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RESEARCH ARTICLE - SPECIAL ISSUE

Detailed analysis of the gravitational effects caused by the buildings in microgravity survey

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Abstract

Gravity (microgravity) research is more frequently carried out in urban areas, in close proximity to various types of buildings. It is necessary to take into account the gravity impact of these buildings on the measurements by calculating and factoring in the appropriate correction. The easiest method to calculate the corrections is to base them on simplified models of the buildings, approximated mostly by a rectangular prism. This paper presents an analysis of correction based on simplified models of six different buildings. It has been clearly demonstrated that density of a simplified model of a building or an element of the building is different from the average density, especially for gravity measurements inside the buildings. The research demonstrates that it is better to approximate the building with two or three rectangular prisms than with only one treated as a whole. However, the difficulty lies in determining the density of the lowest storey, the value of which diverges from the average density the most. Nevertheless, it can be concluded that in calculating building corrections simplified models of the buildings can be used, even for observation stations that are located in a close proximity to the buildings, as long as the conditions described in this article are met.

Keywords Building correction · Microgravimetry · Building density · Urban areas · Simplified building model

Introduction

In recent decades, there has been a rapid expansion of urban areas, where the phenomena that may pose threat to urban infrastructure (and therefore the residents) have been appearing with increased frequency. Some of these phenomena are related to conditions of a near-surface rock mass and can be examined by geophysical methods. An example of such phenomenon are continuous and discontinuous deformations of ground surface. They may have anthropogenic or natural origins. The most dangerous of them, are, obviously, sinkholes. The application of geophysical methods in these areas requires taking into account the urban factor, which is usually associated with the necessity to introduce appropriate corrections.

One of the geophysical methods that can be successfully applied in such conditions is microgravity method (Butler 1984; Gołębiowski et al. 2018; Loj 2014; Styles et al. 2005). An unquestionable advantage of this method lies in its simplicity, but unfortunately it has two basic limitations. One of them is an increased measurement error, resulting from increased ground vibrations, and the other is a gravity impact of a building on the measurements. As much as in the first case it is difficult or impossible to eliminate the error in the second case, but it can be reduced. One possibility is to ensure that the observation stations are not too close to the buildings. However, it reduces the scope of the method applications. The second option is to calculate a correction to eliminate the gravity effect of buildings (Śliz 1978; Panisoval et al. 2012; Dewu 2014; Dilalos et al. 2018). Building correction can also eliminate the impact of identified underground natural or anthropogenic objects (Golebiowski et al. 2016; Porzucek 2014).

Building correction calculation is connected with the determination of building geometry and mass. As it is commonly known, buildings are geometrically very complicated and for this reason in order to calculate the correction their geometry is frequently simplified. Most frequently, a building or its elements are approximated by rectangular prism or, sometimes, by polyhedron (Wójcicki 1993). It involves determining the density of the simplified objects, calculated

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on the basis of the building average density. This solution was submitted by Śliz in 1978. Analysing a typical four-storey tenement house, he calculated the density for each storey and presented the distribution of the building correction only for this case. The question may therefore be posed whether the average density is indeed optimal, and this is the main subject of this article.

Building models

Urbanized areas are areas that have been inhabited, built on and extended over the centuries and are characterized by the presence of buildings of various ages. Building age determines the types of walls, their thickness as well as the material they are made of. There are two types of walls: external and internal walls ([N1]PN-EN 1996-1-1+A1:2013-05/NA:2014-03 Eurokod6). Due to their function, external walls can be divided into load-bearing walls and stiffening walls, while internal walls can be divided into load-bearing walls, stiffening walls and partition walls. Load-bearing walls are used to carry vertical loads, as well as horizontal loads, limiting the displacements of the structure, while stiffening walls are used only to carry horizontal loads and maintain the stiffness of the structure. Partition walls do not carry any loads; they are only used to divide the internal space of the building. Regardless of the age, the function of the wall determines its thickness.

The analysis of a building correction distribution was carried out for three types of buildings, most frequently found in urban areas, i.e. a single-family detached house, tenement house and large-panel system building. The geometry was based on actual building plans, taking into account the type of materials to be used in construction (PN-EN ISO 10456; PN-EN ISO 6946:2017-10; Płuska 2009). For each case, we considered the variant of the building with cellar and without cellar.

The first building was the single-family detached home, composed of two storeys (ground floor and I floor) with external wall length 10 and 12 m. This house was built from external load-bearing wall and two internal load-bearing walls that are also stiffening wall. Due to the size of the wall and their thickness, two cases of house were considered. The first was the old-type house built of brick for which the thickness of the ground floor walls was 51 cm and first floor walls 38 cm. The brick density was taken as 1.8 g/cm^3. The second was the modern house built of silicate brick, for which the thickness of the ground floor and I floor was the same 24 cm and the density was 1.9 g/cm^3. This floor slab for both cases had a thickness of 15 cm and density of 2.3 g/cm^3. On the basis of this, the wall model of these two buildings was created (Fig. 1).

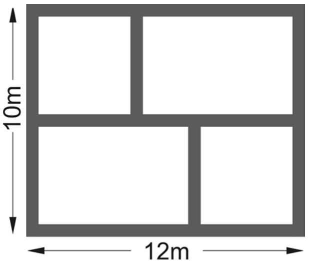

Fig. 1 Wall model of the single-family detached home (pictorial plan of storey)

The second building was the multifamily house of medium size—the tenement house. This building had four storeys (ground floor and three floors) with external wall length 45 and 24 m. Each floor was divided into five flats with an area of about 150 or 200 m^2. The building was designed in a longitudinal system, which means that the external walls and longitudinal internal wall, separating the flat from the corridor, were the load-bearing walls, while the walls dividing the area into flats were the stiffening wall. Internal area of the flat was divided by partition wall. Building with the tenement house size was chosen for one important reason, namely that objects of this size often dominate in city centres, because they were built from the earliest times. Taking into account this fact, three cases of tenement houses of the sizes described above were used for the analysis.

The first case was the building from the Middle Ages for which the thickness of ground floor load-bearing walls was 90 cm, while the stiffening walls were 75 cm thick. The floor load-bearing walls were 75 cm thick and the stiffening walls were 60 cm. The partition walls for all storeys had the same thickness of 45 cm. The walls were made of solid bricks with the density of 2.0 g/cm^3. The second case was the tenement house from the middle eighteenth century for which the ground floor load-bearing walls were 75 cm thick, while the stiffening walls were 60 cm. As in the previous case, the floor walls were smaller than the ground floor walls and had 60 cm thickness for load-bearing walls and 50 cm for stiffening walls. The partition walls for all storeys had the same thickness of 30 cm. The walls were made of bricks with the density of 1.8 g/cm^3. The third was the new tenement house—modern apartment building. The ground floor load-bearing walls had 50 cm thickness and for floor had 38 cm thickness. The stiffening walls for all storeys had the same thickness of 38 cm. Similarly, the thickness of partition walls for all storeys was the same and had 12 cm. For the second and third cases, despite the different sizes of bricks, their density was the same and had 1.8 g/cm^3 value. The floor slab for both cases had a thickness of 25 cm and density of 2.3 g/cm^3. The above-described parameters were the basis for the creation of three wall models of tenement house (Fig. 2).

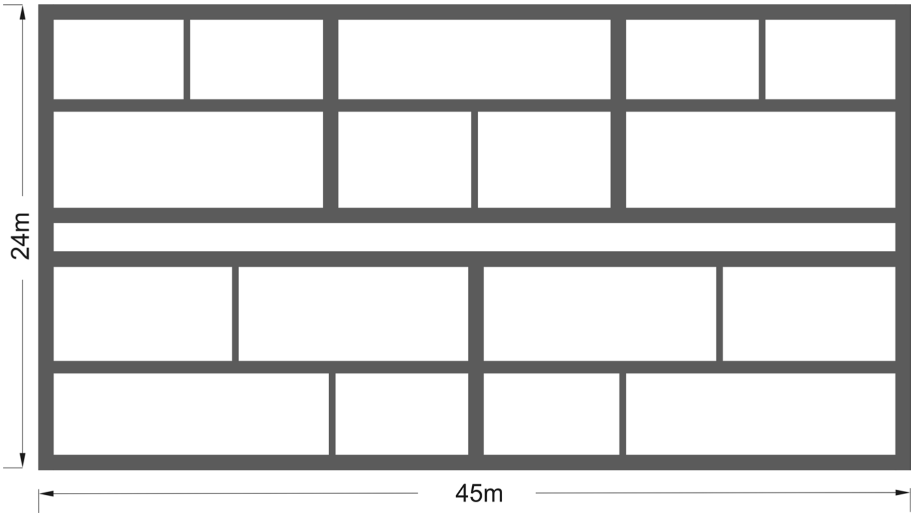

Fig. 2 Wall model of the tenement house (pictorial plan of storey)

The third building was from the twentieth century, named Plattenbau or large-panel system building or LPS (Basista 2001). LPS were multi-storey buildings founded on an identical segment repeated system built of two types of walls: load-bearing walls and partition walls. One segment, known as a tower block, size 72 × 24 m, consisting of 11 storeys (ground floor and ten floors) was selected for the analysis. Every storey was divided into 15 flats with an area of 62, 50 and 30 m^2 and two staircases. This house was built in a mixed system. It means that the load-bearing walls were both perpendicular and parallel to the longitudinal axis of the building and together with floor slab were the stiffing elements of the building and divided the internal space into flats. The partition walls were used to divide the internal flat space.

For all storeys, thickness of the load-bearing walls, partition walls and floor slab was constant and amounted to 30 cm, 14 cm and 20 cm, respectively. LPS was a building system using prefabricated concrete slabs. The slabs were made of reinforced concrete (RC) with 2.5 g/cm^3 density, and this density was adopted for partition walls and floor slab. Due to need to maintain adequate wall heat, the load-bearing walls were built in three-layer system—RC, styrofoam and concrete, and for this type of wall, the density was assumed at 2.2 g/cm^3. The above-described parameters were the basis for the creation of the wall models of LPS (Fig. 3).

Methodology of the building correction analysis

As described above, three types of buildings were selected for the analysis of building correction (Figs. 1, 2 and 3), which was called wall model. For the building correction analysis, it was assumed that the rectangular prism would be used to represent the shape of buildings. Therefore, in the wall model, each wall of the buildings was approximated with a single rectangular prism. The density of each prim was the same as the density of the material from which the wall was built. To calculate the building correction for wall

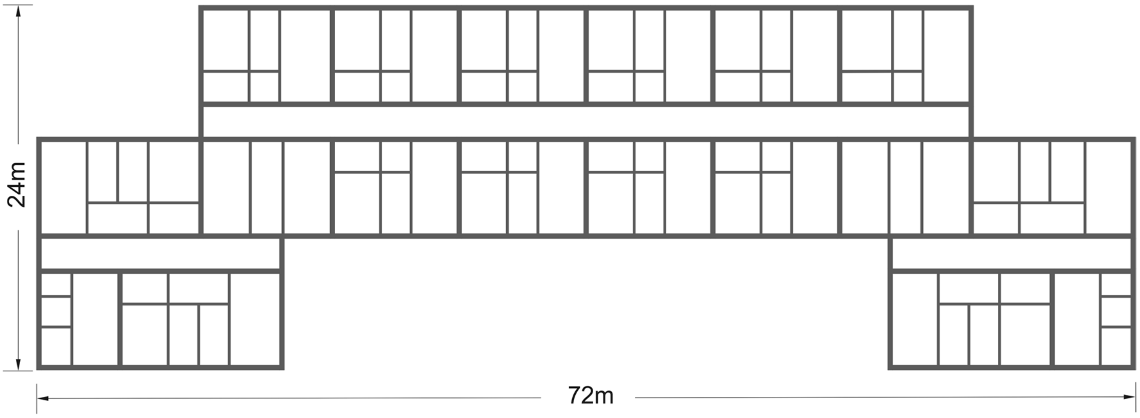

Fig. 3 Wall model of the tower block (pictorial plan of storey)

model, the special program was created, using the Nagy algorithm (Nagy 1966). This is the algorithm used for calculating gravity effect from a rectangular prism, and before using the algorithm in the program, it was tested with Oasis Montaj and other programs for gravity modelling.

In order to analyse building correction, the calculation was done not only for whole building, but also for its parts. Thus, the calculation was done for the following options:

- whole above-ground part of building (called ad whole building),
- cellar (two cases),
- ground floor,
- for each floors separately,
- together from the first floor upwards.

For each building, a grid of observation points was created, both outside and inside the building. Inside the building, the observation stations were located in two variants: for the building without cellar the station was on the ground floor, but for the building with cellar on the cellar floor. The value of density was calculated separately for outside and inside the building.

The calculation was done by introducing some necessary assumptions:

- inside the building, observation stations must be at least 20 cm from any wall,
- outside the building observation stations must be at least 50 cm from any wall,
- the observation was made on tripod and the gravity measurement system was at the height of 30 cm from the surface,
- only these stations were used for calculation in which the correction value for wall model was greater than 20 nm/s2, which was about half of the measurement error of CG-5 gravimeter.

Calculation of building correction from individual walls and floor slab is very uphill, so that the possibilities of using the simplified model were checked. Each building or its element was approximated with rectangular prism, and an optimal density was sought for which the calculated value was as close as possible to the correction calculated from the wall model. For the whole model and its elements, the average density was calculated (ρavg) using basic wall model. This density was a reference value for the optimal density calculated for the simplified model. The minimization of the error described by the following formula was accepted as the criterion for searching for the optimal density:

$$\text{error} = \sqrt{\frac{\sum_{i=1}^{n}\left(W_i - S_i\right)^2}{n-1}}$$

W_i—wall model density value, S_i—simplified model density value, n—number of stations.

Results

For all six buildings, the building corrections were analysed, using the methodology described above, and the results are presented in Tables 1, 2, 3, 4, 5 and 6.

These tables do not include the density for three cases: the cellar simplified model for observation stations on the ground floor; the cellar simplified model for observation station in cellar and ground floor simplified model; and whole building for observation stations on the ground floor. For two of them, it was necessary to calculate the building correction from the wall model because observation stations were affected not only by external but also by internal walls, so that the distribution of the correction was too complicated to use the simplified model to approximate a single object. In the third case, it was illogical to take measurement on the ground floor in the building with cellar.

Table 1 Optimal bulk densities for the simplified model of the old single-family detached home

	ρin+0[a] (g/cm^3)	Δmax[e] (nm/s^2)	ρout[b] (g/cm^3)	Δmax[e] (nm/s^2)	ρin-1[c] (g/cm^3)	Δmax[e] (nm/s^2)	ρavg[d] (g/cm^3)
Whole house			0.61	30	0.52	50	0.57
Ground floor			0.76	20	0.58	40	0.65
I floor	0.40	20	0.51	10	0.42	10	0.49
Cellar[f]			– 1.31	20			– 1.54
Cellar[g]			– 1.84	10			– 1.82

[a] ρin+0—for points inside the building for ground floor, [2] ρout—for points outside the building, [3] ρin-1—for points inside the building for cellar, [4] ρavg—average storey density, [4] Δmax—max. difference between wall and simplified model, [6]—model of the outer contour of foundations, [7]—model of the inner contour of foundations

Table 2 Optimal bulk densities for the simplified model of the new single-family detached home

	ρin+0[a] (g/cm^3)	Δmax[e] (nm/s^2)	ρout[b] (g/cm^3)	Δmax[e] (nm/s^2)	ρin-1[c] (g/cm^3)	Δmax[e] (nm/s^2)	ρavg[d] (g/cm^3)
Whole house			0.44	20	0.39	30	0.43
Ground floor			0.49	10	0.42	20	0.46
I floor	0.32	20	0.41	10	0.33	10	0.40
Cellar[f]			−1.59	10			−1.74
Cellar[g]			−1.93	10			−1.91

Note the same as Table 1

Table 3 Optimal bulk densities for the simplified model of the mediaeval tenement house

	ρin+0[a] (g/cm^3)	Δmax[e] (nm/s^2)	ρout[b] (g/cm^3)	Δmax[e] (nm/s^2)	ρin-1[c] (g/cm^3)	Δmax[e] (nm/s^2)	ρavg[d] (g/cm^3)
Whole house			0.65	140	0.60	240	0.62
I–III floor	0.53	90	0.60	60	0.54	50	0.58
Ground floor			0.91	70	0.69	190	0.75
I floor	0.52	60	0.63	40	0.53	30	0.58
II floor	0.53	20	0.59	20	0.54	20	0.58
III floor	0.54	10	0.58	10	0.54	10	0.58
Cellar[f]			−1.06	60			−1.44
Cellar[g]			−1.73	30			−1.63

Note the same as Table 1

Table 4 Optimal bulk densities for the simplified model of the eighteenth-century tenement house

	ρin+0[a] (g/cm^3)	Δmax[e] (nm/s^2)	ρout[b] (g/cm^3)	Δmax[e] (nm/s^2)	ρin-1[c] (g/cm^3)	Δmax[e] (nm/s^2)	ρavg[d] (g/cm^3)
Whole house			0.52	120	0.49	180	0.53
I–III floor	0.42	60	0.47	50	0.42	50	0.46
Ground floor			0.74	60	0.58	150	0.62
I floor	0.41	50	0.49	30	0.41	30	0.46
II floor	0.42	20	0.47	20	0.42	10	0.46
III floor	0.42	10	0.46	10	0.43	10	0.46
Cellar[f]			−1.25	50			−1.58
Cellar[g]			−1.78	30			−1.72

Note the same as Table 1

Table 5 Optimal bulk densities for the simplified model of the new tenement house

	ρin+0[a] (g/cm^3)	Δmax[e] (nm/s^2)	ρout[b] (g/cm^3)	Δmax[e] (nm/s^2)	ρin-1[c] (g/cm^3)	Δmax[e] (nm/s^2)	ρavg[d] (g/cm^3)
Whole house			0.39	80	0.38	130	0.39
I–III floor	0.31	50	0.36	50	0.32	30	0.35
ground floor			0.57	40	0.47	110	0.50
I floor	0.31	30	0.37	30	0.31	20	0.35
II floor	0.31	20	0.35	10	0.32	10	0.35
III floor	0.32	10	0.34	10	0.32	10	0.35
Cellar[f]			−1.47	30			−1.73
Cellar[g]			−1.88	30			−1.84

Note the same as Table 1

Table 6 Optimal bulk densities for the simplified model of the LPS

	ρin+0^{a} (g/cm^{3})	Δmax^{e} (nm/s^{2})	ρout^{b} (g/cm^{3})	Δmax^{e} (nm/s^{2})	ρin-1^{c} (g/cm^{3})	Δmax^{e} (nm/s^{2})	ρavg^{d} (g/cm^{3})
Whole house			0.47	70	0.42	70	0.47
I–X floor	0.43	70	0.46	50	0.38	70	0.46
II–X floor	0.43	50	0.45	30	0.38	60	0.46
Ground floor			0.62	30	0.57	60	0.59
I floor	0.42	30	0.49	20	0.35	30	0.46
II floor	0.43	10	0.47	20	0.36	20	0.46
III floor	0.43	10	0.46	10	0.37	10	0.46
IV floor	0.43	10	0.45	10	0.38	10	0.46
V floor	0.44	0	0.45	0	0.39	10	0.46
VI floor	0.44	0	0.45	0	0.39	0	0.46
VII floor	0.44	0	0.45	0	0.40	0	0.46
VIII floor	0.44	0	0.45	0	0.40	0	0.46
IX floor	0.44	0	0.45	0	0.41	0	0.46
X floor	0.44	0	0.45	0	0.41	0	0.46
Cellar^{f}			− 1.50	30			− 1.67
Cellar^{g}			− 1.87	30			− 1.85

Note the same as Table 1

After analysing the data from Tables 1, 2, 3, 4, 5 and 6, several regularities can be noticed:

1. The optimal densities calculated for external station were generally higher than the average density, whereas for internal stations they were lower. While for external station the optimal densities for successive storey approached to the average density, for the internal stations they were always lower.
2. The biggest differences between the average and optimal densities for the simplified model were for cellar, ground floor and first floor, that is, for building elements laying closest to the observation station.
3. The biggest differences in density between the simplified model and average density (ρavg) were obtained for the ground floor for external station. This difference clearly increased for massive buildings with thick wall, that is, for old buildings. For mediaeval tenement house, the simplified ground floor model density for ground floor calculated from external stations was as much as 0.16 g/cm^{3} higher than the average density but from internal stations in cellar by 0.07 g/cm^{3} lower.
4. Of course, the higher the floor the closer the calculated density was to the average density and the difference between correction values of both models was smaller.
5. It is worth to note that the calculated optimal density for simplified whole building model was usually very close to the average, but the correction differences (Δmax) were the highest. It follows that it was more correct to calculate the building correction from simplified model of the building consisting separately of the ground floor (eventually separately of the ground floor and first floor) and the rest part of building than to calculate correction from simplified whole building model.
6. The density calculated for light buildings (new single-family detached home, tower block) was very close to the average density, for external observation station.
7. In Tables 1, 2, 3, 4, 5 and 6, there are two variants of density calculations for cellar. In the first, the optimal density was calculated using the volume calculated similarly to the above-ground parts, i.e. the approximating rectangular prism had a base with the building outline. For this model, a large discrepancy between the average (ρavg) and calculated density was obtained. After a thorough analysis, a second simplified cellar model was created, based on internal contours of the foundations, and for this model, the average density was calculated. It is important to realize that foundations real density was similar to density of cellar surrounding rocks and their gravity influence was very small. For this new simplified cellar model, the calculated optimal density was close to the average density.

As is well known, the value of building correction quickly decreases with distance from the building. For this reason, the analysis of the correction in the zones around the building was performed (Table 7). In each zone, the optimal density for simplified model and the percentage of station in which the difference Δmax exceeded 20 nm/s^{2}

Table 7 Detailed results of building correction for the eighteenth-century tenement house for outside observation stations

	From (m)	To (m)	ρ (g/cm^3)	%	Δmax (nm/s^2)
Whole house	0.5	1	0.54	83.8	70
	1	2	0.53	72.3	60
	2	3	0.52	56.3	40
	3	4	0.51	43.4	30
	4	6	0.51	19.6	30
Ground floor	0.5	1	0.76	46.3	40
	1	2	0.74	13.5	30
I–III floor	0.5	1	0.46	43.9	30
	1	2	0.46	45.5	30
	2	3	0.47	14.9	30
	3	4	0.47	6.6	20
	4	6	0.48	2.4	20
Cellar	0.5	1	− 1.80	5.7	30
	1	2	− 1.80	0.7	20

were calculated. Table 7 shows the result of representative example for eighteenth-century tenement house.

As it could be expected, the most stations with the Δmax value above 20 nm/s^2 were observed in zone closest to the building. The analysis for all buildings shows that above 6 m from the building Δmax for all stations was smaller than assumed 20 nm/s^2.

Until now, the solution has been based on finding the optimal density for simplified model, but in real calculations this density is most often assumed on the base of available data on the building. It is therefore necessary to answer the question of how significant the influence of an incorrect estimate of density will be on the calculated correction value. In order to answer this question, the calculations for different densities were done, taking as an optimal value from Tables 1, 2, 3, 4, 5 and 6. Changing the optimal density with values from the interval (− 0.1, + 0.1) every 0.02 g/cm^3, the change in the maximum Δmax of the models was analysed. Table 8 shows the result of representative example for the mediaeval tenement house. It is worth to note that the Δmax was not always the smallest for the optimal density, but the smallest was the error calculated according to the formula given above.

The analysis of calculated Δmax showed that the greatest influence on correctness of calculated correction from building had incorrect density estimation for simplified model: ground floor, jointly higher floor and whole building. This is due to the fact that for these cases the Δmax was significantly increased during the determination of the optimum density values. The observation station distance was also affected, which was confirmed by the small, absolute variation of the correction for floors above the first floor. After analysing all data, it can be assumed that deviation in density from optimal ± 0.04 g/cm^3 can be accepted.

Table 8 Value of Δmax for density different than optimal in ± 0.1 g/cm^3 for the mediaeval tenement house

Density range (g/cm^3)	− 0.1	− 0.08	− 0.06	− 0.04	− 0.02	0	0.02	0.04	0.06	0.08	0.1
ρin+0[a] I–III floor	280	220	190	160	120	90	100	150	190	240	290
ρin+0[a] I floor	140	120	110	90	80	60	50	70	100	120	140
ρin+0[a] II floor	80	70	50	40	30	20	20	40	60	70	90
ρout[b] whole house	330	290	250	220	180	140	110	110	150	190	230
ρout[b] ground floor	120	110	100	90	80	70	60	50	60	70	80
ρout[b] I–III floor	150	120	90	70	40	60	90	120	150	180	210
ρout[b] I floor	60	50	40	30	30	40	50	60	70	80	100
ρin-1[c] whole house	480	430	380	330	290	240	190	260	330	410	480
ρin-1[c] ground floor	290	270	250	230	210	190	180	160	170	190	220
ρin-1[c] I–III floor	210	160	130	100	80	50	80	130	170	210	260
ρin-1 I floor	480	430	380	330	290	240	190	260	330	410	480

[a] ρin+0—for points inside the building for ground floor in nm/s^2, [b] ρout—for points outside the building in nm/s^2, [c] ρin-1—for points inside the building for cellar in nm/s^2

Conclusion

The approximation of building with simplified model, usually rectangular prism, to calculate building corrections has been used for many years. Densities for these prisms have usually been taken as average densities resulting from mass of building's parts and its volume. However, the question may be asked whether densities calculated in this way are optimal for calculating the correction. In this paper, density analysis was performed for six different buildings. The research was carried out for observation stations outside and inside the building. Inside the building, observation stations were on the ground floor and in the cellar.

The obtained results clearly confirmed that it is impossible to use the average density for simplified models of ground floor or cellar for internal station—the differences between the correction values from the wall model and the simplified model Δmax are too big. It also turned out that the calculated optimal density from external and internal stations was different. The first one was greater than the average density and the second smaller.

The analysis of the results also shows that the better results of correction value were obtained when the building was divided into the ground floor and rest of above-ground parts than when whole building was approximated by one rectangular prism. Nevertheless, problem with density of the ground floor still remains. This density was significantly different from the average value, and the differences were greater for building with thick and massive walls.

During the research, it also turned out that in case of simplified cellar model created it should be remembered that the average density should be calculated using its volume calculated on the inside the foundations and not calculated on the outside the building.

The research results clearly show that the closer building the station was the greater calculated error for simplified model was. Incorrect estimation of simplified model density increased of course building correction error calculated in stations. It is not possible to estimate what is the acceptable deviation from the optimal density but it can be assumed that if it does not exceed ± 0.04 g/cm^3 the accuracy of the calculated correction is satisfactory.

It is also worth to note that the calculated error at any station for floor above the first floor was small, so that the range of the optimal density deviation was also larger.

It can be concluded that simplified model can be successfully used to calculate building correction, even for the stations within short distance to the building. However, it is important to remember about conditions specified in the article.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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