JSACE 2/15

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Received 2016/07/10

Accepted after revision 2016/09/07

Productivity Analysis of Concrete Slab Construction by Using Different Types of Formwork

Gintas Brazas, Mindaugas Daukšys*, Jolanta Šadauskienė, Mindaugas Augonis, Šarūnas Kelpša

Kaunas University of Technology, Faculty of Civil Engineering and Architecture
Studentu str. 48, LT-51367 Kaunas, Lithuania

*Corresponding author: **mindaugas.dauksys@ktu.lt**

http://dx.doi.org/10.5755/j01.sace.15.2.15789

In this article the influence of the panel slab, girder slab formwork and tableforms to the effectiveness of solid concrete slab construction works of multi-storey buildings is investigated. The object of investigation is 22-storey high-rise commercial residential building. The effectiveness of solid concrete slab construction works and selecting the formwork system was evaluated taking account of quality requirements, equipment ability, demand of time and labour i.e. complexity of assembling technology, universality of operation and other. Three options of PERI formwork systems were selected for investigation: SKYDECK panel slab aluminum formworks, MULTIFLEX girder slab formworks and UNIPORTAL tableforms. The rating criteria were selected for the evaluation of the effectiveness of selected formwork systems. Using the pairwise evaluation method the following order of criteria importance was obtained: 17.3% – formwork rental price (K_7), 16.3% – complexity of assembling technology (K_3), 15.4% – machinery costs (K_2), 13.9% – labour costs (K_1), 13.0% – required compressive strength of concrete before formwork demoulding (K_5), 12.5% – formworks demoulding time, days (K_6), 11.5% – reliability of suppliers (K_4). The evaluation of formwork systems, as options, according to selected evaluation criteria, was performed by TOPSIS method and the results show that for the mounting of concrete slabs in the investigated building the rational option is to use SKYDECK panel slab aluminum formworks.

KEYWORDS: panel slab formwork, girder slab formwork, tableforms, pairwise comparison, TOPSIS method.

Introduction

Conventional reinforced concrete structures are fabricated by casting concrete in temporary formwork that is usually made from timber or steel. The formwork is often held in place by temporary scaffolding. Upon hardening of the concrete, the formwork and temporary support are removed, revealing the concrete structure within. In tall building construction with reinforced concrete structures, the appropriate selection of the formwork method is a crucial factor in successful project completion. The selected formwork method significantly influences the project duration and cost as well as subsequent activities.

Formwork systems are among the key factors determining the success of a construction project in terms of speed, quality, cost and safety of works. Different types of construction require the use of different types of formworks. The strength of the building components, the speed at which building is constructed, and the cost of construction will depend to a great extent upon the appro-

Journal of Sustainable Architecture and Civil Engineering
Vol. 2 / No. 15 / 2016
pp. 38-46
DOI 10.5755/j01.sace.15.2.15789

priateness of formwork used in the construction. The erection of formwork is a time consuming process and cost of formwork (material+labour) could sometimes be as high as 50% of the cost of the concrete structure. Efficient design of these temporary structures plays a critical role in reducing the cost and ensuring safety.

Formwork can be classified according to a variety of categories, relating to the differences in sizes, location of use, construction materials, nature of operation, or simply by the brand name of the products (Tech Mailer, 2013). Major formwork systems are as follows: traditional timber formwork systems, re-usable plastic/PVC/aluminum formwork systems, table-form systems, jump form systems and slip form systems.

Horizontal formwork system is used to temporarily support horizontal concrete work such as concrete slabs. There are seven horizontal forming systems that can be used to support different slab types (Hanna, 1998). They are: 1. Conventional wood system (stick form); 2. Conventional metal (aluminium) system (improved stick form); 3. Flying formwork system; 4. Column-mounted shoring system; 5. Tunnel forming system; 6. Joist-slab forming system and 7. Dome forming system. Formwork system for horizontal concrete work can be also classified into two main categories: hand-set system and crane-set systems. Conventional wood systems and conventional metal systems are classified as hand-set systems. In hand-set systems different formwork elements can be handled by one or two labourers. Flying formwork systems, column-mounted shoring systems, and tunnel formwork are classified under crane-set systems. In crane-set systems, adequate crane services must be available to handle formwork components.

Formwork can be a permanent part of the structural element, commonly known as stay-in-place (SIP) formwork. SIP formwork is often used to accelerate the construction of structural elements such as flooring, concrete bridge decks and compressed shells (Hasselhoff *et al* 2015).

Authors (Akmaluddin *et al* 2015) investigated flexural behaviour of steel reinforced lightweight concrete slab with bamboo permanent formworks. The slab specimens were achieved by fabricating the formwork using the half bamboo section and plywood. The bamboos formworks were laid on the slab bottom as a part of the permanent formwork. While teakwood were placed on the side of the slab to maintain the slab height.

Authors (Shin *et al* 2012) proposed a formwork method selection model based on boosted decision trees in tall building construction to assist the practitioner's decision making. The proposed model was compared with an artificial neural network model and a decision tree model. The results showed that the proposed model was slightly more accurate than the others in the selection of the formwork method. Moreover, the result also demonstrated the advantages of the new method, i.e., single parameter setting, accuracy and stability improvement, and a comprehensible process in decision making.

Authors (Kannan and Santhi 2013) made comparison of different climbing formwork with the conventional formwork for the lift core-wall in the 20 storey high-rise building model using Building Information Modeling (BIM). Results show that automatic climbing formwork systems may have additional advantages over other systems in-terms of quality and sustainability, it has considerably less safety aspect than the crane-dependent: climbing formwork systems, semi-automated formwork systems. Thus, automated formwork systems are not advisable in the construction site located in the congested area, project with lack of technical sound work crew, and so on. According to authors (Sharifi *et al* 2006) slip-forming is one of the potential concrete formwork methods that improves speed and productivity of repetitive vertical concrete work. Typical projects that employ this technique are: silos, core of high-rise buildings, telecommunication towers, cooling towers, heavy concrete offshore platforms, etc.

By designing optimized concrete structures, significant savings in material use can be achieved, with concomitant reductions in both embodied carbon and construction cost (Orr *et al* 2011;

Veenendaal *et al* 2011). Fabric formwork not only provides a simple means by which such structures can be cast, but by allowing excess pore water to bleed from the surface of the concrete the resulting element is both durable and beautiful. Fabric formwork thus offers exciting opportunities for engineers and architects in the move towards a more sustainable construction industry.

Authors (Neudecker *et al* 2016) work demonstrated a new technology concept for robot-assisted generative manufacturing of concrete parts. The proposed manufacturing strategies include formwork-less shotcrete application using a counter-plate guide, automatic shotcrete application for flat opposing formwork and a combined smoothing process for concrete structures.

The aim of this work is to evaluate the effect of panel slab, girder slab and tableforms formwork systems on work efficiency in constructing solid concrete floor slabs in a high-rise building.

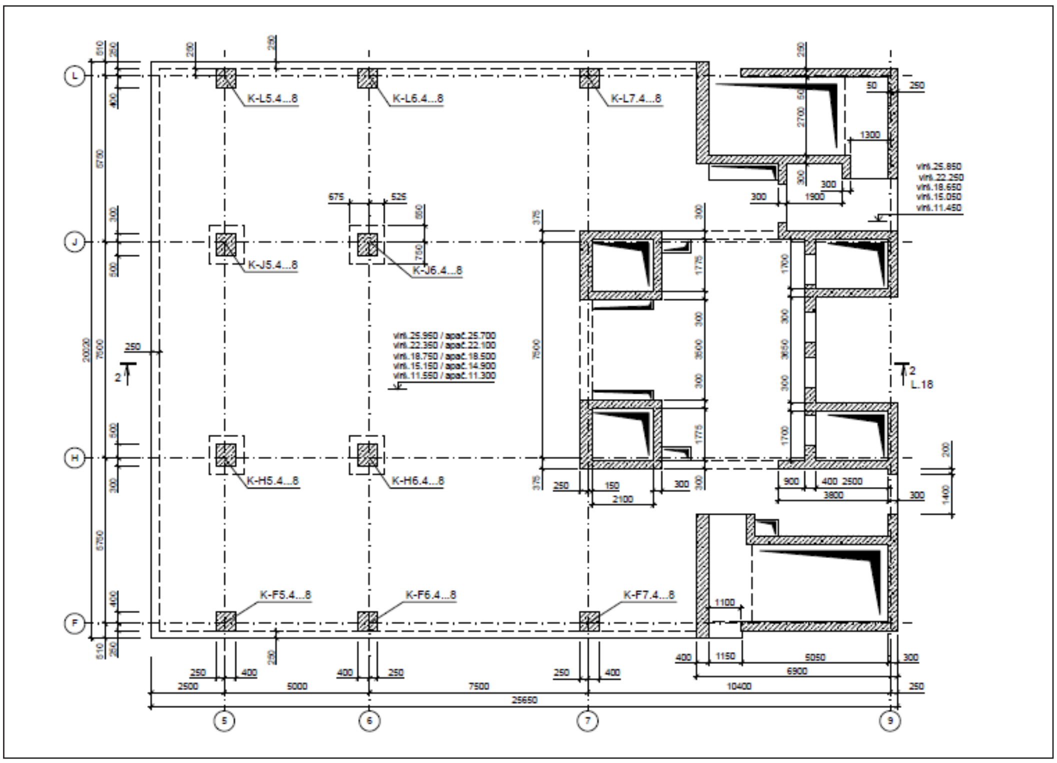
Methods

A solid reinforced concrete frame for 22-storey high-rise commercial residential building was selected for the study (Fig. 1a). Architectural volume of the building is made of the lower and higher parts. The framing scheme of the above-ground part of the building: solid reinforced concrete columns of 650×800 mm and 500×500 mm dimensions; centre-to-centre distance between columns is 7.5 m and 5.0 m; 300-400 mm thick shaft walls of staircases, lifts and vertical mechanical chases rigidly connected by solid concrete floor slabs of 250 mm thickness and 25650×20020 mm surface area (Fig. 1b).

Construction work efficiency in solid concrete buildings and the selection of formwork systems was evaluated taking into consideration quality requirements, equipment turnover, time and human resources, i.e. the complexity of technology, application versatility, etc. The following horizontal slab formwork systems produced by PERI Company and widely used in Lithuanian construction projects were selected for the study: SKYDECK aluminum panel slab formwork, MULTIFLEX girder slab formwork and UNIPORTAL tableforms (Fig. 2). Design and calculation of formwork systems required to produce solid concrete floors in the analysed building were done with PERI CAD 18 software (Fig. 2). As seen from Fig. 2 b, only MULTIFLEX girder slab formwork

Fig. 1

Layout of solid concrete slab



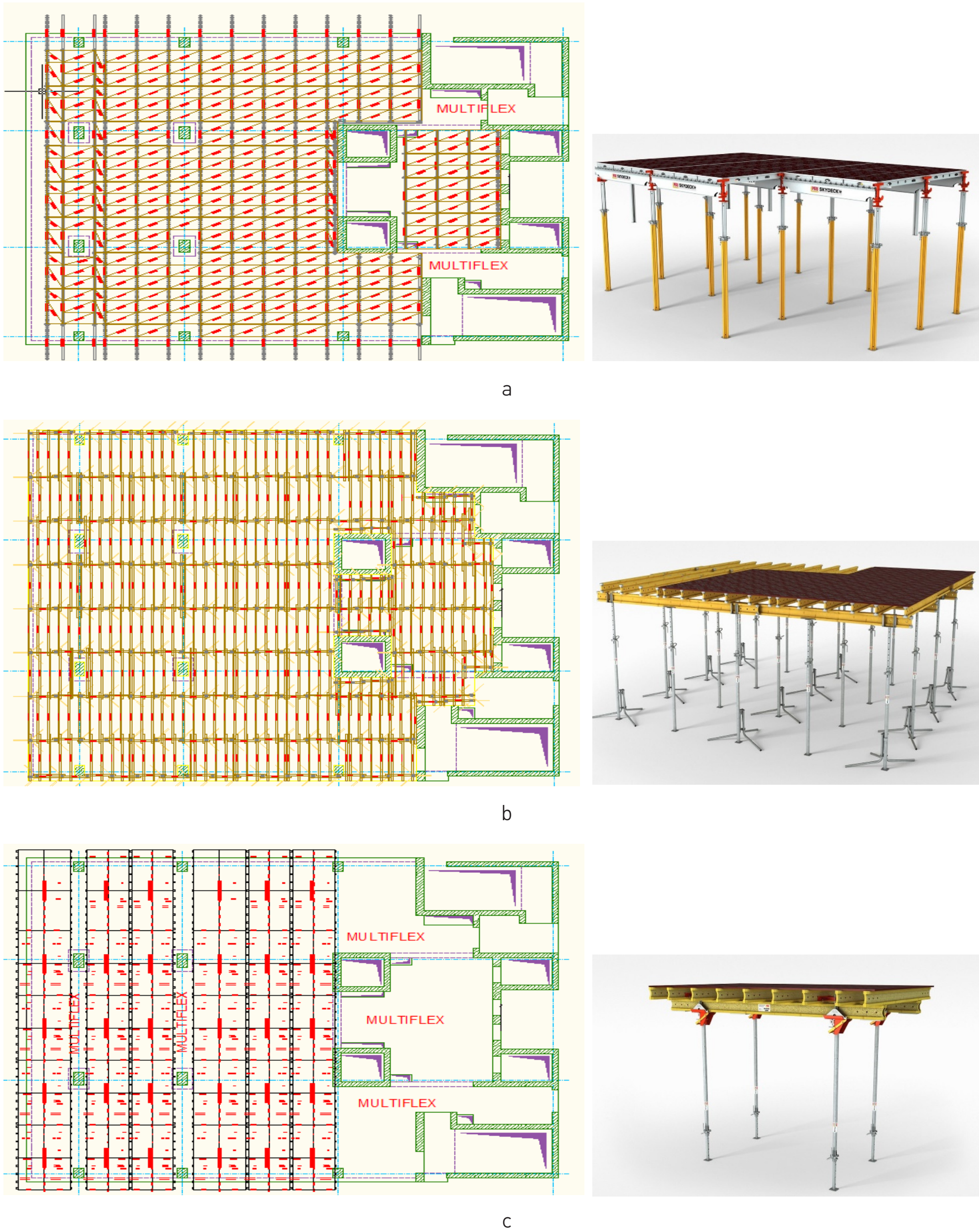


Fig. 2

Formwork systems and their overall view were designed by means of PERI CAD 18 software: SKYDECK panel slab formwork (a), MULTIFLEX girder slab formwork (b), UNIPORTAL tableforms (c)

system is used for the entire surface area of formed solid concrete floor, whereas SKYDECK panel slab formwork (**Fig. 2 a**) and UNIPORTAL modular table formwork system (**Fig. 2 c**) are used in combination with MULTIFLEX girder slab formwork system.

According to PERI Company (www.peri.com) with extensive range of accessories, the SKYDECK slab formwork is ideally suited for markets with very high safety standards. The systematic assembly sequence and lightweight system components accelerate working operations. In addition, early striking with the drophead system reduces on-site material requirements. The small prop requirements ensure more freedom of movement under the slab formwork and simplifies the horizontal transportation of materials. SKYDECK is generally the most cost-effective formwork system where labour is expensive, as in industrialized countries. The main components of the

MULTIFLEX are the VT 20K or GT 24 Formwork Girders. As the main and cross beams, their position and spacing as well as the form lining can be freely selected, MULTIFLEX provides maximum flexibility for a wide range of requirements. If the high load-bearing GT24 Formwork Girders are used, large spans for the main and cross beams can be realized. MULTIFLEX is therefore the ideal solution for complicated ground plans, slabs with offsets or integrated downstand beams, as well as forming operations in confined spaces. MULTIFLEX girder slab formwork keeps the cost of materials down. It is therefore particularly cost-effective where labour is cheap. UNIPORTAL tableforms is the ideal solution for the forming of large slab areas. For buildings with open facades, areas of up to 100 m^2 can be formed with this large-sized slab table. UNIPORTAL tableforms operations are always project-specifically planned. The dimensions are in accordance with the building geometry and are only limited by the maximum dead weight of the table. With the remote-controlled lifting mechanism, UNIPORTAL tableforms can be quickly and safely moved to other storeys. Given sufficient crane capacity, slab tables are the most cost-effective solution where there is a high degree of repetition and open facades.

The aforementioned systems were assigned to the following options: a_1 – SKYDECK formwork system; a_2 – MULTIFLEX formwork system; a_3 – UNIPORTAL formwork system. The following evaluation criteria were selected for measuring the effectiveness of selected formwork systems or options: K_1 – man-hours (for solid concrete slab), h/m^2; K_2 – machine-hours, h/m^2; K_3 – complexity of assembling technology (for solid concrete slab), points (depended on horizontal formwork system erection/demolding time (m^2/h), number of elements (units/m^2) and weight (kg/m^2), degree of repetition and other factors); K_4 – supplier's reliability, points (not all suppliers can offer all horizontal formwork system, especially tableforms system); K_5 – required compressive strength of concrete before formwork demoulding, MPa (for the same concrete and constructive scheme of building); K_6 – time for formwork demoulding, days (time after that it possible demolding formwork system for the same concrete); K_7 – formwork rental price, EUR/m^2 per month (different horizontal formwork system have different rental price). Evaluation criteria for each horizontal formwork system are different (Table 1).

Calculations were done on the assumption that a crane was used for formwork assembling/disassembling, delivering concrete mixture to slab forming place by the crane bucket and solid concrete slab reinforcing costs were identical in all options under evaluation.

A pairwise comparison method was used to establish the relative importance of evaluation criteria. The rational option from the three analysed options was determined using the TOPSIS method.

Table 1

Comparison of selected horizontal formwork systems

Formwork system / Options	SKYDECK	MULTIFLEX	UNIPORTAL
Man-hours, h/m^2	0.48	0.60	0.29
Machine-hours, h/m^2	0.02	0.02	0.01
Number of formwork system elements, units/m^2	2.35	3.10	1.24
Formwork system weight, kg/m^2	28.78	40.00	46.10
Required compressive strength of concrete before formwork demoulding, MPA	~7.0*	~19.0*	~21.0*
Time for formwork demoulding, days	2*	14*	14*
Supplier's reliability	in stock	in stock	need special order
Formwork system rental price, EUR/m^2 per month	12.33	5.79	12.70

* - depended on different types of reinforced concrete construction.

The TOPSIS method was chosen because the basic concept of this method is that the selected option should have the shortest distance from the ideal solution and the longest distance from the negative-ideal solution (Antucheviciene *et al* 2011).

Results

The selected values of criteria (K_1-K_7) that describe the options of SKYDECK (a_1), MULTIFLEX (a_2) and UNIPORTAL (a_3) formwork systems are presented in the initial Matrix A of alternative solutions (**Table 2**).

According to the pairwise comparison method used to determine the importance of evaluation criteria, all criteria were compared with one another in pairs (a scale of 0÷10 was chosen). For example, when the criteria K_3 is better than the criteria K_1, K_3 is assigned 6 points and K_1 – 4 points. When the criteria K_4 is equal K_5 than the above is assigned 5 points. In this manner the importance of evaluation criteria was determined (subjective importance q) according to (1) equation.

$$q_i = \frac{S_i}{\sqrt{\sum_{k=1}^{n} S_i}}\ , k = 1,n; \quad (1)$$

To this end a pairwise comparison matrix A_{cr} was built (**Table 3**).

Pairwise comparison analysis revealed the following rank of evaluation criteria by importance (subjective importance): q_1 = 17.3 % ; q_2 = 16.3 % ; q_3 = 15.4 % ; q_4 = 13.9 % ; q_5 = 13.0 % ; q_6 = 12.5 % ;q_7 = 11.5 %. K_7 – formwork rental price in EUR – was found to be the most important criterion. The priority order of criteria was as follows: $K_7 > K_3 > K_2 > K_1 > K_5 > K_6 > K_4$.

The rational option was found by means of TOPSIS method. The initial Matrix A of alternative solutions A (**Table 2**) was supplemented by two lines: criteria optima (*max* or *min*) and the best value (x^*_j); consequently a new Matrix of solutions was built (**Table 4**).

Afterwards, Matrix A was normalized (**Table 5**). The reason for matrix normalization is that the data in initial matrix A are expressed in different units of measurement and thus are not possible

Table 2

Initial Matrix A of alternative solutions

Options \ Criteria	K_1	K_2	K_3	K_4	K_5	K_6	K_7
a_1	0.48	0.02	31.13	8	7	2	12.33
a_2	0.60	0.02	43.10	7	19	14	5.79
a_3	0.29	0.01	47.34	3	21	14	12.70

Table 3

Pairwise comparison Matrix A_{cr}

Criteria	K_1	K_2	K_3	K_4	K_5	K_6	K_7	S_i	q_i	Priority order
K_1	-	4	4	6	6	6	3	29	0.139	4
K_2	6	-	4	6	6	6	4	32	0.154	3
K_3	6	6	-	7	4	6	5	34	0.163	2
K_4	4	4	3	-	5	4	4	24	0.115	7
K_5	4	4	4	5	-	6	4	27	0.130	5
K_6	4	4	4	6	4	-	4	26	0.125	6
K_7	7	6	5	6	6	6	-	36	0.173	1
							∑	208	1.0	

Table 4

Alternative solutions Matrix A

Criteria / Options	K_1	K_2	K_3	K_4	K_5	K_6	K_7
a_1	0.48	0.02	31.13	8	7	2	12.33
a_2	0.60	0.02	43.10	7	19	14	5.79
a_3	0.29	0.01	47.34	3	21	14	12.70
Optimization direction	*min*	*min*	*min*	*max*	*min*	*min*	*min*
Best value	0.29	0.01	31.13	8	7	2	5.79

Table 5

Normalized Matrix A

Criteria / Options	K_1	K_2	K_3	K_4	K_5	K_6	K_7
a_1	0.584	0.667	0.437	0.724	0.240	0.101	0.662
a_2	0.730	0.667	0.605	0.634	0.651	0.704	0.311
a_3	0.353	0.333	0.665	0.272	0.720	0.704	0.682

to compare. Normalization of initial Matrix A produces non-dimensional values. Matrix A was normalized according to (2) equation:

$$x_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{j} x_{ij}^2}} \quad , \ i = 1,m \ ; \ j = 1,n; \qquad (2)$$

here:

x_{ij} – i – line and j – column of Matrix.

Following the normalization of Matrix A, a weighted normalized Matrix A^* of alternative solutions is created (**Table 6**). To this end the normalized Matrix A is multiplied by the vector of criteria importance (see q_1–q_7 above) according to (3) equation:

$$A^* = [A] \cdot [q], \qquad (3)$$

The ideal best condition a^+ (the best value) and the ideal worst condition a^- (the worst value) are found. Distances between the real option a_i and the ideal best condition a^+, as well as between the real option a_i and the ideal worst condition a^- are computed according to (4,5) equations:

$$L^+_i = \sum_{j=1}^{n} \left| f_{ij} - f_j^+ \right| \quad , \ i = 1,m; \ j = 1,n; \qquad (4)$$

$$L^-_i = \sum_{j=1}^{n} \left| f_{ij} - f_j^- \right| \quad , \ i = 1,m; \ j = 1,n; \qquad (5)$$

Table 6

Weighted normalized Matrix A* of alternative solutions

Criteria / Options	K_1	K_2	K_3	K_4	K_5	K_6	K_7
a_1	0.101	0.108	0.067	0.101	0.031	0.013	0.076
a_2	0.126	0.108	0.093	0.088	0.085	0.088	0.036
a_3	0.061	0.054	0.102	0.038	0.094	0.088	0.078

Table 7

Data obtained by applying TOPSIS method

Options	L_i^+	L_i^-	K_{bit}	Priority order	Efficiency value (N_i), %
a_1	0.127	0.209	0.622	1	100.00
a_2	0.271	0.107	0.283	2	45.51
a_3	0.274	0.104	0.275	3	44.28

The relative proximity of compared options to the ideal option is found, i.e. criterion K_{bit} is calculated. Having the criterion K_{bit} value calculated, the priority rank of compared options is made. In our case, the best option is the one that has the highest value of criterion K_{bit}. In the last stage the efficiency value N_i of compared options is calculated according to (6) equation:

$$K_{bit} = \frac{L_i^-}{L_i^+ + L_i^-}, \; i = 1,m; \tag{6}$$

The computation results are presented in Table 7.

Computations done using TOPSIS method revealed that the most rational option for the building of solid concrete floor slab in a high-rise building is Option a_1 – SKYDECK panel slab formwork system (efficiency value (N_i) is 100%). Option a_2 – MULTIFLEX girder slab formwork system and Option a_3 – UNIPORTAL modular table formwork system received almost equal evaluation. Respectively, their efficiency values (N_i) are: 45.51% and 44.28%.

This method allows to select the optimum solution of horizontal formwork system according to selected criteria system.

Conclusions

1 The effectiveness of constructing solid concrete floor slabs in high-rise buildings, namely the construction work time, price, complexity of technology and other factors can be controlled by selecting the appropriate horizontal formwork system: panel, beam and girder or modular table.

2 Using the pairwise evaluation method the following order of the meaning criteria was obtained: 17.3% – formwork rental price (K_7), 16.3% – complexity of assembling technology (K_3), 15.4% – labour costs of mechanism (K_2), 13.9% – labour costs of employer (K_1), 13.0% – required compressive strength of concrete before formwork removal (K_5), 12.5% – demoulding of formworks, days (K_6), 11.5% – supplier's reliability (K_4). K_7 – formwork rental price in EUR – is the most important evaluation criterion.

3 Computations done by means of TOPSIS method revealed that the most rational option for the building of solid concrete floor slab in a high-rise building is Option a_1 – SKYDECK panel slab formwork system (efficiency value (N_i) is 100%).

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About the authors

GINTAS BRAZAS

Master

Faculty of Civil Engineering and Architecture, Department of Construction Technologies

Main research area

Civil engineering

Address

Studentu str. 48, LT-51367
Kaunas, Lithuania
Tel. +370 37 300479
E-mail: gintas@gmail.com

MINDAUGAS DAUKŠYS

Dr.

Faculty of Civil Engineering and Architecture, Department of Construction Technologies

Main research area

Civil engineering, construction technology

Address

Studentu str. 48, LT-51367
Kaunas, Lithuania
Tel. +370 37 300479
E-mail: mindaugas.dauksys@ktu.lt

JOLANTA ŠADAUSKIENĖ

Dr.

Faculty of Civil Engineering and Architecture, Department of Building Energy Systems

Main research area

Civil engineering

Address

Studentu str. 48, LT-51367
Kaunas, Lithuania
Tel. +370 37 300492
E-mail: jolanta.sadauskiene@ktu.lt

MINDAUGAS AUGONIS

Dr.

Faculty of Civil Engineering and Architecture, Department of Engineering Structures

Main research area

Civil engineering

Address

Studentu str. 48, LT-51367
Kaunas, Lithuania
Tel. +370 37 300473
E-mail: mindaugas.augonis@ktu.lt

ŠARŪNAS KELPŠA

PhD student

Faculty of Civil Engineering and Architecture, Department of Construction Technologies

Main research area

Civil engineering

Address

Studentu str. 48, LT-51367
Kaunas, Lithuania
Tel. +370 37 300479
E-mail: sarunas.kelpsa@ktu.lt