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VERTICAL DEFORMATION ANALYSIS BASED ON REPEATED MEASUREMENTS OF A SHOPPING BUILDING

АНАЛИЗ ВЕРТИКАЛЬНОЙ ДЕФОРМАЦИИ НА ОСНОВЕ ПОВТОРНЫХ ИЗМЕРЕНИЙ ТОРГОВОГО ЦЕНТРА

Самарканддагы Family Park соода борборун куруудa вертикалдык деформацияга мониторинг жүргүзүү үчүн Өзбекстандын Самарканд шаарында, 12 контролдук чекиттерди камтыган мониторинг тармагы түзүлгөн. Жалпысынан курулуш мезгилинде 8 жолу байкоо жургузулгөн жана алардын негизинде имараттын чөгүшүн баалоо максатында эң ылайыктуу геометриялык ийри сызыкты экстраполяциялоо жүргүзүлгөн. Бардык контролдук чекиттерди имараттын чөгүшү токтогондугу аныкталды. Имараттын кыйшаюсун баалоо үчүн кошумча сыноо ишке ашырылган. Кыйшаюнун чондугу 0,06‰ түздү, ошондой эле ал бир жактуу экен, ошондуктан бул конструкциянын күтүлбөйт.

Өзөк сөздөр: *вертикалдык деформация, байкоо тармагы, кыйшаюу, конструкция, экспоненциалдык ийри сызык, нөлдүк өлчөө, жалпы өлчөө.*

Для мониторинга вертикальной деформации при строительстве торгового центра Family Park в Самарканде, Узбекистан, была создана сеть мониторинга, включающая 12 контрольных точек, установленных на стене здания. Всего за время строительства наблюдалось 8 эпох, и на их основе была дана оценка будущего проседания путем экстраполяции наиболее подходящей экспоненциальной кривой. Было установлено, что во всех контрольных точках соответствующее проседание прекратилось. Было проведено еще одно испытание для оценки наклона здания. Величина наклона была оценена в 0,06‰, что также оказалось однонаправленным, поэтому из-за этого нельзя ожидать деформации конструкции.

Ключевые слова: *вертикальная деформация, сеть мониторинга, наклон, конструкция, экспоненциальная кривая, нулевое измерение, совокупные измерения.*

For the vertical deformation monitoring of the construction of the Family Park shopping centre facility in Samarkand, Uzbekistan, a monitoring network has been established including 12 benchmarks installed on the wall of the building. Altogether 8 of control surveys were observed during the time span of the construction, and based on them, an estimation for future subsidence has been provided by extrapolating of best-fitting exponential curve. It was found that in all test points the relevant subsidence has been ceased. A further test has been provided to estimate the tilting of the building. The value of the tilting was estimated to be 0.06‰, which was also found to be unidirectional, so no deformation of the structure can be expected due to it.

Key words: *vertical deformation, monitoring network, tilting, construction, exponential curve, null measurement, cumulative measurements.*

1. Introduction

A significant place in the modern practice of engineering works is occupied by the observation of deformations of buildings and structures. No construction of large structures is complete without monitoring deformations, which contains observations during the entire period of construction and after it is completed. But at the same time, the complexity and the number of observations, the requirements for the accuracy of their production may increase annually [1].

Due to the design features, natural conditions and human activity, structures as a whole and their individual elements experience various kinds of deformation. In general, the term "deformation" is understood as a change in the shape of the object of observation. In geodetic practice, it is customary to consider deformation as a change in the position of an object relative to the original one [2].

Under constant stress due to the mass of the structure, the soil under the foundation is gradually compacted (compressed) resulting in a displacement of the vertical plane. Vertical deformation of the foundation of buildings and structures is a consequence of soil compaction and soil consolidation [3]. Soil compaction is a complex process that describes a strong change in the structure of the soil, and a consequence of densification and displacement of air in the pores of the soil grains. Soil consolidation is a slow deformation that occurs as a result of the reaction of ground water to the weight of the building or structure, at first resisting by increasing the pore water pressure, then gradually leaving the ground resulting shrinkage of the soil [4].

Uniform subsidence occurs when the stress due to the weight of the structure and the compressibility of the soil are the uniform under the foundation. Consequently, uneven subsidence occurs as a result of inhomogeneous stress by the structure and/or diverse compressibility of the soil, which, in turn, causes various kinds of displacement and deformation of the structures. In reality, there are almost no uniform subsidence due to the non-uniform characteristics of the geological structure of the base in both the vertical and horizontal directions, even in small areas. Uniform subsidence would not reduce the strength and stability of a structure, actually, large uniform subsidence may cause complications during the operation of the structure by involving undesired deformations of it. Nevertheless, uneven subsidence is more dangerous for structures.

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Even a slight slope of a high structure can cause malfunctions in the operation of the building engineering systems, such as an elevator, or may lead to overstress of the load-bearing structures. The danger is larger as the differences of the subsidence of the different parts of structures are larger, and if the design of the structure is more sensitive to subsidence. In the case when the compressibility of the soil under the foundation is not uniform or when the load pressing the soil is diverse, there are deformations — displacements, torsions, which can externally manifest themselves in the form of cracks, faults [5].

In the frame of the present investigation, vertical deformation of the building of the shopping and entertainment centre "Family Park" with an area of more than 9000 m^2 is analysed. The building is located in the western part of Samarkand city, the seismicity of the site: intensity 8, according to the microseismic map of Samarkand. The building is three-storeyed, with a parking lot on the subground floor. It is a public place for recreation and entertainment of people, which accommodates shops, a play area for children and adults, cinemas, bowling, go-karts, catering outlets, etc. It can contain a large number of people at the same time. The peculiarity of this building is that the distance between the load-bearing columns is more than 10 meters. Therefore, the monitoring of the building deformations during construction was essential, and to determine when it settles and cease to subside, in order to increase the level of safety of the building by reducing the chance of a structural hazard.

2. Repeated measurement of the shopping centre

For the vertical deformation monitoring of the construction of the Family Park shopping centre building, 12 leveling benchmark have been installed on the wall of the building (see Figure 1).

The leveling marks were installed to the same height, for ease the processing of later measurements. These leveling benchmark can be sighted from 6 stations, which locations has also been marked in order to be able to perform the repeated measurements from similar arrangement of staff and instrument. There are 4 municipal vertical control points are close to the work site (labelled by Rp1 to Rp4 on Figure 1), allowing the determination of the height of the line of sight of the instrument setups. The design of the network has followed the widely applied rules and expectations of an accurate vertical monitoring task [6]. Furthermore, experiences of earlier monitoring works [7, 8], and numerical methods for processing [9] have been considered already in the planning phase.

The so-called “null measurement” (referring to the first epoch of observations, which is the reference of deformation estimates) of the benchmarks was made in October 2018. Then, the control survey of the benchmarks was carried out every 3-4 months, starting from the beginning of construction and until the end (2018-2021). Apart from the null measurement (October 2018), altogether 7 control surveys were performed, namely in March 2019, July 2019, November 2019, March 2020, July 2020, November 2020, and March 2021.

There are several geodetic methods for determining the deformation and subsidence of engineering structures. To observe the vertical deformation of the Family Park Shopping Center building, the geometric alignment method was used. The work was carried out using a Leica Na332 automatic level. Its standard deviation for 1 km double levelling (ISO17123-2) is ±1.8 mm [10]. However, the accuracy of the measurements was found to be in the ±1-3 mm range.

It was expected that the subsidence of the building would be greater, but it turned out that the compaction of the base was done perfectly, so the result of the building's subsidence is quite insignificant. Currently, the facility is already in operation and there is a very large crowd of people in the building. After completion of the work during visual inspection, there are no visible cracks inside the building, and subsidence outside.

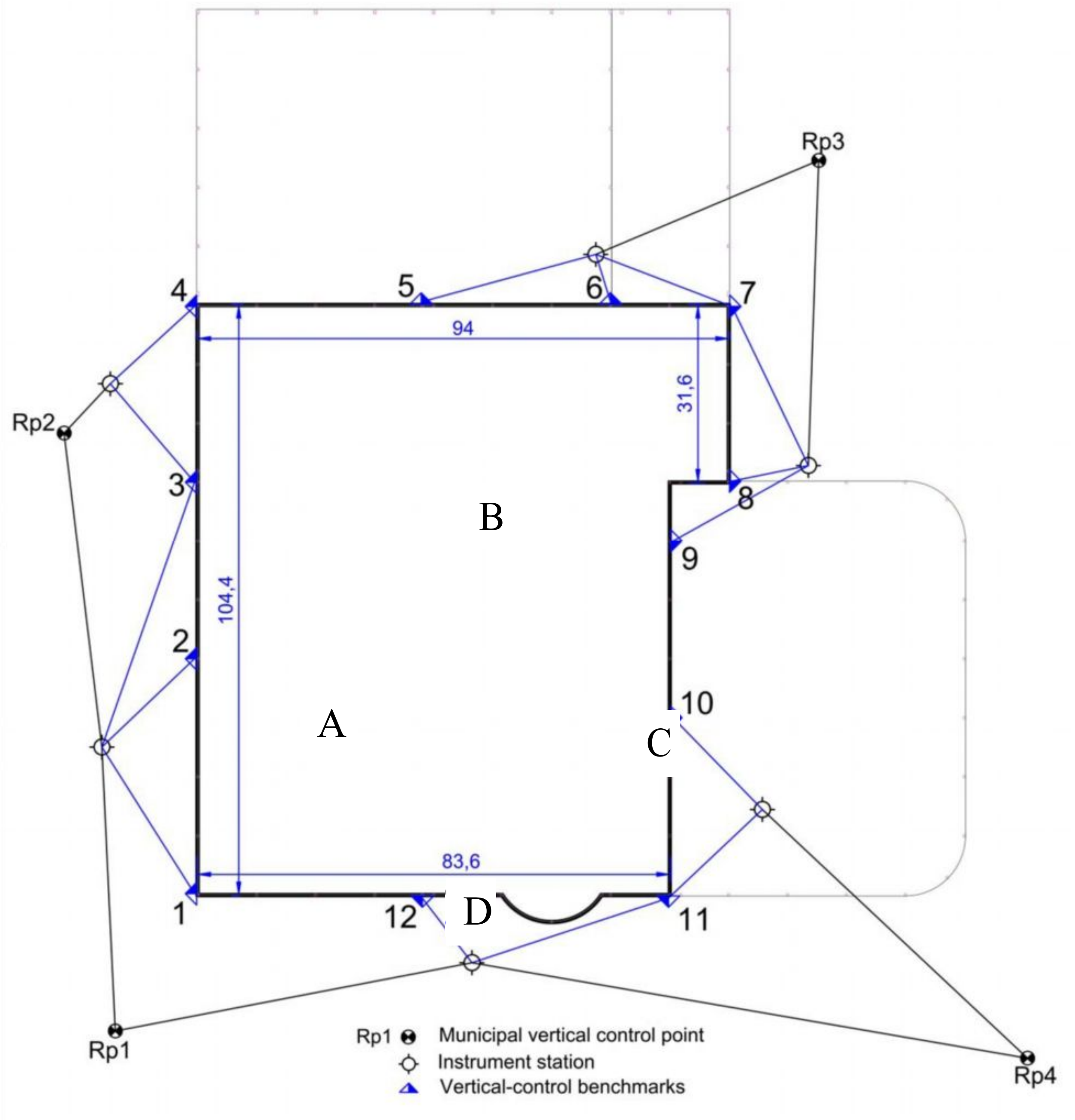

Figure 1. The surveying plan of the building with the location of the municipal vertical control point (Rp1 to Rp4), the stations of the instruments (6 unlabelled points) and the leveling benchmark (controll points) on the wall of the building (1 to 12).

3. Results

Altogether 8 epochs were observed over a period of 2.5 yars in order to monitor the subsidence of the structure. Based on that the subsidence of the building can be determined. Table 1 shows the subsidence values with respect to the null measurement on October, 2018. Time series of the subsidence in each test points are displayed on Figure 2. According to Table 1 and Figure 2, the whole building shows an obvious sinking, although the speed of subsidence is different at the different test points.

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Table 1. Subsidence of the test points determined with respect to the null epoch (Oct. 2018). Unit: mm

№ points	Mar. 2019	Jul. 2019	Nov. 2019	Mar. 2020	Jul. 2020	Nov. 2020	Mar. 2021
1	-9	-12	-15	-16	-16	-16	-16
2	-5	-8	-11	-14	-15	-16	-16
3	-4	-7	-10	-12	-14	-14	-15
4	-7	-12	-15	-17	-20	-20	-20
5	-5	-8	-10	-13	-15	-15	-15
6	-3	-7	-9	-11	-14	-14	-14
7	-6	-10	-13	-15	-17	-17	-18
8	-4	-8	-11	-15	-18	-18	-18
9	-2	-5	-8	-11	-15	-15	-15
10	-5	-9	-12	-14	-15	-15	-16
11	-8	-13	-15	-18	-20	-20	-20
12	-4	-7	-10	-13	-14	-14	-15

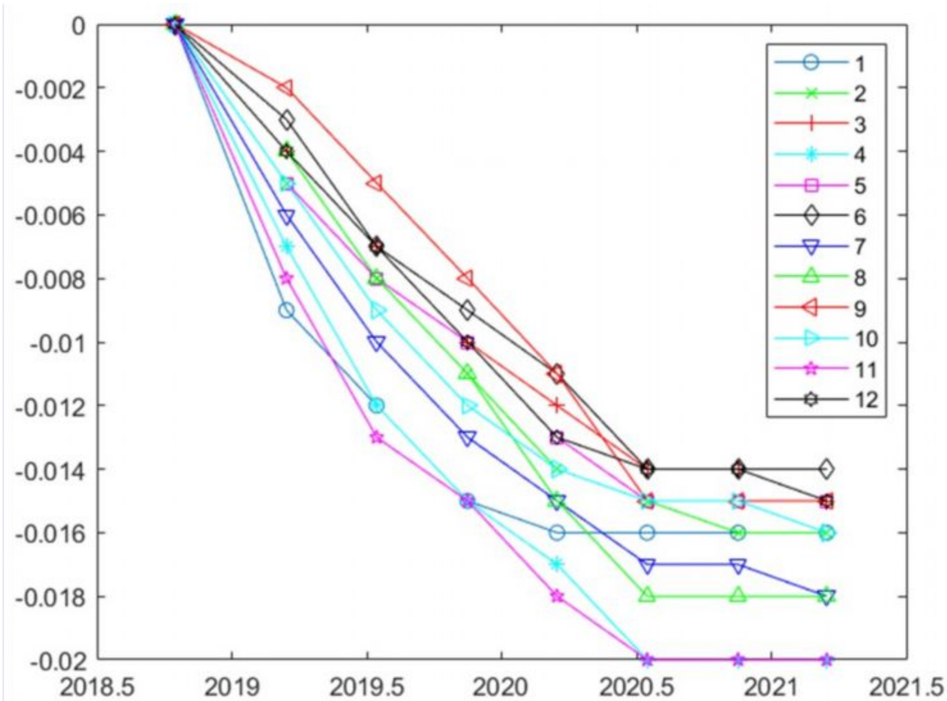

Figure 2. Subsidence of the leveling marks determined with respect to the null epoch (Oct. 2018). Unit: on the abscissa axis - years, on the ordinate axis – mm

3.1 Prediction of future subsidence

The subsidence has been calculated for 20 months after the last measured epoch. By visual check, the temporal change of the subsidence shows an exponential characteristic, therefore an exponential curve has been fit on the time series of the height values at each point by Least Squares Method, and estimating the coefficients of the function

$$H(t) = ae^{bt} + c \quad (1),$$

and the velocity of the height change (subsidence velocity) was derived analytically as

$$v(t) = abe^{bt} \quad (2),$$

By making use of the estimated velocity values derived from (2), future values of the subsidence can be predicted.

Table 2 summarizes the coefficients of the fitted exponential curves (*a*, *b* and *c* parameters of (1)), the accuracy measures of the goodness of fit (R^2 parameter and fit RMS error). The high values of R^2 (which is better as it is closer to 1) indicate a very nice fit for all the test points, thus the exponential curves can be considered to properly describing the characteristics of the subsidence. Therefore, these coefficients were used to estimate the subsidence velocity according to (2); it's coefficients (*ab* and *b*) were determined. This velocity has been used to predict future subsidence until the end of 2022, which was determined by numerically integrating the velocity with respect to time with a temporal resolution of 1 day. As a result, subsidence between the last measurement epoch (March 2021) and the end of 2022 (December 2022) were determined. For comparison, observed subsidence values (between March 2018 to March 2021) already presented in Table 1, are also shown in Table 2. (In Table 2, all quantities are dimensionless, apart from the fit RMS error and the observed and predicted values of subsidence, which are in [mm]).

Table 2. Parameters (coefficients, accuracy estimates) of LSM fit to height variations, and the observed (March, 2018 to March, 2021) and predicted (March, 2021 to December, 2022) subsidence.

№ *points*	a	b	c	R^2	RMS [mm]	ab	$\Delta h_{observed}$ [mm]	$\Delta h_{predicted}$ [mm]
1	0.0754	-1.9190	191.5835	0.9949	0.48	-0.1448	-16	-0.2
2	0.0353	-0.7539	191.5805	0.9886	0.74	-0.0266	-16	-2.3
3	0.0331	-0.6793	191.5810	0.9924	0.56	-0.0225	-15	-2.6
4	0.0503	-1.0089	191.5776	0.9924	0.75	-0.0508	-20	-1.7
5	0.0339	-0.7863	191.5818	0.9858	0.78	-0.0267	-15	-2.1
6	0.0323	-0.6230	191.5807	0.9801	0.89	-0.0201	-14	-2.9
7	0.0427	-0.9285	191.5797	0.9968	0.42	-0.0396	-18	-1.8
8	0.0419	-0.5746	191.5741	0.9769	1.25	-0.0241	-18	-4.3
9	0.0406	-0.3184	191.5692	0.9627	1.39	-0.0130	-15	-6.3
10	0.0395	-1.0007	191.5824	0.9916	0.62	-0.0395	-16	-1.3
11	0.0547	-1.1656	191.5783	0.9939	0.66	-0.0637	-20	-1.1
12	0.0364	-0.9213	191.5832	0.9820	0.87	-0.0336	-15	-1.5

According to Table 2, the predicted amount of future subsidence is 1-2 mm in all test points except for points 8 and 9. Note, however that in these two cases the goodness of fitting the exponential curve is the least convincing, c.f. the corresponding values of R^2 and RMS. Figure 3 displays the time series and the prediction of these two points. As it can be seen on the Figure, the subsidence at these two test points has been completed by mid-2020, which could not be recovered by the fitted exponential curve. Consequently, the predicted future subsidence values are overestimations due to the incorrectness of the curve fitting. Summarily, in all test points the subsidence can be considered generally to be ceased.

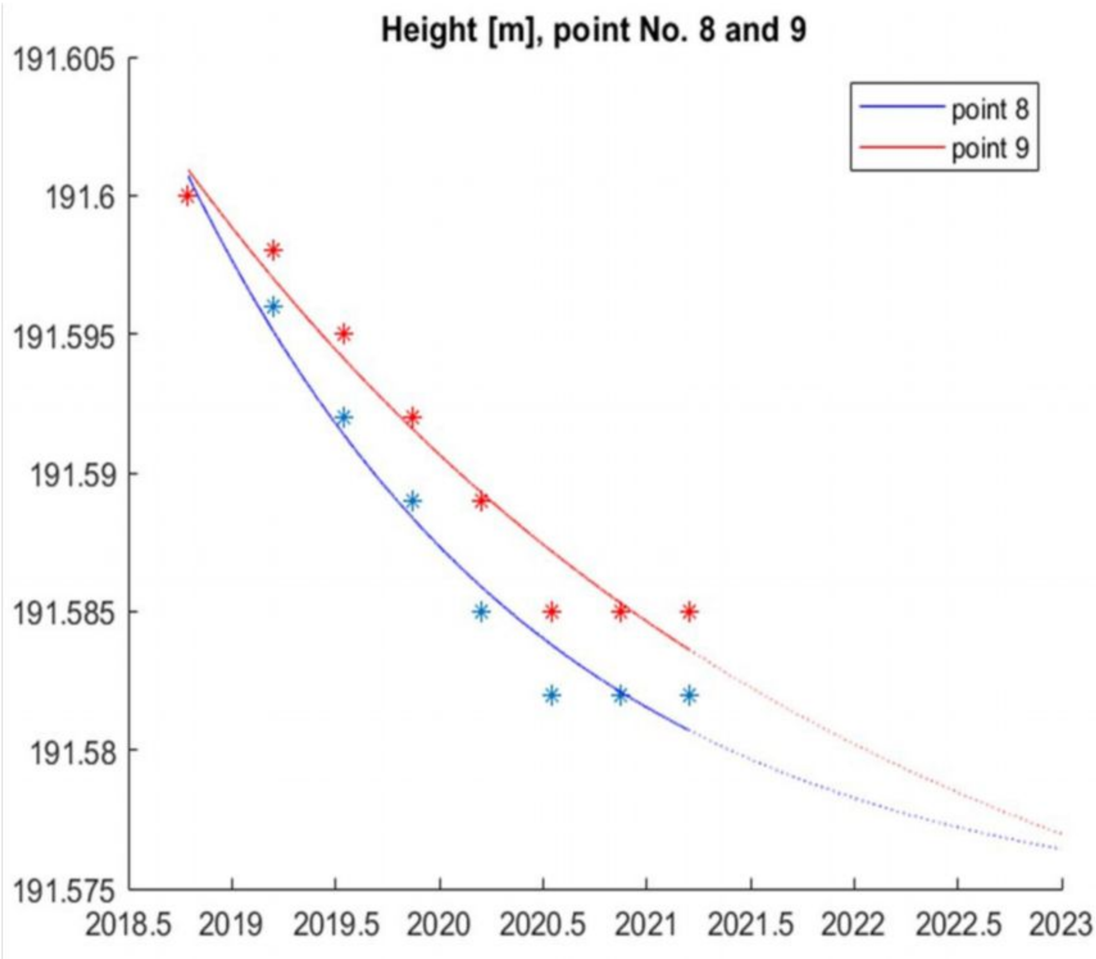

Figure 3. Time series of heights above mean sea level of points 8 and 9, result of the fitted exponential curve and the prediction. Unit: on the abscissa axis - years, on the ordinate axis – m

3.2 Estimation of tilting

The subsidence of the building during the test period is visualized on Figure 4, where the size of the circles at the test points is proportional to the amount of subsidence. As it can be seen, along the sides of the building, the subsidence is inhomogeneous, which may cause deformations of the structure. Therefore, the tilting is estimated to provide for statical analyses.

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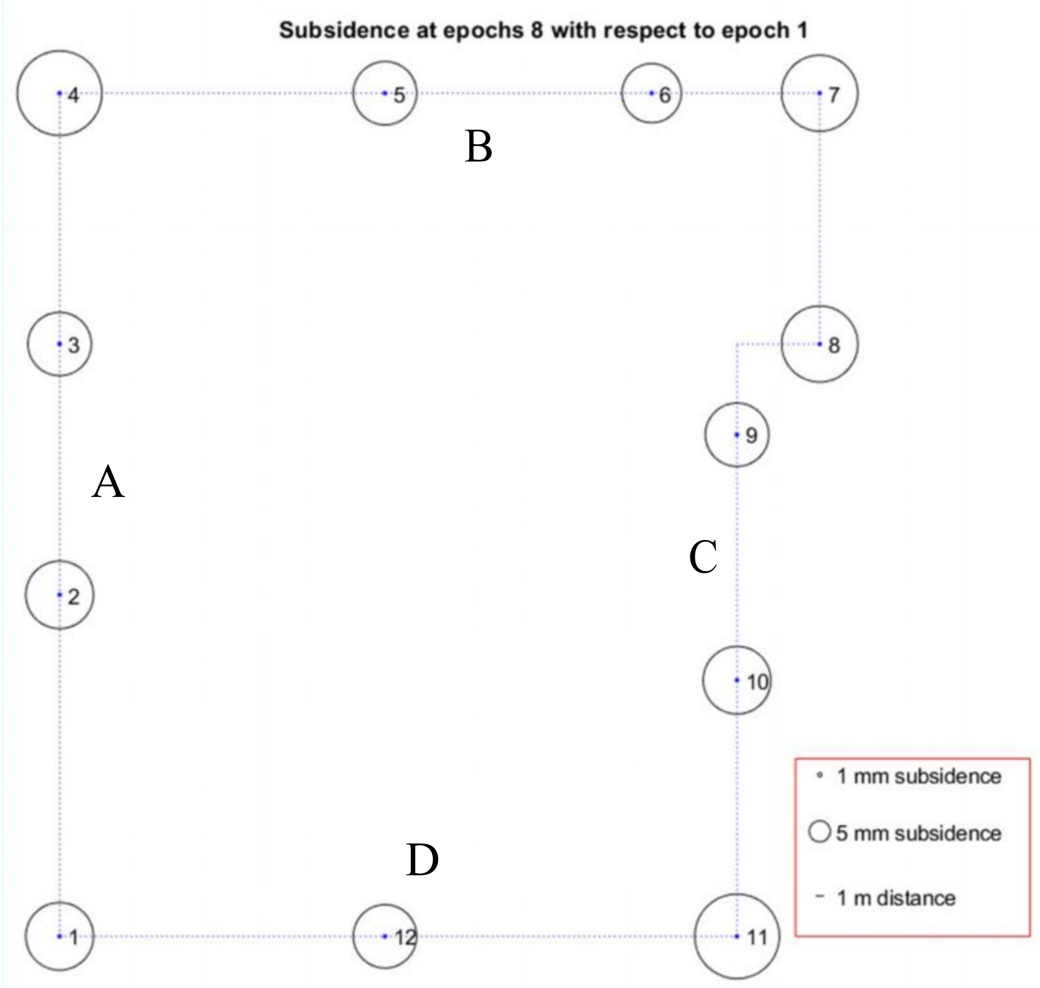

Figure 4. Subsidence of test points of the building at the last measurement campaign with respect to the null measurement. The scale of the figure and of the displayed deformations are different; the magnitudes are defined in the legend.

The tilting is estimated for the four sides of the building separately, labelled as "A" (consisting of test points 1 to 4), "B" (test points 4 to 7), "C" (test points 7 to 11; due to the discontinuity of the side it is taken into two parts), and "D" (test points 11 to 1). The subsidence of each side is shown on Figure 5. According to Figure 5, the tilting of the sides was achieved gradually by time, therefore only the last measured epoch is analysed.

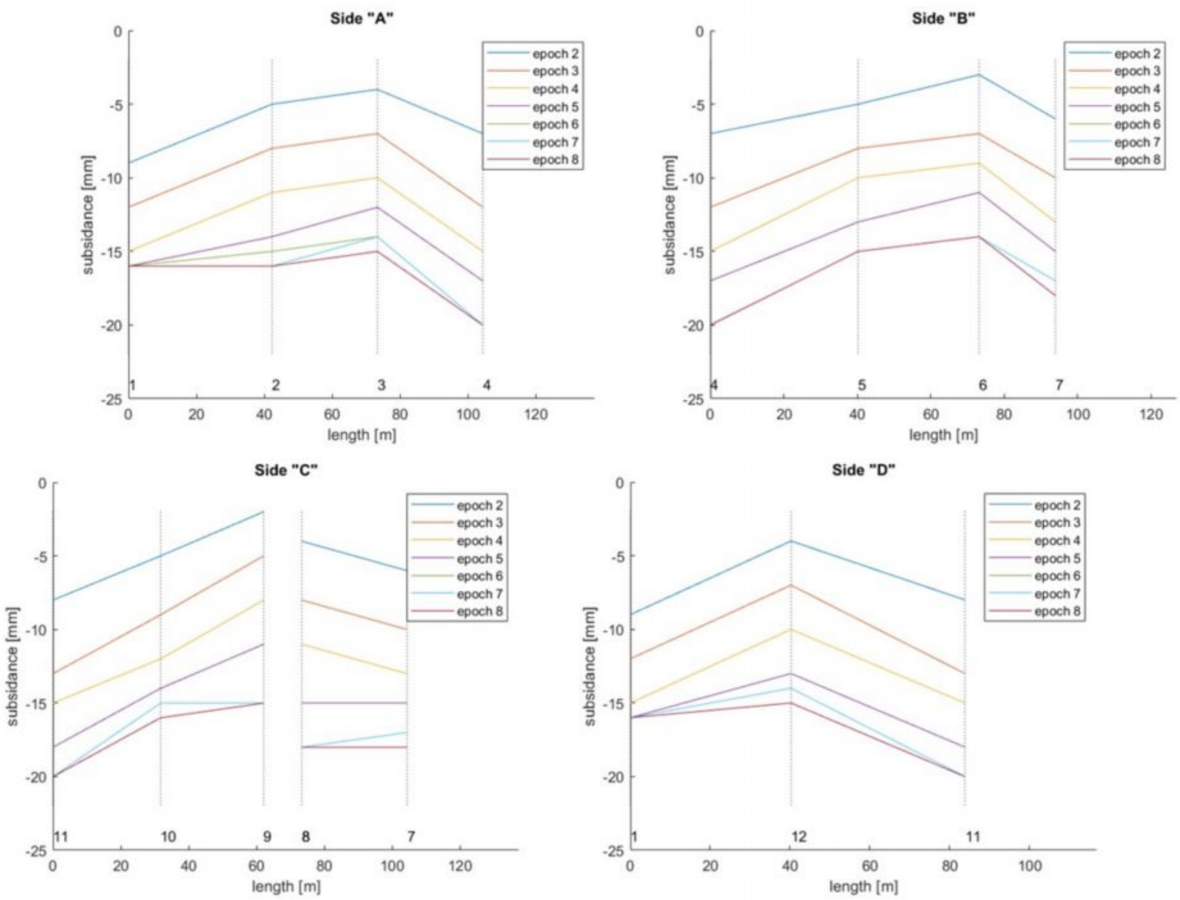

Figure 5. Subsidence of the building sides by time.

The subsidence differences along each side are in the range of 3-4 mm (c.f. Figure 5), which is very similar to the measurement accuracy (±1-3 mm, c.f. chapter 2). Apparently, many of these subsidence variations along the sides are partially the consequence of the measurement errors. Furthermore, the structure can deform only to a limited extent, so none of the subsidence values can be taken as a "ground truth", thus only main tendencies are attempted to be captured. This is done by fitting a linear regression line to each side. The slopes of the resulting lines are -6.2", +6.3", +16.7" and -10.0" respectively for the "A", "B", "C" and "D" sides (the sign of the subsidence is considered by following the increasing order of the test point numbering). Accordingly, the estimated height differences (relatively to the first test point of the corresponding side) are -3.1 mm (point 4), +2.8 mm (point 7), -0.5 mm (point 8), +5.0 mm (at the corner between points 8 and 9), and -4.1 mm (point 11). By cumulatively summing the subsidence values along the different sides, the closure error becomes 0.1 mm, which is surprisingly small in the view of the roughness of the estimation method. The cumulative summation results in a subsidence model with values relatively to test point 1. The relative subsidence values are -3.1 mm (point 4), -0.3 mm (point 7), -0.3 mm (point 8), -0.8 mm (at the corner between points 8 and 9), and 4.3 mm (point 11). The relative subsidence model is presented on Figure 6. Based on this figure, there is an obvious tilting in the direction of the lines of points 4 and 11, approximately perpendicularly to the axis going through points 1 and 7. Considering the size of the building (c.f. Figure 1), the tilting is estimated to be 0.06‰ (7.4 mm along a 133.9 m line). Furthermore, we can conclude that the tilting of the building is unidirectional, so no deformation on the structure due to it can be expected.

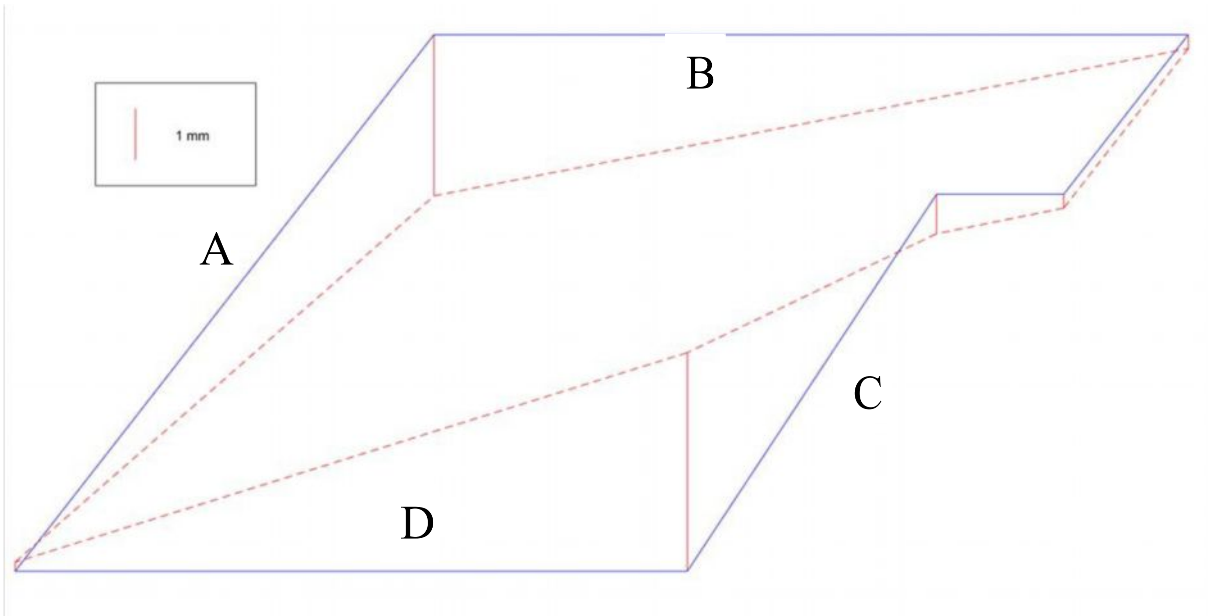

Figure 6. The relative subsidence model. The blue line indicates the floor plan in a tilted view, and the relative subsidence is red. The direction of the relative subsidence (up or down) at the test points indicates the sign.

4. Summary

Due to the design features, natural conditions and human activity, structures as a whole and their individual elements experience various kinds of deformation. Under stress due to the mass of the structure, the soil under the foundation is gradually compacted (compressed) resulting in a displacement of the vertical plane. The peculiarity of the building of the shopping and entertainment centre "Family Park" is that the distance between the load-bearing columns is more than 10 meters. As the building is a public place for recreation and entertainment of people, and it can accommodate a large number of people at the same time, the monitoring of the building deformations during construction was essential, to increase the level of safety of the building.

For the vertical deformation monitoring of the construction of the Family Park shopping centre facility, 12 benchmarks have been installed on the wall of the building. Altogether 8 epochs were observed during the time span of the construction: October 2018, March 2019, July 2019, November 2019, March 2020, July 2020, November 2020, and March 2021.

In this study, based on these measurements, an estimation for future subsidence has been provided, by fitting an exponential curve to the time series of the height values at each point by Least Square Method, then determining analytically the velocity of subsidence, and numerically integrating the velocities by time. As a result, it was concluded that in all test points the relevant subsidence has been ceased.

A further test has been provided to estimate the tilting of the building. Due to the small signal, which is comparable with the measurement accuracy, simplified subsidence characteristics for all the sides of the building was determined by linear regression, and taking into account the corresponding slopes, a subsidence model in relative sense has been derived. The subsidence model has provided a small closure error, the results may indicate actual tilting. The value of the tilting was estimated to be 0.06‰ (7.4 mm along a 133.9 m line) in the direction of the line going through points 4 and 11, approximately perpendicularly to the axis going through points 1 and 7.

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