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Analysis of cost and time required for the construction of RC diaphragms depending on the method of execution

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Load in deep massive foundations is transferred to the substrate through surface elements called the diaphragms. For the last ten years, reinforced concrete diaphragms has been used as a deep foundation cover in a pit for underground levels of buildings in urban areas. On an example of a multi-storey building with a basement level in urban environment, construction of monolithic reinforced concrete diaphragms is planned in several phases. Analysis was conducted of cost and time required to construct two different variants of diaphragms for the purpose of obtaining an optimal construction method. The first variant is with construction of every second lamella (even and odd) and the second variant is with construction of every third lamella. Due to the proximity of surrounding buildings and impossibility of making a wide excavation, analysed reinforced concrete diaphragms are used as protection of the pit for the foundation slab, and at the same time as the walls of the basement level.

Keywords: reinforced concrete diaphragm, construction cost analysis, construction machinery

1. INTRODUCTION

In the last ten years, there has been a need for construction of residential and commercial buildings in urban areas. Due to deficiency location for building, the future building is most often constructed in a small area that is bordered by the adjacent buildings. For the area planned for the construction of the facility to be used to the maximum, it is planned to build basements. Deep massive foundations which are used to protect the vertical excavations of the basement level and to transfer the load to the deeper layers of the soil of higher bearing capacity are reinforced surface elements called the diaphragms.

In addition to diaphragms, deep founding is also made up of foundations that are built in deep supported excavations or foundations that are built with walls and caissons. The characteristic of a deep foundation is that the foundations transfer loads over the overlying horizontal surface to deeper soil layers that have less compressibility and higher bearing capacity.

The beginning of the use of reinforced concrete diaphragms (RC diaphragms) is related to the sixties of the last century, and for the needs of building construction in urban environment, can see the rapid development [1] and improvement both in the design phase and in technologies and methods of execution. RC diaphragms are used if it is not possible to perform a wide excavation due to the nearness of the adjacent building. Wide excavation is excavation with sides at an angle that provides slope stability [2], which is a characteristic in cases when the building is built in urban areas. Excavations for deep foundation pits, which are most often used for basement level, are mostly performed in complex geotechnical conditions with a high groundwater level. Complex geotechnical conditions include the foundation on gravelly, sandy, and dusty-clay soils with a high level of groundwater [3]. In these conditions, before the appearance of the RC diaphragm, the foundation was performed using caisson, wells and piles, which are methods with a more complex procedure of execution and design. These problems at the deep foundation are effectively solved by using a RC diaphragm. The use of RC diaphragms avoids wide excavations and expansion, whereby these surface elements protect the foundation pit from collapsing the surrounding soil. In addition to this form of application, which is the most common, diaphragms can also be used to solve a variety of problems, as load-bearing elements of engineering structures, as supporting structures on roads, as antifiltration curtains under hydraulic structures, as elements in specific drainages, for waterproof cores embankment bodies, etc. The appearance of the RC diaphragm build from the segments is given in Figure 1.

RC diaphragms are made in several phases. It is first necessary to protect the parts around the diaphragm (on both sides of the diaphragm) during excavation from soil collapse, which is most often performed using a special solution of high-value clay - bentonite in water, the so-called clay suspensions as shown in Figure 2 and Figure 3. This special solution of high-value clay is used during excavation as a protection deep slit in which the reinforcement is put down after excavation (if the projected diaphragm is from reinforced concrete), which is shown in Figure 4. After putting down the reinforcement, this deep slit is filled with concrete while extruding the solution of high-value clay, forming a surface element - the RC diaphragm.

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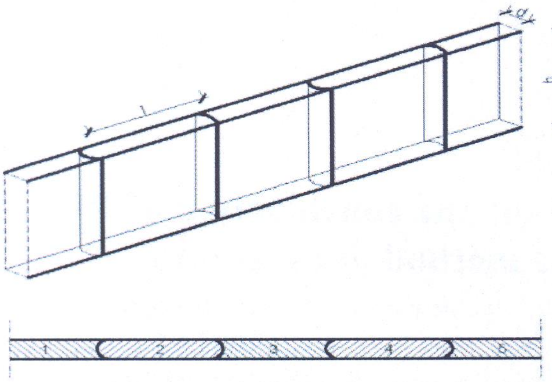

Figure 1: The appearance of the segments that form the RC diaphragm

Figure 2: Excavation of the diaphragm trench

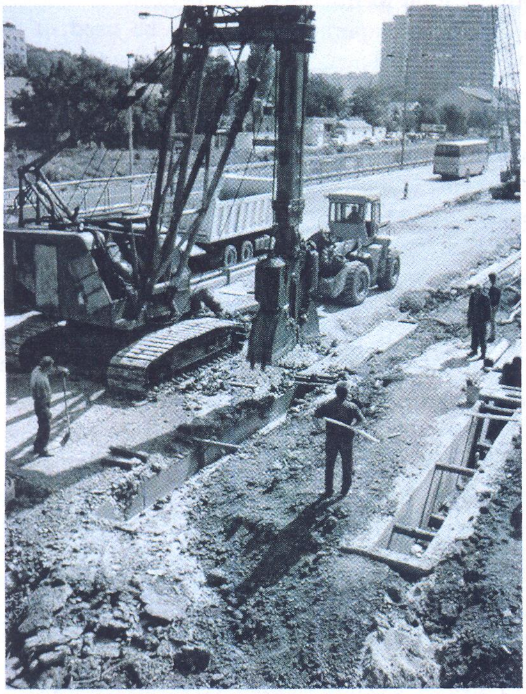

Figure 3: Excavation of the diaphragm trench

Figure 4: Installation of a reinforcing skeleton in a trench of a RC diaphragm

2. TECHNICAL CHARACTERISTICS OF THE BUILDING AND RC DIAPHRAGMS

Reinforced concrete diaphragms are used in multi-storey buildings during construction to protect foundation pits, and later during the exploitation of the building in the function of deep foundations, they transfer loads from the structure to the soil layers of higher load capacity. The construction of a multi-storey building is planned in an urban environment, with neighbouring buildings in the immediate vicinity on both sides of the future building, and on the remaining two sides is the road, as shown in Figure 5.

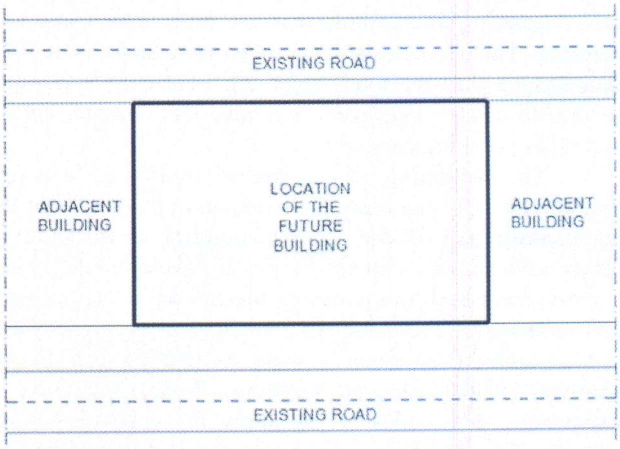

Figure 5: Location of the future building

Since the geotechnical study determined that the soil at the location of the building is sandy and gravelly with a certain content clay with low load capacity, it is necessary to foundation the building using foundation slabs. Due to the proximity of surrounding buildings and impossibility of making a wide excavation, analysed RC diaphragms are used as protection of the pit for the foundation slab, and at the same time as the walls of the basement level. On an example of a multi-storey building with a basement level in urban environment, construction of monolithic RC diaphragms is planned in several phases. Analysis was conducted of cost and time required to construct two different variants of diaphragms for the purpose of obtaining an optimal construction method. The first variant is with construction of every second lamella (even and odd) and the second variant is with construction of every third lamella. For both variants, the construction phases and the analysis of the time required are described for the building of RC diaphragms. The first phase includes preparatory work, followed by the work necessary to make the diaphragm trench. When the excavation of the trench is completed, it is necessary to form a reinforcing skeleton which is embedded in the trench of a certain thickness, and then is performed concreting by a special procedure. Since the monolithic RC diaphragm is built from segments - lamellas, it is necessary to perform the RC connecting beam whose role is to connect all segments of the diaphragm into one whole.

2.1. Technical description of a multi-storey building

For the needs of collective housing, a residential and business building has been designed and its construction is planned. The building is planned to be a reinforced concrete multi-storey building consisting of a basement level, ground level, and six floors, which is shown in Figure 6.

According to the architectural project, it is planned to use the basement level for auxiliary and common rooms, the ground level with 11 shops as business space, and the floors for housing. The building has a rectangular base with dimension 18.5x29.5m. On the characteristic floor level, there are five apartments of different sizes. A solution in the form of a flat impassable roof is planned for the roof construction of the building.

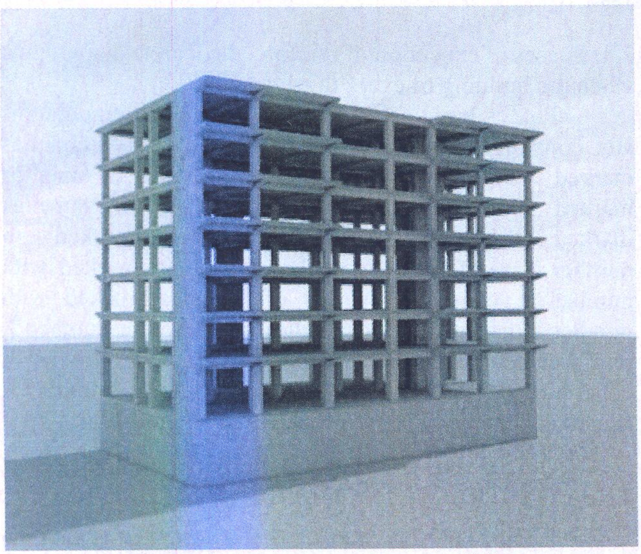

Figure 6: Appearance future building

The load is transferred from the roof over the floor to the soil across a foundation slab thick 80cm [4], whose strength increased is with reinforced concrete beams.

The analysis of all relevant loads that affect the construction and dimensioning of characteristic reinforced concrete elements was done according to European standards - Eurocodes.

2.2. Characteristics of soil and technical characteristic of diaphragm

The data obtained by geotechnical research performed at a given location show that the soil is sandy and gravelly with a certain percentage of clay [5]. The sand and gravel has a characteristic weight density γ=17KN/m^3, effective cohesion c=5KPa and angle of shearing resistance φ=32°. Soil with that characteristics is to the depth of 3.2m, which was determined by geotechnical research. The soil at a depth of more than 3.2m has better characteristics and higher load capacity. According to the geotechnical report, the groundwater level is at a depth of 4.2m measured from the terrain surface, which does not affect the building of reinforced concrete diaphragms and structures.

The load is mostly transferred across line elements - columns of cross-sectional dimensions 60/60cm from higher to lower floors. Then the load is transferred across columns to a foundation slab thick 80cm which is building in underground level on soil lower load capacity. The primary role of RC diaphragms is to protect the pit for the foundation slab during the construction of the basement level, then they are used for the transfer load to the layers of soil better characteristics during the exploitation of the building.

Cantilever RC diaphragms are used to protect the foundation pit because the building of anchored RC diaphragms is impossible due to the proximity of the adjacent buildings [6]. The necessary length [7] of the cantilever part RC diaphragm is calculated using (1), for the soil of the described characteristics and the height of the basement level which amounts to H_c=2.6m, the necessary length h of the cantilever part RC diaphragm must be greater than 1.088m.

$$h \geq H_c - \frac{2 \cdot c_r}{\gamma_1} \cdot \left(1 + \frac{\pi}{2}\right) \qquad (1)$$

According to (1) is being adopted length h of the cantilever part RC diaphragm of 1.2m. The total height of the 0.6m thick RC diaphragm is 3.8m. The dimensions of the RC diaphragm and the position when the diaphragm to build from the segments - lamellas are shown in Figure 7.

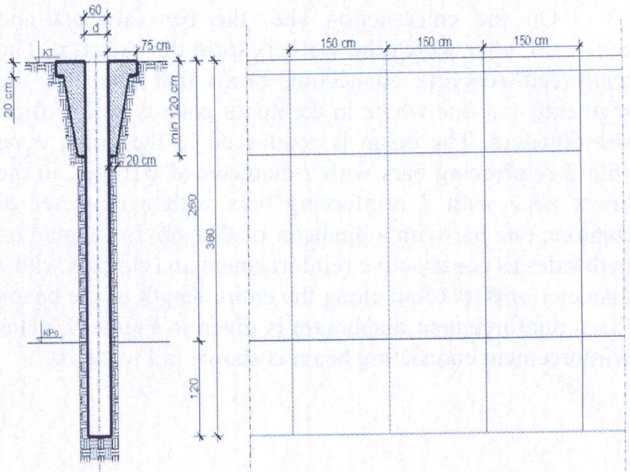

Figure 7: Dimensions of reinforced concrete diaphragm

The RC diaphragm is built of segments - lamellas to prevent changes in the equilibrium state in the soil [8]. A change in the equilibrium state in the soil can cause a loss of stability to the adjacent building. In the following, the times necessary to building the RC diaphragm are considered for two variants: the first variant is with the construction of every second lamella (even and odd) and the second variant is with the construction of every third lamella. In both cases, the wall of the pit for the foundation slab consists of 66 lamellas of different widths.

The longer side of the diaphragm wall consists of 20 lamellas, of which the initial and final ones are 155 cm long, and the others are 150cm long. The shorter side consists of 13 lamellas, with the initial and final ones being 160cm long and the others 150cm long. The RC diaphragms are reinforced with ribbed reinforcement B500B in the vertical direction with bars with a diameter of 14mm at a distance of 10cm and the horizontal direction with bars with a diameter of 12mm at a distance of 20cm. Concreting is performed with concrete class C30/37. The division of the walls in the basement level into segments of the RC diaphragm is given in Figure 8.

Except concrete class C30/37, reinforcing skeletons are used to building diaphragms, which consist of vertical bars Ø14/10cm and horizontal bars Ø12/20cm of reinforcement B500B. The necessary reinforcement on the construction site arrives in the form of bars 12.0m long and of a determined diameter.

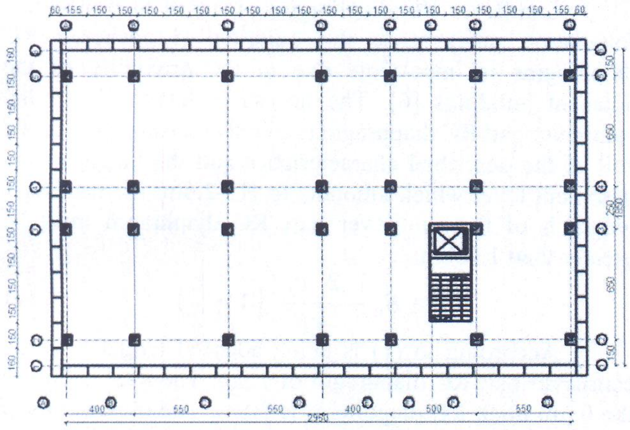

Figure 8: Partition of the diaphragm into segments - lamellas

On the construction site, the bars are cut and cambered, after which the workers form the skeleton. The reinforced concrete connecting beam that connects the segments into one whole in the upper zone is a dimension b/d=60/60cm. The beam is reinforced in the upper zone with 3 reinforcing bars with a diameter of Ø16mm, in the lower zone with 7 reinforcing bars with a diameter of Ø16mm, one bar with a diameter of Ø12mm is adopted on both sides as constructive reinforcement and stirrups with a diameter of Ø10/15cm along the entire length of the beam. Plans reinforcement diaphragm is given in Figure 9, plans reinforcement connecting beam is shown in Figure 10.

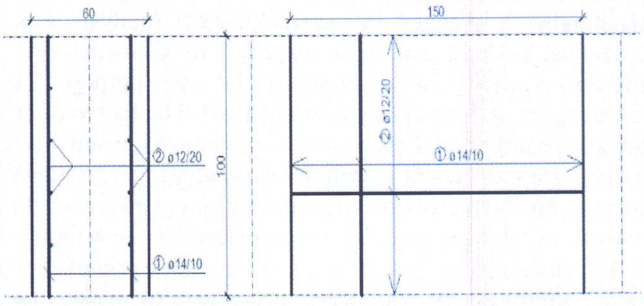

Figure 9: Diaphragm segment reinforcement plan

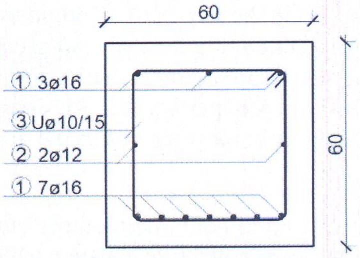

Figure 10: Connecting beam reinforcement plan

2.3. Phases of execution of reinforced concrete diaphragms when the building of every second lamella

Phases building of reinforced concrete diaphragms are: construction site preparation, earthworks of lamellas marked with number 1 reinforcement works of lamellas marked with number 1, concreting works of lamellas marked with number 1, earthworks of lamellas marked with number 2, reinforcement works of lamellas marked with number 2, concreting works of lamellas marked with number 2, finishing concrete works, in Table 4 numbered 1-8.

2.4. Phases of execution of reinforced concrete diaphragms when the building of every third lamella

Phases building of reinforced concrete diaphragms are: construction site preparation, earthworks of lamellas marked with number 1, reinforcement works of lamellas marked with number 1, concreting works of lamellas marked with number 1, earthworks of lamellas marked with number 2, reinforcement works of lamellas marked with number 2, concreting works of lamellas marked with number 2, earthworks of lamellas marked with number 3, reinforcement works of lamellas marked with number 3, concreting works of lamellas marked with number 3, finishing concrete works, in Table 5 numbered 1-11.

3. ANALYSIS OF COST AND TIME REQUIRED FOR THE CONSTRUCTION OF RC DIAPHRAGMS

For the analysis of the cost and planning of the time required for the execution of the reinforced concrete diaphragm, it is necessary to make a bill of quantities for the listed phases of execution. The bill of quantities for the excavation phase consists of calculating the quantity of soil to be excavated with a grapple excavator. Then for the next phase the quantity of reinforcement to be embedded should be determined, and after the reinforcement is embedded the quantity of concrete that is used for concreting.

3.1. Bill of quantities (BOQ) of construction works

For known dimensions of diaphragm segments and reinforcement steel plan, it is possible to determine the quantities of materials required for the execution. The required quantities of material are shown in Table 1 for the first variant of execution and in Table 2 for the second variant of execution.

Table 1: Bill of quantities (BOQ) for the first variant

The phase of lamellas execution	The total length of lamellas [m]	Bill of quantities		
		Excavation soil [m^3]	Quantity of reinforcement [kg]	Quantity of concrete [m^3]
Even lamellas	51.5	117.42	Ø14: 5347.31 Ø12: 2139.39	117.42
Odd lamellas	48.1	109.67	Ø14: 4994.28 Ø12: 1998.15	109.67
Total	99.6	227.09	Ø14: 10341.59 Ø12: 4137.54	227.09

Table 2: Bill of quantities (BOQ) for the second variant

The phase of lamellas execution	The total length of lamellas [m]	Bill of quantities		
		Excavation soil [m^3]	Quantity of reinforcement [kg]	Quantity of concrete [m^3]
Lamellas which are building in the first phase	36.5	83.22	Ø14: 3789.84 Ø12: 1516.27	83.22
Lamellas which are building in the second phase	31.55	71.93	Ø14: 3275.87 Ø12: 1310.64	71.93
Lamellas which are building in the third phase	31.55	71.93	Ø14: 3275.87 Ø12: 1310.64	71.93
Total	99.6	227.09	Ø14: 10341.59 Ø12: 4137.54	227.09

3.2. Practical performance of construction machinery

3.2.1. Performance of construction machinery for excavation soil - grapple excavator

A hydraulic excavator HITACHI ZX-350LC-5B is used to excavate the pit of the reinforced concrete diaphragm. Characteristics of a tracked excavator with a special bucket-grapple are: working part volume is 0,3m^3, engine power is 202KW, weight is 346.17KN, length arm is 5,2m.

The practical performance of an excavator with a grapple is calculated using (2). The coefficients that appear in the given formula are chosen depending on the type of material from the geotechnical study and the conditions on the construction site where the excavation is performed, well as on the condition in which the excavating machine is located. When the values of these coefficients are included in the given formula, the practical performance of the construction machine is 20.36m^3/h.

3.2.2. Performance of construction machinery for concreting - concrete pump

For the building of concrete elements, concrete is used which is produced in a concrete factory and delivered to the construction site as a ready product. A mobile pump MAN TGS SCHWING is used for concrete installation. The theoretical performance of a concrete pump is 30.0m^3/h. The practical performance of a concrete pump is calculated using (3). The coefficients that appear in the given formula are chosen depending on the conditions on the construction site where the concreting is performed. When the values of these coefficients are included in the given formula, the practical performance of the construction machine is 21.80m^3/h.

$$U_{pr} = \frac{T}{t_c} \cdot q \cdot k_{og} \cdot k_{rv} \cdot k_{ds} \cdot k_{vm} \cdot k_{rp} \cdot k_{uv} \cdot k_{kz} \cdot k_{pu} \tag{2}$$

$$U_{pr} = U_t \cdot k_v \cdot k_r \cdot k_p = \frac{T}{t_c} \cdot q \cdot k_v \cdot k_r \cdot k_p \tag{3}$$

3.3. Analysis of cost and time required for the construction of RC diaphragms

The times required to perform works on the construction site were analysed. According to the listed phases of construction, these works include earthworks - excavation of pits for the reinforced concrete diaphragm, reinforcement works - preparation and installation skeleton of reinforcement steel in excavated lamella pit and concrete works - concreting of diaphragm lamellas and concreting of the connecting beam. The cost of construction works is calculated by applying the formula (4).

$$C = M + R \cdot (K + 1) \qquad (4)$$

In (4) [9], the price of the material is marked with M, the price of labor is marked with R, and the coefficient of non-uniformity is marked with K, the adopted value of which is 4. The cost required for the construction of a RC diaphragm is given in Table 3. The time required for the construction of a RC diaphragm is given in Table 4 and Table 5. The cost and time required for the construction of a RC diaphragm [10], for the first variant are given in table 4 and the cost and time required for the construction of a RC diaphragm for the second variant are given in table 5.

For analysis of cost and time required for the construction of RC diaphragms are used norms and standards of work in construction [11]: analysis of cost and time required for earthwork (machine excavation of soil category II with excavator - GN 200-507 5.1 025605), analysis of cost and time required for reinforcement works (machine cutting and bending, manual installation and binding of reinforcement ČBR, simple and medium complex, vertical crane transport, Ø12 - GN 400-106A 145601; machine cutting and bending, manual installation and binding of reinforcement ČBR, simple and medium complex, vertical crane transport, Ø14 - GN 400-106A 145604), analysis of costs and time required for concrete works (mechanical installation of concrete (without making) - GN 400-508 154504).

For the building phases given in the chapters 2.3. and 2.4. and bill of quantities for the two variants given in the tables 1 and 2, based on the calculated cost prices and the time required for building per unit of quantity, when these values are multiplied by the quantities from the bill of quantities, the time required for the execution and the total cost price for building reinforced diaphragm is obtained. It was adopted that the working day has one shift with duration of 8 hours.

Based on the calculated cost prices by phases of performed works, the cost values and the required number of days for building diaphragms using the first variant (when every second lamella is constructed) were calculated which is shown in Table 4, and the required number of days for building diaphragms using the second variant (when every third lamella is constructed) which is shown in Table 5.

Table 3: The cost required for the construction of a RC diaphragm

The phase of lamellas execution	The cost of material [rsd/m^3]	The cost of labor [rsd/m^3]	The total cost [rsd/m^3]
Earthwork	36.76	35.00	211.76
Reinforcement works (Ø12)	1906.54	195.21	2882.59
Reinforcement works (Ø14)	4765.31	325.02	6390.41
Concrete works	12000.00	725.50	15627.50

Table 4: The cost and time required for the construction of a RC diaphragm for the first variant

The phase of lamellas execution	Cost price [rsd]	Time required for the construction [day]
1	24,865.09	2
2	1,088,835.66	5
3	1,834,981.00	4
4	23,223.00	1
5	1,016,969.91	5
6	1,713,867.93	4
7	528,800.70	3
8	560,339.64	3
Total	6,791,883.92	27

Table 5: The cost required for the construction of a RC diaphragm for the second variant

The phase of lamellas execution	Cost price [rsd]	Time required for the construction [day]
1	17,622.83	1
2	771,699.06	5
3	1,378,658.05	4
4	15,232.04	1
5	667,006.89	4
6	1,124,086.08	4

7	15,232.04	1
8	667,006.89	4
9	1,124,086.08	4
10	528,800.70	3
11	560,339.64	3
Total	6,869,770.30	34

4. ANALYSIS OF THE RESULTS

4.1. Cost of performed works for the building of a RC diaphragm

The calculated values of the cost price of the performed works for the two execution variants can be shown graphically. The cost price for the first variant is 6,791,883.92rsd (when every second lamella is build), which is shown by the left bar on the diagram in Figure 11. The cost price for the second variant is 6,869,770.30rsd (when every third lamella is build), which is shown by the right bar on the diagram in Figure 11. These values are shown graphically because it is the easiest way to see the difference between the two described variants of building RC diaphragms.

4.2. The time required for the building of a RC diaphragm

Time analysis was done for each phase of works individually. The phases of the works are described in chapters 2.3 and 2.4. For the first variant (when every second lamella is building) the phases are described in chapter 2.3 and the total time required for construction is given in Table 4. For the second variant (when every third lamella is building) the phases are described in chapter 2.4 and the total time required for construction is given in table 5. The time required to the building of a reinforced diaphragm according to the first variant is 27 days and is shown in the left bar of the diagram in Figure 12. The time required to the building of a reinforced diaphragm according to the second variant is 34 days and is shown in the right bar of the diagram in Figure 12.

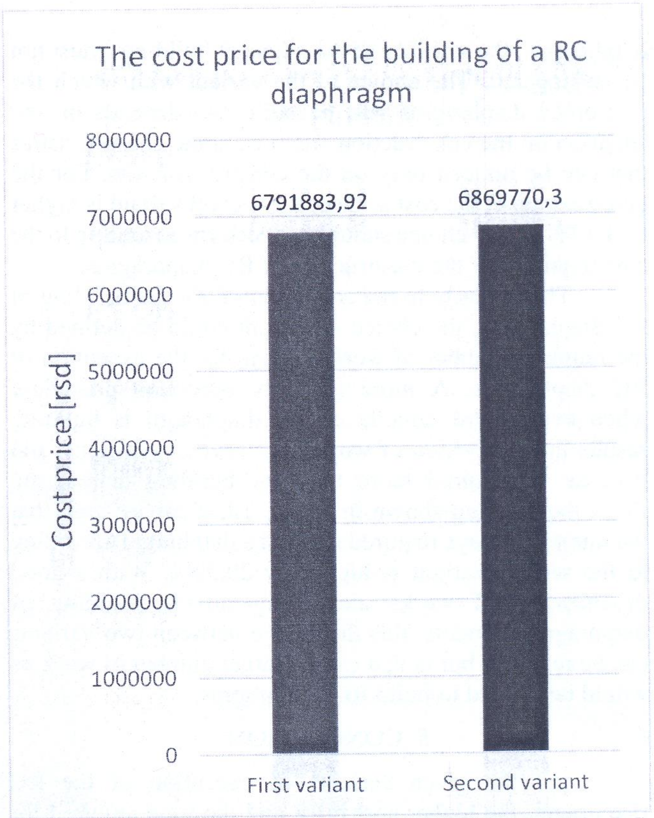

Figure 11: The cost required for the construction of a RC diaphragm

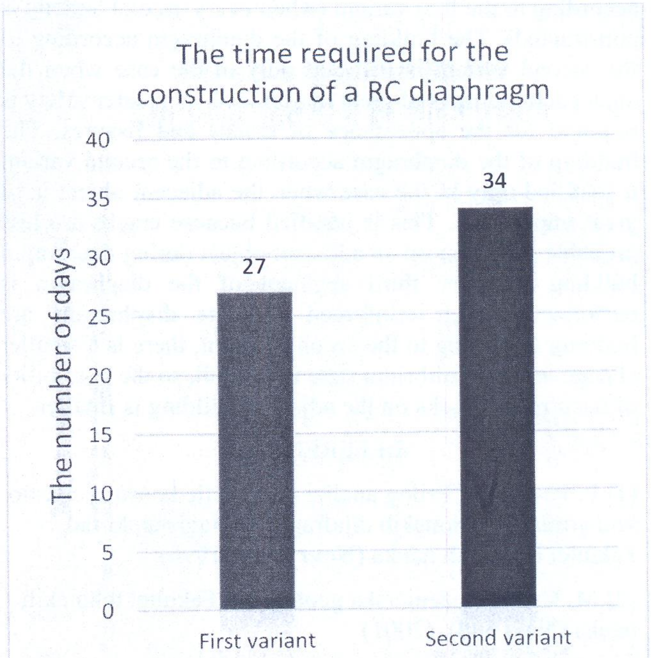

Figure 12: The time required for the construction of a RC diaphragm

4.3. Discussion of the results

From the diagram shown in Figure 11, it can be seen that the cost values of building RC diaphragms are approximate. Since the cost values are approximate, the variant by which the RC diaphragms will be building is chosen based on other factors. The choice of variant usually depends on the security factor for the adjacent buildings. During the excavation of the pit for reinforced concrete diaphragms, the stability of the adjacent buildings must not be endangered. The choice of the variant with which the reinforced diaphragms will be built also depends on the situation on the construction site, i.e., some characteristics that can be noticed only on the construction site. For the given example, the cost price of the second variant is higher by 1.13%, so the choice should not perform according to the cost required for the construction of RC diaphragms.

The opposite to the cost required for the building of RC diaphragms, the choice of variant could be defined by the required number of working days for the execution of RC diaphragms. A more complex execution procedure when every third lamella of the diaphragm is building results in the division of works into several positions, and because is required more time for building diaphragm. From the diagram shown in Figure 12, it can be seen that the number of days required to build a diaphragm according to the second variant is higher by 20.59%. With a good organization of works and comparatively building of diaphragm segments, this difference between two variants can be reduced, but in that case, a larger number of workers would be needed to build RC diaphragms.

5. CONCLUSION

For the given variants of execution of the RC diaphragm, the higher cost price and the time required for execution diaphragm is in the case when every third segment diaphragm is performed. Therefore, it is economically justified to building the RC diaphragms according to the first variant (when every second lamella is constructed). The building of the diaphragm according to the second variant is justified only in the case when the adjacent building is of great importance, so greater safety is required for the appearance of cracks and fissures. The building of the diaphragm according to the second variant is justified only in the case when the adjacent object is of great importance. This is justified because cracks are less probable to appear on an adjacent object during diaphragm building if every third segment of the diaphragm is performed. When reinforced concrete diaphragms are building according to the second variant, there is a smaller change in the equilibrium state in the soil, so the possibility of occurrence cracks on the adjacent building is smaller.

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