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Research Article

Design of Short Wall Timber Formworks Using New Formulas

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Abstract: The construction of reinforced concrete requires formwork, whether from timber, steel, or any other material. Generally, formwork accounts for 20% to 25% of a project's cost. This research aims to come up with new formulas that can guide the engineer in designing timber formwork in a safe, easy, and economical manner. By using the statistical analysis program in this study, we calculated the spacings of studs, wales, and ties in a faster manner than the traditional method by analysing the results of bending, shear, deflection, crushing, etc. The results of the study involve the effects of placement rate, concrete temperature, sheathing thickness, pressure values, and stud and wale sections on the spacing of components of the formwork. There are seven equations built to calculate the spacings of individual components.

Keywords: Formwork; Casting rate; Short wall; Pressure value

1. Introduction

Because the fresh concrete exerts pressure on the wall forms, the latter transferred the pressure through the sheathing, studs, and wales to the tension ties connecting the two sides. The sheathing is often plywood, the studs support the sheathing, and the double wales are long horizontal members that support the studs, often constructed from steel or wood. Moreover, washer plates attached to ties support the wales. During the wall formwork design, there are three stages: the first is determining the spacings between the studs, and this stage requires checking three factors, i.e., bending, shear and deflection. The second is determining the spacings between wales, and four factors must be checked, i.e., bending, shear, deflection, and crushing; it is the last stage where ties are arranged, and for this, the following five factors are examined, i.e., bending, shear, deflection, bearing and load on the tie. The main objective of this study is to present one equation for each stage of the design process and to analyse the effects of concrete temperature, rate of placement, pressure value, sheathing thickness, and studs in the design of wall formwork.

Piechna (2016) [1], Rajeshkumar and Sreevidya (2019) [2], and Radziejowska and Sobotka (2020) [3] covered criteria that could be used to selecting a formwork system and discussed their significance when selecting one. According to time and cost, Deshmukh and Shalgar (2016) [4] compared two methods of formwork (tunnel and aluminum). They concluded that the tunnel method is more advantageous than aluminum. Besides, in the research by Ansari and Kudale (2016) [5] and Kalithasan et al. (2016) [6], aluminum formwork (MIVAN Technology) was compared to conventional formwork. According to the researchers, conventional formwork is economically more advantageous than aluminum formwork. In another study, Biruk and Jaskowski (2017) [7] proposed a programming modelling approach to support the process of planning formwork, taking into account the chances of reusing panels for the next zones. Mansuri et al. (2017) [8] used Building

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Information Modeling (BIM) in conjunction with a cascading tool to demonstrate increases in worker productivity for formwork and a cost reduction. A case study in Cincinnati, Ohio, supported their method. Lee et al. (2018) [9] also used the harmony search algorithm (HSA) in their report in order to demonstrate increased worker productivity and reduced costs by using the least number of nonstandard panels. They concluded that HSA is superior to the genetic algorithm (GA) for planning. Furthermore, Hyuna et al. (2018) [10] developed a building information model to shorten the design process and they validated the model for the hospital case study. The studies by Hussien (2019, 2022) [11, 12] show the relationships between the slab thickness and the dimensions of formwork. He calculated that the ideal dimensions for timber formwork are 3 in x 4 in for the slab thickness equal to 8 in, by calculating the minimum spacings between the formwork components to obtain an economical and safe design and finally calculating the optimum casting rate, which equals 4.92 ft/h, and finding the optimum lateral pressure. Zhang et al. (2016) [13] examined the effect of the concrete slump, casting speed, and vibration on lateral pressure and found that there were huge differences in the values among the specifications. Zhang et al. (2019) [14] investigated the lateral pressure distribution of fresh concrete and the effect of ultra-deep vibrations on the lateral pressure of concrete walls, which was found to correspond with the experimental results.

2. Analysis and Design

Besides the type of concrete and temperature, the rate of placement and the depth of concrete within a form determine the maximum lateral pressure concrete exerts against a form. The American Concrete Institute standard ACI 347R-14 [15] recommends using the following formulas to determine the maximum lateral concrete pressures for concrete with a weight of 150 lb/ft^3.

Type 1) for walls with a casting rate of 7 ft/h or less:

$$P = Cc\,Cw\left[150 + \frac{9000R}{T}\right]\ \text{lb/ft}^2 \tag{1}$$

Type 2) for walls with a casting rate of 7 to 15 ft/h:

$$P = Cc\,Cw\left[150 + \frac{43400}{T} + \frac{2800R}{T}\right]\ \text{lb/ft}^2 \tag{2}$$

Type 3) for walls with a casting rate greater than 10 ft/h:

$$P = w\,h\ \text{lb/ft}^2 \tag{3}$$

For this investigation, the wall-formwork shown in Fig. 1 has been studied by applying the equations from standard ACI 347R-14 [15] in the author’s program to determine the spacings of studs, wale, and ties, with changes in casting rate, concrete temperature, sheathing thickness, and stud and wale sections (assuming the same section for stud and wale) such as:

- The casting rates (R) is based on these values, i.e., 3, 4.5, 6, 9.5, 10, 11.5, 12, 13.5, and 15 ft/h;
- Temperatures of concrete (T) are 74, 78, 82, 86, and 90 F°;
- The sheathing thicknesses (Tsh) are 0.5, 0.625, 0.75, 0.875, and 1 in;
- As both stud and wale have the same section, they will take the values of 1x2, 1x3, 1x4, 1x6, 1x8, 1x10, 1x12, 2x2, 2x3, 2x4, 2x6, 2x8, 2x10, 2x12, 4x4, 4x6, and 6x6 in;
- Limit of deflection = L/360;
- The height of the wall (hw) is 8 ft;
- The width (ww) of the wall is 8 in.

Table 1 lists the allowable stresses for the lumber.

Table 1. The adjusted allowable stresses being used

Property	Lumber (psi)
Allowable stress in bending, σ	1810
Allowable stress in horizontal shear, τ	120
Allowable stress in compression perpendicular to the grain, Fc⊥	485
Modulus of elasticity, *E*	1.7E+06

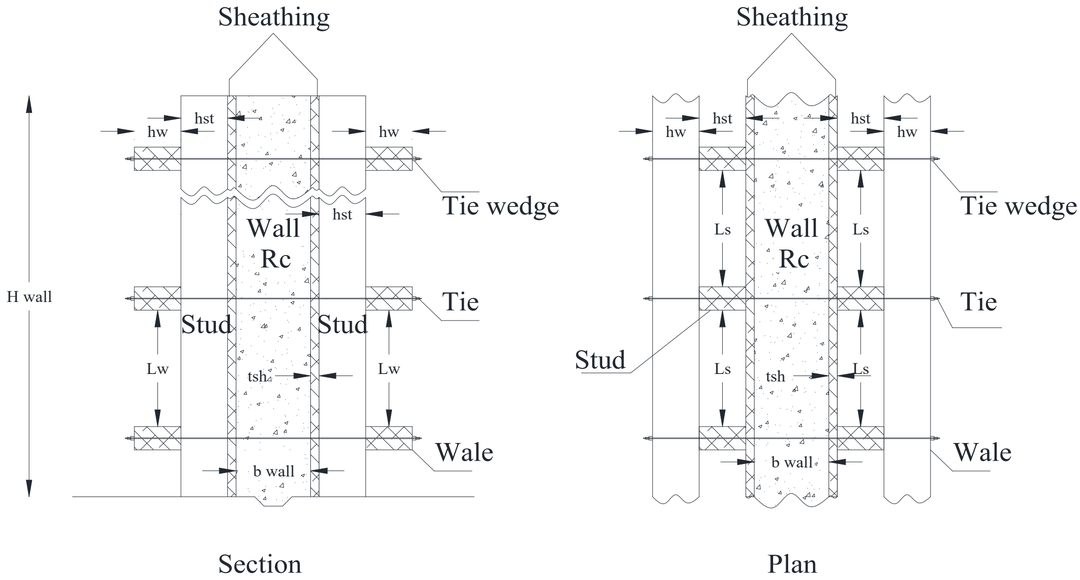


Figure 1. The model

3. Results

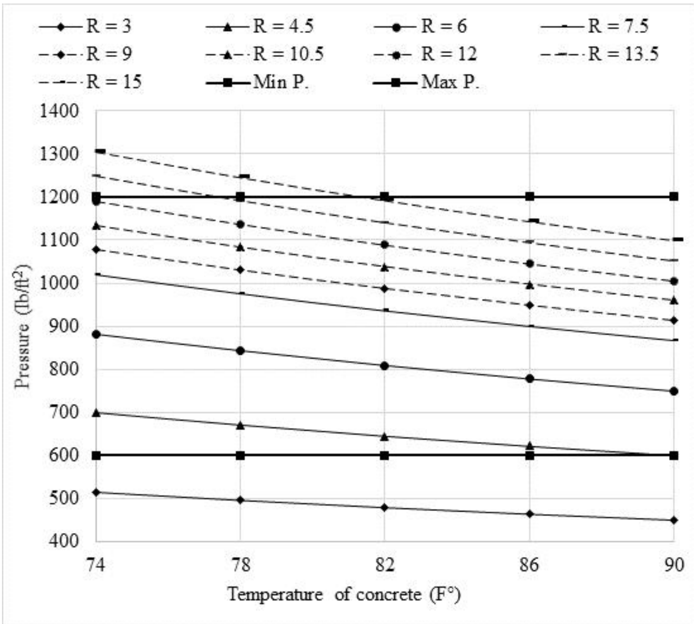


Figure 2. Pressure values for different concrete temperatures and placement rates

In Fig. 2, there are two types of lines: the first are constant lines at 600 and 1200 lb/ft^2 for the minimum and maximum pressures as determined by the The American Concrete Institute (ACI) standard, and the second is an inclined line reflecting the varied pressure values achieved based on the concrete temperature and rate of placement.

Fig. 2 shows that increasing the concrete temperature by one-degree decreases pressure the values by 1% while increasing the placement rate by 1.5 feet/hour causes the pressure values to increase by 20% when placing slower than 7.5 ft/hr and 5% when placing faster than 7.5 ft/hr.

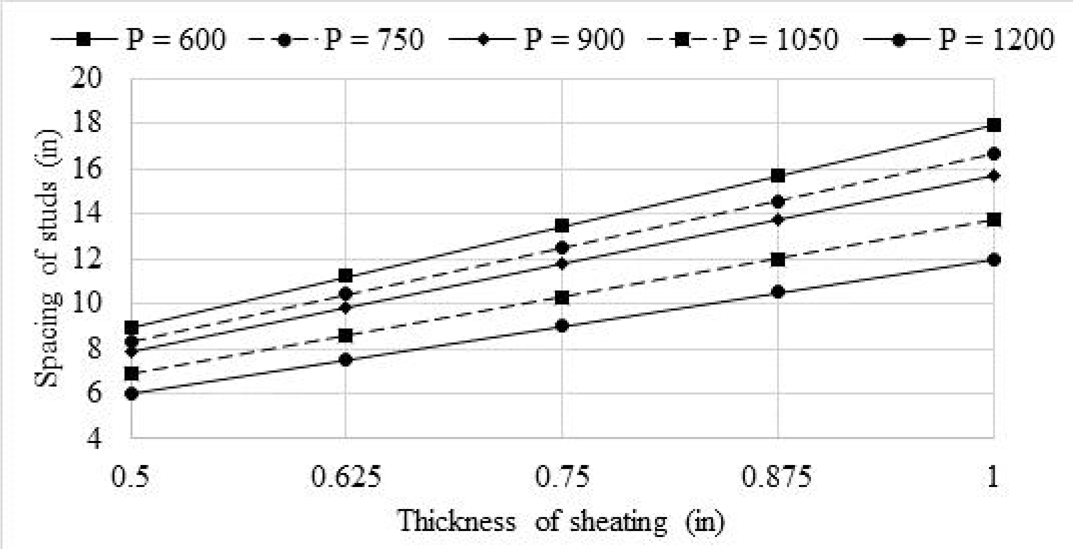


Figure 3. The relationship between the sheathing thickness and stud spacing under different pressures

An increase in the sheathing thickness by 25% from the original thickness results in an increase in the stud spacing by 16%, as shown in Fig. 3. In contrast, an increase in pressure by 25% from the original pressure results in a decrease in the stud spacing by 10%. The results are based on three checks against bending, shear, and deflection. Utilizing the Labfit software, we can find Equation (4) for this relationship.

$$Ss = 0.038671 * Tsh * (2185.64 - P)^{0.8347} \qquad (4)$$

Table 2. Stud spacings calculated by the traditional method and Equation (4)

	Stud spacing by the traditional method					Stud spacing by equation (4)					Error
Tsh (in) P (Ib/ft^2	0.5	0.625	0.75	0.875	1	0.5	0.625	0.75	0.875	1	
600	8.97	11.21	13.46	15.7	17.94	9.07	11.34	13.60	15.87	18.14	1.1%
750	8.33	10.41	12.49	14.58	16.66	8.35	10.43	12.52	14.61	16.69	0.2%
900	7.84	9.8	11.76	13.72	15.68	7.61	9.52	11.42	13.32	15.23	-3.0%
1050	6.86	8.57	10.29	12	13.71	6.86	8.58	10.30	12.01	13.73	0.1%
1200	6	7.5	9	10.5	12	6.10	7.62	9.15	10.67	12.20	1.6%

Table 2 has three parts: the first part is the traditional method that calculates the pressure from Equations (1) or (2) or (3) and checks bending, shear, and deflection to determine the stud spacings, and then takes the minimum spacing. The second part is the stud spacing using Equation (4); the third part is the differences between the stud spacings using the traditional method and Equation (4) can be obtained.

Table 3. Wale spacing

		Stud section													
Tsh (in)	P (lb/ft^2)	1x2 (in)	1x3 (in)	1x4 (in)	1x6 (in)	1x8 (in)	1x10 (in)	1x12 (in)	2x2 (in)	2x3 (in)	2x4 (in)	2x6 (in)	2x8 (in)	2x10 (in)	2x12 (in)
0.5	600	4.0	6.7	9.4	14.6	14.6	14.6	14.6	8.0	13.4	18.7	29.4	38.8	49.5	58.4
	750	3.5	5.8	8.1	12.6	12.6	12.6	12.6	6.9	11.5	16.1	25.4	33.4	42.7	50.3
	900	3.1	5.1	7.2	11.1	11.1	11.1	11.1	6.1	10.2	14.3	22.5	29.6	37.8	44.6
	928	3.0	5.0	7.0	10.9	10.9	10.9	10.9	6.0	10.0	14.0	22.0	29.0	37.0	43.7
	1050	3.0	5.0	7.0	10.9	10.9	10.9	10.9	6.0	10.0	14.0	22.0	29.0	37.0	43.7
	1200	3.0	5.0	7.0	10.9	10.9	10.9	10.9	6.0	10.0	14.0	22.0	29.0	37.0	43.7
0.625	600	3.2	5.4	7.5	11.7	11.7	11.7	11.7	6.4	10.7	15.0	23.5	31.0	39.6	46.7
	750	2.8	4.6	6.5	10.1	10.1	10.1	10.1	5.5	9.2	12.9	20.3	26.7	34.1	40.3
	900	2.5	4.1	5.7	8.9	8.9	8.9	8.9	4.9	8.2	11.4	18.0	23.7	30.2	35.6
	928	2.4	4.0	5.6	8.7	8.7	8.7	8.7	4.8	8.0	11.2	17.6	23.2	29.6	34.9
	1050	2.4	4.0	5.6	8.7	8.7	8.7	8.7	4.8	8.0	11.2	17.6	23.2	29.6	34.9
	1200	2.4	4.0	5.6	8.7	8.7	8.7	8.7	4.8	8.0	11.2	17.6	23.2	29.6	34.9
0.75	600	2.7	4.5	6.2	9.7	9.7	9.7	9.7	5.4	8.9	12.5	19.6	25.9	33.0	38.9

	750	2.3	3.8	5.4	8.4	8.4	8.4	8.4	4.6	7.7	10.8	16.9	22.3	28.4	33.5
	900	2.0	3.4	4.8	7.4	7.4	7.4	7.4	4.1	6.8	9.5	15.0	19.7	25.2	29.7
	928	2.0	3.3	4.7	7.3	7.3	7.3	7.3	4.0	6.7	9.3	14.7	19.3	24.7	29.1
	1050	2.0	3.3	4.7	7.3	7.3	7.3	7.3	4.0	6.7	9.3	14.7	19.3	24.7	29.1
	1200	2.0	3.3	4.7	7.3	7.3	7.3	7.3	4.0	6.7	9.3	14.7	19.3	24.7	29.1
0.875	600	2.3	3.8	5.4	8.3	8.3	8.3	8.3	4.6	7.6	10.7	16.8	22.2	28.3	33.4
	750	2.0	3.3	4.6	7.2	7.2	7.2	7.2	4.0	6.6	9.2	14.5	19.1	24.4	28.8
	900	1.8	2.9	4.1	6.4	6.4	6.4	6.4	3.5	5.8	8.2	12.8	16.9	21.6	25.5
	928	1.7	2.9	4.0	6.2	6.2	6.2	6.2	3.4	5.7	8.0	12.6	16.6	21.1	25.0
	1050	1.7	2.9	4.0	6.2	6.2	6.2	6.2	3.4	5.7	8.0	12.6	16.6	21.1	25.0
	1200	1.7	2.9	4.0	6.2	6.2	6.2	6.2	3.4	5.7	8.0	12.6	16.6	21.1	25.0
1	600	2.01	3.34	4.68	7.3	7.3	7.3	7.3	4.01	6.69	9.36	14.71	19.39	24.74	29.19
	750	1.73	2.88	4.03	6.29	6.29	6.29	6.29	3.46	5.76	8.07	12.68	16.71	21.32	25.16
	900	1.53	2.55	3.57	5.57	5.57	5.57	5.57	3.06	5.1	7.15	11.23	14.8	18.88	22.28
	928	1.5	2.5	3.5	5.46	5.46	5.46	5.46	3	5	7	11	14.5	18.5	21.83
	1050	1.5	2.5	3.5	5.46	5.46	5.46	5.46	3	5	7	11	14.5	18.5	21.83
	1200	1.5	2.5	3.5	5.46	5.46	5.46	5.46	3	5	7	11	14.5	18.5	21.83

We calculate the wale spacings depending on the sheathing thickness, pressure values, and stud section. To calculate this, we need to consider four factors, i.e., bending, shear, deflection, and crushing. Table 3 shows two types of stud sections with widths of 1 in and 2 in.

Increasing the stud section thickness or width will result in a larger wale spacing as shown in Table 4. The wale spacing decreases by an average rate of 8.5% or 100 lb/ft^2 with an increase in the pressure values below 928 lb/ft^2, and remains constant when the pressure is greater than this value because the pressure on the stud is constant.

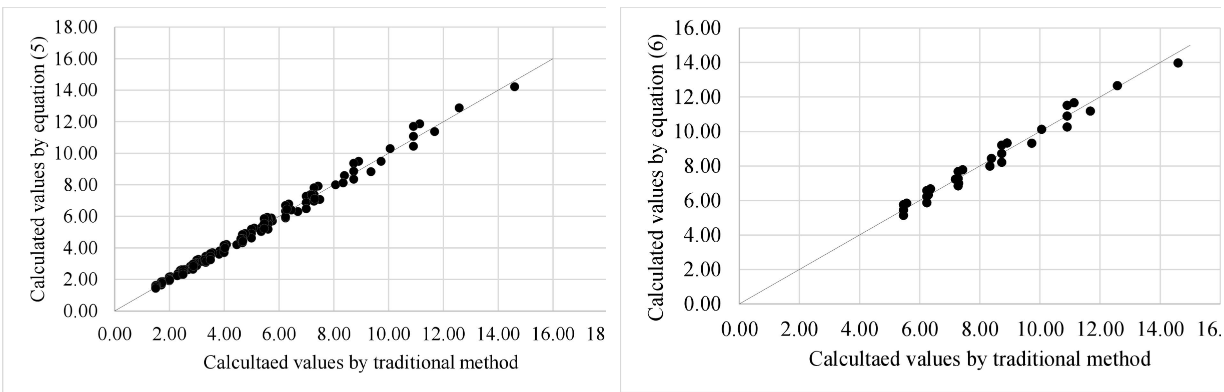
From sections 1x6 to 1x12 in of the grey zone in Table 3, we found the wale spacing to remain constant regardless of whether the stud thickness increased or not because, in this case, the crushing check determines the wale spacing.

By using the statistical analysis program, the author created three equations for determining the wale spacing, Equation (5) is applied to sections 1x2 to 1x6 in, Equation (6) to sections 1x6 to 1x12 in, and Equation (7) to sections where the width of the stud section is 2 inches.

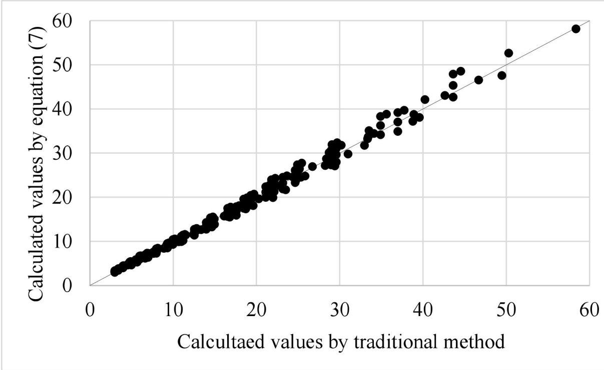
$$Sw = 15.02613 * (Tsh^{-1.00001}) * (P^{-0.4462}) * (Tst^{1.17528}) \quad R^2 = 0.993026 \quad (5)$$

$$Sw = 121.0361 * (Tsh^{-0.99929}) * \left(P^{-0.44571}\right) * (Tst^{1.05E-16}) \quad R^2 = 0.97519 \quad (6)$$

$$Sw = 32.60071 * (Tsh^{-1.00011}) * (P^{-0.44603}) * (Tst^{1.101984}) \quad R^2 = 0.99473 \quad (7)$$



(a) (b)



(c)

Figure 4. Correlations between the traditional method and (a) Equation 5 (b) Equation 6 (c) Equation 7

Figs. 4(a)-(c) display the correlations between the wale spacings obtained by the traditional method and by using Equations (5)-(7). Most of the values are set at an angle of 45°, so the correlations are high between the two methods.

Table 4: Tie spacings

		Wale section													
Tsh (in)	P (lb/ft²)	1x2 (in)	1x3 (in)	1x4 (in)	1x6 (in)	1x8 (in)	1x10 (in)	1x12 (in)	2x2 (in)	2x3 (in)	2x4 (in)	2x6 (in)	2x8 (in)	2x10 (in)	2x12 (in)
0.5	600	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.8	13.5	10.6	9.0
	750	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.5	12.5	9.8	8.3
	900	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.6	11.8	9.3	7.8
	928	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.4	11.7	9.2	7.8
	1050	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.6	10.3	8.1	6.9
	1200	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	11.9	9.0	7.1	6.0
0.625	600	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.3	16.9	13.2	11.2
	750	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.7	15.7	12.3	10.4
	900	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.4	14.8	11.6	9.8
	928	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.2	14.6	11.4	9.7
	1050	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.0	12.9	10.1	8.6
	1200	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	14.9	11.3	8.9	7.5
0.75	600	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.7	20.3	15.9	13.5
	750	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	24.8	18.8	14.7	12.5
	900	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.3	17.7	13.9	11.8
	928	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.1	17.5	13.7	11.6
	1050	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.4	15.5	12.1	10.3
	1200	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	17.9	13.6	10.6	9.0
0.875	600	31.2	31.4	31.4	31.4	31.4	31.4	31.4	31.2	31.4	31.4	31.2	23.6	18.5	15.7
	750	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	28.9	21.9	17.2	14.6
	900	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.2	20.6	16.2	13.7
	928	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	26.9	20.4	16.0	13.6
	1050	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	23.8	18.1	14.2	12.0
	1200	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	20.8	15.8	12.4	10.5
1	600	32.6	35.9	35.9	36.0	35.9	35.9	35.9	32.6	35.9	35.9	35.6	27.0	21.2	17.9
	750	31.8	33.3	33.3	33.3	33.3	33.3	33.3	31.8	33.3	33.3	33.1	25.1	19.7	16.7
	900	31.1	31.4	31.4	31.4	31.4	31.4	31.4	31.1	31.4	31.4	31.1	23.6	18.5	15.7
	928	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	30.8	23.4	18.3	15.5
	1050	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.2	20.6	16.2	13.7
	1200	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	23.8	18.1	14.2	12.0

We should check five items when determining the tie spacing, i.e., bending, shear, deflection, tie load, and bearing of tie wedges on wales. Tie spacing is dependent on the sheathing thickness, pressure values, and wale sections. According to Table 4, the wale sections have been divided into two groups, i.e., the sections with a width of 1 inch and the sections with a width of 2 inches.

Table 4 shows that the tie spacings are constant for sections 1x2 to 2x4 in. To understand why this is the case, these sections are divided into two groups. The first group contains sections 1x2, 1x3, 1x4, 2x2, 2x3, and 2x4 in, the checks on shear determine how close the ties should be spaced, and in the law of checks on shear, there are two variables, i.e., thickness of the wale section and load. In addition to this, we find that the percentage increase in the thickness of the wale section is the same as the percentage increase in the load applied to the wale section. Accordingly, the tie spacing remains unchanged.

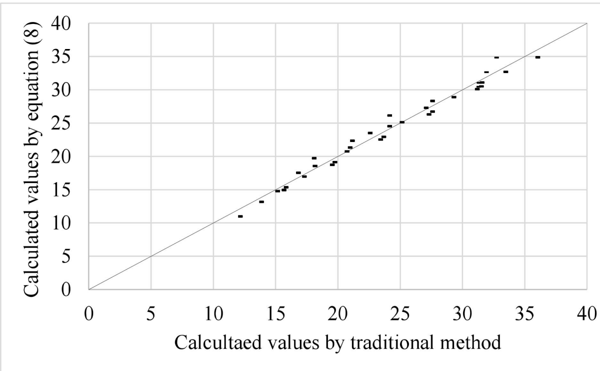
In the second group, which consists of sections 1x6, 1x8, 1x10, and 1x12 in, we found that the checks on the bearing of tie wedges on the wales control the minimum tie spacing, and from Table 3, the minimum spacing is constant. Hence, the load applied to the wale section will remain constant, the width of the wale section will remain the same, and the wedge diameter is constant, so the tie spacing will remain the same.

Based on the results of the statistical analysis program, the author developed three equations to determine the distances between the ties, The first equation is Equation (8) when the width of a wale is 1 inch, and the second equation is Equation (9) for sections (2x2, 2x3 and 2x4 in). The other equation, Equation (10), is for sections (2x6, 2x8, 2x10, and 2x12 in) when the width of a wale is 2 inches.

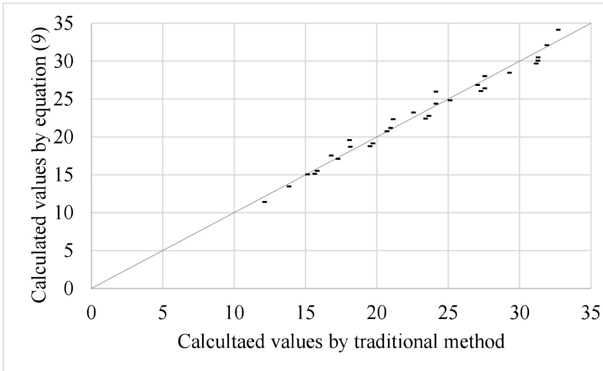
$$St = 13.24337 + 30.3061\,Tsh - 0.01457\,P + 0.009381\,Twa \quad R^2 = 0.980706 \tag{8}$$

$$St = 13.13036 + 29.11867\,Tsh - 0.01356\,P + 1.25E - 15\,Twa \quad R^2 = 0.97519 \tag{9}$$

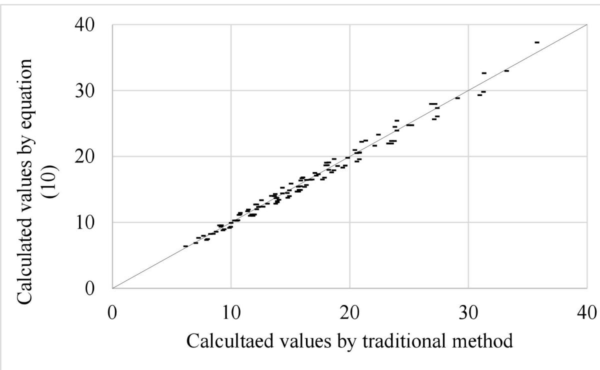
$$St = 7703.998 * (Tsh^{0.999906}) * (P^{-0.55383}) * (Twa^{-0.99862}) \quad R^2 = 0.98723 \tag{10}$$



(a)



(b)



(c)

Figure 5. Correlations between the traditional method and (a) Equation 8 (b) Equation 9 (c) Equation 10

Figs. 5(a)-(c) display the correlations between the tie spacings obtained by the traditional method and by using Equations (8)-(10). Most of the values are set at an angle of 45°, so the correlations are high between the two methods.

4. Conclusions

The results from the current study are for short walls whose heights are equal to or less than 8 ft. From these results, the following conclusions can be drawn.

- The equations were presented for determining the spacing between the studs, wales, and ties.
- An increase of 25% in the sheathing thickness results in an increase of 16% in the stud spacing.
- Increasing the pressure by 25% causes a decrease of 10% in the stud spacing.
- It is not recommended for stud sections to use sections 1x8, 1x10, and 1x12 in.
- The wale sections should be no smaller than 2x4 in in size.

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Conflict of interest

There is no conflict of interest for this study.

Nomenclature

Term	Description
Cc	Chemistry Coefficient
Cw	Unit Weight Coefficient
h	Height of wall formwork (ft)
P	Lateral Pressure (lb/ft^2)
R	Casting Rate (ft/h)
R^2	A statistical measure in a regression model that determines the proportion of variance in the dependent variable that can be explained by the independent variable.
Ss	Spacing of stud (in)
St	Spacing of tie (in)
Sw	Spacing of wale (in)
T	The temperature of concrete at the time of casting (°F)
Tsh	Thickness of sheathing (in)
Twa	Thickness of wale section (in)
Tst	Thickness of stud section (in)
w	Unit weight of concrete, (lb/ft^3)

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