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Analysis of the calculation of support nodes bolted connections of cantilevered steel-reinforced concrete posts

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In order to reduce steel consumption in the installation of support nodes of cantilevered pipe reinforced concrete advertising structures, the optimal ratio of the base plate size and the diameter of the support node anchor bolts of an existing advertising structure was calculated. The analysis of the calculations revealed the total cost dependence of the support node and anchor bolts on the overall node dimensions and the anchor bolts diameter. With an increase in the size of the support node, the cost of the support node metal increases much faster than the cost of the anchor bolts decreases. For more efficient use of materials, it is necessary to reduce the size of the node and increase the diameter of the anchor bolts accordingly. As a result of the research and calculations, the most efficient support node was determined. The savings in the total cost of such a node is 8.9% compared to the existing support node of the studied advertising structure.

Key words: wind load, support node, bolted connection, cantilever construction.

Аналіз розрахунку болтових з'єднань опорних вузлів консольних сталезалізобетонних стійок

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З метою оптимізації витрат сталі при влаштуванні опорних вузлів консольних трубобетонних рекламних конструкцій було розраховано оптимальний варіант співвідношення розміру опорної пластини та діаметру анкерних болтів опорного вузла. Для розрахунку діаметру та перерізу анкерних болтів було пораховано навантаження на вузол обпирання рекламної конструкції для п'яти різних значень вітрового тиску. Проаналізовано вплив зміни розміру опорної пластини консольної конструкції та відповідно відстань між анкерними болтами на розрахункові напруження в анкерних болтах для п'яти вітрових районів України. В результаті аналізу розрахунків було виявлено залежність загальної вартості опорного вузла та анкерних болтів від габаритних розмірів вузла та діаметра анкерних болтів. При збільшенні розмірів опорного вузла вартість металу опорного вузла зростає значно швидше ніж зменшується вартість анкерних болтів. Для більш ефективного використання будівельних матеріалів необхідно зменшити габаритні розміри опорного вузла і відповідно збільшити діаметр анкерних болтів. Для кожного вітрового району існує оптимальне співвідношення розміру бази, товщини бази та діаметру анкерних болтів. В результаті проведених досліджень та розрахунків існуючої рекламної конструкції з рекламним щитом розміром 6,0м на 3,0м що розміщено на висоті 4,0м (у м. Полтава) найбільш ефективним виявився вузол обпирання з габаритним розміром бази колони 500х500мм в комбінації з анкерними болтами діаметром 36мм. Економія загальної вартості такого вузла становить 8,9% в порівнянні з вартістю існуючого вузла обпирання досліджуваної рекламної конструкції. Подальше зменшення габаритних розмірів вузла обпирання веде до збільшення загальної вартості вузла обпирання за рахунок збільшення діаметрів та відповідно і вартості анкерних болтів.

Ключові слова: вітрове навантаження, опорний вузол, болтове з'єднання, консольна конструкція.

Introduction

The support nodes of cantilever structures serve to properly transfer forces and moments from the metal structure of the post to the structure foundation. Most often, bases with traverses are used, where the traverses serve as additional elements that contribute to the uniform loading of the base plate.

The peculiarity of cantilever nodes is the high torque moment acting on the nodes and the relatively low vertical load, unlike the support nodes of industrial buildings, where the nodes perceive high vertical loads from the weight of the supporting structures and the payload of the building.

In cantilevered structures, the connection between the column and the foundation must be rigid, i.e., ensuring that the column base is connected to the foundation without turning the column in relation to the foundation.

Cantilever support nodes are widely used in advertising structures throughout Ukraine and are most often installed on free-standing reinforced concrete foundations.

More than seventeen thousand cantilever advertising structures have been installed in Ukraine. Given the large number of existing advertising structures and the constant installation of new ones, this task is urgent, as cases when the support units do not withstand the design loads are not at all rare.

a)

b)

Figure 1 – Advertising structures that did not withstand the load (a, b).

And since advertising structures, for greater commercial effect, are mostly placed in places with large crowds of people or a large flow of cars, the reliability of such structures is very important.

Examples of advertising structures that failed to withstand the load (see fig. 1).

In most of the cases analyzed, it is the cantilever structure's support node that fails to withstand the load.

Review of the research sources and publications

Ensuring the reliability and failure-free operation of buildings and structures depends to a large extent on the standardization of wind loads. To correctly calculate the forces acting on a structural support node, it is necessary to calculate the wind load on a cantilevered structure.

The issue of calculating wind pressure on structures is covered in the work of Pichugin S.F. [1]. The wind zoning of the territory of Ukraine takes into account the significant territorial variability of the wind load. The territorial zoning of the territory of Ukraine according to the characteristic values of the wind load includes five territorial districts with calculated characteristic values from 0.4 to 0.6 kPa. The lowest wind loads are observed in the central and northwestern regions of Ukraine, as well as in Zakarpattia. The highest wind loads are realized in the Carpathians, Prykarpattia and coastal areas.

The methodology of administrative-territorial zoning of climatic loads on building structures based on the establishment of a single design value for a certain administrative region is described in the work of Pashinsky V.A. [2].

The methodology for determining loads and impacts on building structures based on the data of a local network of weather stations is covered in the work of Pashinsky V.A. [3], where the methodology for determining loads and impacts on building structures at a given local weather station is improved by introducing reserves that take into account the random scatter of data from the nearest weather stations.

Foreign researchers have also covered the issues of calculating the wind load on cantilever advertising structures. In particular, the article “Wind Loads on Solid Signs” [4] calculates the wind load taking into account the overall dimensions of the advertising structure, the height of placement above the ground with the use of correction factors. The calculation of wind loads on buildings and structures is described in [5-6].

A parametric analysis of wind effects on tall buildings according to European, American, and Australian standards was conducted in work “A parametric analysis of wind effects on tall buildings according to European, American, and Australian standards” [7]. The calculation of wind loads takes into account various factors, including wind speed, effective wind speed, orographic factors, dynamic factors, load gust factors, and shape factors. All of these factors vary slightly in different design codes. The impact results are compared using computer programs to find out the similarities and differences in the different design approaches.

Examples of calculating bolted joints for strength depending on the forces in the bolts and the tensile strength of the bolts are given in the textbook Steel Structures in Construction [8].

An increase in the safety margin of threaded connections operating under variable loads is highlighted in the work by Nevdakha Y.A., Pyrogov V.V., Nevdakha N.A., Oleinichenko L.S., Vasylkovsky M.O. [9]. When calculating the ultimate working load acting on a bolt, which varies according to a pulsating cycle for a tightened threaded connection, the conditions of no fracture and no opening of the joint are determined, and the relationship between the safety margin of the bolt and the value of the initial tightening is revealed, which is of great practical importance. The correct choice of the initial tightening value, ceteris paribus, provides the highest safety margin, which is a condition for reliable operation of the bolted joint.

Foreign researchers have also highlighted the problem of calculating bolted connections of the cantilever structure's support node. The calculation of the bolted connection of the end cantilever beam is presented in the article Bolted Connection of an End-Plate Cantilever Beam: The Distribution of Operating Force [10], which presents an alternative method for calculating the distribution of operating forces on bolts and the calculation results were also confirmed by measurements of actual forces in the bolts. The problem of calculating bolted connections of the column support node is also considered in the article "Tensile Behavior of Asymmetric Bolted Square Hollow Section Column Splices" [11].

Modeling of bolted connections is also discussed in other articles [11-12].

Definition of unsolved aspects of the problem

The reliability of an advertising structure largely depends on the reliability of the support node. Calculating all the loads acting on the support node and determining the optimal ratio between the calculated overall dimensions of the support node and the diameter of the anchor bolts is the key to efficient use of building materials and ensuring the standard service life of the cantilever advertising structure.

Problem statement

The purpose of the study is to optimize the size and types of cantilever support nodes and calculate their performance depending on the type of the nodes usage and the load on the nodes for the most rational use of building materials and labor while maintaining the bearing capacity of the support node throughout the entire standard service life of the structure.

Basic material and results

A large number of advertising structures in the region were studied and it was found that most of the existing supporting units of advertising structures have similar dimensions and fundamental solutions. According to the calculations, the total number of existing cantilever advertising structures (billboards) located in Poltava is more than 350.

The general view of the advertising structure accepted for further research is shown in Figure 2.

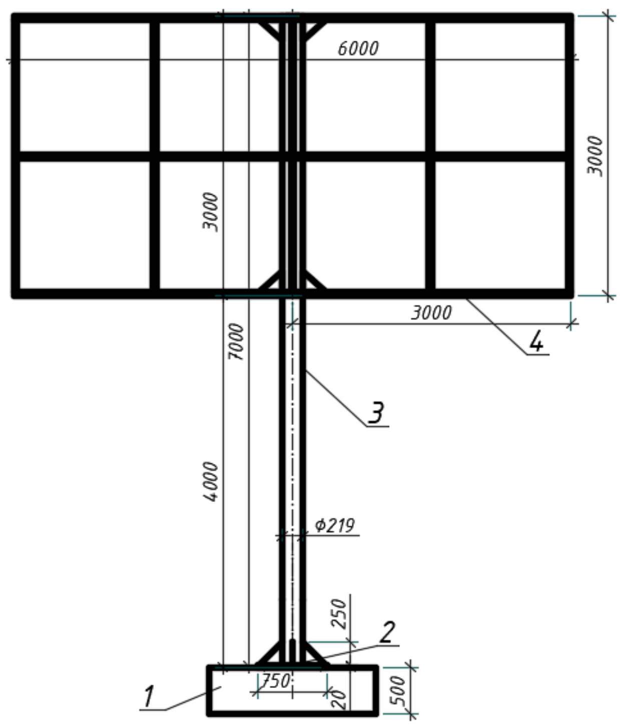

Figure 2 - General view of the cantilever advertising structure.
1 – supporting structure, 2 – supporting node of the advertising structure, 3 – stand, 4 – advertising board.

According to the analysis of the sizes and types of existing structural bases, it was found that more than half of the cantilever structures have the same size and design scheme of the support nodes, as shown in Fig. 3.

a)

b)

Figure 3 - The most common support nodes (a, b).

For further study and demonstration of the calculation methods, the most common support node in the form of a column base measuring 750x750 mm with a base plate thickness of 20 mm was chosen. The studied advertising structure stand is made of a steel pipe with a diameter of 219x8 mm. For rigidity, the assembly has four stiffeners with a thickness of 8 mm each.

The design scheme of the studied node is shown in Figure 5.

The anchor bolt was chosen as one of the most common among the studied support nodes, with a metric thread M27, with a total length of 1000 mm, of which 200 mm is used to secure the base, 400 mm is buried in the concrete foundation and 400 mm is bent at an angle of 90 degrees to securely fix the anchor bolt in the foundation. The most common height of the foundation slab in the studied advertising structures is 500 mm, and the overall dimensions of the foundation itself are 1800×2200 mm.

To calculate the diameter and cross-section of the anchor bolts, the load on the support node of the advertising structure was calculated for five different wind pressure values.

The wind load is a variable load for which two design values are established: the limit and operational design values. The limit design value of the wind load is calculated according to formula 9.1 of DBN B.1.2-2:2006 “Loads and Impacts” [14]:

$$W_m=\gamma_{fm}\cdot W_0\cdot C$$

where, γ_{fm} – reliability factor of the designed wind load limit value, determined according to 9.14 [14]. γ_{fm} = 0,82;

W_0 – characteristic value of wind pressure, determined according to 9.6 [14]. W_0 = 400 Pa;

C – coefficient is determined according to formula 9.3 [14].

$$C = C_{aer} \cdot C_h \cdot C_{alt} \cdot C_{rel} \cdot C_{dir} \cdot C_d$$

where, C_{aer} – aerodynamic coefficient;

C_h – height coefficient of the structure, determined according to Table 9.02 [14], adopted for the II type of terrain;

C_{alt} – geographic altitude coefficient, determined according to 9.10 [14];

C_{rel} – relief coefficient, determined according to 9.11 [14];

C_{dir} – directional coefficient, determined according to 9.12 [14];

C_d – dynamic coefficient, determined determined according to 9.13 [14];

The coefficient C for the stand element and for the billboard will be fundamentally different, so we divide the structure into two parts. Part I is the stand, and part II is the billboard. Determine the wind load for each part separately. Division of the structure for calculation into parts I and II (see Fig. 4).

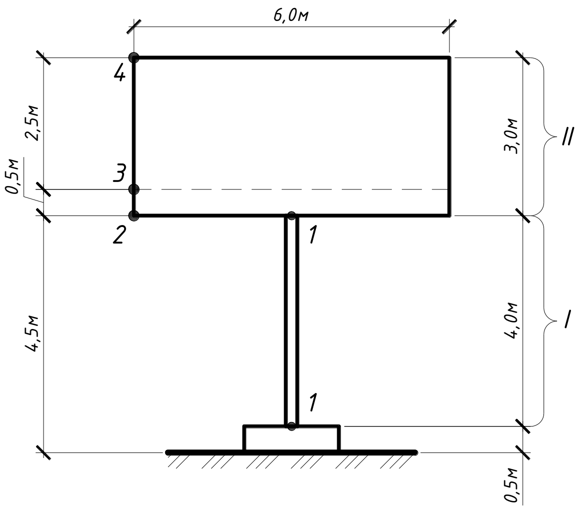

Figure 4 - Division of the structure into parts I and II. Points of determination of the building height coefficient C_h.

Wind load for part of the structure I (stand).

Determine the value of the coefficient C_I.

$$C_I = C_{aer} \cdot C_{h1} \cdot C_{alt} \cdot C_{rel} \cdot C_{dir} \cdot C_{d1}$$

were, C_{h1} = 1,2; C_{alt} = 1; C_{rel} = 1; C_{dir} = 1.

C_d – the dynamic coefficient is taken according to the graph shown in Fig. 9.8 [14]. Since the graph data are not available for such a structure (diameter 0.22 m, height 4.5 m), the value of 1.2 is taken; the dynamic coefficient is taken according to the graph shown in Fig. 9.8 [14]. Since the graph data are not available for such a structure (diameter 0.22 m, height 4.5 m), the value of 1.2 is taken;

C_{aer} – the aerodynamic coefficient for a round pipe in the plan is in the form of Cx – drag coefficient and is determined according to Annex I, Figure 14 [14].

$$C_x = k \cdot C_{1\infty}$$

where, k is determined according to Table 1 of Scheme 13 of Annex I [14];

$C_{1\infty}$ is determined according to the graph in Annex I, Figure 14 [14].

Determine k:

To determine k, we need to find the value of λ_e and λ.

λ_e is determined according to Table 2 of Figure 13 and is equal $\lambda_e = 2\ \lambda$, where $\lambda = L/b$.

$$L = 4 \text{ m},\ b = 0.22 \text{ m}$$

$$\lambda_e = 2 \cdot (4 \div 0{,}22) = 36.4$$

By interpolating the values from Table 1 of Figure 13, we determine that k = 0.86.

Determine $C_{1\infty}$:

To determine the value of $C_{1\infty}$ from the graph, it is necessary to find the value of Reynolds number Re using the formula in the table of Scheme 12a of Annex I [14].

$$\mathrm{Re} = 0{,}88 \cdot d \cdot \sqrt{W_0 \cdot k(z) \cdot \gamma_{fm}} \cdot 10^5$$

where, d = 0.22 m (diametr);

$k_{(z)} = C_{h1} = 1{,}2$; $\gamma_{fm} = 0.82$; $W_0 = 400$ Pa.

$$\mathrm{Re} = 0{,}88 \cdot 0{,}22 \cdot \sqrt{400 \cdot 1{,}2 \cdot 0{,}82} \cdot 10^5 = 3{,}84 \cdot 10^5$$

According to the graph of Figure 14 [14], we find the value of $C_{1\infty}$, which is 0.45.

We ignore the value of Λ, since in this calculation the range of determination from the graph does not depend on the specified indicator.

Thus, the drag coefficient Cx is equal

$$C_x = 0.86 \cdot 0{,}45 = 0.387$$

Now we calculate the coefficient C_I:

$$C_I = 0.387 \cdot 1{,}2 \cdot 1 \cdot 1 \cdot 1 \cdot 1{,}2 = 0.557$$

Calculate the wind pressure on the stand

$$W_1 = 0.82 \cdot 400 \cdot 0.557 = 183 \text{ Pa}$$

Wind load for part of the structure II (billboard)

Taking into account the height of the billboard above the ground, the billboard structure is divided into three points (#2, #3, #4, see Fig. 4) to more accurately determine the wind load.

$$C_i = C_{aeri} \cdot C_{hi} \cdot C_{alt} \cdot C_{rel} \cdot C_{dir} \cdot C_d$$

where, $C_{alt} = 1$; $C_{rel} = 1$; $C_{dir} = 1$;

i – the number of the point for which the calculation is performed

C_d – is determined according to Figure 9.8 [14] and is equal to 1;

$$C_{h2} = .2;\ C_{h3} = 1.2;\ C_{h4} = 1.35;$$

C_{aer} – has the form C_e and is defined in Annex I, Scheme 1. This coefficient takes into account drag pressure (C^+_e) and wind pressure (C^-_e) and will have the same value for all points, namely C^+_e=0.8, C^-_e= -0.6.

We calculate the coefficient C_i for each of the points, taking into account drag and wind pressure:

$$C^+_2 = 0.8 \cdot 1.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 0.96$$

$$C^-_2 = -\ 0.6 \cdot 1.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = -0.72$$

$$C^+_3 = 0.8 \cdot 1.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 0.96$$

$$C^-_3 = -\ 0.6 \cdot 1.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = -0.72$$

$$C^+_4 = 0.8 \cdot 1.35 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 1.08$$

$$C^-_4 = -\ 0.6 \cdot 1.35 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = -0.81$$

Since the actual movement of the structure due to drag and wind pressure is in the same direction and to reduce the number of calculations, we add these two coefficients for each of the points. The calculations show that the values of the coefficients C for sections 2 and 3 are identical, so we further assume the values at these points to be equal.

$$C_{2,3} = C^+_{2,3} + |C^-_{2,3}| = 0.96 + 0.72 = 1.68$$

$$C_4 = C^+_4 + |C^-_4| = 1.08 + 0.81 = 1.89$$

Calculate the wind pressure on the billboard:

$$W_{2,3} = 0.82 \cdot 400 \cdot 1.68 = 551 \text{ Pa}$$

$$W_4 = 0.82 \cdot 400 \cdot 1.89 = 620 \text{ Pa}.$$

Thus, the maximum calculated value of wind pressure on the billboard W_m is 585.5 Pa.

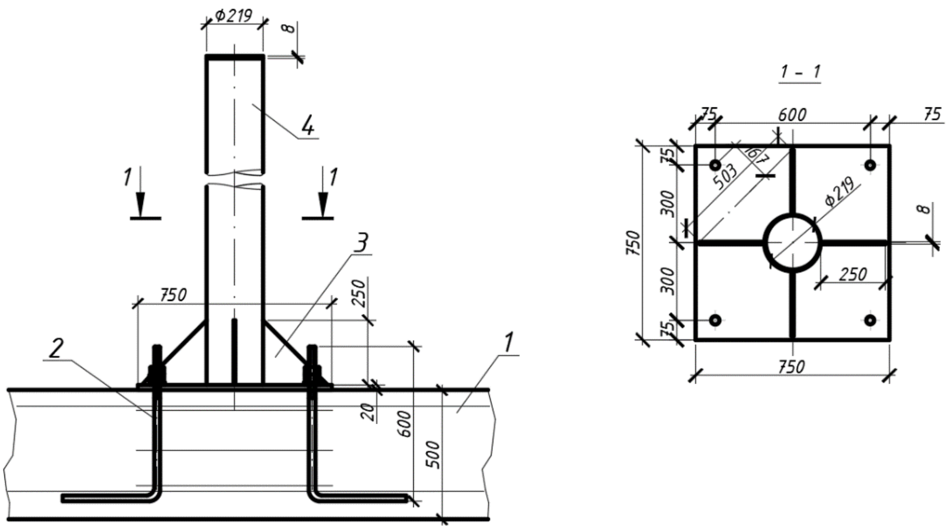

Figure 5 - Design scheme of the studied support node:

1 – supporting structure, 2 – anchor bolt, 3 – supporting node of the advertising structure, 4 – stand.

The dimensions of the base plate in the plan depend on the design requirements for placing the column cross-section, traverses and stiffeners on the plate. The slab works as a plate on an elastic base that absorbs the pressure from the column and the traverses.

The thickness of the slab was determined based on its bending behavior in the areas between the traverses. The thickness of the base slab was calculated using formula 11.1 of DBN B.2.6-198:2014 [15]:

$$\delta_n = \sqrt{\frac{6 \cdot M_{\max} \cdot \gamma_n}{R_y \cdot \gamma_c}}$$

The maximum and minimum stresses in the base plate of the support node are determined by the formula:

$$\sigma = N/A \pm M/W$$

The length of the compressed zone of the slab is calculated by the formula:

$$c = (\sigma_{max} / (\sigma_{max} + |\sigma_{min}|)) \cdot L$$

The distance from the equidistant compressed zone to the center of the bolts of the tensile zone is:

$$y = L - c/3 - e \quad [8].$$

The force in the tensile anchor bolts is determined by the formula:

$$Z = (M - N \cdot a) / y$$

The following condition must be observed:

$$z / (n \cdot S) \leq R_{ba} \cdot 0{,}8$$

The tensile resistance of anchor bolts (R_{ba}) is taken from Table D6, Annex D, DBN B.2.6-198:2014 [15].

At the next stage, we calculated the loads acting on the support node of the advertising structure and, accordingly, on the bolted connections, depending on the location of the advertising structure in different wind regions of Ukraine. The calculated values of the loads of the existing advertising structure located in different wind regions of Ukraine are shown in Table 1.

Table 1. Calculated load values of an existing advertising structure located in different windy regions of Ukraine.

Windy region	Wind pressure characteristic value W_0, Pa	Maximum design value of wind pressure on a billboard W_m, Pa	Moment at the bearing node, kN*cm	Forces in ten-sile bolts, kN
1	400	585,5	6171,0	106,14
2	450	658,7	6941,0	120,24
3	500	731,8	7712,0	134,35
4	550	805,0	8484,0	148,49
5	600	878,2	9255,0	162,61

Rigid column bases should have at least four anchor bolts, which prevents the column from turning on the support after the bolts are tightened.

At the next stage of the research, the size of the column base was reduced and increased, and the loads acting on the support node of the advertising structure were calculated to determine the optimal ratio. In total, eight variants of the size of the support nodes were calculated for five windy regions of Ukraine.

The effect of changing the size of the base plate of the structure and, accordingly, the distance between the anchor bolts on the calculated stresses in the anchor bolts for five windy regions of Ukraine was analyzed.

The results of calculations of the base size changing effect and, accordingly, the change in the force in the anchor bolts for the third wind region of Ukraine (Poltava) are shown in Table 2.

As a result of the calculations, the following dependencies were noted: with an increase in the overall size of the base and, accordingly, an increase in the distance between the anchor bolts, the stress in the anchor bolts decreases, which means that their diameter decreases, but the total weight of the support assembly increases and, consequently, its cost.

Given that the cost of anchor bolts per unit weight is one and a half times higher than the cost of metal structures per unit weight of the support node, there is an optimal ratio of base size, base thickness, and anchor bolt diameter for each wind region.

The analysis of the calculations revealed the dependence of the total cost of the support node and anchor bolts on the overall dimensions of the assembly and the diameter of the anchor bolts.

The verification calculation of the bearing capacity of the existing support node under study (type 5), column base size 750x750 mm, and anchor bolt diameter 27 mm) showed that the anchor bolts with a diameter of 27 mm used in this assembly cannot withstand the design load for the third wind area. The force in the anchor bolts is 1.6% greater than the design resistance of the anchor bolts. It was proposed to increase the size of the column base to 800x800 mm (type 6) - in this case, the force in the anchor bolts is less than the maximum resistance.

Table 2. Estimated values of loads and cost of different sizes of the advertising structures supporting nodes.

Indicator	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node
Overall size of the support node base	**mm**	**400x400**	**500x500**	**600x600**	**700x700**	**750x750**	**800x800**	**900x900**	**1000x 1000**
Distance between anchor bolts	**mm**	**250x250**	**350x350**	**450x450**	**550x550**	**600x600**	**650x650**	**750x750**	**850x850**
Force in two stretched bolts	**kN**	**285,25**	**215,84**	**173,66**	**145,31**	**134,35**	**124,94**	**109,61**	**97,64**
Resistance to stretched bolts, 2 pcs	**kN/cm²**	**12,73**	**13,23**	**10,64**	**12,95**	**14,64**	**13,61**	**11,94**	**13,83**
Weight of the support node with anchor bolts	**kg**	**120,34**	**104,04**	**110,40**	**118,32**	**121,87**	**126,87**	**133,37**	**147,63**
Cost of the support node with anchor bolts	**UAH**	**15923**	**13411**	**14115**	**14413**	**14514**	**15069**	**15791**	**17151**
Percentage of anchor bolt cost in the support node cost	**%**	**46,55**	**40,56**	**38,54**	**26,18**	**20,71**	**19,95**	**19,03**	**13,88**
Percentage of anchor bolt weight in the total weight of the support node	**%**	**36,23**	**30,76**	**28,99**	**18,76**	**14,51**	**13,94**	**13,26**	**9,48**
Anchor bolts design diameter	**mm**	**42**	**36**	**36**	**30**	**27**	**27**	**27**	**24**
Cost of anchor bolts	**UAH**	**7412**	**5440**	**5440**	**3774**	**3006**	**3006**	**3006**	**2380**
Cost of the support node without anchor bolts	**UAH**	**8511**	**7971**	**8675**	**10639**	**11508**	**12063**	**12785**	**14771**
Design thickness of the column base	**mm**	**40,3**	**28,9**	**20,5**	**16,3**	**15,8**	**14,4**	**12,1**	**10,3**
Accepted thickness of the column base	**mm**	**40,0**	**30,0**	**25,0**	**20,0**	**20,0**	**16,0**	**14,0**	**12,0**

After analyzing the results of research and calculations of different sizes of the column base, we can conclude that the existing support assembly (type 5), which costs 14514 UAH, is not optimal in terms of material efficiency (see Fig. 6).

As the size of the support node increases, the cost of the support node metal increases much faster than the cost of the anchor bolts decreases.

For more efficient use of materials, it is necessary to reduce the node size and increase the diameter of the anchor bolts accordingly.

As a result of the analysis and calculations, the most effective was the support node type 2, the overall size of the column base is 500x500 mm in combination with anchor bolts with a diameter of 36 mm. The cost of such a unit is UAH 13411.

The savings in the total cost of such a node is 8.2% compared to the existing support node (type 5).

A further reduction in the overall dimensions of the bearing node leads to an increase in the total cost of the bearing node due to an increase in the cost of anchor bolts.

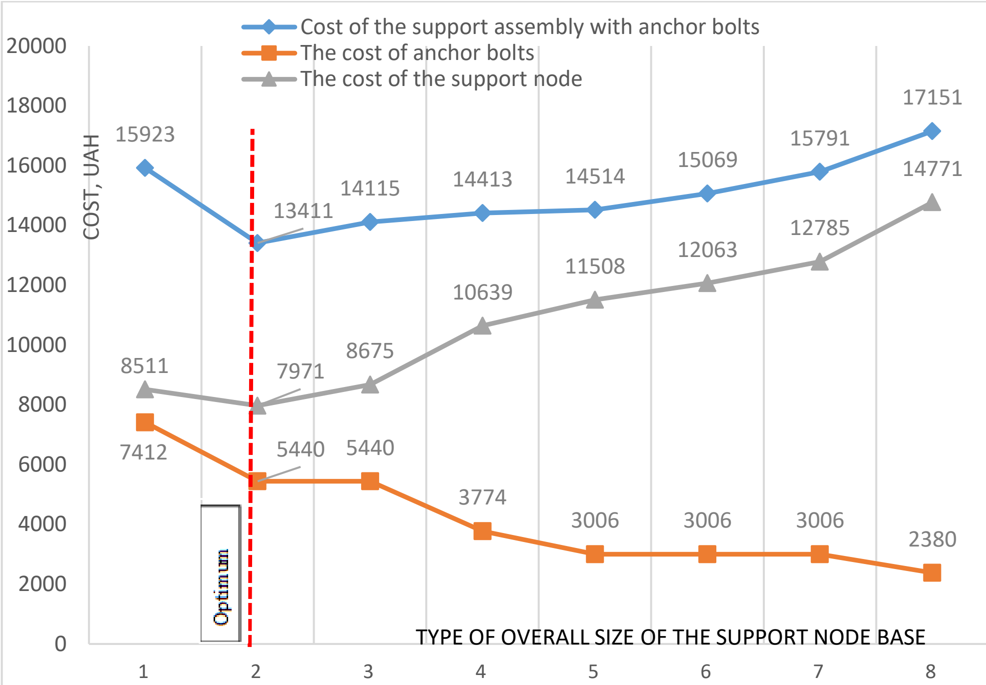

Figure 6. Dependence of the the support node cost on the support node base size and anchor bolt diameters for the third wind region of Ukraine.

Conclusions

For each wind region, there is an optimal ratio of base size, base thickness, and anchor bolt diameter. As a result of the calculations, and analysis of the graphs presented in Figure 6, the most efficient support node for Poltava was proposed. The savings in the total cost of such a node is 8.9% compared to the cost of the existing support node of the studied advertising structure.

In particular, in our opinion, filling the advertising structure's stand with concrete has relatively low financial costs, but it can significantly improve the bearing capacity of the support node, and therefore the bearing capacity of the cantilever structure as a whole, which will positively affect the reliability of the node and may increase its failure-free time.

If the destroyed tubular advertising structures that were destroyed due to the failure of the support node had been filled with concrete, half of the node failures could have been avoided.

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