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STRUCTURAL FAILURES OF BUILDINGS CAUSED BY VOLUME CHANGES OF STEEL SLAG

PORUCHY STAVEBNÍCH OBJEKTŮ VLIVEM OBJEMOVÝCH ZMĚN OCELÁRENSKÉ STRUSKY

Abstract

The paper deals with structural failures of buildings caused by volume changes of steel slag in subsoil of hospital in Ostrava-Poruba. The building consists of a monolithic reinforced concrete frame structure with floor slabs on slag sub-base. Latest measured increases in deformations show that the slag swelling in the sub-soil continues, and as the measured dependences show, there is no stabilization of the movement.

Keywords

Steel slag, volume changes, structural failures of buildings

Abstrakt

Článek se věnuje poruchám stavebních objektů vlivem objemových změn ocelárenské strusky v podloží nemocnice v Ostravě – Porubě. Budovu tvoří monolitická železobetonová skeletová konstrukce s podlahovými deskami založenými na struskovém podloží. Poslední naměřené přírůstky deformací prokazují, že bobtnání strusky v podloží pokračuje a dle naměřených závislostí nedochází k ustálení pohybů.

Klíčová slova

Ocelárenská struska, objemové změny, poruchy staveb

1 INTRODUCTION

The load-bearing structure of the entrance building of the Faculty Hospital in Ostrava-Poruba consists of a monolithic reinforced concrete skeleton structure with hidden beams and ceiling slabs with dimensions of approx. 64 x 31 m. One floor of the building is projected above ground, and the other two floors are sunk beneath it. Transitions between different elevation levels were, during the construction completed with a slag sub-base, which in some parts reaches up to 4 m of thickness. The floor structures of 100 to 200 mm thickness made of class C 16/20 concrete sit on a concrete base of 150 mm thickness with a welded grid [1].

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When examining the building in 10/2006, inclined shear cracks in external walls and connecting non-load bearing walls were recorded in the entrance area, public areas, grocery shop, storage rooms, and connecting corridors. The door openings and doorframes are distorted and skewed; the floor surface is bulged upward and penetrated by cracks. See Figure 1 for the bulges and the peeled tiles at the entrance area outside the public area facilities (men's and women's restroom, cleaning room).

Figure 1: Deformation of the floor and tiles

In some places deformations already reach values such that it resulted in the destruction of the brickwork and crumbled parts of perforated bricks, see Figure 2 [1].

Figure 2: View of damaged brickwork of the non-load bearing wall

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2 RECORDED INCREASES OF VERTICAL DISPLACEMENT

To verify whether there is a settling of the foundations and/or rising of the floor, measurements of the vertical deformations using mounted stable points were done. The measuring points situated on the load-bearing columns of reinforced concrete frame are in the charts with measured values marked by a number only. Points mounted to the floor are then marked with a serial number with the "P" index. Measurements of vertical displacements were initiated on September 18, 2001. The recorded continuous unevenness of the floors reached up to 110 mm, however the height was not related to fixed points.

Further measurements as of January 23, 2002 have been related to the firm fixed (stabilized) elevation points mounted on the floor and load-bearing columns.

The measurement results clearly show that there is no subsidence of pile foundations present, but the upward bulging of floor structures is present. The upward deformation of some columns is even measured (negative subsidence).

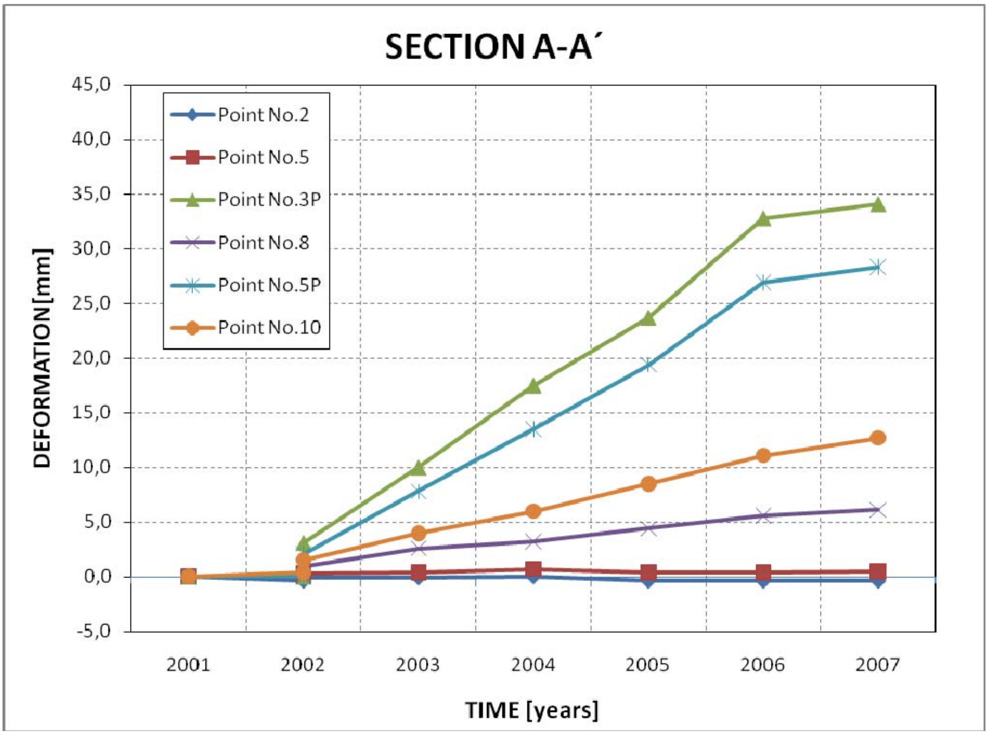

Figure 3: Vertical deformations of measured points A-A in time

Time course of deformations in individual cross section profiles and points is shown in Figure 3 to 6. The maximum bulge of the floor reached the value of 39.6 mm within the period of January 23, 2002 to January 24, 2007, and then the value of even 46.1 mm within next 15 months to April 24, 2008 (maximum increase of 6.5 mm in 15 months). However, the initial deformations of approximately 110 mm need to be added to this value, so the last height unevenness of the floor reached over 150 mm as of the date of the last measurement, and the deformations are still continuing.

The ongoing deformations are probably related to another reaction with water or water vapour, which could be fed into the subsoil primarily in the form of rainwater infiltration, but also secondarily through a damaged horizontal water and sewerage system due to the ongoing subsoil deformations [1].

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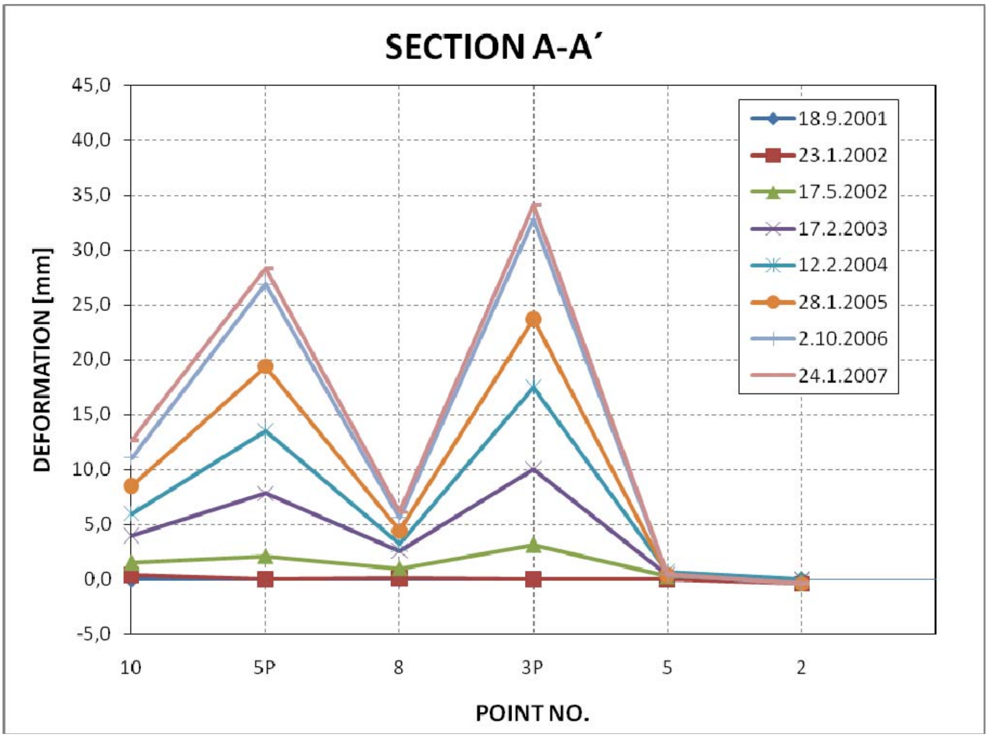

Figure 4: Vertical deformations of measured points in section A-A

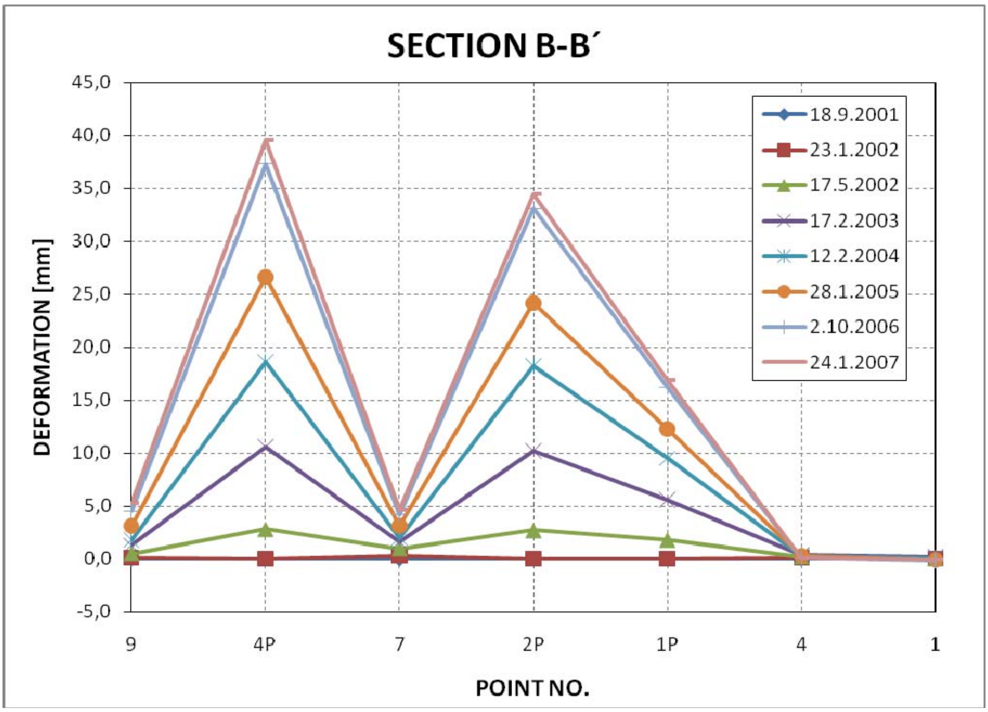

Figure 5: Vertical deformations of measured points B-B in time

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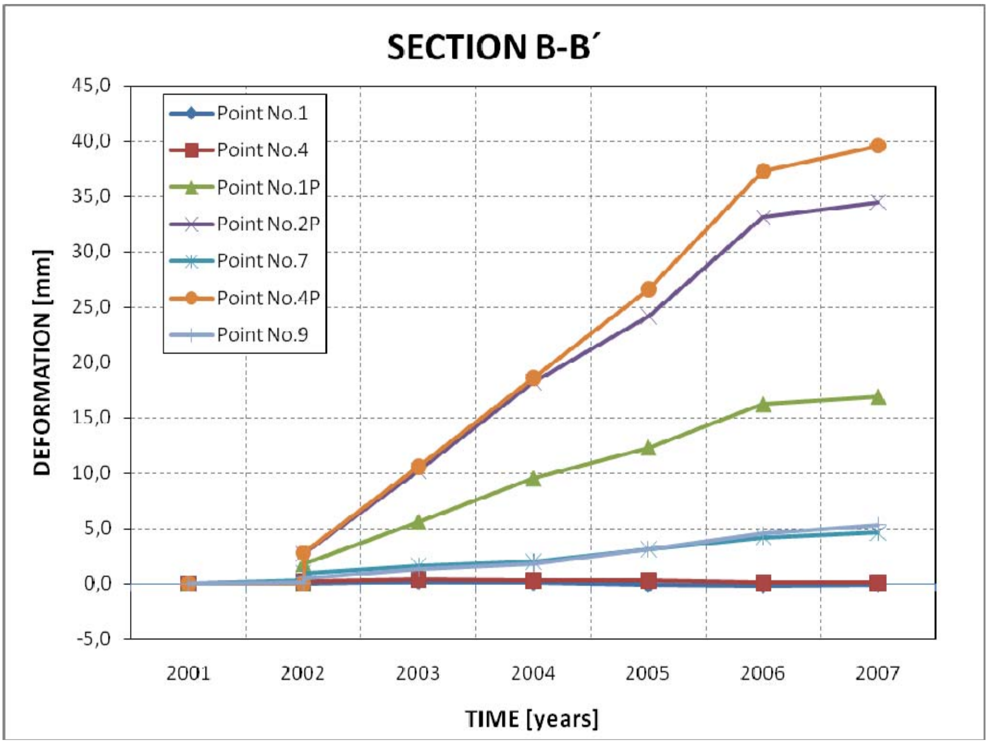

Figure 6: Vertical deformations of measured points in section B-B

3 ANALYSIS OF SECONDARY MINERAL FILLERS

The analysis of secondary mineral fillers from the backfill under the floor was conducted to make a final decision on the real options of subsoil rehabilitation and reconstruction of the building [2]. For additional laboratory tests, an 8kg sample was taken at the side of the probe, approximately 10-20 cm above the bottom of the probe. The sample was taken by P. Martinec and R. Čajka in the presence of the representative of the owner of the building [1], [2].

3.1 Method of sample processing

The sample was sorted by hand, and loose pieces of steel slag over 5 mm were separated. Small lumps of lightly cemented crushed material and dust with particles less than approx. 5-10 mm were separated.

Dark pieces of steel slag were inspected and described, secondary minerals on the surface of the pieces of black steel slag were separated, and preparations for analysis were prepared.

Screening of finely cemented powdery mass from grains and dust of the steel slag, as well as manual separation of secondary minerals in the cement of cemented particles was done. The preparations for analytical analysis, and aqueous extract obtained from working cemented material without grinding along with determining the pH of the extract were provided.

Analyses are performed for each material separately.

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Figure 7: Sampling probe dug inside of the building

Figure 8: The analyzed slag samples taken from the probe dug in sub-soil of the building

3.2 Pieces of steel slag

It concerns grain-heterogeneous material consisting of mainly black or gray steel slag pieces, often porous of up to 25 cm grain size, crystalline and semi-crystalline, less often glassy. There are some bright, powdery creamy white fillings of up to approx. 6 mm on the surface of slag in the pores. The coarse-grain fraction contains the fragments of brick, dinas, metallurgical ceramics, concrete and steel ingots. Summary percentage of foreign substances in the sample is approx. 5%. Metallurgical ceramics, and fire bricks are amongst these foreign materials that show the most significant decomposition and volume changes.

Optical microscopy using the transmitted polarized light shows thin seams of a hydrated slag-forming glass in the cut on the surface of the slag glassy grains. The power can be estimated (depending on the proportion of gehlenite crystals and glass in a particular space) with an accuracy of the first tenths to millimetres. Using infrared spectroscopy, the light, silty creamy white fillings of up to approximately 5-6 mm were found on the surface of the pieces of slag in their pores.

The reaction of the infusion is alkaline (pH 8-9). The spectroscopic analysis can be used to identify the product of the MgO periclase hydration to the brucite Mg(OH)2, and its carbonized product - magnesite MgCO3 in the separated material. These are minerals whose volume is greatly increasing during the hydration and carbonation.

The separated sample taken from the surface of the glassy slag pieces includes some hydrated Ca(Mg) silicates (CSH) together with brucite Mg(OH)2 and opal material again during the hydration and increasing the volume of secondary, hydrated mineral.

3.3 Gently reinforced silty-sandy material in the piece steel slag

The space between the pieces of steel slag is filled with a very variably cemented finely fragmental to silty-sandy material. Dark, grey-black grains can be isolated during the separation. When separating the cemented material the following grains can be isolated:

- Pieces and fragments of gray to black steel slag with white secondary minerals
- Sandy and silty grains of black, gray, often glassy slag from steel
- Brownish to light whitish-brown minerals in work fraction.

The reaction of the infusion is slightly acidic to neutral (pH 6.1). The mineralogical analysis shows that the filler of this silty-sandy material with fragments of steel slag greater than 2 mm consists of the secondary minerals resulting from hydration and carbonation of steel slag, particularly brucite and carbonate (magnesite and calcite) and then the material, which is similar to opal as well as the CSH from the surface of the grains, especially those of the glassy steel slag. Infrared spectroscopy has shown:

- Sandy to silty black, or gray grains, frequently glassy ones made from the steel slag. The spectroscopic analysis can identify mainly gehlenite, or Ca-silicates with weak hydration to CSH in the separated material, i.e. the volume of newly formed phase on the grains surface is rising again.
- Brownish to light whitish-brown minerals in the silty fraction. These minerals can only be separated gravitationally and manually on a paper and with a different proportion of the steel slag grains.

The separated fraction of the creamy light brownish color is dominated by the product of the MgO periclase hydration into the brucite Mg(OH)2 and its carbonated product – magnesite MgCO3 along with calcite Ca (CO)3.

Furthermore, the hydrated silicates such as CSH from the slag are present. These are minerals greatly increasing the volume of the hydration and carbonation.

The gray working fractions are typical by the increasing proportion of steel slag grains with more or less intense hydration to CSH. Association of secondary minerals, however, remains unchanged.

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4 EVALUATION OF THE ANALYSIS

The secondary minerals associated with hydration and carbonation of the steel slag in the environment with higher humidity and CO2 presence under favourable temperatures (approximately above 10 ° C) were clearly identified in the slag backfill consisting mainly of unsorted dark steel slag at the bottom of the probe in the supermarket floor located on the first floor of the Faculty Hospital in Ostrava - Poruba. All of these secondary minerals have proven to greatly change their volume and lead to the total volume changes in the backfill. This process is uneven and slow, but steady. According to performed analyses and determination of mineral associations, this process has not finished.

Quantification of the process of increasing the volume of material in the backfill required more detailed analyses of different fractions of the backfill for disproportionately high costs. Discontinuation of the hydration and carbonation processes in the backfill is, according to current experience and possibilities, difficult if not impossible (= complete drying of the backfill - steam is even more effective hydration medium than water - and deprivation of air in the CO2 backfill).

5 STRUCTURAL FAILURE CAUSES AND PROPOSAL OF MEASURES

The current results of deformation measurements, cracking characteristics, inspection of sewage and laboratory analysis of slag lead to the following conclusions:

- Latest measured increases in deformations show that the slag swelling in the sub-soil continues, and as the measured dependences show, there is no stabilization of the movement.
- The last inspection of the state of cracks in the assessed building found that the cracks grow larger, due to an increasing vertical pressure on the deformation of the floor, and a crushing of non-load bearing walls, door frames and doors takes place.
- Vertical pressures caused by the slag swelling have been progressing even into the load-bearing structure of the mounted frame. There are deformations (bulges) of vertical columns, ceiling structure, and subsequently even of the filling masonry on the 1st floor of the building.
- Slag sub-base under the floor of an entrance building consists primarily of unsorted dark steel slag, in which secondary minerals associated with hydration and carbonation of steel slag in an environment with higher humidity, and in the CO2 presence under favourable temperatures (approx. above 10 ° C) were found.
- All these secondary minerals have proven to greatly change their volume and lead to general volume changes in the backfill. This process is uneven and slow, but steady. According to performed analyses and determination of mineral associations, the process has not yet terminated.
- According to the screen test results and data in the report on the revision of sewerage system, the horizontal sewer pipes under the floor are damaged by the cracks in many places along with diagnosed wastewater leaks.
- Given the same location of the main branch of horizontal sewerage system with the area of maximum floor deformations, it is clear that chemical changes and slag swelling in the sub-soil is secondarily caused by wastewater leaks.
- Primary damaging of sewerage system was either caused during construction, or later due to increasing pressure in the sub-soil caused by the slag swelling.

Extent of deformations of the floors and walls have already reached such an intensity that it puts the bearing capacity and stability of the filling masonry in danger according to a definition of limit usability state (failure of masonry) and serviceability limit state (deformation of floors) in accordance with applicable Czech technical standards in EN [4], [5] and [6]. The aforementioned failures currently threaten the safety, health, and in extreme cases the lives of employees or patients (falling of the masonry, wall, broken limbs on an uneven and unsuitable surface, but also the beginning of deformation of the load-bearing skeleton).

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6 CONCLUSION

With regard to these findings it can be stated that the floor structures, non-load bearing brick walls, but also the load-bearing structures of the mounted frame are in disrepair, and with regard to security it is necessary to stop use of the mentioned areas.

To be able to reliably use the entrance building in the future it is necessary to prevent volume changes in slag sub-base and sewage leaks into the ground. Given the findings, it is unrealistic to stabilize the slag swelling and prevent further increase of deformations. Also, damaged sewer pipes cannot be fixed without their removal. Therefore it is necessary to urgently implement the following measures:

- Terminate the operation of the parts of the building affected, especially in the grocery shop, storage rooms, and other deformation-affected premises.
- Disconnect all bricked-up wiring and tear down any damaged walls, which transmit the swelling pressures from below the ground throughout the entire structure, and cause its failures.
- Diagnose, evaluate deformations and cracking initiated in a prefabricated reinforced concrete skeleton of the building and assess the static strength and usability.
- Remove damaged horizontal sewer pipes and build new ones.
- Extract the volume-unstable slag sub-base and provide the new base made from sorted and volume-stable sub-base material (gravel, sandy gravel, slag, recycled concrete) from a certified supplier.
- Build new floor structures, non-load bearing walls and wiring, with the possibility of vertical dilatations.

Manifestations of the volume-involatile steel slag in the embankments were also recorded in the construction of roads [3].

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