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Influence of Vibration and Ground Deformation on Historic Structures: Case Study

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Abstract
When discussing historic structures, a significant problem is how to preserve and protect these structures. The presented paper deals with some issues of the unfavourable impact of industrial activity on some historic structures. Long-term influences from the industrial activity are one of the common sources of damage observed in these structures. Due to the size and volume of such structures, they are characterized by very low resistance to vibration and ground deformations. At the same time, the high cultural and material value of historic structures necessitates their costly protection and repair. Knowing the origin of problems, one may take proper actions to protect them. This paper discusses two important types of impact typical for industrial areas, especially affected by mining, seismically induced vibrations and continuous ground deformations from underground extraction. The presented discussion is based on the case study examples of historical sites located in some industrial areas in the Czech Republic and Poland. They point to different sources of damage to those structures that may arise as well as a combined effect of mining-induced seismic events and land subsidence. The medieval Jeronym Mine represents an underground structure loaded with natural and technical seismicity. The paper also includes a short overview of the process of seismic loading evaluation and basic information about historic structures with respect to seismic standards and land surface subsidence caused by underground mining.

Keywords
historic structures, vibration, seismic loading, ground deformation, underground extraction, mining damages

Introduction

One of the basic activities of humankind from the very beginning is construction. It began with the purely functional need for a controlled environment to moderate the effects of climate. Constructed shelters were one way human beings could adapt themselves to a wide variety of climates and become global species. Construction today is an important part of industrial culture, a manifestation of its diversity and complexity and a measure of its mastery of natural forces, which can produce a widely varied built environment to serve the diverse needs of society (Swenson, 2021). If we walk through a built-up area, we are attracted by various structures or even just parts of them. Historical structures are often the subject of our interest. Generally, historical sites/structures are official locations where pieces of political, military, cultural, or social history have been preserved due to their cultural heritage value. Historic sites are usually protected by law, and many have been recognized with the official national historic site status (according to Historic site, 2020).

When considering historic structures, a significant problem is how to preserve and protect these structures (Boyer, 2018). Historic preservation is the practice of protecting and preserving sites, structures or districts which reflect elements of local or national cultural, social, and historic preservation of structures, but it is a broader effort that began mainly in museums. The actual job is much more complex. Historic preservationists not only need to know how to preserve and protect historic structures, they need to be able to research, determine what is worthy of historic designation and navigate local, state and national regulations when working with historic places. They also must abide by national guidelines for treating historic properties. In many instances, they have to be able to diagnose what needs to be done to preserve a structure. This work includes examination, documentation, treatment and preventive care, i.e. to protect from harm or destruction (according to Boyer, 2018).

Generally, structures are affected by a number of occasional and/or permanent loadings (Chudley and Greeno, 2014). The effect of vibration on the structures is one of the negative effects (Villaverde, 2009; Kaláb, 2018). The sources of vibration are different; especially earthquakes are a purely natural source. The properties (parameters) of earthquakes are studied in detail by seismologists (for instance, Bolt, 1999; Lee et al., 2002; Shearer, 2019); special attention is given to the influence of earthquakes on structures which are the subject of seismic engineering (Towhaka, 2008; Elnashai and Di Sarno, 2015). However, so-called technical seismicity can significantly affect the "acceleration of ageing" of older structures or their damage. Blasting in quarries is a typical and the most intensive source of this seismicity. The duration of this vibration effect is usually short but with a very strong peak and higher frequencies than vibration generated by earthquakes (Dauetas, 1993; Pijush, 2005). Other types of technical seismicity (such as the effect of traffic or industrial seismicity) usually cause smaller vibration load and, therefore, smaller damage to structures (Thompson, 2009; Kondela and Pandula, 2012; Kaláb and Hrubešová; 2015). A number of surface manifestations can be observed in the mined areas (for instance, Kwiatek et al., 1997, Doležalová et al., 2008; Kwiatek, 2010). For the purposes of this article, vibration induced by mine-induced seismicity is also necessary to mention (for instance, Gibowicz, Kijko, 1994; Lednická and Kaláb, 2016), and manifestations after the end of mining can be observed for a longer period (Martinec et al., 2006).

The second selected negative influence is ground deformation caused by underground mining. Such deformations are often an important factor favouring the creation of structure damage. The scale of damage depends on the type of deformations and their intensity. Two main types of deformations may occur: continuous and discontinuous (Kratzsch, 1983; Whittaker et al., 1989; Peng, 1992; Strzałkowski, 2010). Discontinuous deformations manifested as ground steps, cracks or fissures, although very dangerous for urban constructions, do not always accompany underground extraction. It may even be said that they occur rarely. On the other hand, continuous deformations manifested in the form of subsidence troughs always occur as an effect of underground mining. Hence, the ability of their precise prediction is of great importance due to the development planning and the protection of existing infrastructure against mining damage.

More detailed information about occasional and permanent loads of structures was presented in, for instance, Chudley and Greeno (2014) or Kaláb (2018).

The paper presents case studies of the influence of vibrations and post-mining deformations on historic structures in the Czech Republic and Poland. The article also deals with a short overview of the process of seismic loading evaluation and basic information about historic structures with respect to seismic standards and land surface subsidence caused by underground mining.

Seismic loading evaluation

The Eurocodes are the ten European standards specifying how structural design should be conducted within the European Union (Eurocodes, 2021). For this topic, "Eurocode 8: Design of buildings for earthquake resistance" (abbreviated EN 1998 or, informally, EC 8) describes how to design structures in the seismic zone using the limit state design philosophy. It was approved by the European Committee for Standardization (CEN) on 23 April 2004. Its purpose is to ensure that in the event of earthquakes, human lives are protected, the damage is limited, and structures important for civil protection remain operational.

In seismic regions, the aspect of seismic hazard shall be taken into account in the early stages of the conceptual design of a building, thus enabling the achievement of a structural system which, within acceptable costs, satisfies the fundamental requirements (see EC 8):

- structural simplicity;
- uniformity, symmetry and redundancy;
- bi-directional resistance and stiffness;
- torsional resistance and stiffness;
- diaphragmatic behaviour at storey level;
- adequate foundation.

A certain number of structural members (for instance, beams and/or columns) may be designated as "secondary" seismic members (or elements), not forming part of the seismic action-resisting system of the building. The strength and stiffness of these elements against seismic actions shall be neglected. Nonetheless, these members and their connections shall be designed and detailed to maintain the support of gravity loading when subjected to the displacements caused by the most unfavourable seismic design condition. All structural members not designated as being secondary seismic members are taken as being primary seismic members. They are taken as being part of the lateral force-resisting system and should be modelled in the structural analysis in accordance with the rules of EC8. For the purpose of seismic design, structures are categorized into being regular or non-regular, which has an impact on the design model, calculation method and ductility coefficient. Criteria of regularity in a planar or a spatial model are defined (for detail, see EC8).

If we study the above requirements, it is quite clear that monuments usually do not meet most of them. Nor is it possible to make additional repairs/adjustments to meet the requirement. It, therefore, follows that monuments are very vulnerable to seismic loading.

However, not only do vibrations contribute to the deterioration of the technical condition of monuments, respectively, their gradual destruction. One of the examples is the information presented on the website of the Auroville Earth Institute (Earthquakes and structures, 2021). The diagram of the masonry building shows various damages with more detailed information about the cause of the damage (Fig. 1). Structural elements, such as walls, columns and beams, are only bearing the weight of the building and the live load under normal conditions: mostly compression forces for the walls and columns, and vertical bending for the beams. Under dynamic load, they also have to withstand horizontal bending and shear forces and extra vertical compression forces. Depending on their current conditions, any damage can cause a serious threat to historic buildings, especially if the load-bearing elements are damaged.

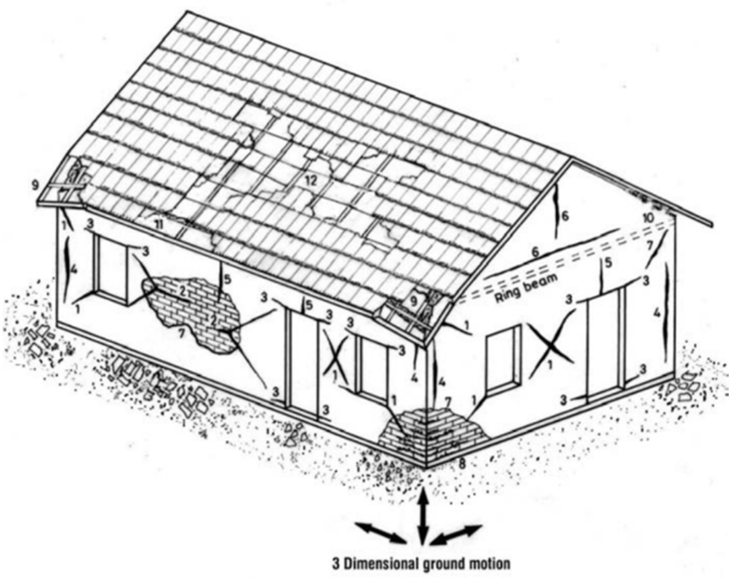

Fig. 1 Typical damages in a masonry building (Earthquakes and structures, 2021).
Legend: 1: Diagonal shear crack of piers;2: Horizontal shear crack of the long pier; 3: Bending cracks at feet and lintels; 4: Bending crack of the wall (bad corner bond); 5: Bending crack of spandrel; 6: Bending crack of gable; 7: Plaster peeling off; 8: Crushing of weak masonry under vertical ground motion; 9: Damage of corner eaves under vertical ground motion; 10: Badly anchored roof, pulled out by vertical ground motion; 11: Falling of tiles from the roof eave; 12: Damage of tiles roof with shear (roof not braced)

It is also possible to state another characteristic of cracks on the structure due to seismic loading. An essential feature for determining the origin of cracks is that cracks caused by dynamic effects in most cases do not have a clear course. They are scattered completely unevenly and do not form a continuous pattern. Thus, differently than, for example, in the case of cracks caused by static stress (tensile, compressive or shear cracks), from which the direction of the influence of their force effect is evident (according to Solar, 2017).

Technical seismicity can also sometimes be a serious problem; some cracks or damages may occur. "Czech Technical Standard 73 0040 Loads on buildings by technical seismicity and their response" (valid up to 2019) is used in the Czech Republic to evaluate buildings' responses to technical seismicity. This standard defines acceptable limit values of maximum velocity for different types of seismic loading and acceptable degree of damage. This evaluation is established according to the class of resistance (A – F) and the class of economic and social significance of buildings and structures (U, I – III). Structures of A type are usually historical monuments and buildings, the oldest and poorly structures and buildings with large plastic decorations; structures of B type are common masonry buildings, usually up to three levels and surface up to 200 m^2. The determination of the resistance class depends on the constructional technology and the material used. From the constructional point of view, there are monolithic structures with resistance class E, framed structures with class D, half-timbered structures with class D, buildings up to three storeys with class B and prefabricated panel structures with class C. Resistance class is based on the material used: stone - resistance class A, masonry - resistance class A, B, C, concrete - resistance class C, D, steel - resistance class D, E and steel concrete – E. Class of significance U represents structures of an extraordinary economic and/or social significance (for instance, dams, significant bridges …), the following class I is represented by structures of great significance (for instance, schools, churches …), classes II and III include structures of medium and small importance, respectively. Of course, local geology is necessary to take into account because it significantly influences the values of vibrations and their characteristics. According to the Czech Standard, historical structures of resistance class A and the significance class of type U require dynamic calculation for the response of the structure at an effective velocity value of 0.6 mm.s^{-1} (not valid for blasts, see Czech teščhnila standard 73 0040, tab. 10).

Summarizing all these remarks, vibrations can cause minor damage (damage to paintings, flaking of plaster ornaments, small cracks in plaster, etc.), as well as extensive damage to the complete destruction of monuments. Therefore, it is necessary to conduct expert research on damaged monuments to gain additional knowledge enabling the right mitigation of damage and minimizing the effects of vibration. Obviously, this must be done in close cooperation with a number of different professions, in particular fields including architecture, architectural history, conservation, engineering, landscape architecture, historical archaeology, construction, museums, city/state agencies, advocacy, and heritage tourism.

Seismic measurements in the church in Světí

The church dedicated to St. Andrew in the village of Světí (near Hradec Králové, Czech Republic) is first mentioned in archival sources as early as 1365 (Fig. 2A). The church has preserved its late Gothic layout to this day, although it was remodelled in the Renaissance style at the end of the 16th century and later in the slightly Baroque. The last significant building modifications took place in the second half of the 19th century (more Kostel svatého Ondřeje ve Světí, 2021/). The area of the church is about 20 * 10 m, and the tower's height is about 23 m (personal communication). The church is registered in the List of Immovable Cultural Monuments of the Czech Republic. However, the walls and the ceiling have considerably fractured. The typical examples of failures generated by traffic are presented in Fig. 2B.

From a geological point of view, the area is characterized by very thick Quaternary sediments. The main cause of failures is probably the instability of soils under the basement, partly in a slow slope. Vibrations generated by traffic, especially by agricultural vehicles and trucks, increase the loading of this historic church. The minimum distance between the sensor and the road was 14 m. (see Fig. 3). To evaluate seismic loading, seismic measurements were performed in 2010. The measuring points were located not only in the church (ground floor and higher places under the roof) but also on the profiles leading from the church to the road. Seismic apparatuses GAIA and seismometers Le3D type were used (frequency range of seismic channels is 0.5 – 100 Hz, dynamic range is more than 130 dB).

The example of a wave pattern was obtained from the seismometer that was located inside the church near the wall with the most significant failures (Fig. 4 and Fig. 5). This vibration was caused by a passing truck. Generally, the maximum component value of velocity (horizontal component towards the road) during an experimental measurement was 0.44 mm.s^{-1}, important harmonic vibration about 8 – 12 Hz, and the duration of seismic effects was approximately 7 s (Kaláb et al., 2012).

Experimental measurements have shown that the primary cause of damage to the church in Světí is the foundation of the building in a sloping area. The vibrations generated by traffic on nearby roads do not reach values that would directly cause damage to the building. Thanks to the historical value of the building, we can reduce the values of maximum permissible vibrations. It can be reasonably assumed that the vibrations significantly worsen the technical condition of the building.

Fig. 2A Church dedicated to St. Andrew in the village of Světí (near Hradec Králové, Czech Republic); photo: Kaláb

Fig. 2B Fractures of the walls and on the ceiling in the St. Andrew church; photo: Lednická

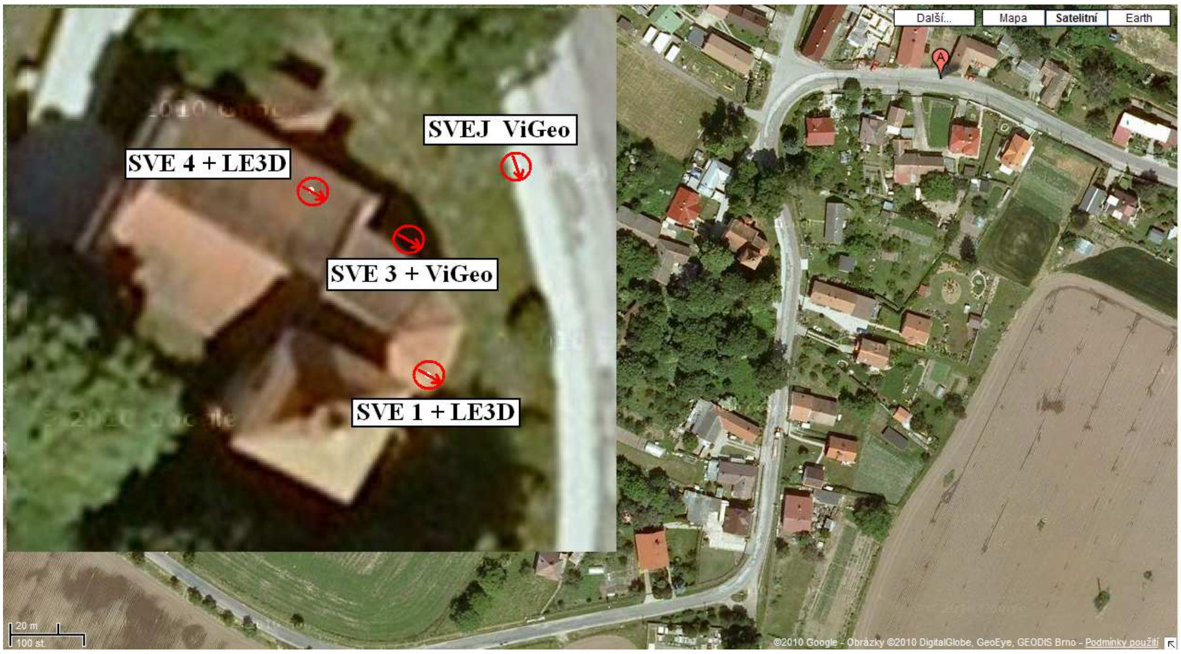

Fig. 3 Sketch of location of sensors during experimental measurements; base: www.mapy.cz

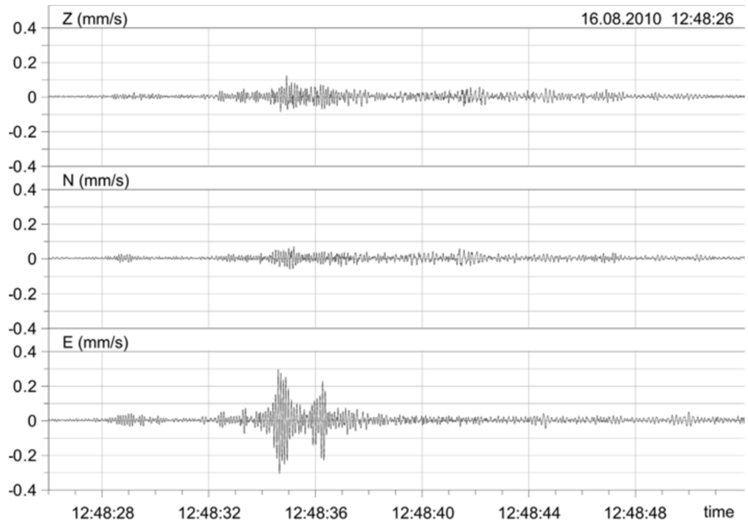

Fig. 4 Wave pattern of vibration induced by road traffic (the sensor signed as SVE was located inside the church)

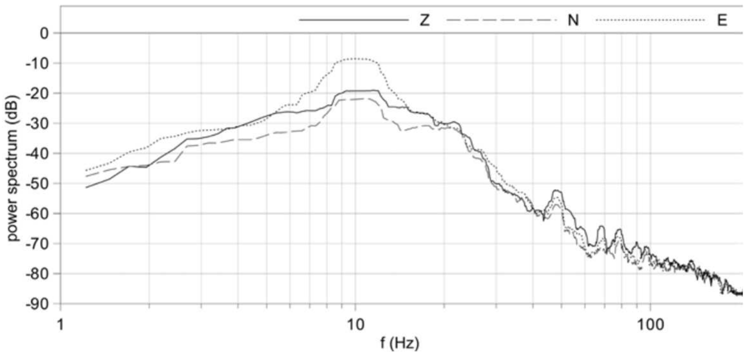

Fig. 5 Frequency spectrum of vibration induced by road traffic (the sensor was located inside the church)

Seismic measurements in the medieval Jeroným Mine

The second example of seismic loading of a building monument is a medieval mine. Industrial Heritage Site, the Jeroným Mine, is located in West Bohemia, the Czech Republic. The Jeroným Mine is a valuable example of preserved historical mining operations dating back to the 16^{th} century (for instance, Žůrek, Kořínek, 2001/2002). The Jeroným Mine consists of an underground system of workings, galleries, shafts and chambers on at least three horizontal levels (10 – 55 m below the surface). The lowest level is permanently flooded. In an underground complex, we can find mine workings made by different medieval mining methods such as the extraction using a picker and miner's hammer, fire setting, underhand or overhand stopping, chamber mining, etc. (Fig. 6). For many years, uncovered underground rocks in this complex had been exposed to devastation and weathering.

The territory where the Jeroným Mine deposit is found consists of metamorphized rocks of the Slavkov mantle crystalline complex (primarily the biotite paragneisses that are migmatitized in various intensities and granitized upon the intrusion of granites) and of Variscian granites of the Ore Mountain pluton. The Jeroným deposit came into existence by the action of mineralizing solutions in the already solidified rock of the Krudum massif. The Sn-W mineralization is bound to two types of formation, either the quartz vein with cassiterite and wolframite or the impregnation of cassiterite and wolframite in altered granites.

The closest focal area of natural earthquakes to the monitored area of the Jeroným Mine in Čistá is located approximately 25 km to the west (for instance, Fischer et al., 2010, 2014). Young tectonic movements accompanied by volcanic activity influenced the geological pattern of this region as early as during the Tertiary. Even today, weaker earthquakes are detected in West Bohemia and Vogtland (Germany), the strongest of which are felt by people who live here, or they can damage buildings. This area is characterized by seismic swarms lasting several days up to a few months. Critical places from the viewpoint of vibration effect are fissured and weathered supporting pillars, hanging layers on the roof in chambers, and caving falls of rock leading into the chambers due to collapsed overburden.

Fig. 6 Photos taken in the historical parts of the mine (fire setting, extraction using a picker and miner's hammer, underhand stopping or overhand stopping); photo: Lednická

The mine is exploited, among other things, as a natural laboratory for geomechanical and geophysical experiments, for which a distributed monitoring system is used (for instance, Kaláb et al., 2010, 2011; Lednická and Kaláb, 2013; Lyubushin et al., 2014; Kaláb and Lednická, 2016; Lednická and Kaláb, 2016a). Permanent seismic monitoring has been carried out since 2004 using a seismic station JER1, installed in the mine about 35 m below the surface in one of the largest chambers. Three seismometers SM3 in geographical orientation are anchored on the concrete pillar; seismic recording apparatus PCM3-EPC3 has a special modification for the environment with high air humidity and drip water. From 2004 to 2006, the seismic station JER 1 monitored especially the effects of blasting operations during the reconstruction of drainage adit. The aim was to determine the critical value of vibrations in order to avoid damage to the mining spaces.

The main aim of long-term seismic monitoring is to obtain information about the seismic loading of historical mine workings. The most significant sources of loading of the Jeroným Mine are (for instance, Kaláb et al., 2015):

- earthquakes from the area in West Bohemia/Vogtland (maximum measured component vibration velocity is 0.8 $mm.s^{-1}$ in the frequency range 2 – 10 Hz for local magnitude 3.6, maximum expected component vibration velocity is 8 $mm.s^{-1}$ in the frequency range 1 – 10 Hz for local magnitude 5.0),
- blasting operations from adjacent quarries (body wave: maximum measured component vibration velocity is 0.01 $mm.s^{-1}$ in the frequency range 1 – 6 Hz,
- traffic from the road above the mine (maximum measured component vibration velocity is 0.05 $mm.s^{-1}$ in frequency range Hz 9 – 15 Hz,

- blasting operations as a part of technology for driving underground spaces(maximum measured component vibration velocity is 0.2 mm.s^{-1} in the frequency range 40 – 80 Hz.

Since 2010, five natural swarms have happened: in 2011, 2014, 2017, 2018, and 2020 (not finished until the end of the year). The strongest earthquake occurred during the swarm in 2014, with a local magnitude of 4.4 (doi:10.7914/SN/WB). To document the seismic loading of the mine due to natural seismicity, the following number of earthquakes were recorded from the mentioned area: in 2017 – 202 earthquakes; in 2018 – 124; and in 2019 – only 27 earthquakes. The example of the wave pattern recorded by the seismic station JER1 placed in the mine and the spectra are presented in Fig. 7.

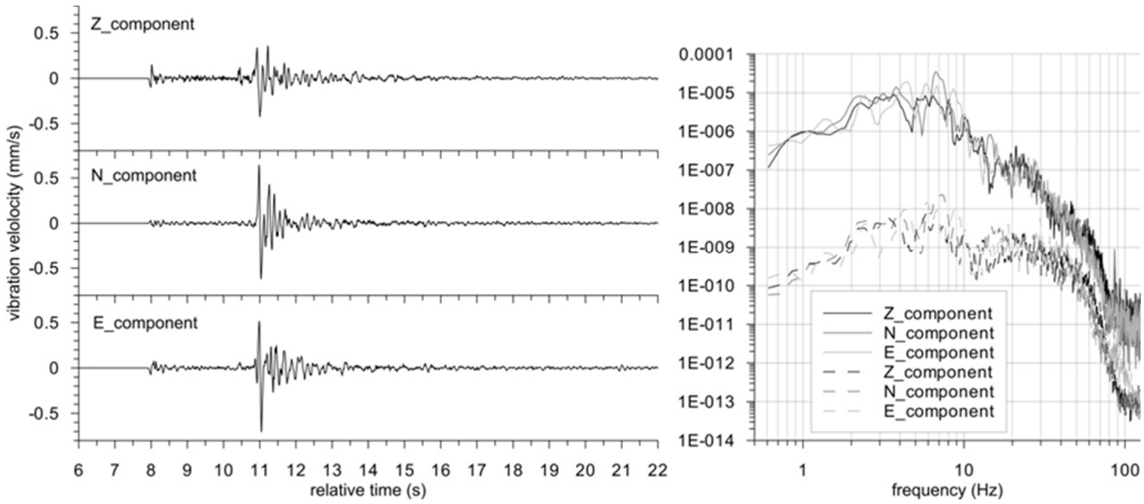

Fig. 7 Wave pattern and spectra of the earthquake from the West Bohemia focal zone recorded at the seismic station JER1; left – wave pattern of ML 3.6 earthquake occurred on 4 August 2014; right – spectra of ML 3.6 earthquake (solid line) and spectra of ML 2.1 earthquake (dashed line)

Although earthquakes cause the maximum vibration effect, technical seismicity also causes not negligible vibration effect in underground spaces (as mentioned above). Detailed analysis of the vibration effect caused by individual seismic sources is performed in the time and frequency domain. The example of the wave pattern and spectra of a quarry blast recorded at the seismic station JER1 are presented in Fig. 8. The fall of a rock block from the ceiling is a long-term process that is the consequence of deformation, weathering, and seismic loading. Currently, these situations were described first of all in the inaccessible part of the mining work but not only (Kaláb, Loskot, 2020).

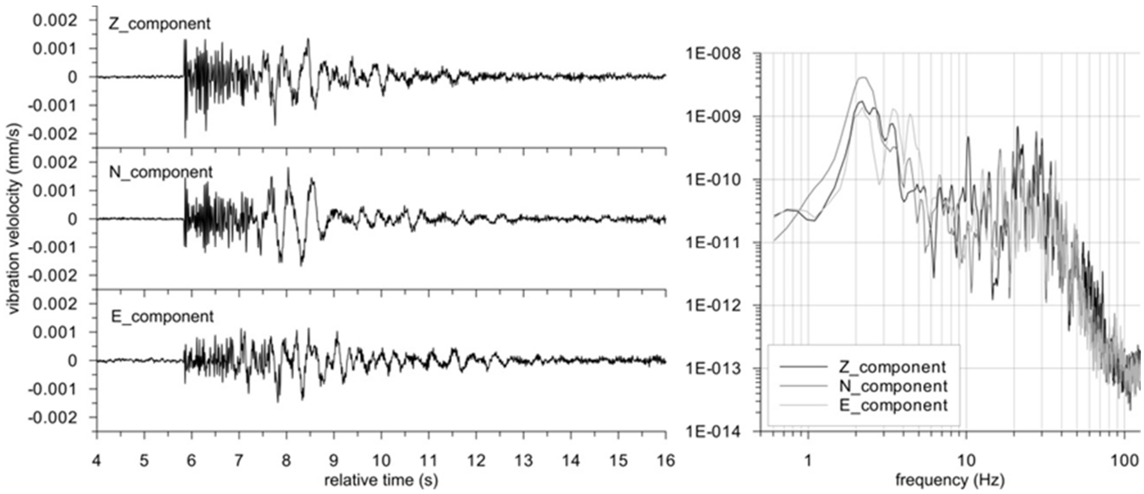

Fig. 8 Wave pattern and spectra of a quarry blast at Vítkov recorded at the seismic station JER1

The Church of the Body of God, Upper Silesia, Poland

A separate issue is the phenomenon of seismic activity induced by underground mining. In Poland, these phenomena have been observed during hard coal extraction in the Upper Silesian Coal Basin and, in particular, in the LGOM Copper Basin. Nowadays, these phenomena often occur as an effect accompanying underground extraction and are the cause of damage to objects. The impact of the underground extraction on the church object in the town of Polish Silesia, both in terms of land subsidence and mining-induced seismic impacts, is presented below.

The Church of the Body of God was erected in the years 1914-17 according to the design of the architect Theodor Ehl (Fig. 9). The building is 48 m long and 29 m high and has an area of 777 square meters. The object was built of brick on a cross plan; the walls were plastered. The spire of the tower was covered with copper sheets when the building was renovated in 1996. After World War II, the church was damaged several times as a result of mining operations. Therefore, the building was repeatedly renovated in the years 1949-50, 1963-65, 1986-1989, and 1999-2000. The building is the best-preserved example of a neo-baroque structure. Therefore, it was entered in the Register of Monuments of the Silesian Voivodeship.

Fig. 9 General view of the church construction; photo: Ścigała

Last twenty-two years, underground mining has been carried out in the area of the church in the coal seams: 503 at the height of 2.3 m, 507 in two layers with a thickness of 2.0 m each, 509 in two layers with a thickness of 2.0 m each, and in the seam 510 also in two layers with thicknesses of 2.0 - 2.4 m. The mining was carried out using a longwall system with a roof caving. Levelling measurements were taken on the benchmark stabilized on the wall of the building every six months from May 2010, using technical levelling. Measurements were performed between May 2010 and October 2017. In the period covered by the measurements, the subsidence of the building was 200 mm. The results of the calculations applying the Budryk-Knothe theory (Knothe, 1953) show that the extraction led from the year 2000 resulted in subsidence of approx. 0.70 m, tilt of 6.8 mm/m and horizontal strain of 5.3 mm/m. Thus, according to the Polish classification of mining areas, there were deformations in category III of mining areas. The mining-induced seismic events of the rock mass also affected the church object. In Poland, the intensity of the impact of mining-induced seismic events on the buildings is assessed with the GSIS-2017 scale (Mutke et al., 2018).

Primary is the scale based on the PGV values (peak ground velocity), and the auxiliary scale lies in the PGA values (peak ground acceleration). Both scales take into account the duration of the intense vibration phase. The scale intensity is read from specially developed diagrams for the given PGV or PGA value and the duration of the intense vibration phase - Fig.10. The diagrams were developed on the basis of statistical analysis of practical cases of mining-induced seismic events and related to them damages to structures (Mutke, 1991). The scale is numerical, consisting of levels from 0 to VI (Roman numerals). The vibrations of levels 0 and I do not damage objects; vibrations of level II usually intensify existing damages. The first new damage appears when the vibration intensity reaches level III. When assessing the impact of shocks on the building, the first is to determine the PGV and PGA values at the site location. Calculations of PGV & PGA are conducted with empirical formulae worked out by (Mutke, 1991) unless measurements were taken on the site. The obtained values should then be multiplied by the value of the amplification factor to get the results for the object located on the land surface (the formulae relate only to propagation over Carboniferous rocks). With the values of PGV and PGA and with a duration of the intense phase of vibrations, one should use diagrams to determine the degree of vibration intensity according to the GSIS-2017 scale.

A scale based on the PGA values was used in the discussed case. The calculation results are presented in Table 1. The table columns show the dates of the mining-induced seismic event, coordinates - X, Y of the epicentre, epicentral distances from the object - D and duration of the intense phase of vibrations - t. Then the PGA values are obtained from the formula and multiplied by the value of the amplification factor - PGA_{amp}. The last column shows the level of vibration intensity according to the scale used.

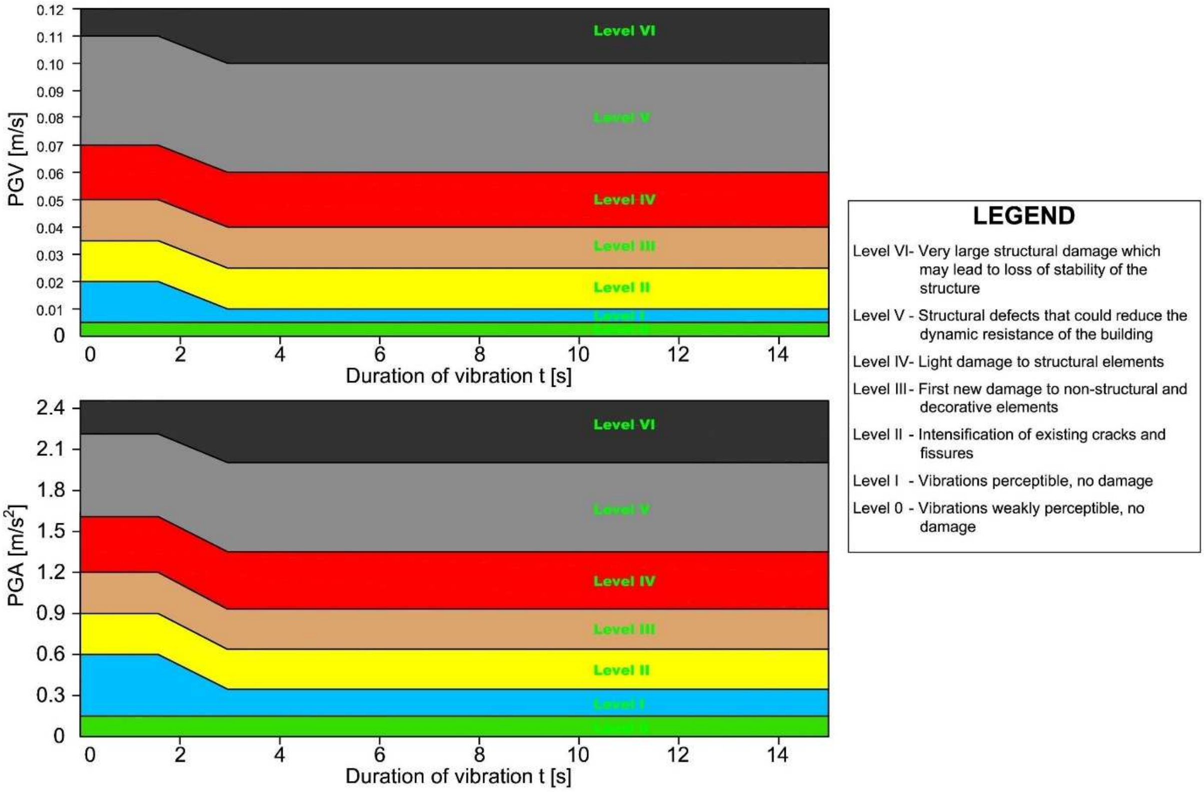

Fig.10 The GSIS-2017 scale diagrams (Mutke et al., 2018).

Fig.11 Fractures on the walls of the church; photo: Ścigała

As can be seen from the table, according to the GSIS-2017 scale, mining-induced vibrations at the church location did not affect the building in a way that would cause new damages or intensify the existing ones.

A separate issue is whether the combined effect of continuous deformations (subsidence, tilt and horizontal strain) together with mining-induced vibrations could generate new damage. The answer to this question is not easy and requires detailed research for each case. In general, it can be concluded that the impact on the church of underground mining extraction was not intense enough to cause significant damages, although some damages occurred, as shown in Fig 11.

Table 1 The results of PGA calculations for the church location

Date	*X* [m]	*Y* [m]	*D* [km]	*t* [s]	*E* [J]	*PGA* [m.s^{-2}]	PGA_{amp} [m.s^{-2}]	GSIS 2017 Scale Level
28-03-2012	5520	2050	0.497	-	2.00E+06	0.0828	0.1324	0
15-12-2012	6160	770	1.468	2.05	5.00E+06	0.0737	0.1179	0
22-12-2012	6110	690	1.490	-	3.00E+06	0.0620	0.0992	0
26-03-2013	6350	590	1.729	-	6.00E+06	0.0679	0.1086	0
06-02-2014	5670	1140	0.861	-	2.00E+06	0.0724	0.1159	0
15-02-2014	5620	1080	0.876	1.25	2.00E+06	0.0720	0.1152	0
28-05-2014	5880	1160	1.000	0.87	8.00E+06	0.1057	0.1691	I
16-06-2014	5880	1260	0.940	1.28	7.00E+06	0.1045	0.1673	I
25-06-2014	5870	1200	0.967	-	2.00E+06	0.0692	0.1107	0
04-07-2014	5890	1150	1.014	1.95	7.00E+06	0.1012	0.1619	I
31-07-2014	5930	1170	1.033	0.88	8.00E+06	0.1041	0.1666	I
11-09-2014	6030	1230	1.083	1.86	2.00E+07	0.1287	0.2059	I
24-09-2014	6000	1220	1.063	2.2	2.00E+06	0.0663	0.1060	0
17-10-2014	5990	1010	1.180	1.17	9.00E+06	0.1004	0.1606	I
05-11-2014	6090	1220	1.140	2.78	8.00E+06	0.0991	0.1585	I
15-12-2014	6090	1150	1.176	4.5	8.00E+06	0.0974	0.1558	I
05-01-2015	6110	1150	1.193	1.35	5.00E+06	0.0844	0.1350	0
10-02-2016	6480	1050	1.564	-	5.00E+06	0.0701	0.1122	0
03-06-2016	6620	80	2.284	5.4	3.00E+08	0.1198	0.1917	I

The leaning Church of St. Peter of Alcantara

(according to The leaning Church of St Peter of Alcantara – the "Czech Pisa", 2021)

The Church of St. Peter of Alcantara (the town of Karviná, Silesia, Czech Republic) was built in 1736 in the Baroque style. It was built by the local nobleman František Wilhelm Larisch on the site of the wooden church of St. Martin, mentioned as early as 1447. Since several churches were already dedicated to St. Martin in the Těšín region (Silesia), St. Peter of Alcantara was chosen as the patron of the new church. The church was consecrated by Bishop Filip Gothard Schaffhotsch of Wrocław in 1759. The uniqueness of the church lies not only in its historical value but especially in the circumstances that affected the building and permanently marked it. After the start of hard coal mining, 27 seams with a total thickness of 46.82 meters were mined under the church from 1854. In the early 1990s, the church was in danger of collapsing and was destined for demolition. In the years 1994-1995, the building was overhauled and secured, and the church shone again in full beauty (Fig. 12).

Due to the negative effects of coal mining in this area, the original high tower was demolished. The ground where this church stands subsidence by 37 meters (the mining started in 1891, with mining depth up to 682 m) in just a few decades due to the collapse of mine spaces under the site (Tab. 2); the sinking caused deep and wide cracks in the walls. Now the church is leaning 6.8 degrees to the south (in 1968, it was 7.8 degrees) – but it is still standing, and it has become a unique and renowned tourist attraction. It leans almost as much as the world-famous Leaning Tower of Pisa, and its history is just as fascinating in its own way. Visitors can enjoy the strange sensation of standing on level ground while the building next to them seems to be falling down. The church is listed in the Czech Book of Records and Curiosities.

The expanding cooperation of the Ostrava-Karviná Mining Company with the private and public sector, the Municipal Council of Karviná and other regional and local stakeholders bring tangible positive results to the region after a long period of time. The cooperation shows the possibilities of coexistence of industry in the region and the possibilities of recreational utilization of the anthropogenic landscape; it allows seizing opportunities for the development of various forms of tourism, development of the essential infrastructure and services in the region that has been devastated by mining for many years (Havrlant, Krtička, 2014).

Fig.11 Church of St. Peter of Alcantara, the town of Karviná, Silesia, Czech Republic (sinking by 37 meters, leaning 6.8 degrees to the south); photo: Kaláb

Table 2 Documented subsidence of the Church of St. Peter of Alcantara (personal communication)

Year	Subsidence	Remark
1736	0	New Baroque church
1935	About 5 m	Reconstruction
1957	About 10 m	
1969	About 15 m	Reconstruction
1977	About 27 m	
1994-1996	About 32 m	Reconstruction

The Church of Holy Cross, Upper Silesia, Poland

The object of the Church of Holy Cross was built in the years 1856-1864 according to the design of August Soller in the neo-Gothic style on a cross plan. The characteristic dimensions of the building are as follows: length: 45.0 m; width: 27.4 m; tower height from the ground level to the lower level of the cross crowning the roof: 61.3 m.

The building is founded at a maximum depth of about 4.5 m. On the west side, there is a tower joined with the structure of the church. In the horizontal projection, the tower has a variable shape: on the ground floor, the shape is similar to a square with dimensions of 9.4 m x 9.5 m, at the height of about 29.8 m - octagonal, above the third level (about 30 m high). In the corners, there are pinnacles in the form of towers 8.15 m high and window openings with clock faces. The wooden structure of the roof, topped with a metal cross, is supported by the octagonal plan of the tower. The general view of the church building is shown in Fig. 12.

The church building was not protected against mining damage during its construction. The protection of the structure, described below, was carried out successively from 1956. Originally, at the height of 10.0 m, steel ties made of Ø30 rods were installed in the church building, running in the longitudinal and transverse directions of the building along the line of all the pillars. The tie rods were anchored outside the walls with 250mm x 250mm x 15mm retaining plates. The tie rods were joined outside the pillar with turnbuckles enabling adjustment. At that time, two reinforced concrete struts were also made in the side transepts at the height of 5.0 m. Additionally, beams made of steel I-sections were built under the gallery.

Despite the applied protections, the church building underwent further damage after the year 2000. For this reason, in 2006, an additional stiffening was made horizontally at the base of the vaults. In order to absorb the compressive stresses along the ties, complementary struts were installed. Further elements of C sections (covering the existing bar ties) were installed, too. The structure made this way, working in compression or tension, stiffens the level of the base of the vaults in case of longitudinal or transverse curvature of the land surface, both concave and convex. Figures 13 and 14 show some of those protection elements.

Fig.12 General view of the church; photo: Ścigała

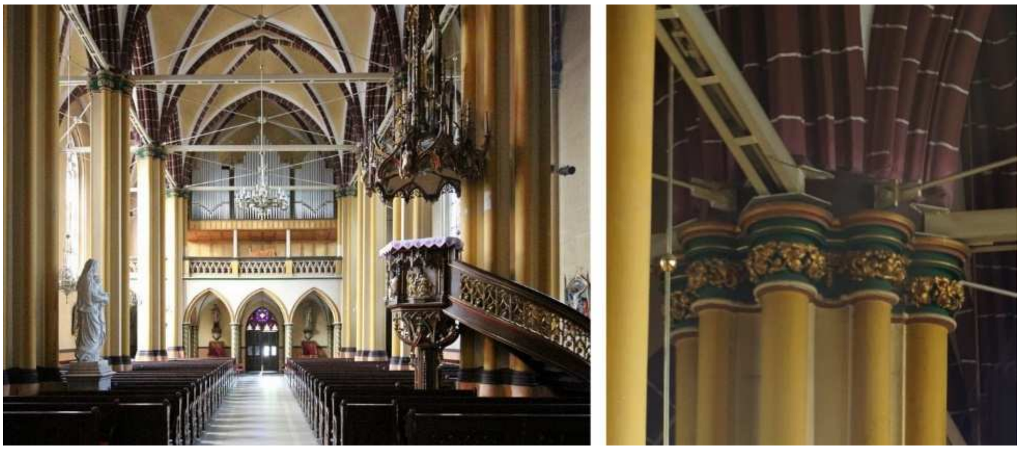

Fig.13 Some elements of inner reinforcement of the church construction; photo: Ścigała

Fig.14 Some elements of outer reinforcement of the church construction; photo: Ścigała

The influence of underground extraction on the church building

From the beginning of the 20th century, more than 20 coal seams of groups 400 and 500 were extracted in the area of the church. The extraction was led mainly using a longwall system with caving and stowing. Wide-ranging measurements of deformations (in particular subsidence) were carried out using geodetic methods from 1965 on benchmarks located over the area neighbouring the church. The measurements performed until 2012 show the subsidence of 15 m in the church area, while the last extraction, affecting the building after 2012, resulted in further subsidence of about 1.5 m. So it gives a total of 16.5 m of mining-induced subsidence.

In recent years the object has undergone renovation, during which all damage to the structural and architectural elements that could endanger their stability was removed. All works were carried out under the supervision of the restorer of monuments, who ensured the restoration of the historical values of the building to the maximum extent. The current technical condition does not raise any objections. The photographs of selected reconstructed parts of the building are shown in Figure 15.

Fig.15 Some elements of the outer architecture of the church after reconstruction and renovation; photo: Ścigała

Discussion of presented results

The first case study represents seismic loading of the surface structure – the church in Světí. Extensive damage can be observed in the church, especially the fractured masonry and the ceiling. The maximum measured vibration effect reached the value of 0.44 $mm.s^{-1}$, so it is low according to the Czech technical standard and does not cause damage to the evaluated structure. Experimental seismological and seismic measurements have shown that the most important factor is probably the instability of soils under the basement, partly in slow slope. Nevertheless, the influence of heavy traffic on the nearby road, which causes vibrations in the structure, cannot be neglected. As mentioned, these vibrations are not the primary cause of these damages, but they significantly contribute to the opening of existing fractures and, thus, to the gradual deterioration of the technical condition of the church.

The following study presents the results of long-term seismic monitoring performed in the shallow medieval mine. The mine is located about 25 km southeast of the Nový Kostel focal zone, where seismic activity occurs in the form of seismic swarms. The maximum vibration effect is caused by these earthquakes. Technical seismicity also causes vibration effects in underground spaces. Documented maximum velocity values and prevailing frequencies of records from individual sources significantly range. This information is important, especially for stability assessment and numerical modelling of seismic loading of the mine. Based on the presented results, we can state that the Jeroným Mine, as the whole complex of underground spaces, should be stable from the viewpoint of damage caused by vibrations.

An example presented by the Polish Church of the Body of God shows that one should be aware that even when results coming from separate analyses of two different impacts of underground mining do not show the potential threat to the object, aggregate influence may be the cause of damages to structures. In the presented case, the assessed PGA and PGV values (according to Polish regulations) point out that no damages should occur due to mining-induced vibrations. Moreover, measured and calculated deformation indices in the area surrounding this object should not significantly impact the object. Finally, it is very important to keep in mind the possible scenario of combined influences, which acting together may pose a significant threat to the object's construction.

The last topic covers the impact of underground mining on surface objects. The leaning of the Church of St. Peter of Alcantara in Karvina documents its sinking of about 37 meters due to underground exploitation. The current effect of this situation is deep and wide cracks in the walls; the church is inclined 6.8 degrees. General reconstruction of the church (including fortification of walls and ceiling) and arrangement of the surroundings caused the structure is registered as a historical monument.

The Church of Holy Cross comprises similar problems. The history of building deformations is very rich. It was reconstructed several times after successive extraction of mining fields had affected the structure and caused serious damage. After the last reconstruction, the object returned to good condition though its construction had to be strongly protected and reinforced. It is worth mentioning that according to Polish mining-geological law, the mining entrepreneur is obliged to restore the facility to its original condition.

Conclusions

In urbanized and industrial areas, several negative influences from human activities may affect some structures. The problem of great importance is in the case of historic structures that have a special significance to the culture of a region or country. The general problem with historic structures is tied to the fact that such structures, due to their age, were not designed and constructed with any protection measures.

This paper has presented several examples to document the effect of vibration and surface subsidence from underground mining on historic buildings. The medieval Jeroným Mine proves that the loss of stability is influenced not only by the weathering of underground spaces but also by the seismic loading caused by both natural and technical seismicity. Although the underground spaces are stable as a whole, some places where stability must be verified have been identified.

The influence of vibrations, landslides and surface subsidence is documented in a number of examples involving important ecclesiastical monuments (churches). It is necessary to reconstruct all these buildings repeatedly so that the building and its parts still fulfil their function (for use and decorative function). The examples given in the article prove that if the influence of vibrations is weaker and the monuments are not demolished, they can be preserved for future generations.

In case of landslides and mining-induced subsidence, the preservation of monuments must be the intensity of such deformation low. Abrupt changes or discontinuous deformations often result in significant damage to the structure or its destruction, even if it is protected. It is important to bear in mind that if several different negative impacts act on the structure, each with a low, sometimes neglected level, their aggregate influence may cause damage to the construction.

In conclusion, it should be stated that historical monuments are very sensitive to any kind of deformation. Such structures exposed to typical threats coming from industrial activity, especially connected with a heavy industry like mining, may be seriously damaged if not protected. In order to maintain their good condition, it is necessary to carry out up-to-date activities aimed at periodic measurements of unfavourable influences and making ongoing repairs. In the Czech Republic and Poland, relevant legal provisions regulate the principles of designing and conducting industrial activities as well as the entrepreneurs' participation in the costs of repairs. This significantly helps to keep historical structures in good technical condition. Presented examples in this paper certainly show that historical monuments, when treated with special attention, may be preserved even when exposed to several negative influences from human activity.

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