CZASOPISMO INŻYNIERII LĄDOWEJ, ŚRODOWISKA I ARCHITEKTURY
JOURNAL OF CIVIL ENGINEERING, ENVIRONMENT AND ARCHITECTURE
JCEEA, t. XXXV, z. 65 (1/18), styczeń-marzec 2018, s. 53-62, DOI:10.7862/rb.2018.6

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MONITORING VERTICAL DISPLACEMENTS OF AN ENGINEERING OBJECT WITH MASONRY WALLS

The paper presents a method for conducting measurements and processing the results that makes it possible to determine the vertical displacements of measurement and control network points stabilized outside and inside a building in which changes in the form of scratches and cracks on the external and internal walls were noticed. These changes were so disturbing that a number of technical opinions were issued on the technical condition of the building, the ground and water conditions as well as the location of other buildings in relation to that object. The measurement methodology is generally known, but the problem of correctly defining a reference system and estimating the values of vertical displacements still remains to be solved. Moreover, the paper presents the characteristics of the object subjected to research, its technical condition in 2006 and in 2015 as well as an analysis of the impact of a heating duct on the behaviour of the building.

Keywords: vertical displacements, geodesic monitoring, engineering object

1. Characteristics of the object

The object has four storeys and a basement. The above-ground storeys are: the ground floor, the first and the second floors (Fig. 1). The object is used as an office and administration building. The main construction work was carried out in the years 1988–1998; however, in 2004 construction work was still in progress. Although the building was not built long ago, the construction documentation has not been preserved. At present, there are inspection documents (2008) and technical opinions.

The basement (the first storey) is used for technical purposes related to telephone installations. On the second (the ground floor), the third (the first floor)

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and the fourth (the second floor) storeys there are offices. In the central section of the building there is a staircase, halls and toilets. The central section with the staircase, the hall and the other rooms is 2.40 m wider. The total length of the building is 47.14 m, its width is 12.60 m (without the protruding parts of the central section of the building), and its height is about 12.0 m.

Fig. 1. The building's elevation from of the main entrance, east side. The building's elevation from the north-east side

The building has masonry walls with interchangeably arranged prefabricated reinforced concrete ceilings of the "Żerań" type (hollow core slabs). The staircase has two flights of stairs with a 1.50 m wide well. No tie-beams were used in the building. The roof is flat and ventilated.

There is a heating duct running along the building, and its exact location is shown in Fig. 2.

Scratches and cracks have appeared on the inner and outer walls of the building. It is not known when it happened. The first scratches were described during an inspection carried out in 2004 when construction work was still in progress, but it was not exactly mentioned where they appeared.

1.1. Technical condition of the building in 2006

The technical condition of the building was first examined in 2004 and then in 2006. A particularly large number of scratches and cracks were observed on the walls in the hall on the second and first floors as well as on the top sections of the northern and southern walls and in their vicinity [10].

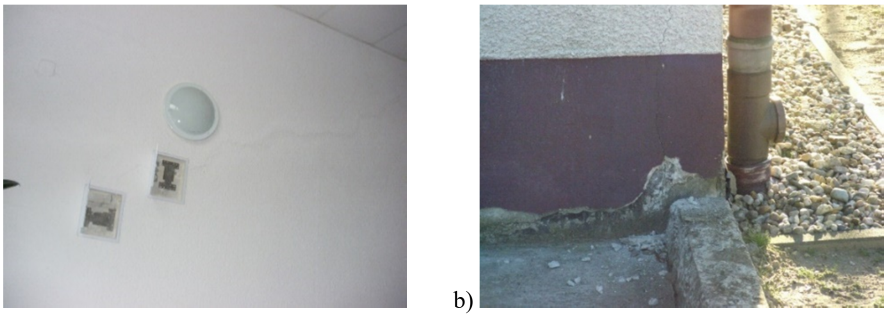
In the areas with particularly disturbing scratches and cracks, ten chalk control bands were installed. The bands were installed in June, 2006. After two weeks it was found that two of the bands were broken. At the beginning of August, 2006 another three bands broke. The old, broken bands were replaced with new ones.

Chalk seals are made of brittle material with a small tolerance for elastic and plastic deformations. Because of this feature a small change in the crack opening (below 0.1 mm) immediately causes the band or the plaster used to fasten it to brake. The information that an expert obtains says only that "the crack has changed its width". It is also often the case that gypsum breaks in the binding phase due to thermo-contractile deformations. Unfortunately, there is no information on the direction of the change (whether the gap becomes wider or narrower) and its value.

The width of the cracks on the intact bands (chalk control seals) ranged from 0.40 to 1.10 mm.

1.2. Technical Condition of the building in 2015

In December 2012 six crack width indicators WR-05 of stainless steel, manufactured by the company Neo-Strain were installed in the places where the chalk indicators had been installed (2006). The indicators were installed in rooms on the second floor (the fourth storey) [5, 6, 10, 11].



a) b)

Fig. 2. a) The hall- landing (I-II), the width indicators installed; Fig. b) The corner of the north-west wall, the crack on the wall

The indicators made it possible to measure the width of the cracks in two perpendicular directions. The use of geometrical relations also made it possible to determine the rotation angle of the parts of the structure separated by the crack. The resolution of the readings from the indicator was 0.05 mm, and the measurement range was from -15 mm to +20 mm. There was no documentation (or a photograph) with a description of the indicators just after installation. It is not known whether the indicators were correctly installed. At present, the readings have to be regarded as 0.0.

Numerous scratches and cracks on the walls were found especially on the second floor of the building. They were the same cracks that had been described in the inspection report from 2006. No other, significant cracks were found inside the building (on lower storeys).

The scratches and cracks were plastered over or covered with nonwoven fabric wallpaper. They did not get wider and the wallpaper was intact, which indicates that the settlement of the building was stable.

Fig. 2 shows the inner corner of the north-west wall. At that place the wall is cracked. Point 4 of the external measurement network is located not far from that place. At that point the displacement is greatest (-2.93 mm).

1.3. Impact of the existing heating duct on the building

In order to determine and identify ground and water conditions, 11 holes were made with a depth of 4.0 to 6.0 m. A macroscopic description of the soils was prepared and observations of the groundwater were carried out.

The research showed that under a layer of humus or hardened surface, the ground in the area consisted of Holocene and Pleistocene sediments from the Quaternary Period. The Holocene is represented by building embankments with a thickness of up to 3.2 m, located on a series of Pleistocene sands. These are medium and coarse sands with an interbedding of fine-grained sands of fluvioglacial origin. No groundwater was found in the holes to a depth of 3.0 m. According to archival data, the first level of usable water is at a depth of 2.0–25.0 m below ground level.

The heating duct running in the vicinity of the building was built earlier than the building. Fig. 3 shows a sketch of the location of the structure in the ground vertically in the place closest to the heating duct.

The building was built on sandy made ground covering the area for many decades. After many years' deposition, sandy made ground can have the characteristics of medium compacted sand.

The heating duct, built earlier than the building, is located deeper. Fig. 3 shows that during the construction of the duct there was no need to prepare the ground for the future building.

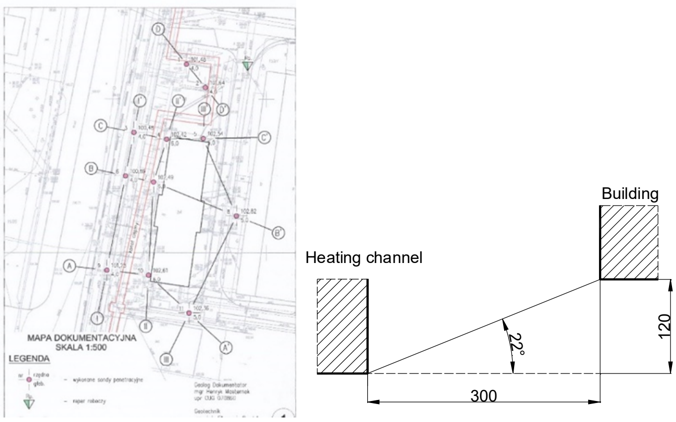


Fig. 3. A sketch of the location of the structure in relation to the heating duct

2. Course of the research

The central idea of the research presented in this paper was to estimate the value of uneven settlement of the building on the basis of known displacements of control points. The attempt to identify the dynamism of the phenomenon of uneven settlement of the engineering object was carried out on the basis of the results of measurements carried out in a measurement and control network set up inside and outside the building on whose walls scratches and cracks had been noticed [7]. A sketch of the network set up on 10 control points is presented in Fig. 4, and the internal network consisting of 6 points is presented in Fig 5.

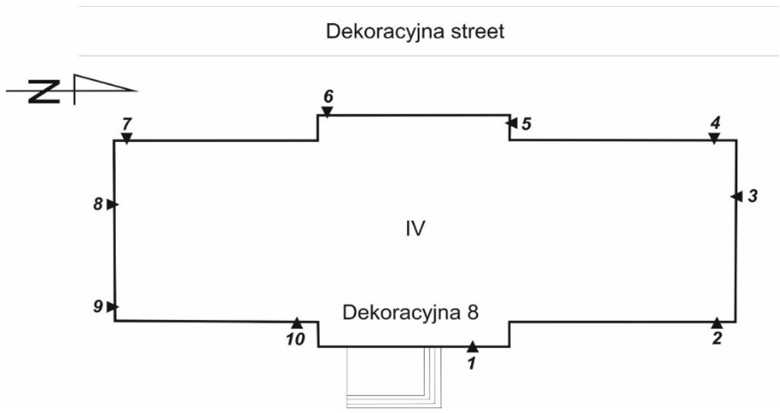


Fig. 4. A sketch of the measurement and control network set up outside the building

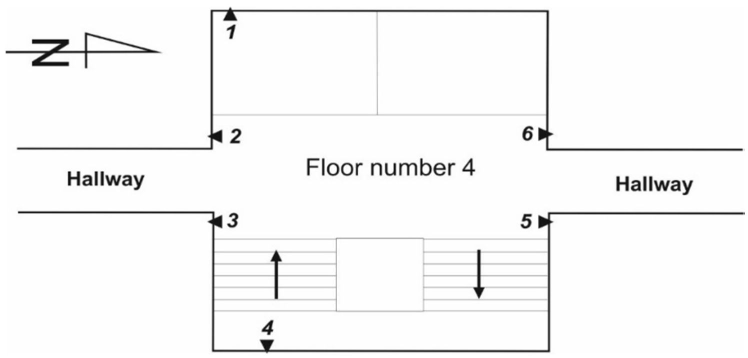


Fig. 5. A sketch of the measurement and control network set up inside the building on the fourth storey

The first measurement campaign, using the precision levelling method, consisted of five periodic measurements, which were carried out between June, 2006 and April, 2007. In the following years measurements were discontinued until 2014, when a periodic measurement was performed again. A reference point for all measurements and calculations was the zero measurement carried out in June 2006. The displacements of the measurement points that were determined are relative and provide sufficiently precise information about the stability of the building.

3. Algorithm for identifying a set of reference points

Determination of a geometrical displacement model for predicting the uneven settlement of engineering structures consists in identifying mutually fixed points on which the reference system is defined, and then determining the values of vertical displacements for all control points [4, 8, 9]. In the paper the reference points were identified on the basis of an algorithm consisting of two stages. The first stage, as a preliminary step in defining a reference system, consisted in minimizing the objective function in the form of a sum of absolute deviations, assuming that there were two n - element sets of points in the space R_1: $\{S^1\}$ and $\{S^2\}$, which were sets of projections of physical points of the objects (O^1) and (O^2) under research onto the number line [3]. The points of both sets had definite heights $h_i^{(1)}$ and $h_i^{(2)}$ were obtained by adjusting the observations with minimum restrictions on the degrees of freedom [1]. If we denote the distances between the respective points of both sets by [2]

$$h_i=d(S^1,S^2)=|S^1\text{-}S^2|,\ \ i=1,2,\ldots,n \tag{1}$$

then we will search for a mutual location of the objects (O^1) and (O^2) which satisfies the condition

$$F(y)=\min_{x\in A}\sum_{i=1}^{n}|h_i-\mathbf{x}| \tag{2}$$

In order to eliminate the points that are not mutually fixed, it is necessary to use the iterative method to check if the dependency is satisfied

$$w=|h'-h''|\le m_0 1{,}4\sqrt{n'+n''} \tag{3}$$

where: $w=|h'-h''|$, (i=1,2,…,n) – the difference between the heights of a point in the initial and current measurement,

m_0 – the mean error of a single measurement, and n' and n'' denote the number of positions of the levelling instrument in the initial and current measurement.

The dependency (3) is tested in terms of the shortest path, and the points that satisfy this condition form a preliminarily identified reference system.

In the second stage, the reference system is finally defined. This is done by checking the reaction of the observation system consisting in an increase in the square of the norm of the correction vector. This is done by arranging changes of the absolute height differences w_i (i=1,2,…,n) in order, and then by further adjusting the observations, assuming that the increasing number of fixed points is stable. An increase in the restrictions on the degrees of freedom will cause an increase in the sum of squares of corrections from the minimum value E_0 (adjustment with minimum restrictions on the degrees of freedom) to the value E_{max}.

For any concentration of k fixed points, the critical value of the increment of the vector of the norm of corrections $\Delta E_k = E_k - E_0$ will be obtained from the formula [3].

$$\Delta E_k = -2\left(m_0^2 + \frac{m_0^2}{2}\right)\ln\left(1 - 0{,}95^{\frac{1}{k}}\right) \tag{4}$$

where: m_0 – the mean error of a single observation from adjustment with minimum restrictions on the degrees of freedom,
r – the number of extra observations.

The above course of makes it possible to define a reference system and to determine the values of vertical displacements (adjustment with conditions on the reference system) for all subsequent periodic measurements. For example, for the latest periodic measurement (August 2014) the reference system for the external network has been defined on points 1, 8, 9, and for the internal network on points 2, 3, 6. The values of relative displacements of points in the measurement and control networks for all periodical measurements are included in Tables 1 and 2, and presented in Figures 6 and 7.

Table 1. A compilation of the vertical displacements of points in the external measurement and control network

Nr pkt	Displacements of points				
	06.2006-07.2006 [mm]	06.2006-08.2006 [mm]	06.2006-12.2006 [mm]	06.2006-04.2007 [mm]	06.2006-08.2014 [mm]
1	-0,05	-0,02	-0,22	-0,09	-0,01
2	-0,24	-0,13	-0,50	-0,24	-1,36
3	-0,29	-0,42	-0,78	-0,67	-2,11
4	-0,39	-0,52	-0,96	-1,12	-2,93
5	-0,06	-0,05	-0,17	-0,20	-1,13
6	0,02	-0,03	-0,30	-0,33	-0,49
7	0,02	0,10	0,04	0,06	-0,46
8	-0,01	0,02	0,00	0,14	0,01
9	-0,01	-0,02	0,02	0,03	0,00
10	0,09	0,13	-0,09	-0,09	0,41

Table 2. A compilation of the vertical displacements of points in the internal measurement and control network

Nr pkt	Displacements of points				
	06.2006-07.2006 [mm]	06.2006-08.2006 [mm]	06.2006-12.2006 [mm]	06.2006-04.2007 [mm]	06.2006-08.2014 [mm]
1	-0,17	-0,36	-0,19	-0,17	0,45
2	0,10	-0,02	0,00	-0,03	0,07
3	0,03	-0,02	-0,10	-0,13	-0,08
4	-0,04	0,04	-0,05	0,03	1,18
5	-0,03	0,20	0,18	0,01	0,46
6	0,10	0,18	0,07	-0,20	0,01

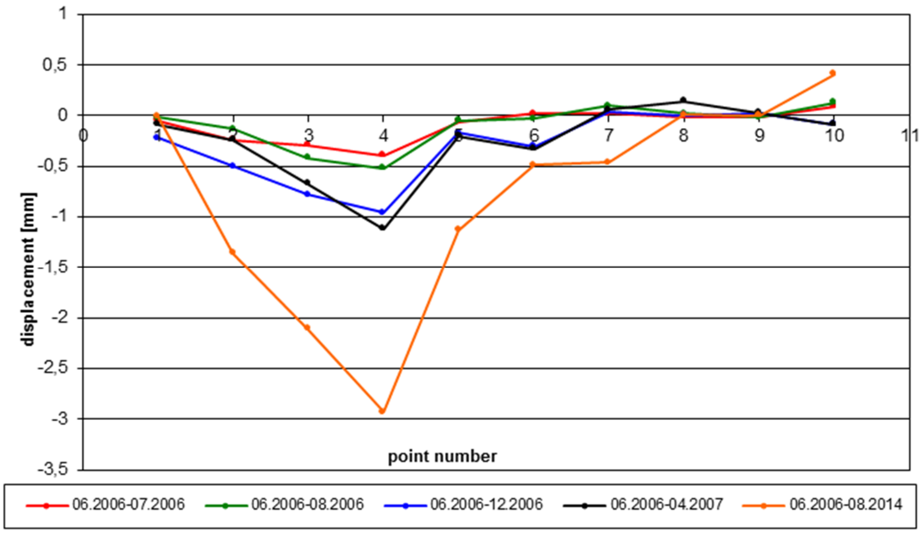


Fig. 6. A diagram of the displacements of points in the external measurement and control network between June 2006 and August 2014

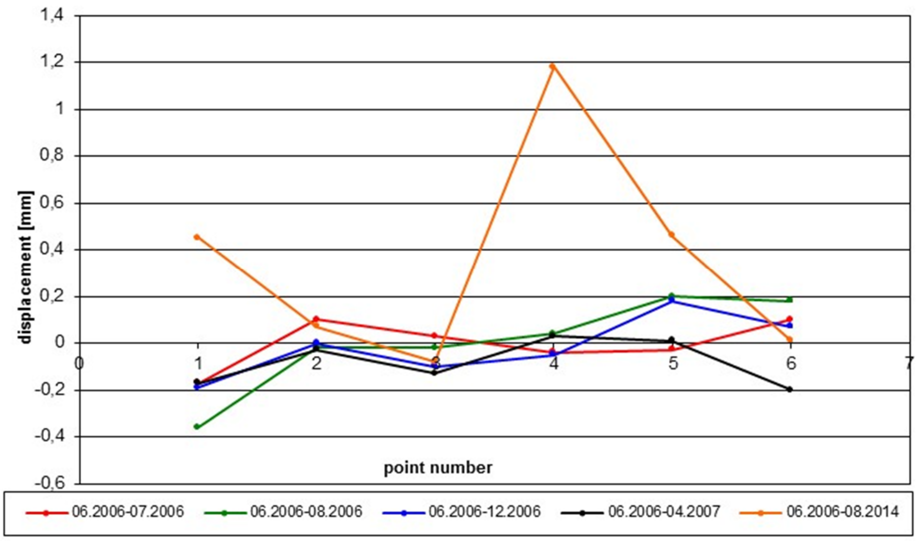


Fig. 7. A diagram of the displacements of points in the internal measurement and control network between June 2006 and August 2014

Knowing the displacement values for points in the external measurement and control network located at the foundations, it is possible to notice that these values range from 0.01 mm to -2.93 mm. The largest displacement (-2.93 mm) occurred for point 4 located in one of the corners of the building in the north-west. It should be emphasized that during the measurement campaign (June

2006–April 2007), the largest displacement values were also recorded for point 4. Significant displacements were also observed at points 2 and 3 located on the north wall of the building and at point 5 located on the west wall. The displacements at these points were -1.36 mm, -2.11 mm and -1.13 mm respectively. During the whole research period (June 2006–August 2014), the greatest displacements were observed for point 4. Counting from the beginning of the research, the total displacement of this point is 2.54 mm, which was recorded during the measurement carried out in August 2014.

The displacements of points in the geodesic network located inside the building have values from 0.01 mm to -1.18 mm. The greatest displacement was observed for point 4 located in the staircase on the east wall of the building and in comparison to the initial measurement (June 2006) there was an increase in displacements by 1.22 mm. At the other points of the internal network, displacement values are within the limits of the accuracy of the measurements carried out and do not change significantly in comparison to the initial measurement.

4. Conclusions

The analysis of the measurement data and the calculations carried out makes it possible to say that between 2006–2014 uneven settlements ranged from 0.01 to over -2.93 mm (the external network) and from 0.01 to -1.18 mm (the internal network). Because of the seven-year interval between the measurements, it cannot be determined whether the displacement values obtained during the latest measurement are maximum values and whether the changes observed are continuous or abrupt in character. It cannot be ruled out that there will be a further increase in uneven settlements caused by a number of random factors. In the case of objects susceptible to uneven settlement, it is important that settlement measurements should be continued and performed cyclically at regular intervals. The geodesic monitoring of engineering objects carried out in this way can be helpful in making decisions about the need to carry out protective work. It is worth emphasizing that the procedure for defining a reference system on the basis of minimization of absolute deviations is more efficient from the practical point of view, because a set of mutually fixed points is determined with the smallest value of the sum of the squares.

The results of geodetic measurements show that the building's settlement is not even, however, the displacements are very small. The highest value of internal displacement was recorded for point No. 4 and amounted to 1.2 mm. Compared with the previous measurements, this value refers to the rise of the building and not to its settlement.

There is sandy made ground under the street side of the building. The displacements measured under the building are small, and if the building had been properly built, with the use of tie-beams on the level of each storey, the small differences in displacements that occurred would not be visible in the form of the existing open scratches.

The existing heating duct located next to the building and its possible disassembly will not affect the behaviour and safety of the building if the construction or demolition work is carried out properly and according to an appropriate plan.

The current state of the building should be regarded as stable.

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Przesłano do redakcji: 17.03.2018 r.
Przyjęto do druku: 31.03.2018 r.