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Research paper

The influence of temperature change on force increase in steel struts supporting diaphragm walls

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Abstract: The intense development of urban infrastructure and the construction of deep excavations mean, that diaphragm walls are becoming one of the typical structural elements of this type of facilities, the stability of which is ensured by a system of steel struts. The paper focuses on the assessment of the value of the force in the steel tubular strut caused by the temperature difference and values of parameters necessary for proper analysis of diaphragm wall displacements. Using statistical methods to analyse more than 100,000 data from various measurements, the values of the *m* coefficient describing force increase in the strut at a temperature change of 1°C were determined. The analyses allowed to determine values of the *m* coefficients recommended in the design of strutted diaphragm walls. These values can be used in design practice and allow to determine an additional force in the steel tubular strut due to the temperature difference.

Keywords: diaphragm wall, force increase due to the temperature change, steel tubular strut

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1. Introduction

In the static analysis of the soil-support-steel strut system, the basic design criterion is the value of horizontal displacement of the excavation wall. The displacement approach guarantees the safety of both the deep trench support and the ground surface behind the wall and adjacent buildings. Therefore, determining the value of the force in the strut necessary to maintain the stability of the support is the most important element in the design of this structure. High safety requirements require designers to analyze all possible load combinations. One of the loads that has not been taken into account very often is the influence of temperature. Due to their physical properties of steel, tubular struts are very susceptible to this influence [1]. In the design of supports, it is necessary to separate the individual load components and predict the load differences in struts accordingly depending on the temperature. The influence of temperature on the change of the force value in the strut may result in overloading of struts and the formation of additional displacements, and even to the failure or disaster of the system. In most cases, steel struts are temporary elements installed only for a certain period of time, usually lasting from a few to several dozen months. Over the last few decades, many researchers have attempted to estimate the empirical and analytical value of the force in steel struts resulting from temperature changes. Standards and design guides recommend different approaches for determining the influence of changes in ambient temperature on the values of forces in struts, and they are described in [2–6]. In the "Technical code for excavation in Shanghai" (CCEMS) [2], it is recommended that in the static analysis of the trench lining, the increase of force due to temperature should be equal to 10% of the total value of the force in the strut if its length does not exceed 40 m. Determining the increase of the force in the strut under the influence of temperature changes is still difficult. Data from the literature [7] indicate the magnitude of this increase reaching up to 37% of the value of the total force in the strut.

Nomograms used for static calculations of trench supports contain formulas for taking into account the influence of temperature on strutted elements [8, 9]. According to Boone and Crawford [10], the value of the force in the strut that arises as a result of temperature changes depends on the stiffness of the soil behind the excavation wall and the support system. The first measurement systems allowed to measure the physical elongation of an element [11]. Already in the early 1960s, research on steel struts was carried out in Oslo with the use of relatively new vibrating wire strain gauges [12–14]. The relationship between the increase of the force in the strut and the increase in ambient temperature was analysed in the works of Endo and Kawasaki [15] by presenting the following formula:

$$P_T = \frac{K_E A_S E_S \alpha_S \Delta T L}{K_E L + 2 A_S E_S} \tag{1.1}$$

where: P_T – the measured value of the force resulting from the temperature gradient, K_E – the empirical constant describing the stiffness of the supported soil, A_s – cross-sectional area of the strut, E_s – Young's modulus of steel, ΔT – temperature difference, L – length of the strut, α_s – coefficient of thermal expansion of steel.

The estimation of the value of the force in a steel strut resulting from temperature changes was carried out in 1972 by Chapman and his team [16]. Based on measurements taken on the construction site in Washington, Chapman [16] suggests the following approximate values of the force in the strut, depending on the temperature difference:

$$P_T = \frac{A_S E_S \alpha_S \Delta T}{[1 + (3.0 n A_S E_S H)/(A_{\text{cut}} E_d L)]} \tag{1.2}$$

where: A_{cut} – rectangular surface of the exposed wall for which the force is determined in struts, E_d – modulus of elasticity/deformation of the soil behind the wall, H – wall height, n – number of struts on the wall on the A_{cut} surface.

Another attempt to formulate a formula that would allow to determine the force in the strut as a result of an increase in ambient temperature was made by Boone [10]. He presented following formula:

$$P_T = \frac{-\alpha_S \Delta T L}{\dfrac{2I}{s E_{s(m)}} + L/(A_S E_s)} \tag{1.3}$$

where: s – width of the trench lining on which the force in the strut acts.

The practical application of formulas (1.1), (1.2) and (1.3) requires additional measurements or analyses aimed at determining the value of the soil deformation modulus, which is difficult to determine precisely, along with the depth of the excavation. That's why the simplified method for determining the value of the additional force in the struts as a function of the increase in its temperature was developed. This method is based on the classification of the soil behind the excavation wall and assigning the type of support to a specific category. Displacements of the support and force changes in the strut are treated as linear-elastic [10]. Therefore, it is possible to determine the incremental changes of the load ΔP with respect to the incremental change of temperature ΔT and plot them. The result of the best fit graph in the statistical sense is a straight line passing through the origin of the coordinate system with a slope of m [17]. The coefficient m represents the stiffness of the entire strut-wall-soil system and is referred to as the heat load coefficient. This means that on the basis of a sufficiently large number of measurements, it is possible to determine the equation of a line using statistical functions and read the coefficient m as the directional coefficient of the equation. In practice, the m-factor determines how much the force in the strut will increase when the strut temperature changes 1°C:

$$m = \Delta P/\Delta T \tag{1.4}$$

Knowing the assumed difference of the temperature of the strut, it is possible to determine the additional force that will arise in the strut after it is heated. In this case, in order to correctly predict the force in the strut, it is important to determine the range of its temperature increase. The increase of force due to the change of temperature is directly proportional to this change. However, if the temperature drops and the strut is freely shortened, the diaphragm wall can move and the ground can loosen behind. This means that the increase of strut temperature assumed in the calculation of the additional force in the strut should be a change from the local minimum.

After determining the equation of the most fitting line and determining the coefficient m, it is possible to separate the measured force into two components – P_E caused by earth pressure and P_T caused by temperature increase according to the formula (1.5) given in [17]:

$$P_E = P - m\,(\Delta T) \tag{1.5}$$

As mentioned above, the factor m according to the procedure presented in [10] represents the stiffness of the strut-wall-soil system and should be determined independently for each of them if there is more than one level of support.

The dependence of the force in the strut on temperature changes was dealt with by the authors of individual CIRIA reports prepared in the years 1999–2017 [3–6], presenting the results of measurements and detailed guidelines for determining the value of this additional force. In the CIRIA 517 report [6], as a result of extensive consultations, it was reported that in the case of flexible walls, designers usually ignore the effects related to the influence of temperature on struts (based on their experience, they conclude that they are not important for the structure), but take them into account when analysing rigid walls. In the UK, the British Standard BS 5400 or the Bridge Standard BD42 (DMRB Volume 2 Section 1 Part 2 (BD 42/00) are used to design trench supports and determine the effects of temperature. The recommended values of temperature, m-factor for the analysis of thermal force changes in steel struts come mainly from tests and measurements carried out in Great Britain (London and Essex) and the United States (Washington) as well as from Asian countries. The literature on the issue is extensive and contained in the thesis [18]. However, there are no data for others European countries.

2. Description of the experimental research

The aim of the experimental research was to investigate the effect of temperature changes on the values of forces in steel tubular struts supporting diaphragm walls. Force measurements were made in struts at different levels with simultaneous measurement of air temperature and temperature of struts – steel tubes. The survey schedule was designed to cover the longest possible period of time and the largest possible ranges and gradients of the excavation ambient temperature. The range of measurements included maximum daily temperature fluctuations depending on the season (usually spring and autumn) and a daily temperature gradient resulting from the maximum and minimum values (night and day). The four experimental plots were located in different European countries (Poland, Hungary, France) due to the similar climate and similar temperature differences, both daily and between seasons [18]. In the paper the results from research plot located in France (Paris) are presented. The results of the measurements were analysed in a monthly cycle and the maximum daily temperature differences and strength in individual struts were compared. On the basis of the data from all analyzed measurements, an attempt was made to determine the value of the factor m, which represents the stiffness of the strut-wall-soil system.

Research plot was located in Paris at the construction site of the starting shaft of TBM No. 5 with a diameter of 8.25 m, which at a later stage served as a structure allowing the passage of a larger TBM (diameter 10.35 m) drilling the line 15 of Grand Paris Express. The shaft structure has the following dimensions: width 14.8 m to 27.6 m and length about 72.5 m. The excavation walls are diaphragm walls with a thickness of 1.50 m. The plan view of diaphragm walls with the support scheme for both levels of steel struts, locations of inclinometers and monitored steel struts is shown in Fig. 1. To measure the horizontal displacements of diaphragm walls, 8 inclinometers were installed (1). In the same location as the inclinometers, stress gauges in steel tube struts for both levels B1 and B2 were installed. Stress gauges were installed at three points in each tube cross-section every 120 degrees The measurements were carried out using Vibrating Wire Strain Gauges OVK4000VS00 (Sisgeo) with an accuracy of ±0.5% FS and ±0.5°C. Measurements of the force in the struts and temperature were carried out from 23/05/2019 to 11/10/2021, which allows all seasons to be taken into account. From the upper B1 level, 3 struts No. 5_1, 12_1 and 15_1 were monitored throughout the year, while 6 struts of the lower B2 level No. 2_2, 5_2, 6_2, 12_2, 15_2 and 17_2 were monitored during the summer months from 05-09.2019.

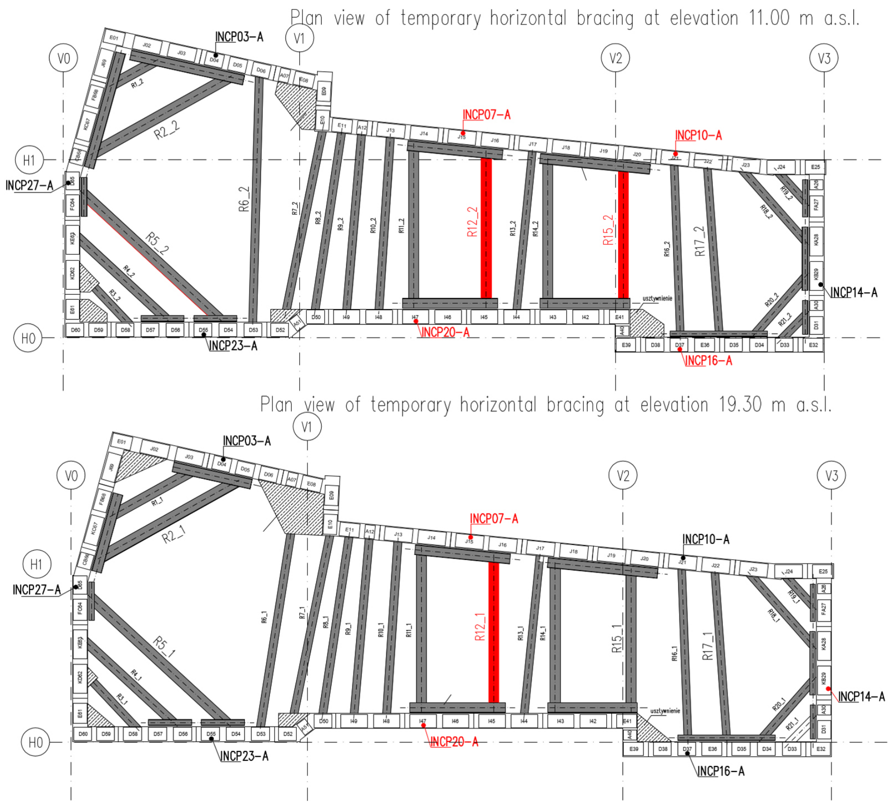

Fig. 1. The plan view of bracing of diaphragm walls in both levels (B1 at elevation 11.00 m and B2 at elevation 19.30 m), locations of inclinometers (INCP) and analyzed steel struts [17]

3. Analysis of experimental results

3.1. Introduction

Figure 1 shows the plan view of the first and second levels of temporary bracing of diaphragm wall, with the monitored struts marked in red, the results of which are presented in the article. From all the measurements of forces and temperature in the struts, the ranges that meet the basic assumption were selected graphically. The measurement ranges include the time during which the force in the strut is affected only by the temperature without external influences. In order to determine these ranges and then determine the directional coefficient of the *a*/*m* simple regression, the simple regression analysis were performed for each strut. In the first step a diagram of the dependence of the force in the strut on the strut temperature and the difference in the force in the strut on the difference in the strut temperature for the entire measurement period were performed. In the second step the data from the entire measurement period were divided into monthly ranges with the use of different colors to distinguish the individual ranges graphically. Next, for statistical analyses and determination of the simple regression equation, graphs made in the first two steps were changed to a system suitable for statistical analysis so that the values of the temperature of the strut are on the horizontal axis and the values of the force in the strut are on the vertical axis. For individual graphically selected measurement ranges (monthly or shorter) determination of the trend line and, using statistical functions, determination of the coefficients of the equation of simple regressions was performed. The search value is the directional coefficient, which determines the slope of the line and indicates how much the force in the strut will increase with a given increase in temperature. The directional coefficient a is equivalent to the m-factor in Eq. (1.4).

3.2. The results of the analysis

The most representative data were obtained for struts 12_1, 12_2 and 15_2 due to the number of matched measurement cycles and these results are shown below. The results from the rest of monitored struts and the results of simple regression analysis can be found in the publication [18].

The 12_1 strut (Φ1117,6/22,22 mm; S355, length l = 13.91 m) was installed 14.32 m below the top of the diaphragm wall (Fig. 1). The measurements were performed every hour from 20/05/2019 to 21/01/2021 (for about 20 months) and 13 399 measurement cycles were obtained. In the next stages of the analysis, the scope of measurements corresponding to the assumptions was selected and 9125 measurement cycles were obtained from 23/05/2019 to 31/07/2020. Figure 2 shows a diagram of the dependence of the force difference ΔP in the 12_1 strut on the temperature difference ΔT from the entire measurement period. In the next graph (Fig. 3), the data are separated by colors according to individual measurement months. In the months for which the points distribution shows a regular relationship, a monthly analysis was performed. On the basis of the month-by-month graph (Fig. 3) due to the high correlation of data, months in which measurements can be analyzed together were distinguished (Fig. 4). For the statistical analysis and regression curve determination, the data with the high correlation were presented as the relationship between ΔP on the y-axis and ΔT on the x-axis (as shown in Fig. 4). Table 1 presents the temperature difference, the force difference and the simple linear regression equation in strut 12_1.

Table 1. Results of statistical analysis of strut 12_1 measurements

Time interval	ΔT **[°C]**	ΔP **[kN]**	**Simple linear regression equation**	**Determination coefficient** R^2
23–27.05.2019	6.75	607.07	$y = 86.43x - 772.15$	0.9841
29.05–6.06.2019	11.65	1046.47	$y = 77.51x - 273.62$	0.9469
8–20.06.2019	9.84	694.65	$y = 68.99x + 59.25$	0.9375
21.06–25.09.2019	16.52	1279.22	$y = 69.32x - 116.52$	0.8478
1–7.10.2019	9.39	855.44	$y = 78.5x + 1035.8$	0.6505
10–31.10.2019	9.09	802.93	$y = 76.58x + 337.37$	0.9043
1.11.2019–30.04.2020	1.,45	1364.18	$y = 91.01x + 185.92$	0.9162
1.05–30.06.2020	18.11	1846.22	$y = 85.86x + 103.46$	0.9461
1–31.07.2020	10.16	1086.00	$y = 101.26x - 397.09$	0.9440

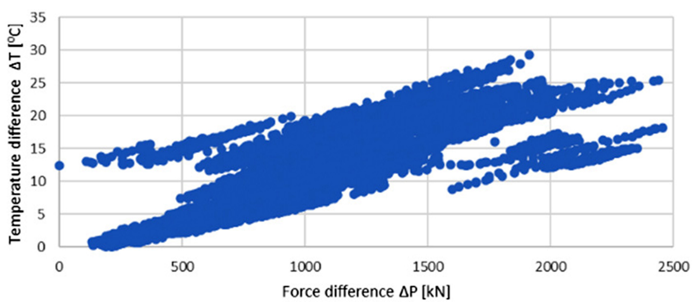

Fig. 2. Dependence of ΔP on ΔT in strut 12_1 over the entire measurement period

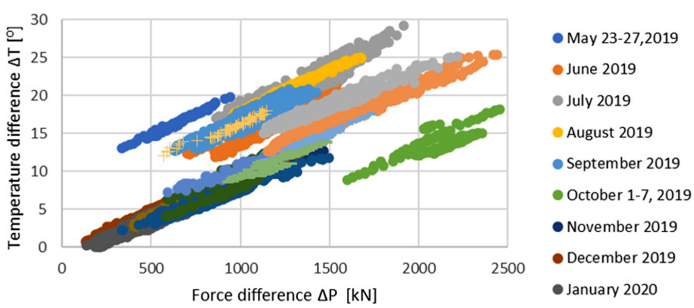

Fig. 3. Dependence of ΔP on ΔT in the 12_1 strut, based on month-by-month breakdown data

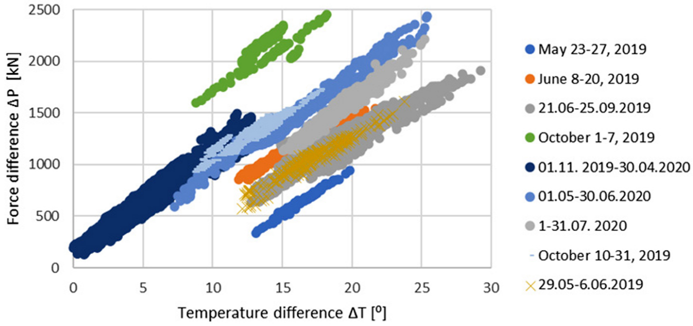

Fig. 4. Dependence of ΔP on ΔT in the 12_1 strut for the separated measurement ranges

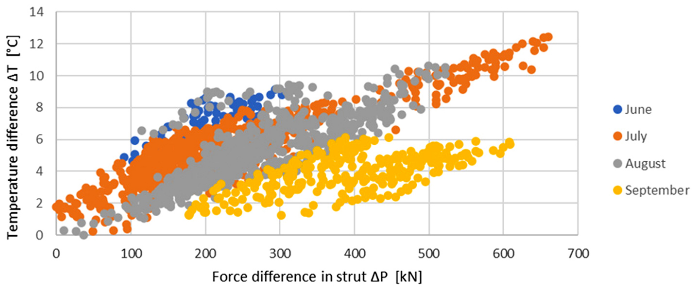

Fig. 5. Dependence of ΔP on ΔT in the 12_2 strut, based on month-by-month breakdown from the entire measurement range

The 12_2 strut (Φ863,6/17,48 mm, S355, length l = 13.91 m) is installed 22.62 m below the top of the diaphragm wall (Fig. 1). Measurements were taken every hour from 27/06/2019 to 17/09/2019 (for about 3 months) and 1743 measurement cycles were obtained (Fig. 5). The struts installed in the second bracing level were monitored for a shorter period of time due to the later date of assembly and earlier disassembly related to the work phases of the temporary structures. In the next stages of the analysis, the range of measurements corresponding to the assumptions was selected and 1522 measurement cycles were obtained from 27/06/2019 to 10/09/2019. In Fig. 6, the data separated by colors according to months or decades (Fig. 7) are shown. The trend line for 12_1 strut is presented on Fig. 8. In Table 2 the temperature difference, the force difference and the simple linear regression equation in strut 12_2 are presented.

Table 2. Results of statistical analysis of strut 12_2 measurements

Time interval	**ΔT [°C]**	**ΔP [kN]**	**Simple linear regression equation**	**Determination coefficient R^2**
29.06.2019	3.27	178.80	$y = 46.313x + 47.897$	0.8843
22.07–31.07.2019	10.40	533.37	$y = 51.832x + 47.985$	0.9257
28.08–10.09.2019	8.85	344.23	$y = 51.499x + 50.493$	0.9535

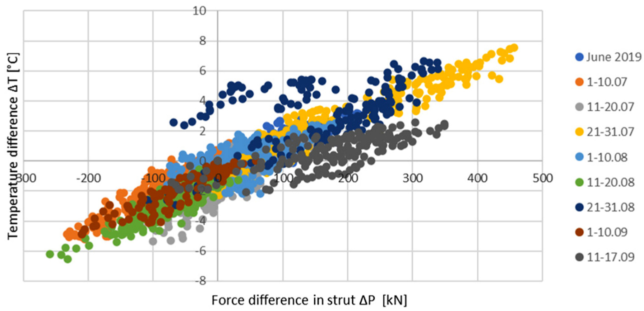

Fig. 6. Dependence of ΔP on ΔT in the 12_2 strut, with a 10-day division for the entire range of data

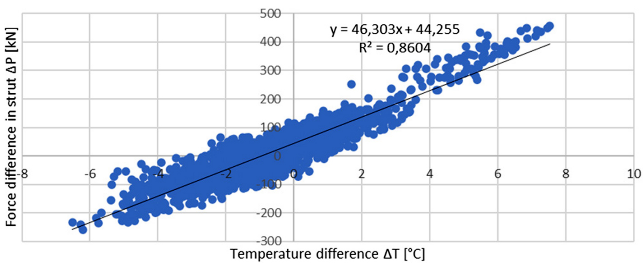

Fig. 7. Summary graph of results from the entire measurement range from strut 12_2, with trend line and determination coefficient

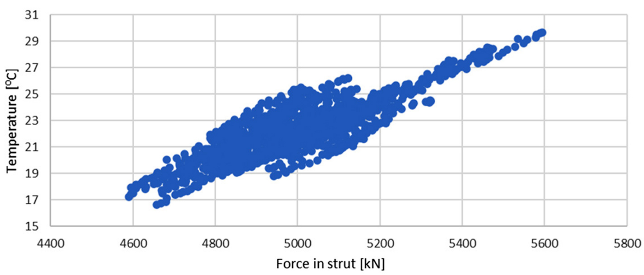

Fig. 8. Dependence of the force in the 15_2 strut on the temperature, over the entire measurement period

The 15_2 strut (Φ762/14,27 mm, S355, l = 16.38 m) was installed 22.62 m below the top of the diaphragm wall. The measurements were performed every hour from 27/06/2019 to 24/08/2019 (for about 2 months) and 1415 measurement cycles were obtained (Fig. 8). In the next stages of the analysis, the range of measurements corresponding to the assumptions was selected and 1103 measurement cycles were obtained from 27/06/2019 to 19/08/2019 (Fig. 9–12). Table 3 presents the temperature difference, the force difference and the simple linear regression equation in strut 15_2.

Table 3. Results of statistical analysis of strut 15_2 measurements in August 2019

Time interval	ΔT [°C]	ΔP [kN]	Simple linear regression equation	Determination coefficient R^2
6.08.2019	3.60	206.50	$y = 55.579x + 165.04$	0.9621
7.08.2019	3.55	257.54	$y = 67.837x + 92.883$	0.9870
8.08.2019	4.09	281.15	$y = 64.729x + 118.09$	0.9930
10.08.2019	2.60	224.91	$y = 86.128x - 250.26$	0.9433
11.08.2019	3.51	243.27	$y = 75.394x - 81.203$	0.9422
12.08.2019	2.81	195.26	$y = 70.716x - 8.4663$	0.9564
13.08.2019	3.73	330.65	$y = 87.39x - 17.854$	0.9820
14.08.2019	3.86	289.14	$y = 73.175x + 81.875$	0.9924
15.08.2019	2.47	188.63	$y = 69.763x + 124.26$	0.9879
16.08.2019	3.50	284.32	$y = 75.309x + 136.55$	0.9866
17.08.2019	2.18	140.59	$y = 61.185x + 243.53$	0.9870
18.08.2019	1.17	89.41	$y = 65.195x + 236.37$	0.9247
19.08.2019	3.24	215.57	$y = 65.995x + 218.88$	0.9813

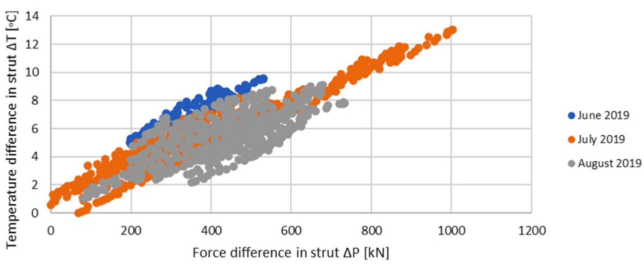

Fig. 9. Dependence of ΔP on ΔT in strut 15_2, based on month-by-month breakdown

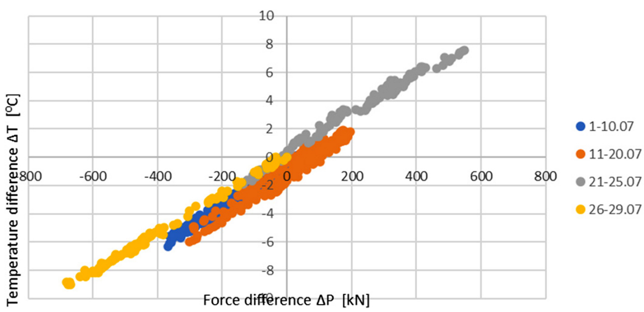

Fig. 10. Dependence of ΔP on ΔT in strut 15_2 , with a 10-day division, July 2019

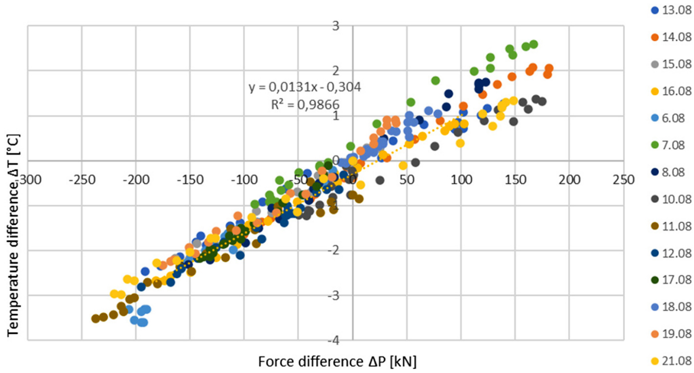

Fig. 11. Dependence of Δ*P* on Δ*T* in strut 15_2, with trend line and determination coefficient, August 2019

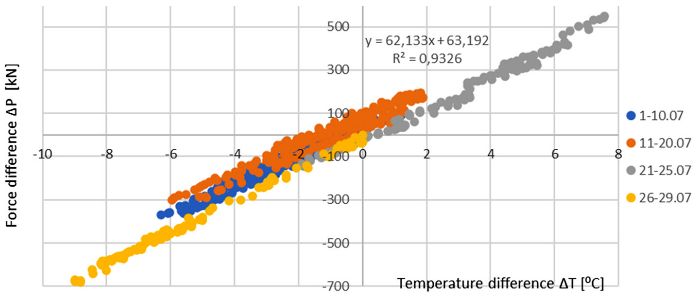

Fig. 12. Dependence of Δ*P* on Δ*T* in the 15_2 strut, with trend line and determination coefficient, July 2019

4. Conclusions

In Table 4 the average values of the directional coefficient of the regression equation *m* for every strut analyzed within the research plot are presented. Table 5 presents extreme value ranges depending on the strut level and the calculated average values of the coefficient *m.*

The *m*-factor indicates how much the force in the strut will increase when its temperature changes by 1°C. The value of the *m* coefficient, i.e., the directional coefficient and the simple regression coefficient, determined on the basis of the results of own experimental research, ranges from 81.72 to 116.49 in the first bracing level B1 and from 37.21 to 86.7 in the second B2. On average, its value for the first level B1 is 65.5% higher than for the second. This results in a much greater force increase in the upper level of struts with the same change of the temperature of the struts. The recommended values of the *m*-factor are average values given in Table 5 – 97.78 for the first level of support and 59.08 for the second. These values can be used in design practice when it is necessary to determine an additional force in the steel tubular strut due to the temperature difference.

Table 4. Summary of results from all struts in the test field – average values of the slope coefficient m

Strut number	**Installation level**	**Measurement period**	**Number of measurement cycles**	**Coefficient m from the linear regression equation**
2	2	27.05–20.08.2019	2041	86.70
5	1	1.07.2020–27.09.2021	8937	116.49
	2	25.05.2019–25.06.2019	662	37.21
6	2	16.06.2019–26.09.2019	2289	67.76
12	1	23.05.2019–31.07.2020	9125	81.72
	2	27.06.2019–10.09.2019	1522	48.76
15	1	1.11.2019–11.10.2021	14062	95.14
	2	27.06–19.08.2019	1103	68.61
17	2	13.06.2019–2.09.2019	1489	45.42
			Average	**71.98**

Table 5. Extreme value ranges depending on the strut level and the calculated average values of the coefficient m

		Coefficient m from the linear regression equation
Level 2 B2	max	86.70
	min	37.21
	average	59.08
Level 1 B1	max	116.49
	min	81.72
	average	97.78

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Wpływ zmian temperatury na wzrost siły w stalowych rozporach ścian szczelinowych

Słowa kluczowe: gradient temperatury, stalowe rozpory, ściany szczelinowe, współczynnik *m*, wzrost siły

Streszczenie:

Rozwój infrastruktury miejskiej, budowa głębszych wykopów sprawia, że ściany szczelinowe stają się jednym z typowych elementów konstrukcyjnych tego typu obiektów, których stabilność zapewnia system stalowych rozpór. W pracy skoncentrowano się na ocenie wartości siły w stalowej rozporze rurowej wywołanej różnicą temperatur oraz wartości parametrów niezbędnych do prawidłowej analizy przemieszczeń ścian szczelinowych. Za pomocą metod statystycznych do analizy ponad 100 000 danych z różnych pomiarów wyznaczono wartości współczynnika *m* opisującego wzrost siły działającej w stalowej rurowej rozporze przy zmianie temperatury o 1°C. Przeprowadzone analizy pozwoliły na wyznaczenie rekomendowanych w analizach statycznych ścian szczelinowych wartości współczynnika *m*.

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