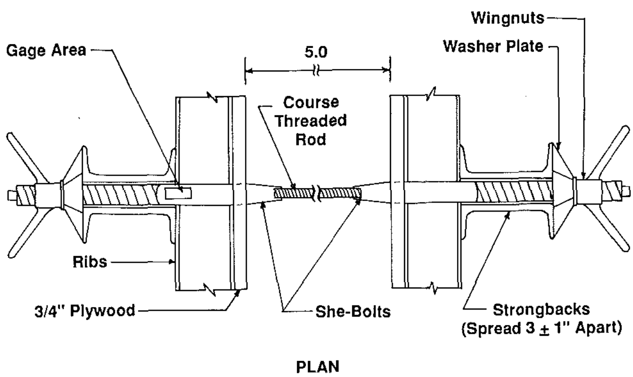

FIG. 3. She-Bolt and Form Assembly

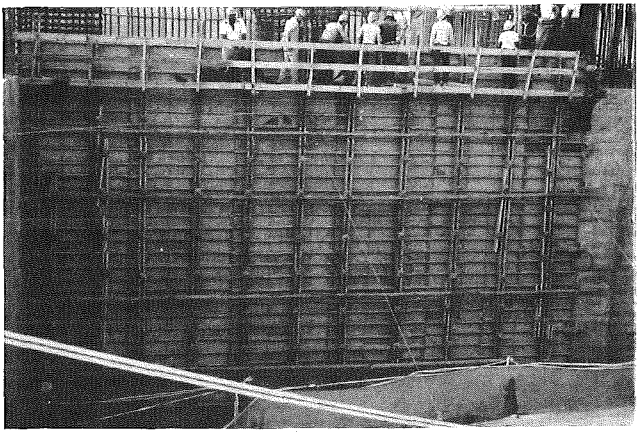

FIG. 4. Formwork for Wall I

Form Tie Instrumentation and Calibration

Fourteen she-bolts were used in the first field test (Fig. 4) and 12 were used in the second field test at the numbered locations shown in Figs. 1 and 2. Each she-bolt was instrumented as a load cell with a full bridge of temperature compensated electrical resistance strain gages. Moisture and abrasion protection was provided by a combination of polyurethane and polysulfide epoxy coatings wrapped with electrical tape.

Calibration of the she-bolts was performed in a universal testing machine. Each tie was calibrated for load versus strain at 1-kip intervals to a maximum load of 18 kips. From these loads and strains, a linear relationship was established for determining the load corresponding to any strain level within the elastic load range.

Concrete Mix and Properties

The concrete mix was made from Type II cement, sand, and coarse aggregate, using mix proportions of 1:1.27:1.50 (by weight) with a water cement ratio of 0.34 (by weight) for Wall I, and mix proportions of 1:2.02:2.53 with a water cement ratio of 0.38 for Wall II. Table 1 shows the quantities used per cubic yard of mix and Table 2 presents the physical properties measured in the field during each pour. The coarse aggregate varied in the two mixes, with Wall I being 1/2 in. (pea gravel) and Wall II being a 3/4-in. stone. A retarding water-reducing admixture (modified lignosulfate) and air entraining admixture (vinsol resin) were incorporated into the mix. The concrete was produced at an on-site batch plant and was transit mixed. A concrete pump was used for placement and the concrete was sampled at the end of the discharge line.

Placement and Consolidation

The concrete pump conveyed 6 to 8 cu yd batches from the transit mix truck discharge point to the formwork. Two of the flexible discharge chutes in both wall placements were in the vicinity of the instrumented rows of she-bolts.

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TABLE 1. Concrete Mix Quantities per Cubic Yard

Mix (1)	Quantity: Wall I (2)	Quantity: Wall II (3)
Cement (Type II)	900 lb	640 lb
Water	305 lb	246 lb
Sand	1,145 lb	1,294 lb
Coarse aggregate	1,349 lb	1,621 lb
Water reducing retarder (Protex PDA-25R, 4 oz/100 lb)	36 oz	26 oz
Air entraining agent (Protex AES)	11 oz (1.25 oz/100 lb)	3.2 oz (0.5 oz/100 lb)
Unit weight	137 pcf	141 pcf

TABLE 2. Concrete Physical Properties

Elapsed time (min) (1)	Slump (in.) (2)	Temperature (°F) (3)	Air (%) (4)
(*a*) Wall I			
4	5	79	7.6
85	3.5	83	5.5
165	3.5	86	4.7
191	4.25	84	3.8
276	4.5	86	5.0
336	3.5	86	5.3
(*b*) Wall II			
5	4.75	71	5.9
50	5.75	68	5.8
58	3.75	69	4.6
154	4.00	71	4.8
296	3.75	71	4.6

The pour was consolidated by internal vibration with motor-in-head-type electric vibrators of 2.5-in. head diameter and 19-in. head length. Since the walls were long and required placement of 222 and 138 cu yd, respectively, the concrete was placed locally in lifts of 2 to 3 1/2 ft. Within each lift, the concrete was deposited in layers 12 and 16 in. high. Each layer was vibrated with the vibrator immersed up to 12 in. into the previous layer. The lower lifts were not revibrated.

Presentation and Analysis of Data

Rate of Concrete Placement

The increase in concrete height versus time in the vicinity of lines C and D is shown in Fig. 5 for Walls I and II. For Wall I, the batch size was reduced after 2.5 hr from 8 cu yd to 6 cu yd per transit truck due to batch plant problems. Since a sufficient number of trucks was not available, the delivery capacity lagged the pumping capacity. Thus, there were occasional

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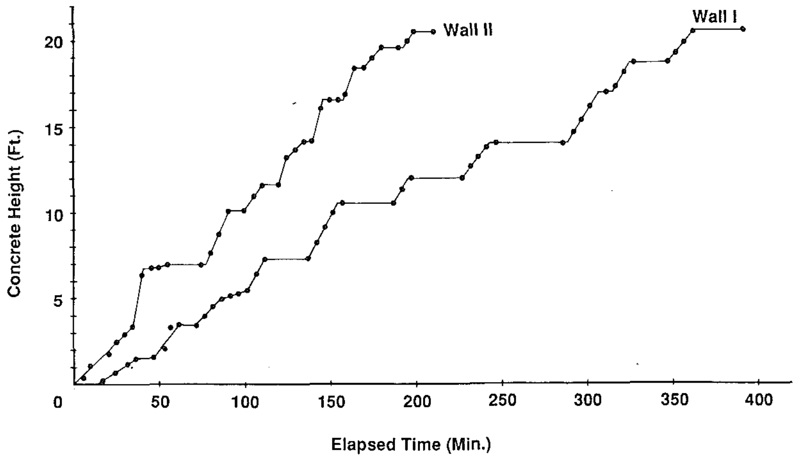

FIG. 5. Concrete Height as Function of Elapsed Time

interruptions in concrete placement. Fig. 5 reflects these delays in the lower average placement rate above a depth of 10 ft for Wall I. The periods of no increase in concrete head represent times when concrete was being placed in other areas of the wall. During the placement of concrete in Wall II, there were no delays due to concrete supply.

Approximately 6.1 hr were required to place Wall I. The inclined portions represent placement rates ranging from 11.0 ft/hr to 4.0 ft/hr, and even 2.0 ft/hr in the fourth lift. The first four lifts averaged 5.1 ft/hr. The second three lifts were nearly constant, at 10 ft/hr, and the last four lifts ranged from 7.5 ft/hr to 8.7 ft/hr. Due to interruptions in concrete delivery, the overall placement rate for Wall I averaged 3.5 ft/hr.

The placement of concrete in Wall II required a much shorter time of 3.32 hr. The placement rates varied from as high as 36 ft/hr in the second lift to 2.1 ft/hr in the eighth lift. There were shorter periods of no increase in concrete height. The overall placement rate for Wall II was 6.2 ft/hr.

Determination of Pressure

The tie loads were recorded at 5-min intervals during the placement process. In order to compare the measured tie loads with pressure theories, each tie load was divided by the associated tie tributary area. This tributary area was assumed to be bounded by lines located at one-half the distance to the adjacent ties both laterally and vertically. For the bottom ties, the lower limit of the tributary area was the base of the wall. For the top ties, the upper limit of the area was the top of the concrete pour.

Tie forces were reduced to concrete pressure in the vicinity of each tie. The results for tie lines C and D were also averaged at each tie level. Note that the instrumentation of tie number 12 for Wall I and tie numbers 8 and 12 for Wall II were damaged during installation. Thus, in Wall I only tie number 5, and in Wall II only tie numbers 1 and 4 contributed data to the average pressures at their respective elevations. When the concrete was being placed and vibrated in the instrumented area, the pressures increased. When

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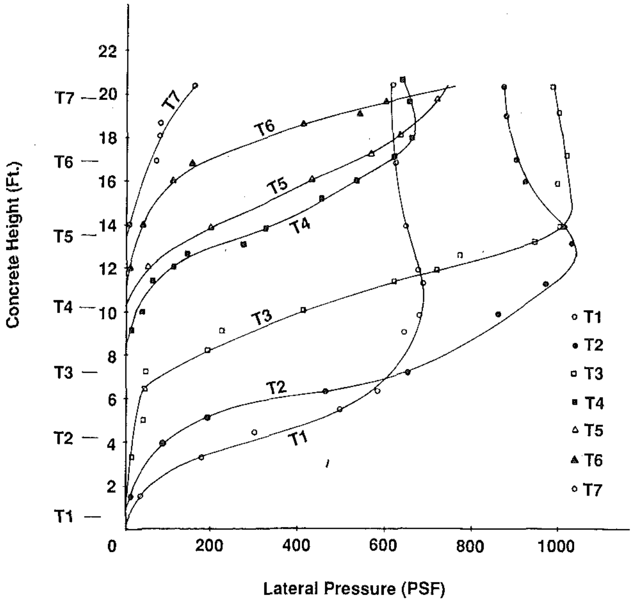

FIG. 6. Lateral Pressure at Ties 1–7 versus Concrete Height (Wall I)

delays occurred or activity shifted to other areas of the wall, the pressure subsided somewhat.

Analysis of Measured Pressures

Concrete lateral pressures at each tie were plotted separately for both Walls I and II. Figs. 6 and 7 show the concrete pressures plotted versus concrete height for Wall I, and Figs. 8 and 9 for Wall II. An examination of the test results revealed that pressure envelopes were essentially linear for an initial depth, thus indicating that fresh concrete behaves almost as a fluid. The pressure reached a maximum before starting to decrease with an increase in concrete head as a consequence of concrete stiffening and becoming capable of supporting surcharges.

The stiffening time of concrete at each tie level for the walls was estimated to be the approximate time required to place concrete from the tie elevation to the point of maximum pressure. The stiffening time of the concrete for Wall I ranged from 1.97 hr to 3.25 hr at different tie elevations. The average for the entire wall was calculated to be 2.78 hr. For Wall II the stiffening time of the concrete ranged from 0.92 to 2.02 hr for different tie elevations, with an average of 1.56 hr.

Average lateral pressure as a function of form height is shown in Figs. 10 and 11 for Walls I and II, respectively. The pressure curves are shown for different concrete heights, with the effect of concrete setting apparent. At concrete heights of less than about 7 ft, the maximum lateral pressure was located at the form bottom. As the concrete head increased, the location of the maximum lateral pressure shifted upward. In both walls, the maximum pressure was located at approximately 4 to 6 ft from the form bottom, when

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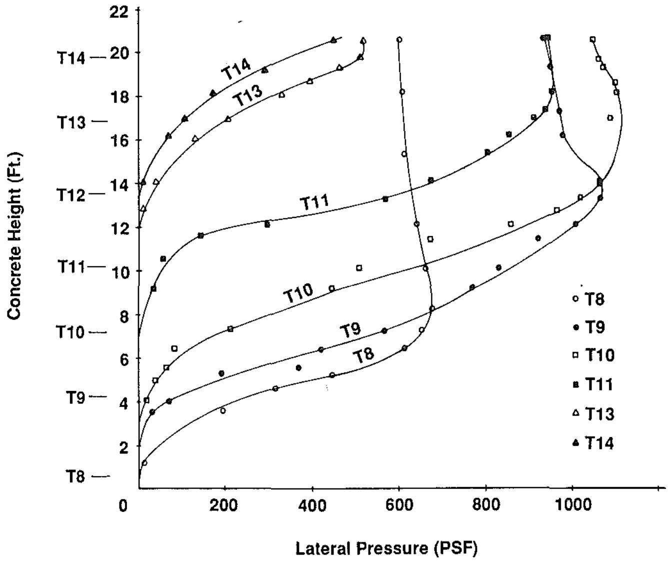

FIG. 7. Lateral Pressure at Ties 8–14 versus Concrete Height (Wall I)

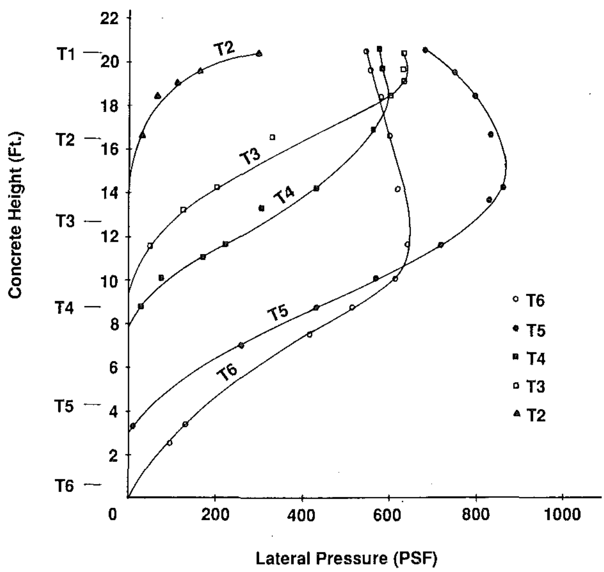

FIG. 8. Lateral Pressure at Ties 2–6 versus Concrete Height (Wall II)

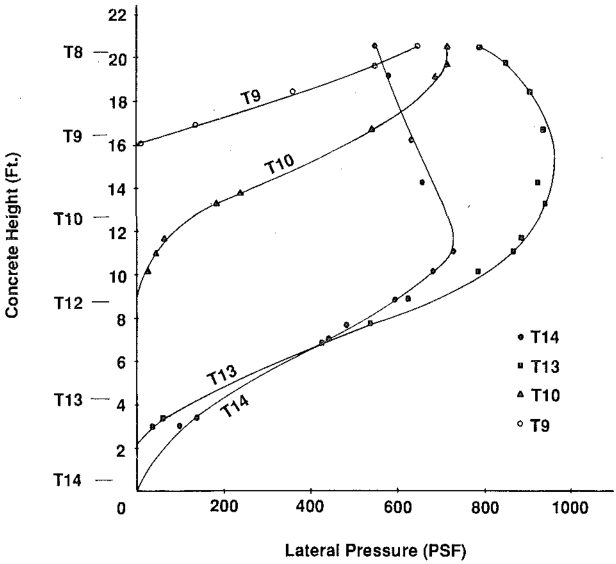

FIG. 9. Lateral Pressure at Ties 9–14 versus Concrete Height (Wall II)

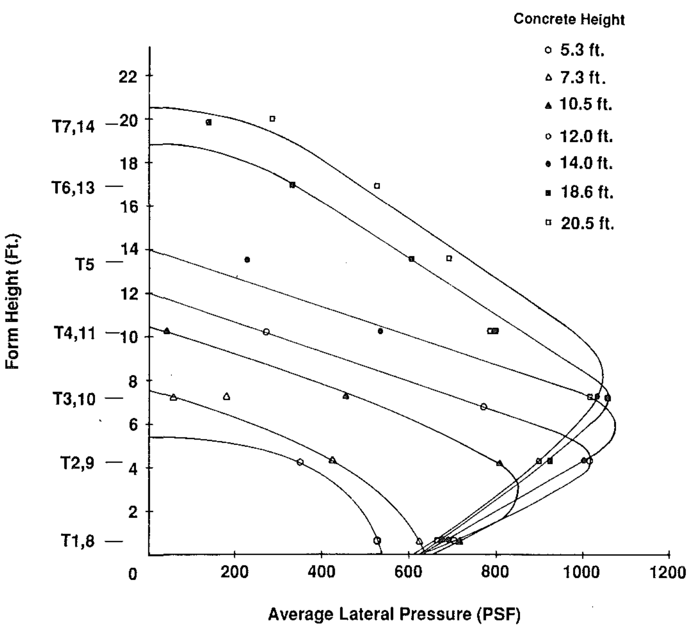

FIG. 10. Average Lateral Pressure versus Form Height (Wall I)

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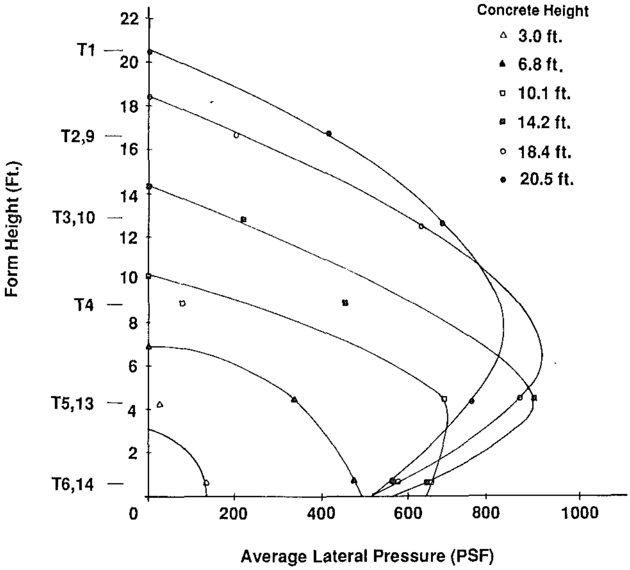

FIG. 11. Average Lateral Pressure versus Form Height (Wall II)

the total concrete height from the form bottom was about 14 ft. Thereafter, even though the concrete height increased, the pressure subsided somewhat below the maximum lateral pressure. After reaching a maximum of 1,062 psf for a concrete total height of 12.0 to 18.2 ft for Wall I and a maximum of 891 psf for a concrete height of 14.2 to 16.6 ft for Wall II, the pressure decreased as the concrete height increased.

Comparison with Theories

Gardner, ACI, and CIRIA assume the pressure envelope to be a liquid head from the free surface to a maximum level, and at greater depths to be constant at that maximum. A plot of the maximum average lateral pressure versus form height (Fig. 12) shows that near the free surface, the lateral pressure exerted by the concrete is approximately hydrostatic, but decreases significantly at lower levels. After reaching a maximum level, the pressure decreases towards the bottom of the form instead of remaining constant, as assumed by the three theories.

Data ("Water" 1979) obtained from the water reducer manufacturer indicate that 4 oz of the water reducer per 100 lb of cement retards the normal set time of Type I cement by 1.0 to 2.0 hr. Actual retardation varies significantly with materials and field conditions. Since a set retarding water reducing admixture and Type II cement were employed in both tests, the setting time was expected to increase further. A negative adjustment to the concrete temperature is sometimas used in the ACI equations as a modification to consider the effect of retarded set, although this approach is not a part of the ACI recommendations.

Table 3 shows the variables which are to be used in the calculations of the pressures by the ACI, CIRIA, Gardner, and Rodin methods. Table 4

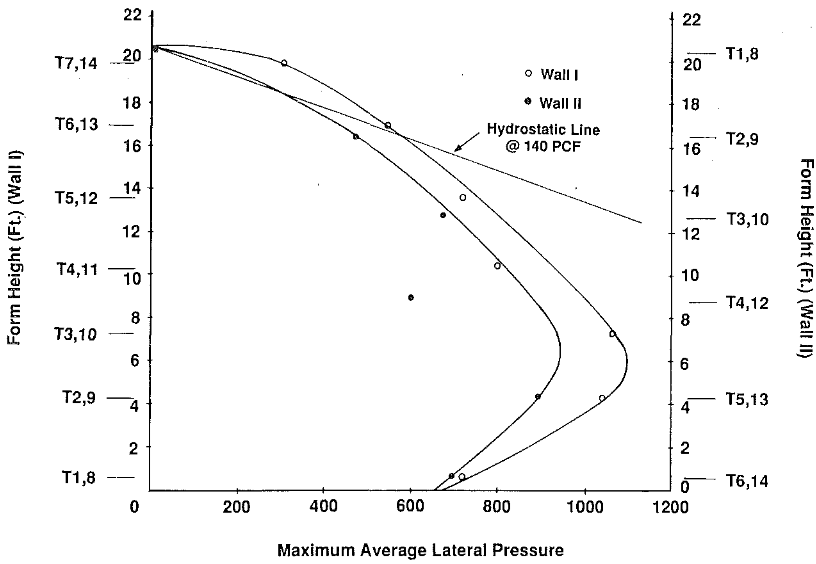

FIG. 12. Maximum Average Lateral Pressure versus Form Height

TABLE 3. Summary of Variables for Two Walls

Variable (1)	Wall I (2)	Wall II (3)
Maximum average lateral pressure	1,062 psf	891 psf
Concrete height at which maximum pressure occurred	16.2 ft	15.2 ft
Form height at which maximum pressure occurred [h(max)]	6.0 ft	6.2 ft
Average concrete temperature (T)	84° F	70° F
Average rate of pour (R)	3.5 ft/hr	6.2 ft/hr
Immersed depth of vibrator [$h(i)$]	20 in.	20 in.
Minimum form dimension (d)	60 in.	48 in.
Average unit weight (w)	137 pcf	141 pcf
Average slump	4.0 in.	4.4 in.
Water cement ratio	0.34	0.38
Mix	1:1.27:1.50	1:2.02:2.53
Coarse aggregate size	#78 (1/2 in. to No. 8)	#67 (3/4 in. to No. 4)
Air entraining admixture (fl oz/100 lb)	0.9	0.5
Retarding water reducing admixture (fl oz/100 lb)	4.0	4.0
Average air percentage	5.3	5.1

TABLE 4. Comparison of Theoretical and Measured Pressures

Pressures (psf) (1)	Wall I 84° F (2)	Wall I 64° F (3)	Wall II 70° F (4)	Wall II 50° F (5)
Measured	1,062	—	891	—
Rodin[a]	749	749	930	930
Gardner[b]	1,332	1,390	1,313	1,431
CIRIA[c]	760	—	1,072	—
ACI	480	587	920	1,188

[a]Lateral pressures based on h(max) calculated from equation (Eq. 1) as proposed by Rodin: h(max) = 5.5 ft for Wall I; and h(max) = 6.6 ft for Wall II.

[b]In Eq. 9, power of vibrator = 1 hp.

[c]Coefficient C_1 = 1.0 (for walls) and C_2 = 0.45 (for ordinary, rapid hardening, or sulphate resisting portland cements with retarding admixture).

compares the measured lateral pressures and those predicted by the four theories. The approximate retarding effect of 4 oz of retarder is suggested by one source (Richmond 1977) to be a −20° F adjustment to the concrete temperature. This possible effect is evaluated in Table 4.

Comparison shows that the equations proposed by Gardner give pressures which are quite conservative, even when temperature adjustments are not made to account for the effect of a set retarding admixture. The third term in Gardner's equation, $13.26d$, where d is the minimum form dimension in inches, contributes a significant fraction of the total pressure because the minimum form dimensions were 60 in. and 48 in. for Walls I and II, respectively. For Wall II, the rate of placement of concrete was higher and the temperature was lower, which tends to increase the calculated lateral pressure, but the smaller dimension of Wall II reduced the calculated pressure. With the variables compensating, pressures calculated using Gardner's formula were about equal for the two walls, although the measured pressures were not very similar.

Comparisons with the results of CIRIA show an underestimation of the pressure in Wall I and an overestimation of the pressure in Wall II. No temperature adjustment effect was calculated, since the effect of the retarder and cement type is already included in the CIRIA results through coefficient C_2.

The ACI equation considers only the rate of pour and the mix temperature. For Wall I, which had a lower rate of pour, the predicted pressures are very low compared with the measured pressures, even with the −20° F adjustment to the concrete temperature. The comparison is better for Wall II, which has a higher rate of pour and a lower temperature mix. It is disturbing that the calculated pressure for Wall I is even less than the allowable immersion depth times the unit weight (4 ft × 140 pcf = 560 psf). Some minimum value appears to be needed, since the placement rates in lifts can be higher than the average rate R, and since vibration could produce such a liquid head magnitude.

Although a thorough report of the investigation was not made, a recently published discussion (Sturrup and Deans 1985) indicates that field measurements by Ontario Hydro have also produced data showing similar results on

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tall and thick walls with low rates of pour. Pressures were reported to have exceeded the ACI equation prediction by as much as 50%, while Gardner's equation overestimated the pressures. Their results appear to be compatible with the findings of this study.

Conclusions and Recommendations

Based upon the field tests and analysis conducted in this study, the following conclusions can be made.

1. The average maximum pressure measured was 1,062 psf and 891 psf for Walls I and II, respectively. The rate of placement of concrete was greater in Wall II than in Wall I; if all other conditions had been the same, this difference should have resulted in a larger pressure in Wall II compared with the pressure exerted on Wall I. However, due to a shorter stiffening time for the concrete in Wall II, the overall effect was a relatively smaller pressure on Wall II compared to the pressure on Wall I. The possible effect of the aggregate type, air content, and cement content variations could not be determined but may contribute to the differences.
2. Among the three primary theories available, the ACI equation substantially underestimated the pressure in one case and slightly overestimated the pressure in the second, Gardner's equation substantially overestimated the pressure in both cases, while the CIRIA equation results were somewhat low in one case and somewhat high in the other.
3. The three theories agree that with a decrease in temperature, the lateral pressure exerted by fresh concrete increases. However, the increase in lateral pressure for the same reduction of temperature (20° F), in the three methods (ACI, Gardner, and CIRIA) is inconsistent. The percentage increase in lateral pressure for a 20° F reduction in temperature for each of the three theories is listed in Table 5.
4. The term in Gardner's equation for the influence of wall thickness may need an upper limit. This term seemed to dominate unusually for the very thick walls in the field tests.
5. The ACI equation underestimated the pressure, although it must be made clear that the conditions did not meet the limitations of the ACI provisions because of the admixtures and cement type in the mixes. However, the calculations revealed that the ACI formula can result in pressure estimates less than the liquid head at the allowable immersion depth of the vibrator. Due to the effects of the vibrator immersion and liquid heads in lifts, it may be desirable to revise the ACI provisions. The ACI equations could have a P(min) for design at depths greater than 4 ft of 600 psf, which would be equal to the allowable vibrator

TABLE 5. Percentage Increase in Pressure for 20° F Temperature Reduction

Theory (1)	Wall I (2)	Wall II (3)
Gardner	4.4	9.0
ACI	22.3	29.1
CIRIA	29.2	41.5

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immersion of 4 ft times the concrete density, or, alternately, a P(min) of 150 $h(i)$, where $h(i)$ is the maximum vibrator immersion or the maximum height of a lift, whichever is greater, but not less than 4 ft.

A better understanding of stiffening time and how it is affected by temperature, type of cement, workability (including water cement ratio, aggregate size, and cement content), and the type and duration of vibration would lead to its better prediction and a more accurate lateral pressure.

Since the scope of the program involved only two studies, with variations in pour rate, temperature, mix, and minimum form dimension, the effect of any one variable could not be determined conclusively. Additional data on these variables and type and duration of vibration, their effect on the stiffening time of concrete, and to what extent these parameters affect the lateral pressure need to be collected and analyzed, before a more accurate prediction of the pressure can be made. The results do make it clear that the caveats and limitations of the ACI theory with regard to effects of admixtures and cement type must be taken seriously by users.

Acknowledgments

The writers gratefully acknowledge Carolina Power and Light Company, owner, and Daniel Construction Company, contractor, for their cooperation in allowing the field study to be conducted at the Shearon Harris Generating Station located near Raleigh, N.C. Particular thanks are due Ronald Gurganus of the CP&L staff for his assistance and patience. The writers assume full responsibility for the accuracy and interpretation of the data.

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Appendix II. Notation

The following symbols are used in this paper:

C_1	=	coefficient dependent on size and shape of formwork;
C_2	=	coefficient dependent on concrete materials;
D	=	weight density of concrete;
d	=	minimum form dimension;
HP	=	power of vibrator;
H	=	vertical form height;
h	=	vertical pour height;
$h(i)$	=	immersed depth of vibrator;
$h(\max)$	=	head at which maximum pressure occurs;
K	=	temperature coefficient;
$P(\max)$	=	maximum lateral pressure;
R	=	rate of concrete vertical placement; and
T	=	temperature of concrete at placement.

APPENDIX III. CONVERSIONS TO SI UNITS

To convert	To	Multiply by
in.	mm	25.4
ft	mm	304.8
fl oz	L	0.0296
lb	kg	0.454
pcf	kg/m^3	16.02
psf	Pa	47.9

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