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An empirical model to predict fresh concrete lateral pressure

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HIGHLIGHTS

- An empirical model to predict fresh concrete lateral pressure has been developed.
- Predictions are always under hydrostatic distribution.
- Principal objective: predicting lateral pressure for high placement rates.
- The model presents very good approximation to the experimental data.

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ABSTRACT

In construction practice, an accurate model to predict fresh concrete lateral pressure is needed in order to design vertical formwork. In this work, an empirical model to predict lateral pressure for vibrated concrete was developed. A total of 226 experimental data recompiled from the literature were used in the formulation of the model.

The model considers seven of the variables that affect fresh concrete lateral pressure: placement rate, slump cone, the height of the concrete piece, concrete temperature, minimum form dimension and cross section size. Due to the formulation of the model, the prediction obtained is always lower than the hydrostatic distribution.

The principal objective of the model is to have an accurate prediction for high placement rates (over 10 m/h), which is a common practice today. Based on this idea, experimental data for self-compacting concrete compiled from the literature were used to verify the model's accuracy.

The results show that, in general, applying the proposed model produces predictions that are better than those obtained from preexisting models. In particular, for high placement rates the model presents a very good approximation to the experimental data.

1. Introduction

The design of vertical formwork is governed by the lateral pressure exerted by fresh concrete. With the objective of reduce the construction periods, high rates of placement are used. Leemann et al. [1] established that rates of placement higher than 10 m/h are now commonly expected. Therefore, as preexisting models for vibrated concrete were mainly developed for lower rates of placement, an adequate equation to predict maximum lateral pressure at high placement rates is needed.

The simplest solution is to consider fresh concrete as a fluid. This assumption is an upper limit for maximum lateral pressure. Santilli et al. [2] for vibrated concrete and Omran [3] for self-compacting concrete established that this distribution is conservative for high placement rates. As established by Hurd [4] formwork cost is very important in concrete structure, therefore, overestimating the pressure produces a significant increase in the global cost of the structure.

But the economic factor is limited by safety. For vertical formwork, an underestimation of the pressure could generate pieces with poor dimensional quality or, in the worst case scenario, the failure of the formwork.

For vibrated concrete, the most common process of filling a wall or a column are subsequently lifts, which are vibrated to consolidate the mix. Gardner [5] states that, as depth and time increase, concrete develops an internal structure and the lateral pressure is lower than the hydrostatic one. The author also states that the major factors controlling the magnitude of the lateral pressure are: depth of fluidized concrete and the ability of the mix to develop shear strength and friction with the wall. These factors depend on various variables related to concrete, formwork characteristics and placement method.

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The envelope of fresh concrete lateral pressure could be determined by means of a phenomenological or an empirical method. The large numbers of variables that can affect lateral pressure produce very complex phenomenological models which are difficult to use in practice. Therefore, empirical methods are currently used in practice.

The European Standard UNE EN 12812 [6] recommends for vertical formwork design the models proposed by DIN 18218 [7] or by CIRIA Report 108 [8], which, together with the model proposed by ACI Committee 347 [9], are the most common ones for vibrated concrete.

CIRIA Report 108 [8] proposes a model where pressure value is hydrostatic up to a maximum value (P_{MAX}) which remains constant down to the bottom of the formwork. The value of P_{MAX} is determined by Eq. (1), and it must always be lower or equal to the hydrostatic distribution.

$$P_{MAX} = \left[C_1\sqrt{R} + C_2K\sqrt{H_1 - C_1\sqrt{R}}\right]\gamma \quad (1)$$

where P_{MAX} is the maximum lateral pressure (kPa), C_1 is a coefficient which depends on the size and shape of the formwork, C_2 is a coefficient which depends on the cementitious materials, γ is concrete specific weight (kN/m^3), H_1 is the vertical form height (m), K is a coefficient which depends on the concrete temperature, R is the rate of placement (m/h).

The ACI Committee 347 [9] proposes the same envelope as CIRIA Report 108 [8], but where the maximum pressure is determined by means of Eqs. (2a) and (2b) depending on the characteristics of the structural element, having to be always lower than the hydrostatic distribution.

For walls with $R < 2.1$ m/h and $H < 4.2$ m and columns:

$$P_{MAX} = C_W C_C\left[7.2 + \frac{785R}{T + 17.8}\right] \quad (2a)$$

For walls with $R < 2.1$ m/h and $H > 4.2$ m and all walls with rates of placement between 2.1 and 4.5 m/h:

$$P_{MAX} = C_W C_C\left[7.2 + \frac{1156}{T + 17.8} + \frac{244R}{T + 17.8}\right] \quad (2b)$$

where P_{MAX} is the maximum lateral pressure (kPa), C_W is a unit weight coefficient, C_C is a chemistry coefficient, R is the rate of placement (m/h), T is concrete temperature (°C), H is depth of concrete (m).

The German Standard DIN 18218 [10] proposes an envelope where the lateral pressure value is hydrostatic until up to a maximum value which remains constant down to the minimum value between formwork height and the product between concrete setting time (t_E) and rate of placement. If the latter value is the minimum, then the pressure is zero under this height. The general value of the maximum lateral pressure is expressed in the following equation:

$$P_{MAX} = (\alpha R + \beta)K_D \quad (3)$$

where P_{MAX} is the maximum lateral pressure (kPa), R is the rate of placement (m/h), α and β are coefficients which depends on concrete consistency, K_D is a coefficient which depends of concrete setting time (t_E).

A better description of the models is presented in Santilli et al. [11].

In general, for high rates of placement (>10 m/h) these models present a value of P_{MAX} higher than the hydrostatic distribution; therefore, hydrostatic distribution must be considered for formwork design at high rates of placement. Nevertheless, Gardner and Ho [12] measured, in three different tests, concrete lateral pressure on a 5 m high steel formwork, with a rate of placement of 45.8 m/h, obtaining a maximum lateral pressure of 45.5, 44.5 and 43.6 kPa. These values were considerably lower than the one obtained from the hydrostatic distribution (117 kPa).

Moreover, Santilli et al. [11] and Santilli et al. [2] for columns and walls, respectively, used experimental data obtained by different authors for comparing the adequacy of different models. It was concluded that the hydrostatic distribution seems to be a conservative approach, and for high placement rates (>10 m/h) a new model is needed, as the principal models equal this distribution under these conditions.

This work presents an empirical model to predict fresh concrete lateral pressure for vibrated concrete, using experimental data obtained by different authors. The main objective of the model is to obtain less conservative predictions for formworks that are going to have an extended control level and will be filled at high placement rates.

2. Formulation of the model

The experimental data considered for the formulation of the model were those supplied by Peurifoy [13], Ritchie [14,15], Adam et al. [16], Ore and Straugham [17], Gardner and Ho [12], Gardner and Quereshi [18], Gardner [19], Douglas et al. [20], Gardner [21], Habgood [22], Harrison [23,24], Douglas et al. [25], Johnston et al. [26], Dunston et al. [27], Arslan [28], Billberg [29], Leemann and Hoffmann [30], Arslan et al. [31], O'Janpa III [32], Assaad and Khayat [33], Dhir et al. [34] and Santilli et al. [2]. A total of 226 experimental data of maximum pressure for fresh vibrated concrete has been used to develop the empirical model.

A bilinear envelope was considered, where pressure value is hydrostatic up to a maximum value which remains constant down to the bottom of the formwork. In this way, two magnitudes should be determined in order to apply the model: concrete density and maximum lateral pressure.

2.1. Concrete density

Concrete density is an important parameter in the determination of fresh concrete lateral pressure since, after vibration of the first lift, Gardner [5] established that the pressure distribution is equal to the hydrostatic pressure.

Concrete density in common practice varies within a rather limited range, approximately between 2300 and 2500 kg/m^3, although both values could change in special cases. For the application of the model, if concrete density is an unknown parameter, a medium value of 2400 kg/m^3 is recommended.

2.2. Maximum lateral pressure

The maximum lateral pressure (P_{MAX}) is determined by Eq. (4). In all cases, the K parameter is less than or equal to one, to guarantee that the prediction of the model is less than the hydrostatic distribution.

$$P_{MAX} = K\gamma H \quad (4)$$

where P_{MAX} is the maximum lateral pressure (kPa), K is a coefficient which depends on the variables that affect fresh concrete lateral pressure, γ is concrete specific weight (kN/m^3), H is the height of the concrete piece (m).

Seven of the variables that can affect fresh concrete lateral pressure have been considered in the determination of K: rate of placement (R), slump cone (α), the height of the concrete piece (H), concrete temperature (T), minimum form dimension (d), cement type (C) and cross section size (ST).

The model considered each of the variables separately and progressively. In this way, the coefficient K is determined by means of Eq. (5):

$$K = K_R K_\alpha K_H K_T K_d K_C K_{ST} \quad (5)$$

where K is the coefficient to apply in Eq. (4), K_R is the coefficient of correction by rate of placement, K_α is the coefficient of correction by slump cone, K_H is the coefficient of correction by the height of concrete piece, K_T is the coefficient of correction by temperature, K_d is the coefficient of correction by minimum form dimension, K_C is the coefficient of correction by cement type, K_{ST} is the coefficient of correction by cross section size (columns or wall and bases).

The first five variables could be expressed as a continuous function. Therefore, the coefficients K_i are determined from the prediction confidence intervals of a new observation, considering simple linear regressions.

The last two variables are discrete. Therefore, the coefficients K_i are determined in an arbitrary manner. Based on cement type, three groups have been determined considering the division proposed by the European Standard UNE EN 197-1 [35]. For cross section size, the division proposed by CIRIA Report 108 [8] and ACI Committee 347 [9] in walls and bases or columns was used.