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Computer simulation of complex-shaped formworks using three-dimensional numerical models

E. Gallego [a,*], J.M. Fuentes [b], A. Ramírez [c], F. Ayuga [b]

[a] BIPREE Research Group, Universidad Politécnica de Madrid, Ciudad Universitaria s/n. EUIT Agrícola, 28040 Madrid, Spain
[b] BIPREE Research Group, Universidad Politécnica de Madrid, Ciudad Universitaria s/n. ETSI Agronomos, 28040 Madrid, Spain
[c] BIPREE Research Group, Universidad Politécnica de Madrid, Ciudad Universitaria s/n. EUIT Industrial, 28040 Madrid, Spain

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ABSTRACT

This work describes a three-dimensional numerical model, developed with the ANSYS finite element software package, which simulates the behaviour of fresh concrete and formwork walls to obtain the resulting pressures in complex-shaped formworks. The results obtained with the proposed model highlight the influence of the inclination of a formwork on the lateral pressures exerted on its walls by fresh concrete. The normal pressures on the lower inclined formwork wall were found to be larger than those exerted on the upper inclined wall. In addition, it was also found that normal pressures vary along the formwork wall in the longitudinal direction in a different way depending on the sidewall. The proposed computer model allows examining load distributions in complex-shaped formworks, which is not contemplated in current standards.
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1. Introduction

Formworks play an important role in civil engineering projects, retaining fresh concrete until it sets and acquires adequate resistance. The determination of the lateral pressures exerted by fresh concrete on formwork walls is important, and should always be borne in mind when designing formworks and the structures that support them [1,2]. Underestimating the size of these pressures can lead to the deformation of support elements or even the rupture of the formwork itself, with the danger to the workforce and the economic losses that this entails.

The size of the lateral pressures exerted by Normal Vibrated Concrete (NVC) on formwork walls are conditioned by numerous variables such as the composition and consistency of the mix, the temperature of the concrete during setting, the shape of the formwork, the rate of placement (the rate at which the concrete rises vertically up the form), and the surface properties of the formwork walls [3–7]. In recent years, research has led to the proposal of different empirical equations for determining the lateral pressures exerted by fresh concrete on formwork walls, and the appearance of standards for use in engineering and architectural practice [5,8,9].

The pressure distribution laws generally abide by a hydrostatic model similar to that corresponding to a non-viscous fluid, at least until a certain depth is reached when the maximum pressure remains constant until the bottom of the formwork.

American standard ACI 347–04 [9] proposes that the lateral pressures be calculated using Eq. (1), where P_{max} is the maximum lateral pressure on the formwork wall expressed in kPa, R is the rate of placement (between 2.1 and 4.5 m/h), T is the temperature of the concrete during pouring (°C), Cw is a non-dimensional correcting coefficient relative to the specific weight of the fresh concrete, and Cc a coefficient that depends on the type of concrete in question and the additives in the mix.

$$P_{máx} = Cw \cdot Cc \cdot \left(7.2 + \frac{1156}{T+17.8} + \frac{244 \cdot R}{T+17.8}\right) \quad (1)$$

German standard DIN-18218 [8] proposes a series of expressions, such as that shown in Eq. (2):

$$P_{máx} = K_1 + K_2 \cdot R \quad (2)$$

where K_1 and K_2 are coefficients dependent of the consistency of the fresh concrete determined by the Abrams cone assay, and R the rate at which the concrete rises vertically up the form (in m/h). This standard contemplates an increase or reduction in the maximum pressure of 3% for every 1 °C difference between environmental temperature during setting and a baseline temperature of 15 °C.

Finally, monograph 108 of the CIRIA [5] proposes the lateral pressures be measured by Eq. (3):

$$P_{máx} = D \cdot \left(C_1 \cdot R^{0.5} + C_2 \cdot K \cdot \sqrt{H - C_1 \cdot R^{0.5}}\right) \quad (3)$$

where P_{max} is the maximum lateral pressure exerted (kN/m^2), D is the specific weight of the fresh concrete (kN/m^3), R is the rate of placement (m/h), H is the height of the formwork (m) and C_1 and C_2

* Corresponding author. Tel.: +34 913363705; fax: +34 913365406.
E-mail addresses: eutiquio.gallego@upm.es (E. Gallego), jm.fuentes@upm.es (J.M. Fuentes), alvaro.ramirez@upm.es (A. Ramírez), francisco.ayuga@upm.es (F. Ayuga).

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are coefficients that contemplate the formwork shape and the composition of the mix and K is a non-dimensional coefficient to take into account the temperature of the concrete when it is poured.

During the initial phase of setting, the lateral pressures exerted by Self-Compacting Concretes (SCC) – developed in Japan at the end of the 1980s and requiring the addition of plastifying additives that allow for compaction of the concrete under its own weight [10] – are dependent on (amongst other variables) the rate of placement, the use of flying ashes and chemical stabilizers, and the sand/total aggregates ratio [11–13].

Djelal et al. [14] and Arslan et al. [15] highlight the influence of variables such as the roughness of the formwork material and the use of demoulding agents on the lateral pressures exerted by NVC. The latter variables are not, however, contemplated in current standards. Further, the empirical formulae proposed by these standards only take into account vertical formworks of very simple shape. For example, they do not contemplate the inclined supporting walls so commonly used in the construction of bridge decks, retaining walls, tanks, and many other engineering and architectural structures. The finite element technique, however, offers solutions to this, allowing models for complex-shaped formworks to be produced, and the simulation of situations involving different types of mix, their different mechanical behaviours, and different coefficients of friction between the concrete and the formwork walls [16,17].

The finite element models developed by the authors allow for the simultaneous simulation of formwork walls and the fresh concrete between them. These models provide accurate information regarding the structural behaviour of such systems, as well as the lateral pressures exerted by the fresh concrete on the formwork walls. The numerical results obtained have indicated that a high rate of placement used in tall formworks can lead to pressures greater than those contemplated in current standards [17].

The present work tests the applicability of numerical analysis techniques to the design of complex-shaped formworks. A three-dimensional model was used to calculate the pressures on the walls of a formwork for a V-shaped section of a bridge deck (Fig. 1). The pressures obtained were compared with those suggested by a two-dimensional model previously developed by the authors [16,17], and with the values calculated according to international standards DIN-18218, CIRIA-108 and ACI-347. The influence of the inclination of the formwork on the lateral pressures exerted by the fresh concrete are discussed, as are the different wall-pressure distribution curves suggested by the different models.

2. Description of the numerical model

This work proposes a three-dimensional finite element model developed with ANSYS v.10.0 software [18] to analyse pressures in complex-shaped formworks.

The shape of the formwork used in the present research was that required to make a V-shaped section of a bridge deck some 4.68 in height and 3.00 m in length (Fig. 1). However, it would be quite easy to generate different shapes by changing the values of α, Li, Yi and LZ that define the formwork shape.

A simpler two-dimensional model was previously developed and validated by the authors [17] to calculate the pressures on the walls of a 70° inclined formwork 4.68 m in height and 0.45 m in width. The fresh concrete was numerically simulated according to the elasto-plastic model and the formwork wall was assumed to be rigid. Friction between the formwork and the fresh concrete was determined according to the Coulomb model. A more comprehensive description of the two-dimensional model can be found in [16,17].

The proposed three-dimensional model also considers the formwork wall to be rigid, with the displacement of all its nodes impeded in all directions. If the design of the formwork wall is correct, the wooden or steel boards that form the wall will be locked into position by a complete structure of horizontally- and vertically-arranged steel beams, such that any displacement of the wall is restrained (Fig. 2). The displacement of the nodes at the base of the formwork, as well as those of the extremes of the bridge deck section, will also be restrained since sections are added successively during construction.

The interaction between the fresh concrete and the formwork walls was simulated in both 2D and 3D models using the surface-to-surface contact procedure [19] via the use of target elements corresponding to the formwork wall, and contact elements corresponding to the fresh concrete. Friction between the wall and fresh concrete elements was formulated according to the Coulomb model, which requires the coefficient of friction (μ) between the wall and the concrete be defined. The value given to this variable that depends on the composition and stage of hardening of the mix or the formwork surface, among some other questions, was obtained from the literature [20].

The behaviour of the fresh concrete was simulated according to the elastoplastic model in both numerical models [17]. This allows one to define quite well the mechanical behaviour of concrete when in a phase between fluid and completely hardened. Numerous authors indicate that, immediately after mixing, fresh concrete behaves like a

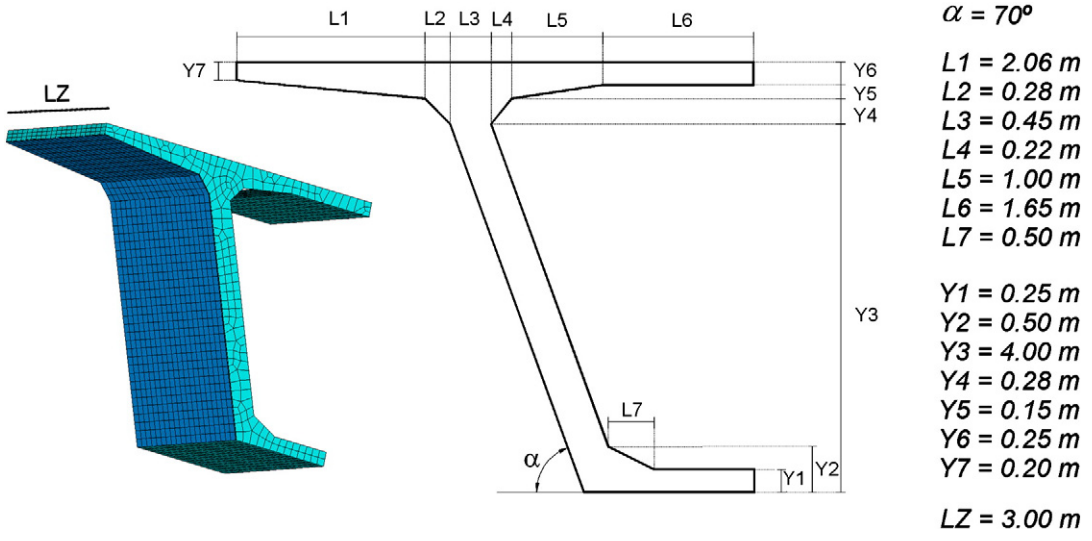

Fig. 1. Shape of the formwork considered in the present analyses.

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Fig. 2. Support structure for a vertical formwork.

non-Newtonian fluid [21–26]; its properties are therefore defined via its viscosity and its yield stress.

This hypothesis of behaviour affords satisfactory results for the first moments of the setting of conventional concretes, and when high-fluidity mixes (such as SCCs) or strongly vibrated concrete are being simulated. However, as the concrete sets its behaviour becomes more like that of a cohesive, granular material based on the principles of soil mechanics [6,27–29], and well described via a hypothesis of elastoplastic behaviour. When the concrete is fully hardened it no longer exerts any pressure on formwork walls.

The elastic part of the elasto-plastic model assumes a classic isotropic and linear behaviour of the concrete. This requires that the modulus of elasticity (E) and the Poisson coefficient (ν) of the fresh concrete at the beginning of hardening be determined; these data were gathered from the existing literature [30]. With respect to the plastic domain, the plastification criterion of Drucker and Prager [31] was used, which states that the yield function of fresh concrete can be obtained from the angle of internal friction (ϕ), the cohesion (c), and the dilatancy angle (ψ) of the material. The inclusion of the dilatancy angle allows the application of a non-associated flow rule [32]. Gallego et al. [16] indicate the variables with the most influence on lateral pressures to be the friction coefficient between the fresh concrete and the formwork, the Poisson coefficient, and the angle of internal friction.

A more detailed description of the elastic and plastic parts of the material model used in the simulation of fresh concrete can be found in Gallego et al. [16]. The values of the mechanical variables corresponding to the plastic domain were obtained from the results of the triaxial tests of fresh concrete of different composition and consistency undertaken by Ritchie [33], Olsen [34] and Alexandridis and Gardner [35]. No more recent information was found in the literature. Table 1 shows the values of the mechanical variables examined. The characteristics of the concrete and the pouring conditions used in the calculations of normal pressures correspond to a common type I cement with no additives nor setting retardants, with a density of 2000 kg/m^3 and a slump of 100 mm in an Abrams cone [36,37], at a setting temperature of 20 °C, and with a rate of placement of 3 m/h.

The fresh concrete was simulated using prism-shaped isoparametric elements formed by eight nodes with linear approximation of displacement (SOLID45) and with three degrees of freedom corresponding to the displacements along the three main spatial axes (x,y,z). The above element also allows the simulation of the non-elastic behaviour of the material, and takes into account the effects produced by large deformations.

3. Results and discussion

Fig. 3 shows the distribution curves for the pressure exerted by the fresh concrete against the formwork wall in the central section of the bridge deck section shown in Fig. 1 – inclined in this case at 70° to the horizontal – obtained using standards ACI 347, DIN 18218 and CIRIA 108 and the proposed three-dimensional finite element method. The results obtained with the analogous two-dimensional model are also shown.

The results obtained with the numerical models show that the maximum foreseeable pressures are below those suggested by the international standards for formwork calculation. The two-dimensional model returned a maximum pressure of 32.7 kPa, the three-dimensional model returned a value of 26.9 kPa, the American standard ACI-347 returned 54.1 kPa, and CIRIA-108 and DIN-18218 gave values of around 45 kPa.

A comparison of the results obtained with the two-and three-dimensional models developed by the authors shows those of the latter to return lower values over most of the height of the formwork. At the bottom of the formwork, however, the pressures indicated by both are much closer. At formwork heights between 2 and 4 m, the lateral pressure returned by the three-dimensional model is about 45–50% lower than the value provided by the two-dimensional model. This discrepancy is due to the redistribution of the pressure along the longitudinal dimension included in the three-dimensional simulation.

Table 1
Fresh concrete mechanical variables contemplated in the proposed model.

Mechanical variable	Symbol	Value
Unit weight [kg/m^3]	γ	2000
Angle of internal friction [º]	ϕ	30
Cohesion[kPa]	c	10
Modulus of elasticity [kPa]	E	$6 \cdot 10^6$
Poisson coefficient	ν	0.40
Concrete-wall friction coefficient	μ	0.05
Dilatancy angle [º]	ψ	20

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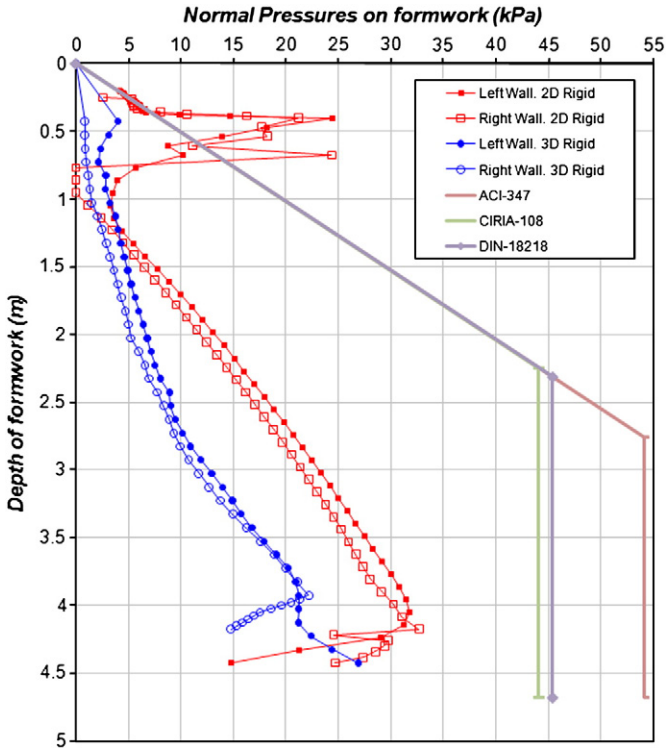

Fig. 3. Comparison of lateral pressures obtained with the two- and three-dimensional numerical models and the equations of the current standards.

The redistribution has the effect of reducing the edge condition which in the two-dimensional model is more acute in the upper part of the formwork. The difference between the values obtained in the simulation with those obtained using the standards is owing to the fact that the latter do not take into account the tangential stress derived from friction forces between the mass of concrete and the formwork encasing it (referred to as "silo effect"). Only at great depths of concrete are values obtained with the numerical model higher than those obtained with the current standards. These standards are excessively conservative for small and moderate depths of concrete.

The three-dimensional simulation performed also provides the distribution of pressures longitudinally. Fig. 4 shows the pressure distribution obtained longitudinally on the left and right walls of the contemplated complex-shaped formwork (inclination 70° to the horizontal) at different depths (H = 3.5 m; H = 2.5 m; H = 1.5 m). It is important to notice that, at any height, the lateral pressure varies along the formwork walls in a longitudinal direction, but remains symmetrical with respect to the mid plane (L = 1.5 m). Maximum pressures occur at the ends of the brick deck section (L = 0 m and L = 3 m) because the nodes that are placed at the end walls are completely constrained. This induces an increase in the rigidity of these parts of the formwork which resulted in greater stresses.

However, differences are seen in the variation of the lateral pressure along the formwork walls. At H = 3.5 m a pressure peak occurs at the ends of the bridge deck section. The lateral pressure on the left wall then falls to 13.8 kPa for L = 0.3 m and L = 2.7 m, but then increases to reach a new maximum of 19 kPa at the centre of the formwork (L = 1.5 m). The distribution of the lateral pressures at H = 1.5 m and H = 2.5 m, however, is such that the maximum pressure is exerted at the ends of the bridge deck section, with a slow reduction until a minimum is reached at the centre (L = 1.5 m) and values on the left wall of 8.6 kPa at H = 2.5 m and 4.8 kPa at H = 1.5 m. The bottom of the formwork wall is constrained and this induces a great rigidity in this part, especially in the right wall, where there is a change in the formwork inclination. This would induce that the formwork walls behave like a shell clamped in three edges: the end walls of the bridge deck section and the lower part of the walls, which would cause this change in the distribution of lateral pressures appeared for formwork depths below 3.5 m. Thus, the bottom of the formwork and the ends of the walls tend to face greater pressures, while the central area of the wall has to withstand lower pressures (Fig. 4).

Fig. 5 shows that, for the simulated bridge deck section, the pressures on the left wall are greater than on the right at equal heights. This difference can be observed for every angle of inclination, except for the vertical formwork (90° angle of inclination), where the pressures differences between left and right walls are almost negligible. It can be also seen that the lower the angle of inclination, the greater the pressures difference between the left and right walls. It can be also observed in Fig. 5 the existence of a great increase in

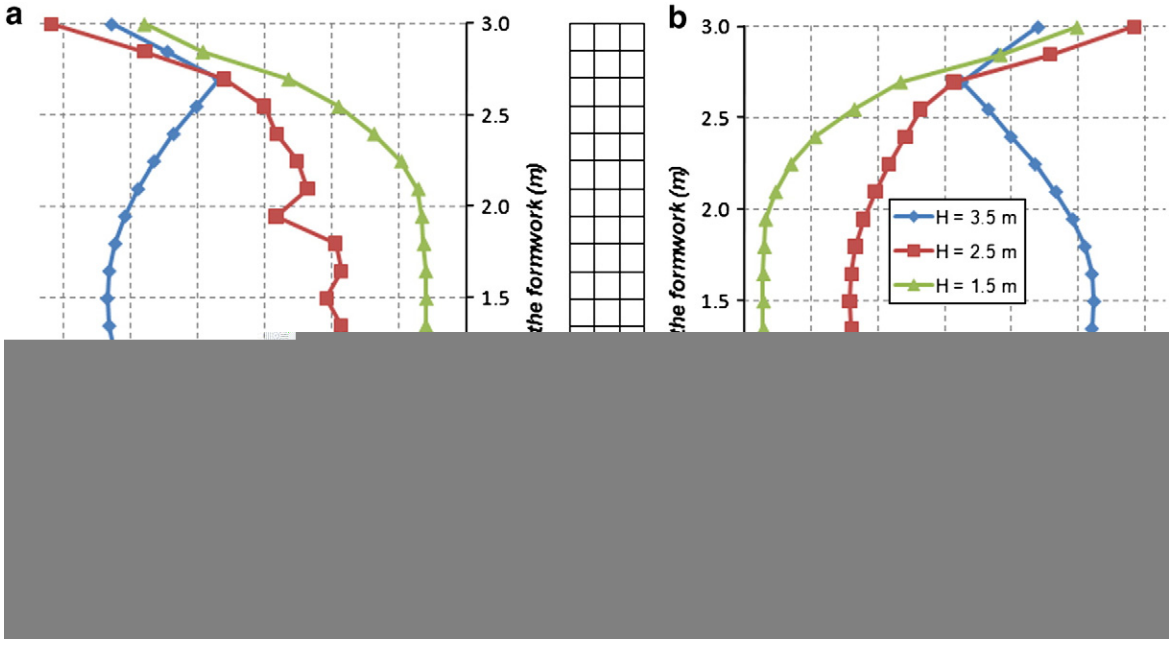

Fig. 4. Lateral pressures exerted by fresh concrete over the length of the formwork at different heights a) left wall b) right wall.

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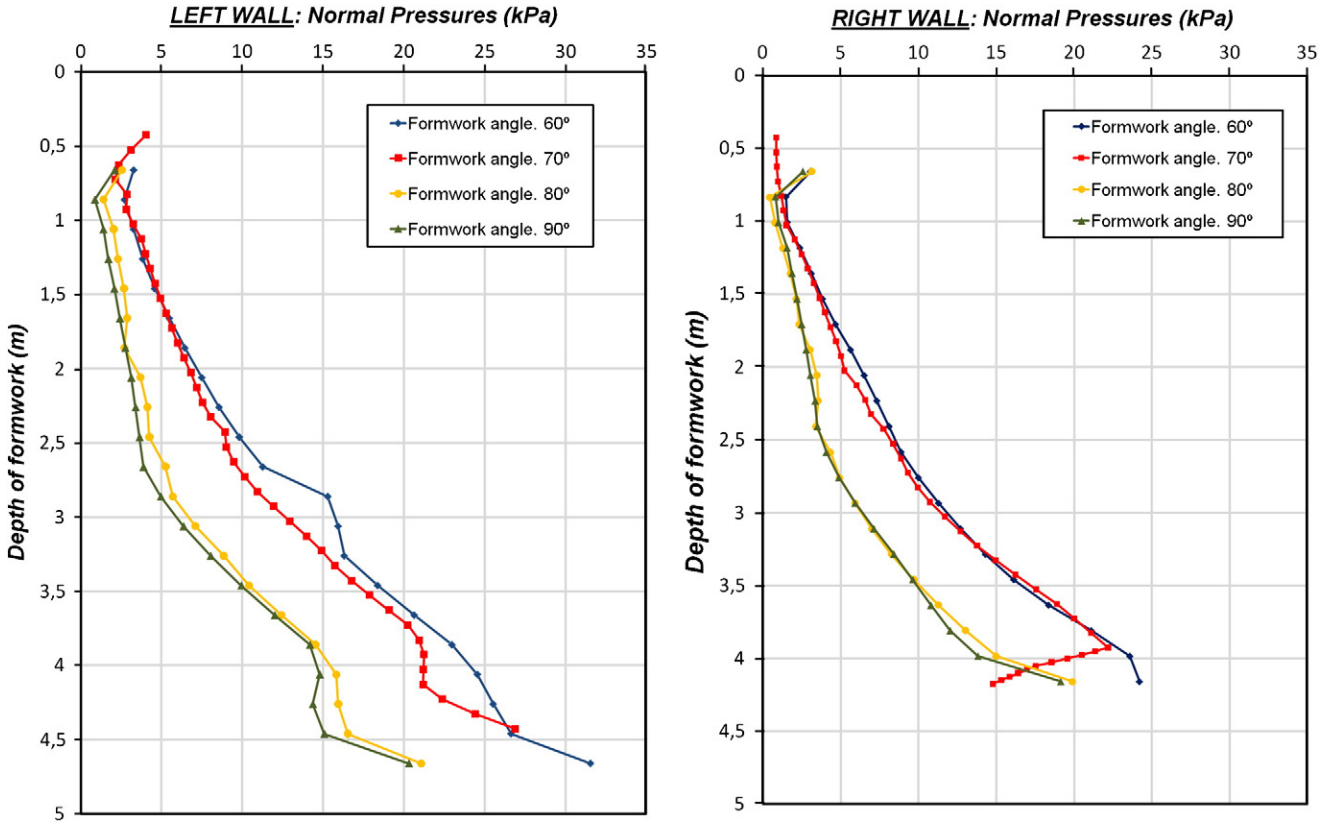

Fig. 7. Influence of the angle of inclination of formwork on the normal pressures.

three-dimensional simulation is also justified in terms of analysing the distribution of pressures along the longitudinal direction of the formwork.

- The lateral pressures exerted on the left or hanging wall of the inclined formwork considered in this work were slightly greater than those exerted on the right wall at all heights. This is due to the appearance of small subpressures on the right wall.
- The pressure distribution curve varies depending on the inclination of the formwork wall, decreasing with the angle of inclination with respect to the horizontal plane. Thus, the minimum lateral pressures correspond to completely vertical walls. The effect of inclination is not taken into account in current standards, but is naturally of great interest to all those involved in formwork design.

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