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ORIGINAL PAPER

Geodynamic phenomena in hazardous fault zones affected by extensive surface mining in Central Europe

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Abstract

This article presents a comprehensive interpretation of long-term and very precise levelling and tiltmeter monitoring in an exploration gallery opened 42 years ago in the Krušné hory Mts. The importance of the detailed investigation of the crystalline rock mass is a result of the nearby brown coal open pit mine, which prolongated the natural 500-m long fault slope by an additional 200 m of the working face. Slope movements may be generated under such conditions. Moreover, Jezeří Castle (gothic monument) could be affected by slope instability. The exploration gallery together with the surrounding slope serve as a natural laboratory for registering a) rock mass block tilting; b) possible elastic uplift resulting from an enormous mass unloading of basin sediments during coal mining; and c) tectonic movements along the Krušné hory fault (part of the ECRIS). The entry section of the gallery showed long-term gravitational creep of the surface formations, which has been accelerated due to the mining activity. On the other side, the back part of the gallery showed a long-term uplift, and the very end of the gallery is without any signs of exogenous or anthropogenic influence. Strict seasonal variability in the trend of rock mass tilting with typical winter/spring vertical acceleration corresponds to the landslide activity in the gallery surroundings. The overall evaluation of the monitoring has not indicated a significant risk for the Jezeří Castle. It is a successful result of geotechnical works from the 1980s and long-term monitoring, which was incorporated into mining projects and proper hazard management.

Keywords Geodynamics · Tiltmeter and levelling monitoring · Natural hazards · Exploration Gallery · Open pit mine · Czech Republic

Introduction

Mountain ranges within European continental interiors represent earlier stages of continental deformation (Spotila 2004). Nevertheless, active geodynamic processes (such as mass movements, block tilting, tectonic uplift, and elastic uplift) are still very common (Kalvoda et al. 1990). Moreover, these geodynamic processes usually pose a serious natural hazard when mountain ranges are bound to active tectonic fault lines. An example of these intercontinental mountain ranges is the Mittelgebirge in Central Europe (Peterek and Schroder 1997), as well as the Massif Centrale in France, Harz in Germany, and the Krušné hory Mts. (Erzgebirge) on the border between Germany and the Czech Republic (Fig. 1A).

The Krušné hory Mts. have a special position among these mountains for several reasons. First of all, its south-eastern slope, locally having the character of a well pronounced fault slope with facets, is a part of the tectonically active Eger Graben (seismicity and post-volcanic phenomena), which in turn belongs to the European Cenozoic Rift System (ECRIS), an over 1000-km long system of rifts disjointedly formed in the foreland of the Alps (Dezes et al. 2004). In addition, brown coal is excavated in extensive open pit mines in the Neogene basins of the Eger Graben. Moreover, open

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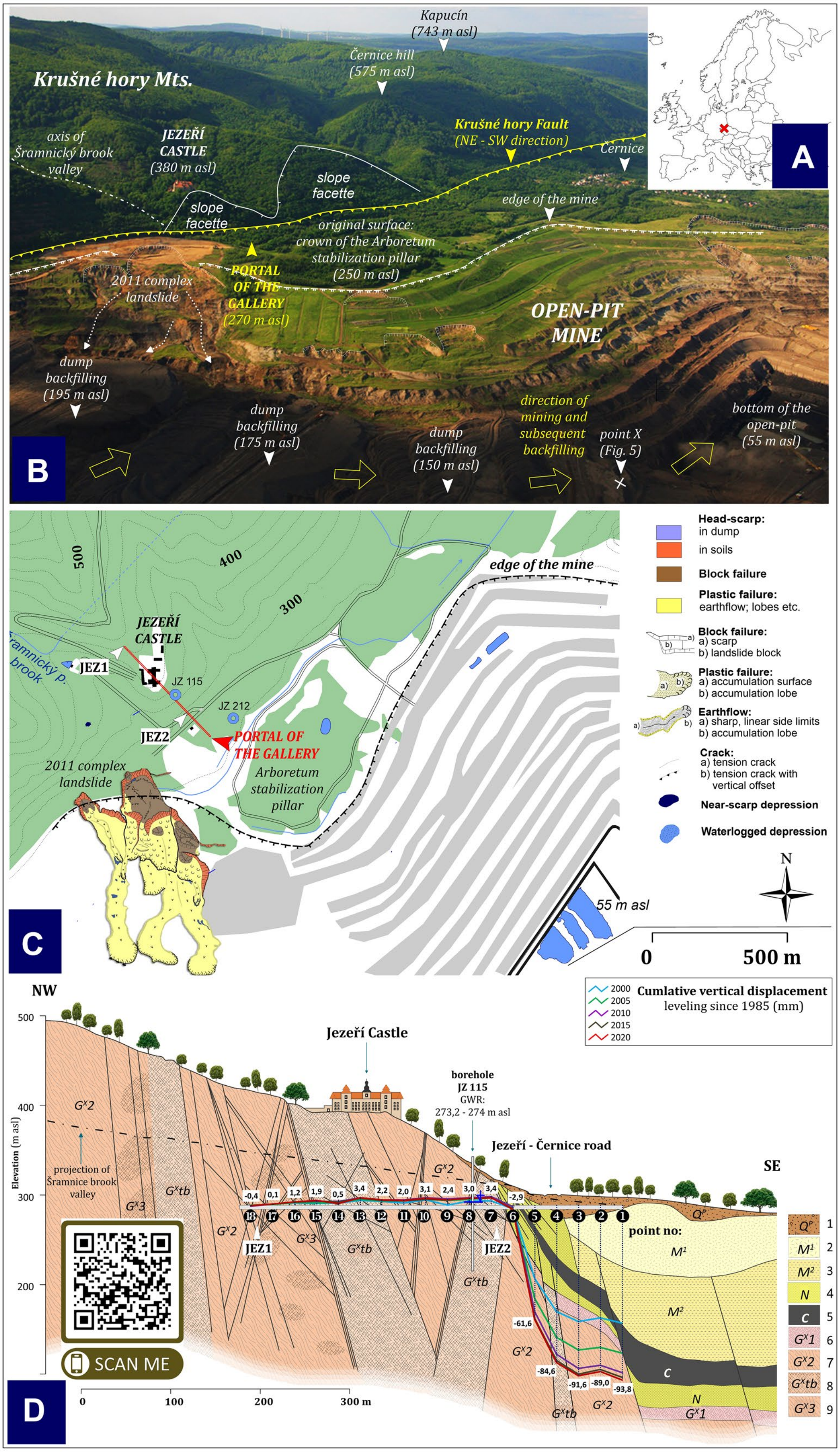

A
B
Kapucín (743 m asl)
Černice hill (575 m asl)
Krušné hory Mts.
axis of Šramnický brook valley
JEZEŘÍ CASTLE (380 m asl)
Krušné hory Fault (NE - SW direction)
Černice
slope facette
slope facette
edge of the mine
original surface: crown of the Arboretum stabilization pillar (250 m asl)
PORTAL OF THE GALLERY (270 m asl)
2011 complex landslide
OPEN-PIT MINE
dump backfilling (195 m asl)
dump backfilling (175 m asl)
dump backfilling (150 m asl)
direction of mining and subsequent backfilling
point X (Fig. 5)
bottom of the open-pit (55 m asl)
C
500
400
300
edge of the mine
JEZEŘÍ CASTLE
Šramnický p. brook
JEZ1
JZ 115
JZ 212
JEZ2
PORTAL OF THE GALLERY
2011 complex landslide
Arboretum stabilization pillar
55 m asl
0 500 m
N
Head-scarp:
in dump
in soils
Block failure
Plastic failure: earthflow; lobes etc.
Block failure: a) scarp b) landslide block
Plastic failure: a) accumulation surface b) accumulation lobe
Earthflow: a) sharp, linear side limits b) accumulation lobe
Crack: a) tension crack b) tension crack with vertical offset
Near-scarp depression
Waterlogged depression
D
NW
SE
Elevation (m asl)
500
400
300
200
Jezeří Castle
borehole JZ 115 GWR: 273,2 - 274 m asl
Jezeří - Černice road
projection of Šramnice brook valley
2000
2005
2010
2015
2020
Cumlative vertical displacement leveling since 1985 (mm)
-0,4 0,1 1,2 1,9 0,5 3,4 2,2 2,0 3,1 2,4 3,0 3,4 -2,9
18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
point no:
-61,6
-84,6
-91,6
-89,0
-93,8
JEZ1
JEZ2
G^x2
G^x3
G^xtb
Q^P
M^1
M^2
N
C
G^x1
SCAN ME
0 100 200 300 m
Q^P 1
M^1 2
M^2 3
N 4
C 5
G^x1 6
G^x2 7
G^xtb 8
G^x3 9

◀**Fig. 1** Position of the Eger Graben (**A**); tectonic boundary of the Krušné hory Mts. and the Neogene basin affected by coal mining (**B** and **C**); geological cross section across the Krušné hory fault along the Jezeří exploration gallery (**D**–modified after Mühldorf (1981): 1) loamy to rocky colluvium and sandy proluvial gravels with boulders of solid orthogneiss; 2) soft Miocene clays, usually disintegrating into small shards; 3) stiff Miocene kaolinitic-illitic clays, horizontally bedded with indistinct tectonic disturbances; 4) littoral and shoal Neogene sediments of medium to coarse-grained sandstones with a kaolinic binder; 5) coal without (or only with thin) clay bands, at the basin's edge passing into carbonaceous siltstone; 6) crystalline rocks, strongly weathered especially by kaolinisation; 7) solid leaf-gneiss, foliation with an inclination of 40–60° into the basin; 8) tectonic breccia chemically altered in the wide zones of a steep inclination, usually cemented gneiss, kaolinised debris, mostly without water; and 9) loosened solid gneiss with strong groundwater inflow, irregular occurrence of crushed zones). A 3D virtual tour through the Jezeří gallery was made using a Matterport Pro 3D camera and is available by scanning the QR code. The coordinates of the gallery portal are latitude 50.55°N and longitude 13.50°E

pit mining also took place in the close vicinity of the southeastern fault slope of the Krušné hory Mts. (Fig. 1B, C). This is an exceptional case in Europe. The 200-m high working face of the open pit passes fluently into a (natural) 500-m high fault slope where the gothic Jezeří Castle is situated (Fig. 1D). Due to a combination of the hazardous tectonic situation and anthropogenic pressure on the rock environment, Jezeří Castle has been put on the list of the Seven Most Endangered Monuments in Europe (!) by the cultural heritage organisation Europa Nostra (https://www.europanostra.org/european-call-to-save-7-most-endangered-heritage-sites/). The confluence of coal mining and slope deformation is certainly not exceptional, as may be documented from SW China, where monitoring data indicated a continuous creep deformation (Zheng et al. 2016). Nevertheless, the rarity of our locality under study lies in the concourse of mining activities, slope deformation, tectonic fault zone occurrence, and the presence of a natural heritage site.

Finally, it is planned to fill the large residual pit of the open pit mine with several hundred million tons of water during the final landscape reclamation within the next two decades. Due to the necessary uplift of the water table in the crystalline rock mass, several slope stability issues may be expected.

As a result of all these factors, the contact of the southeastern fault slope of the Krušné hory Mts. with the Neogene basins (different geomorphological units of the Eger Graben) provides a unique potential for the evaluation and quantification of anthropogenic influences on the geodynamic phenomena of an active fault slope. Moreover, the results (covering almost 40 years) from the multidisciplinary long-term monitoring system in the Jezeří exploration gallery (Marek 1983) are presented and evaluated in this paper. Levelling measurements began in the exploration gallery in 1985 (Burda and Vilímek 2021) and tilt measurements in 1982 at the JEZ-1 tilt station, and at the second tilt station JEZ-2 in 2001 (Chán et al. 2003). Tilt measurements are applied worldwide to control the stability of slopes in open-pit and deep mines, in various engineering-geological constructions or dams. For example, in an Indonesian gold mine, inclinometers are applied "to achieve zero accidents for employees and contractors" (https://www.inclinesensor.com/news/zc-inclinometer-empowers-indonesian-gold-mine, 2020). Timofeev et al. (2021) described high-accuracy ground-based measurements of height and tilt for studying the current crustal movements in Siberia (e.g., a large open-pit mine in the Kuzbass basin). Another example is given in Spottiswoode and Milev (2006) who reported tilt observations in a deep-level gold mine in South Africa, which was mostly coseismic (affected by blasts), but also aseismic resulting from stress redistribution. Timofeev et al. (2015) applied tilt measurements in the underground gallery at the Talaya Seismological Station for almost three decades and they revealed deformation cycles ranging from 3 to 18 years. The tilt measurements were also used to identify tectonic activity without any other influences such as meteorological phenomena or gravitational creep (Kaczorowski et al. 2019). Lesparre et al. (2017) observed a tight relation between tilts with rainfall and water infiltration in a highly porous inclined rock mass in France, as we did in our case described below. An example of regional/global effects on tilts related to enormous atmospheric phenomena (cyclones) and large earthquakes was presented by Volkov et al. (2020).

In addition to the above-mentioned monitoring, several other surface processes have been studied in this area, such as landslide stability (Burda and Vilímek 2021; Rybář 1981; Rybář and Novotná 2005), dendrogeomorphology (Burda 2011; Tumajer and Burda 2013; Tumajer et al. 2015), analysis of surface levelling measurements (Kalvoda et al. 1990, and geophysical profiling (Burda et al. 2011, 2013). These processes are not a direct subject of this study, but they help us to understand and in particular to interpret geodynamical processes.

The aim of this paper is firstly to describe and interpret the geodynamic phenomena found during four decades of in-depth monitoring of the Krušné hory Mts. main fault zone; secondly to estimate their hazardous potential for the cultural monument of Jezeří Castle; and finally, to evaluate the direct influence of human activities (extensive surface mining with accompanied hazardous processes) on geodynamic processes of the most important graben structure in Central Europe. Moreover, the evaluation of this multidisciplinary long-term monitoring is compared to a robust large-scale 2D numerical model in order to obtain a more precise theoretically interpretation of these in situ measurements. In general, we intend to highlight how the near surface human induced hazardous geodynamic phenomena may be controlled in order to protect people's lives, advanced mining technology, and valuable historical monuments.

Regional settings

As a part of the Saxothuringian zone, the Krušné hory Mts. consist of crystalline complexes consolidated during the Cadomian orogeny, and the mantle of Lower Palaeozoic rocks weakly metamorphosed during Variscan orogeny, where two parts with different geological structures may be distinguished (Kachlík 2003). The western part is formed by mesozonally metamorphic rocks (migmatised paragneisses, two-mica paragneisses, two-mica and granite-muscovite schists and phyllites), while the eastern part is formed by a granitoid core (ortometamorphites) with granite solitaires (two-mica to muscovite orthogneisses, migmatised orthogneisses or migmatites (Škvor 1975). From the southeast, the mountain range is separated from the Neogene basins by the Krušné hory fault zone. This fault zone, including the adjacent Neogene basins below the mountains, belongs genetically to the tectonic system of the Eger Graben (Domácí 1977; Zeman 1983), which is part of the European Cenozoic Rift System (Peterek and Schroder 1997; Dezes et al. 2004; Kopecký 1989) and is a leading structural-geological element.

The rock mass of the Krušné hory Mts. was uplifted along this fault zone in the Miocene–Pleistocene, while a Neogene syn-rift basin evolved in its foreground (Malkovský 1977). The Krušné hory Mts. and the Most and Sokolov basins represent the main geological and geomorphological units of this part of the Eger Graben (Balatka and Kalvoda 2006).

Extensive surface mining in the Eger Rift

Surface coal mining has extended to the Krušné hory fault zone, mainly in the Most Basin (Fig. 1B, C). The mountains consist of orthogenesis and metagranites with both longitudinal and transverse faults, and prevailing azimuth directions of 60°, 70° and 150° (Kopecký 1989; Král 1968). The basin sediments consist mainly of clays and claystones, and span a time interval from the Oligocene to Miocene. These sediments belong stratigraphically to the Paleogene-age Střezov Formation and dominantly to the Neogene-age Most Formation (Domácí 1977, Grygar and Mach 2013). The dominant Miocene lithofacies unit of the Most Basin (Libkovice Mbr) consists of Miocene silty clays (up to 230 m thick) and cover the 30-m thick Miocene-age coal seam (Holešice Mbr), which has been excavated by open pit mining since 1901.

The open pit mining passed in a NE direction (Fig. 1B) along the foot of the Krušné hory Mts. during the last half-century. The relative depth of the open pit exceeds 230 m, with its base at 55 m above sea level (m a.s.l.), and its working face passes into a well pronounced fault-slope. This created a single slope with an elevation of 700 m over 2 kms. Hence, the mining activities are associated with different types of mass movements (Pichler 1998) and concerns about the stability of the adjacent crystalline fault-slope were raised in the 1970s and 1980s (Marek 1977; Hurník 1982; Mejzlík and Mencl 1989; Rybář 1997). Therefore, the Jezeří exploration gallery was excavated for deep underground in situ monitoring of the tectonically affected crystalline rock mass (near the fault slope) covered by stretched basin sediments (Marek 1983; Horáček 1994). The excavation of the exploration gallery took place between April and November 1980. The gallery has a semicircle cross section with a diameter of 3 m and is 431 m long, including the entrance portal. In total, four short tunnel eyes are embossed along the route on the left side (see the 3D virtual tour via the QR code in Fig. 1D).

The exploration gallery in its initial part passes through Quaternary sediments, proluvial and deluvial debris, which then pass into Neogene clays. The inclination of these clay strata is given by Marek (1983) to be 45–55° towards the basin. The gallery then continues through a coal seam with a similar inclination of 50° towards the basin (Fig. 1D). This is followed by a major fault zone, approximately 40 m thick. This tectonic breccia (G^x *tb*) limits from the SE a solid block of less disturbed crystalline rocks (G^x2) on which the cultural monument of Jezeří Castle is situated. This compact crystalline-castle block, approximately 100 m thick, is separated by another significant fault zone (G^x *tb*) from the relatively solid part of the mountain range. The thickness of this second fault zone is estimated to be 70 m, where mechanically and chemically very strongly altered gneisses are typical. The first fault zone (40 m thick) at the foot of the slope is steeply inclined towards the mountains (at an angle of approximately 70°), while the second fault zone (70 m thick) is inclined towards the basin (Fig. 1D). Finally, the exploration gallery continues to the solid crystalline rock mass, which Marek (1983) still defines as a transitional zone several tens of meters thick, where the solid rocks are twisted and scattered (G^x3). According to Horáček (1994), at the 383 m station, technically healthy honeycomb gneiss (G^x2) occurs, but its pass into the solid crystalline rock mass is not well distinct.

The geological and tectonic conditions found in the Jezeří exploration gallery supported the previous concerns about the stability of the adjacent crystalline fault-slope with Jezeří Castle. Therefore, an Arboretum stabilisation pillar was left at the foot of the fault-slope (Fig. 1B). The border of open pit mine is located approximately 500 m from the fault zone. The aim was to eliminate the influence of the extensive open pit mining on fault-slope stability (Mejzlík and Mencl 1989) and on Jezeří Castle itself (Marek 1983).

Methods

Tiltmeter observations

Tiltmeter stations in the Jezeří gallery have a very long history. The JEZ-1 station was established in 1982 and has been recording tilts continuously for almost 40 years. The aim was to monitor the stability of the crystalline basement blocks under the steep slope of the Krušné hory Mts. A pair of photoelectric tiltmeters (later replaced by ASNS tiltmeters), each measuring one tilt component N-S and E-W, respectively, were set up on a hard stone plate at the end of the gallery. The space was separated from the rest of the gallery by a double door to minimise environmental effects. This site is located at a distance of 409 m from the gallery entrance. The JEZ-2 station began operation in 2001 and was established in order to monitor the crystalline basement block nearest to the contact with the stretched up Tertiary sediments of the basin, including the coal seam (see the locations in Fig. 1C, D). This site is situated 140 m from the gallery entrance. The instrumentation and setup are identical to the JEZ-1 station (Chán et al. 2003). The data were originally recorded with a pen-paper system (as described by Mrlina et al. 1997), later the data were recorded on site to a PC, and nowadays a wireless data transfer system is in place to provide data to the mine authorities in real time.

The performance of tiltmeters is controlled by calibration impulses each 12 h and regular testing of resolution, including mutual exchanges of tiltmeters between N-S and E-W directions, is performed. The tiltmeters show long-term consistency and reliability. The data are corrected for temperature variations, and barometric pressure is also considered during the data processing. After the removal of the Earth tide effects, the tilt data are converted to vector-graphs that present the tilt as a line on a map with azimuth changes (trajectory), and daily (monthly) velocity intervals (arcsec/day or arsec/month, respectively), see Fig. 2. The sensitivity of the tiltmeters is exceptionally high at the level of 10^{-4} arcsec (relevant to a displacement of 1 mm on a 2000 km long baseline), which is totally unique in geoengineering applications. Therefore, all the important features on the vector graphs may be considered as the real tilt of the rock mass.

Geodetic monitoring

In 1985, precise levelling observations of 18 geodetic points became the foundation of long-term underground monitoring in the Jezeří exploration gallery. Since 2000, complex biannual (spring and autumn) levelling data are available.

Measurements are performed by a Leica DNA03 digital compensator levelling machine with standard deviation per kilometre (m_o) ± 0.3 mm. The reference point for the measurement is the point *MUS-J1*, which has a relative height of 292.3333 m a.s.l. The control point is $Z_2b3\text{-}134.1$ with a relative height of 269.8666 m a.s.l. The identity and the invariance of the reference point *J1* to control point *134.1* are verified before every stage of the measurement, and its relative height is verified periodically every five years by very precise levelling (Jiříkovský and Seidl 2018) of a surface levelling circuit (Kalvoda et al. 1990).

Climatogenic and hydrogeological factors

The influence of climatogenic factors on slope stability as well as on mass movement activity is generally accepted (Schuster and Wieczorek 2002), and has been confirmed both on the fault slopes of the Krušné hory Mts. (Burda 2011) as well as in the Neogene basin (Rybář and Novotný 2005; Burda et al. 2013). Therefore, water table levels (WTL) from two hydrogeological boreholes JZ 212 and JZ 115 near the Jezeří exploration gallery (Fig. 1C) were analysed to investigate the possible influences of climatogenic factors on the mass movement behaviour observed in the gallery. These boreholes are equipped with DIVER Solinst loggers, which have been measuring the WTL every hour since 2006.

Numerical modelling

The main purpose of the FEM modelling is to evaluate the influence of open-pit mining activities (Francioni et al. 2015; Burda and Vilimek 2021; Reanud et al. 2021) associated with exposure of mountain foothills on values measured in the exploration gallery. FEM analysis was performed in order to simulate the evolution of shear strain values resulting from excavation of a 200-m thick layer of overburden soils and to clarify and interpret the monitoring results (Stead et al. 2006).

The analysis was performed using the 2D FEM analysis software GEO5-FEM. Laboratory specified local material properties were used and a Drucker–Prager failure criterion (Vanneschi et al. 2018) was adopted for the analysis. The plastic response of the different materials was simulated using geotechnical values based on an extensive geotechnical survey of 75 in situ as well as laboratory tests directly from the exploration gallery or its close surroundings at the beginning of the 1980s (Möhldorf et al. 1981).

FEM deterministic analysis was performed using an idealised profile as shown in Fig. 2, considering the presence of water in all of the geological strata. To simulate the progressive mining activity under the exploration gallery, the following four excavation stages were included in the numerical analysis–Stage I: the original surface before the mining activities; Stage II: the surface affected by the initial mining activities–before 2000; Stage III: the mining surface between 2000 and 2005; and Stage IV: the maximum extent of the mining activities between 2005 and 2010.

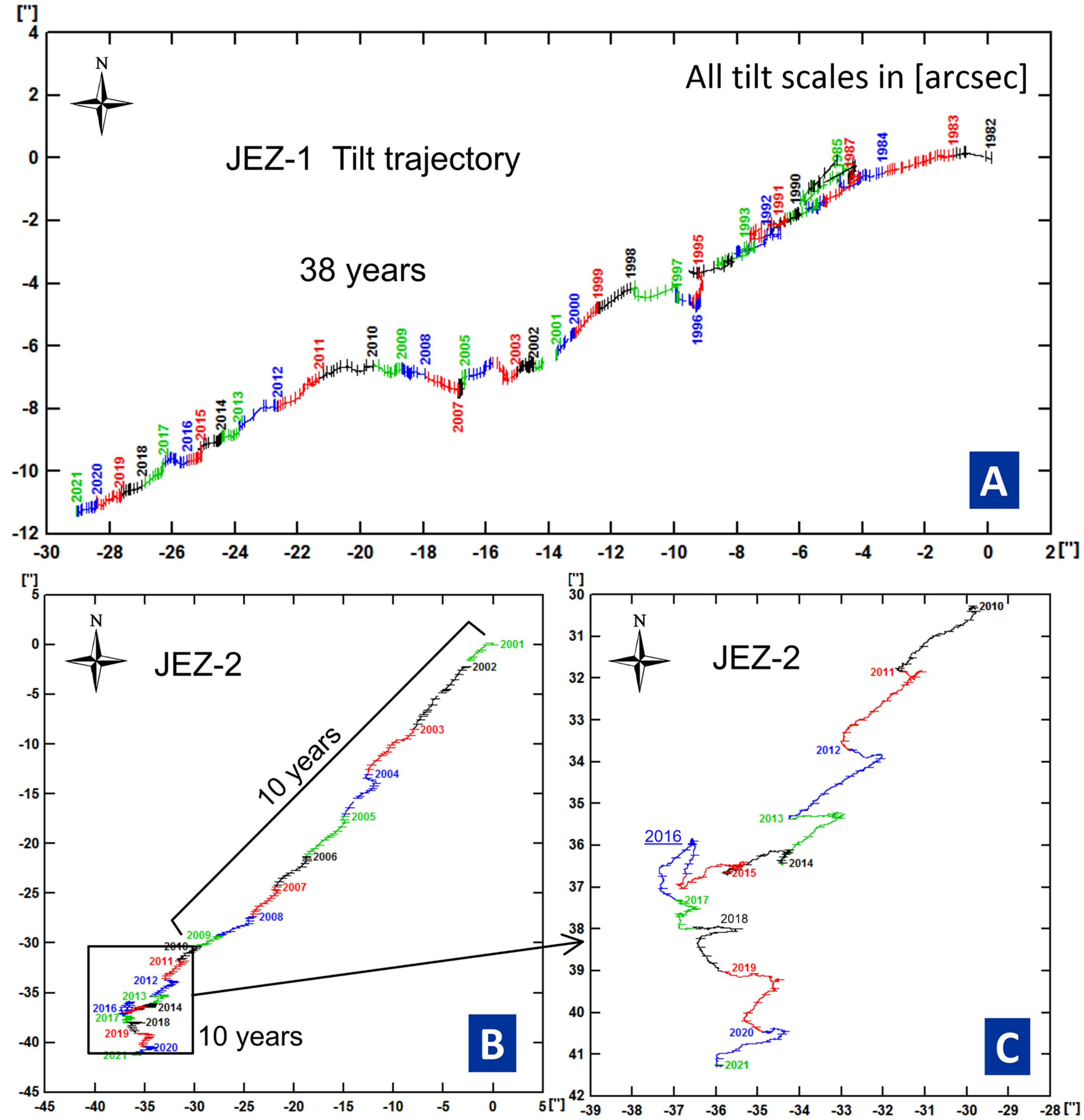


Fig. 2 Tilt trajectories from the JEZ-1 tiltmeter station in 1982–2020 (**A**) and JEZ-2 in 2001–2020. Each year is marked by a different colour and particular month intervals are marked by a short cross-dash. The tilt from the JEZ-2 tiltmeter station is shown as complete in 2001–2020 (**B**) and in detail in 2010–2020 (**C**). In JEZ-2, it is clear that the velocity of tilting significantly decreased in 2010, as the total final trajectory of 2010–2020 is three times shorter than 2001–2009. This effect was caused by the mining front progress behind the stabilisation pillar and also due to the consecutive backfilling of the mine. The units of the X and Y axes are arcseconds, so that the lines in the graphs reflect the azimuth of progress of tilting over time

Results

Tiltmeter results

The tiltmeter observations at both the JEZ-1 and JEZ-2 stations show one principal fact–the long-term tilting of the rock mass to the SW (into the open space of the valley of Šramnický Stream). In detail, the JEZ-1 station inside the more or less homogeneous and compact mass of the crystalline rocks of the Krušné hory Mts. exhibits a mostly WSW tilt azimuth with certain minor changes in 1995–2010, when the station recorded a regional geodynamic impulse described in detail by Košťák et al. (2011). However, there are no striking changes in either the tilt azimuth or velocity (Fig. 2A).

The JEZ-2 station is located in a fractured crystalline rock block (tectonic breccia) near the contact with the stretched-up sedimentary formations. The tilt trend in the period between 2001 and 2005 was from the NE to SW (Fig. 2B), similar to that of the JEZ-1 station. This period of tilting may be explained in the same way–into the valley of Šramnický Stream, at the entrance to the open pit mine. The slight difference between the WSW and SW azimuth may be explained by the close vicinity of the mine (located several hundred meters from the gallery). The deepest part of the mine (the mining front) moved to the south of the gallery between 2005 and 2010, and there was no immediate impact on the tilt trend up to 2016 (for an explanation see the Discussion section). One striking change occurred in this period–the tilt velocity decreased significantly after 2010, see Fig. 2B.

However, in 2016 we observed a very significant change to the tilt azimuth (JEZ-2) from the SW to SSE (Fig. 2C). We assume that the disintegrated crystalline block G^x *tb* close to the gallery entrance reached its critical stability point. In addition, deep mining under the Arboretum pillar began around 2015. Both these phenomena may be responsible for the observed azimuth change. Since 2016, the block around the JEZ-2 station has been characterised by a general tilt to the SSE, see Fig. 2B, C, towards the deepest part of the mine. Therefore, the reaction time is approximately 5–10 years.

The other substantial phenomenon on the JEZ-2 tilt trajectory is represented by frequent semi-regular short-term tilt changes related to seasonal groundwater inflow into the Arboretum stabilisation pillar. These “winter bends” from the SW to ESE were observed 12 times between 2001 and 2016 (Fig. 2B). The water saturated block of a relatively large mass (density increase) may affect the stress field around the gallery. We correlated the tilt azimuth changes with groundwater levels in the JZ212 well (Fig. 3) located close to the gallery entrance (Fig. 1C) and found a strong relation between the two quantities.

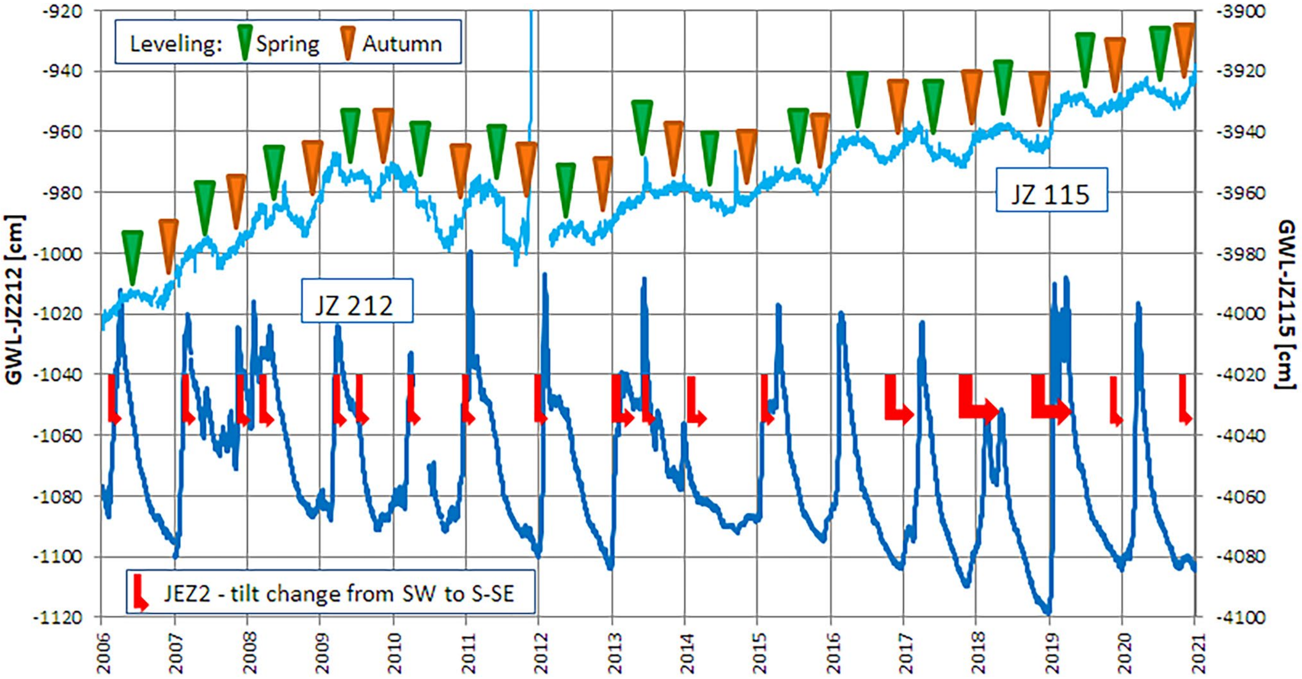


Fig. 3 GWL monitoring in wells JZ115 and JZ212 (locations in Fig. 3). Levelling campaigns are presented by triangles along the JZ115 GWL curve. Correlation of tilt azimuth changes in the JEZ-2 tiltmeter station (red) with positive spikes of GWL in well JZ212 shows the principal tilt azimuth changes right before or during the maximum increase in GWL

Most of the recent landslides (Burda et al. 2013) occurred nearby the gallery portal during these tilt bending episodes (Mrlina et al. 2010, 2016; Mrlina 2021). We consider fast saturation of the stabilisation pillar (Arboretum) and the surrounding soft sediments stretching over the mountain slopes during winter periods as the principal triggering mechanisms of the landslide. The correlation between water input and tilt trajectory is shown in Fig. 3 (red symbols versus groundwater level (GWL) peaks). Local geomechanical stress conditions may change abruptly due to increased pore-water pressures (Burda and Vilímek 2021). If this effect surpasses a certain limit, the tilt velocity may also increase dramatically, as documented in Fig. 4A, B. It may be concluded that sudden changes of tilt velocity and azimuth may precede the weakening of slope stability, which may lead to the occurrence of a landslide.

Despite the fact that prediction of such hazardous natural phenomena is generally very challenging, if not impossible, we have observed the specific behaviour of tilting during landslide events several times. An example is given in Fig. 4, where we observed (during the winter bend period) increasing tilt velocity with a maximum velocity on 14 January 2011, during the day of the main landslide activity (see in Fig. 4). This event was classified by Burda (Burda et al. 2013) as the reactivation of a former "underground-mining induced catastrophic landslide". During this period, the tilt azimuth was without any spikes, and showed a smooth bend of trajectory from the SE to NEE between 10 and 23 January. Figure 4 shows the extremely high tilt velocity in both the tilt vector graph (top) and the red line graph (bottom). As the velocity increase started on 12 January, we consider the data as predictive. However, we do not have any strong statistical proof of such indications, rather we demonstrate its potential.

Levelling observations

A projection of the cumulative vertical displacement of all 18 geodetic points in the period between 1985 and 2020 is shown in Fig. 1D, where it is clear that points 1 to 5 are situated in the basin sedimentary fill, while points 6 to 18 are situated in the more or less homogeneous and compact mass of the crystalline rocks of the Krušné hory Mts. In this more solid zone, cumulative vertical displacement was between +0.1 and +3.4 mm. The only exceptions are point 18, with a cumulative vertical shift of –0.4 mm (which is significantly below the measurement accuracy limit) and point 6, with a cumulative vertical displacement of –2.9 mm (placed nearby the boundary of the basin sedimentary fill and crystalline rocks). The face of the gallery, represented by points 1 to 5, showed a very different trend, whereby instead of a slight uplift of the measured geodetic point, their significant cumulative vertical drop from -61.6 mm to -93.8 mm is evident (in the period between 1985 and 2020).

It is not possible to describe the detailed results before 2000, because regular and comprehensive data are not available.

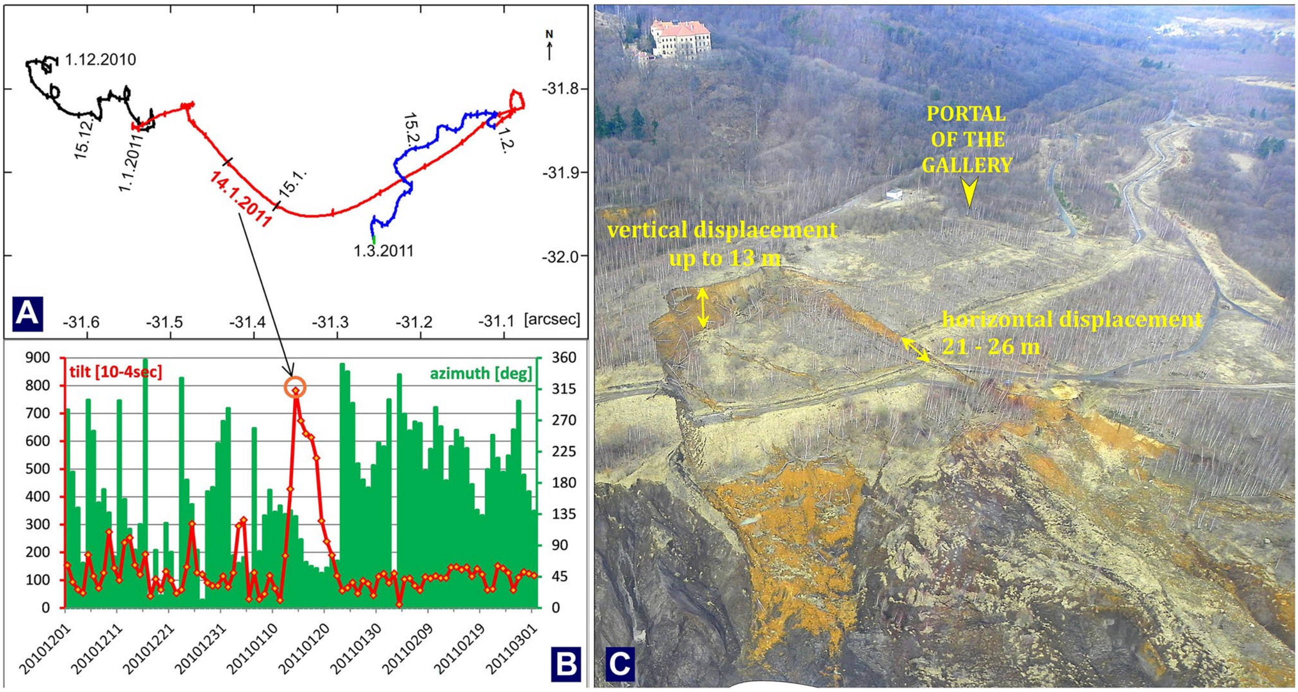


Fig. 4 Extreme increase in the tilt velocity on 14 January 2011, correlating with a landslide occurrence (**A**); however, on 12–13 January we observed an increasing tilt velocity as an indicator of the event (**B**). Photo documenting the landslide (**C**)

Nevertheless, detailed data analysis is possible using the complete data set after 2000 (Fig. 5). These measurements are regularly performed twice a year (spring–April/May, and autumn–September/November) and, therefore, several trends may be described. The first is a significant difference between spring and autumn displacement trends. While the initial part of the gallery (points 1–5) is characterised by different spring/autumn subsidence rates, the rest of the gallery shows a completely reverse trend of autumn and spring measurements.

The results of detailed biannual levelling measurements available since 2000 are shown in Fig. 5. There is a cumulative vertical shift span between +2.1 and –32.8 mm, while again an intensive vertical drop (from –22.3 to –32.6 mm; the long-term average is –1.3 mm^{-yr}) is evident at points 1 to 5. The decrease in vertical subsidence rates of these points is evident since the beginning of 2010, when the average annual rates reached –0.5 mm^{-yr}, while before 2010 it reached –2.4 mm^{-yr}.

In the entry section of the gallery, the spring subsidence rates reached an average of –1.0 mm^{-yr} during spring measurements and -0.4 mm^{-yr} during autumn measurements; hence, they are two to three times lower than the spring subsidence rates. This disparity has become even more pronounced since 2010, when the average spring rate decreased to –0.5 mm^{-yr} (it was -1.7 mm^{-yr} before 2010), while the average autumn rate was 0.0 to less than +0.1 mm^{-yr} (it was –0.9 mm^{-yr} before 2010). It may be summarised that the spring observations recorded an acceleration of the subsidence rates (Fig. 5B), whereas all of the autumn observations recorded movement deceleration (Fig. 5C). This trend intensified after 2010, when the significant autumn long-term deceleration also affected the whole year trends (Fig. 5A).

In the part of the gallery characterised by points 6–18, the spring cumulative vertical displacements span between –0.3 and –2.8 mm in the period 2000–2020 (with the exception of point 15 (+0.7 mm) and point 13 (+0.1 mm)). In the same period, the autumn cumulative vertical displacements span between + 0.1 and + 3.8 mm.

Comparing the spring and autumn observations (Fig. 5D and E) shows not only different long-term trends, but these trends clearly imply an indirect correlation, when the average correlation coefficient is r = –0.78 (with the strongest correlation exceeding r = –0.9 at points 7, 14, 16 and 17, and the weakest r = –0.26 at point 18).

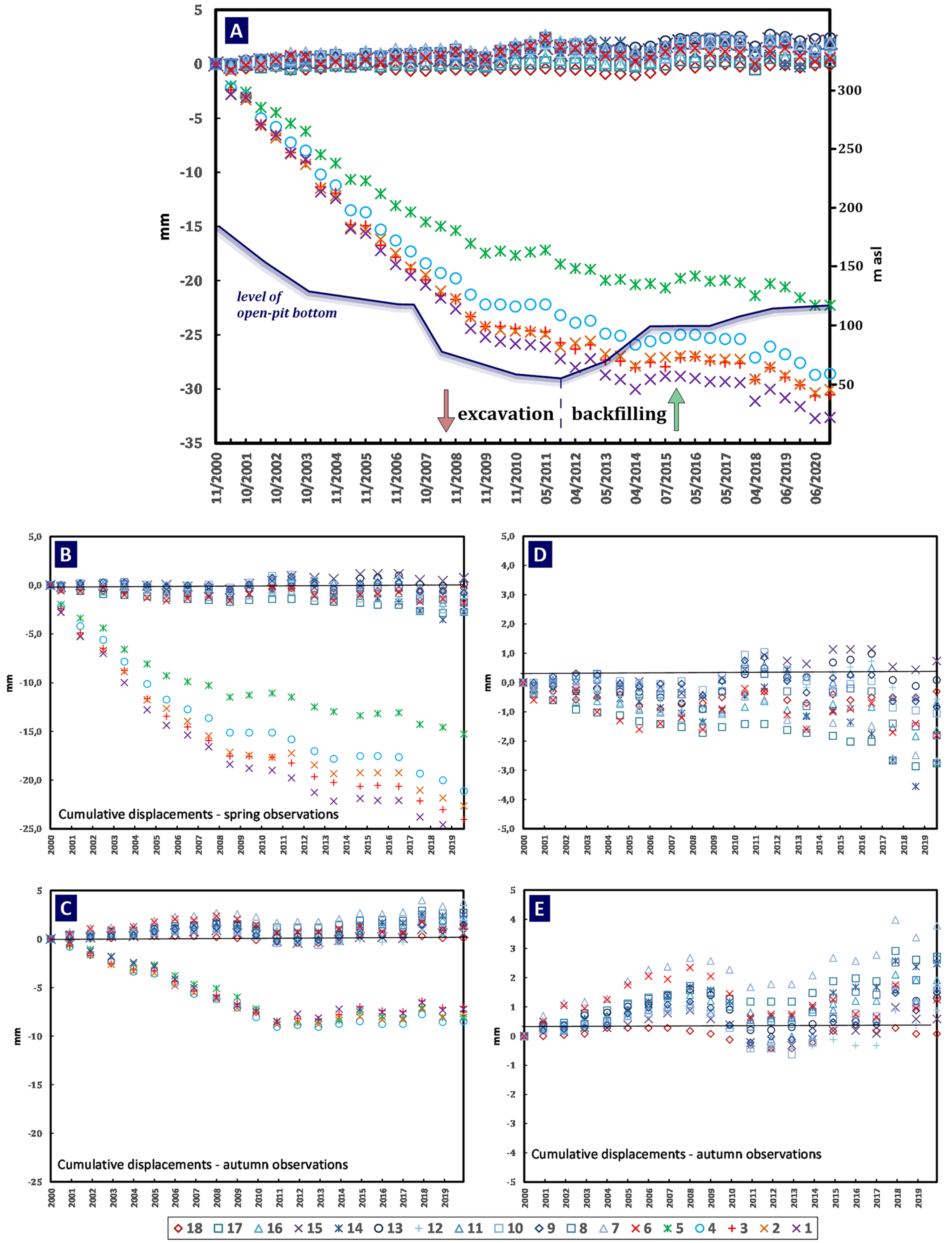
In addition to precise levelling measurements, there is also an automated total observation station in place, recording displacements on benchmarks located around the edge of the Arboretum stabilisation pillar. An example of the results is presented in Fig. 6.

Groundwater level monitoring

The monitoring in wells JZ115 and JZ212 revealed a completely different character of the annual GWL variations. While JZ115 (on the mountain slope, see Figs. 1C, D) shows a slowly increasing GWL over 15 years (Fig. 3) with a total uplift of +0.80 m, JZ212 in the stabilisation pillar reveals very significant annual spikes of up to + 1.00 m during short winter periods. The continuous increase in GWL in JZ115 may contribute to the slope instability level by saturating the fault zone. JZ212 spikes reflect repeated inflow of groundwater into the sediments of the pillar, which may also have a triggering effect for surface mass movements (landslides)–in winter 2011 this well showed the maximum GWL peak when the landslide described in Fig. 4 occurred.

Results of numerical modelling

Measured in situ deformations were compared to FEM numerical models in order to theoretically clarify the movement mechanism and anthropogenic influences. The spatial and temporal course of the mining activities is schematically show in Fig. 7. Intensive mining and deepening of the open-pit occurred between 2000 and 2010, when the mining face was moved to directly around the stabilisation pillar (Arboretum) and the relative depth of the open-pit exceed 200 m. After 2010, the relative depth of the mine decreased due to backfilling of dump soils into the open pit bottom. This open-pit progression is taken into account in the FEM contour plots of the total displacement (d_z) shown in Fig. 7, and in the plot of equivalent plastic strain shown in Fig. 8. Moreover, both the in situ measured and theoretical vertical displacements (d_z) are shown in Fig. 8. A very good match of theoretical and measured displacements is evident in 14 of the 18 points (points 6 to 18 and also point 1), while the theoretical displacements of points 2 to 5 are underestimated compared to the in situ measurements. The analyses show the development of shear strain values in two zones, which correspond to different failure mechanisms (shallow landslide and deep-seated movement) also described by Vanneschi et al. (2018). The first zone is in deeper strata and is bound to Tertiary sedimentary fill that stretched out very steeply along tectonically uplifted crystalline rock mass. The maximum shear strain values were allocated approximately 100 to 110 m from the portal of the gallery, i.e., very close to the first tunnel eye and between levelling points 5 and 6. In the contour plots of total displacement (d_z), this first zone represents a strict boundary between a relative stable part of the gallery situated in more or less homogeneous crystalline rock mass and the front part of the gallery, which shows significant vertical displacements—both calculated and observed by levelling measurements. The second zone is lithologically represented by soft dish-shaped Miocene clays, lying in thicknesses of up to 60 m. These clays are usually water saturated and, therefore, plastic and very sensitive to slope stability problems (Burda et al. 2013).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◂**Fig. 5** Cumulative vertical displacements measured in the exploration gallery in between 2000 and 2020 **(A)** and comparison to the evolution of the depth of the open pit at point **X** in Fig. 1B. Cumulative vertical displacements during spring (**B**) and autumn (**C**) measurements. Detail of spring (**D**) and autumn (**E**) measurements of points 6–18

Moreover, the results of the FEM modelling show an increasing plastic strain as well as cumulative vertical displacements (d_z) in parallel to the excavation of sedimentary fill as the open-pit approaches. According to the expected assumptions, the values of equivalent plastic strain and d_z increase up to the maximum extent/depth of the open pit, when the general shear reduction factor falls to very low values as was described by Vanneschi et al. (2018). However, when backfilling of the open pit begins, the FEM model does not show any other significant increase in deformation and thereby earlier deformations fade away during the backfilling stage. According to the FEM results, this scenario is visible in the front part of the gallery (points 1 to 5) situated in the sedimentary fill and in a part in the adjacent tectonic breccia (point 6 and station JEZ2). The crystalline rock mass itself does not show any significant deformations due to its mining-induced relaxation.

Discussion

The above-described results show one principal fact–long-term deformations (tilting and subsidence/uplift trend) within the whole exploration gallery–in both geologically different areas, which confirms the expected geodynamic processes on the fault-slope zone. Therefore, the principal questions are whether it is possible: *i)* to distinguish the anthropogenic movements (mining-induced) from natural gravitational processes, which were described on the local steep slopes earlier (Burda 2011); and *ii)* to distinguish processes of an exogenous and endogenous origin.

In general, all of the results are in concordance with the geological setting in the surroundings of the exploration gallery–Quaternary and Tertiary soils of the Most Basin in the initial part of the gallery (0–115 m) versus more or less tectonically disintegrated crystalline rock mass at the stationing 115–432 m. These two geologically different areas are characterised by various trends of measured deformations (by both tiltmeters and by levelling) and FEM calculated deformations. Of course, there are many other differences not described in this paper (different aquifers with different water regime influences in both zones, climatological zonation etc.,), which affect mass movement dynamics in the mountains as well as their foot/basin (Burda 2011).

The influence of exogenous factors and open pit mining and the effect of deepening of the open pit (Fig. 5A) are particularly evident on the levelling results of points 1 to 5. Annual subsidence rates decreased by four to five times after 2010, when the bottom of the open pit reached its elevation minimum and backfilling began below the gallery (Fig. 5). The results of these in situ measurements correspond very well to numerical FEM models (presented by us as well as by Vanneschi et al. 2018): deep-seated gravitational creep deformations of steep stretched plastic sediments are accelerated during winter/spring as a result of saturation of basin sediments by groundwater, but also by stress/strain changes due to open pit deepening before 2010. Moreover, the ratio of long-term deformation trends may also be affected by old deep tension cracks caused by underground mining prior to 1950 (Špůrek 1974; Burda and Vilimek 2021). Confirmation of this hypothesis is beyond the possibilities of our measurements due to a lack of exact information from the 1950s and the considerable age of these cracks.

Apart from the initial part of the gallery (0–113 m), the influence of open pit mining is also documented in the tectonic breccia limiting the crystalline-castle block from the SE, which is demonstrated by the very significant tilt velocity decrease at the JEZ-2 station after 2010 (Fig. 2B). At the same time, there are seasonal effects, represented by characteristic “winter bends” when the SW tilt azimuth is replaced by a strict ESE azimuth with a smooth and fast tilt trajectory. We assume that the JEZ-2 station partially responds to exogenous events in the initial part of the gallery when the winter/spring acceleration of deep-seated mass movement in the basin sediments evokes stress relaxation in the neighbouring crystalline rock mass. This relaxation causes the change of tilt trajectory directly into the basin (south). This fact that the JEZ-2 station responds directly to processes within the basin is unequivocally proved by correlations of local landslides with both tilt velocities and trajectories (Figs. 4 and 6). If the JEZ-2 station corresponds to these local landslides (up to 500 m^3), it may be assumed that it will respond to movements that are many times larger and deeper, although much slower, that are bound to the whole upper strata of the basin sediments.

The relation between the various observations and geodynamic activity is documented by a typical example of landslide events recorded and indicated by complex geophysical-geodetic measurements at the fault zone, see Fig. 6. The first landslide occurred between 20 and 25 December 2012 (exact date unknown) and was indicated by two unusual tilt trajectory loops (Fig. 6 top left). The tilt data further suggest that the landslide movement started at the beginning of 23 December, as during this day the tilt velocity increased dramatically (blue section). At the end of the landsliding on 25 December, the azimuth of the tilt trajectory changed significantly from SWW to SEE. During

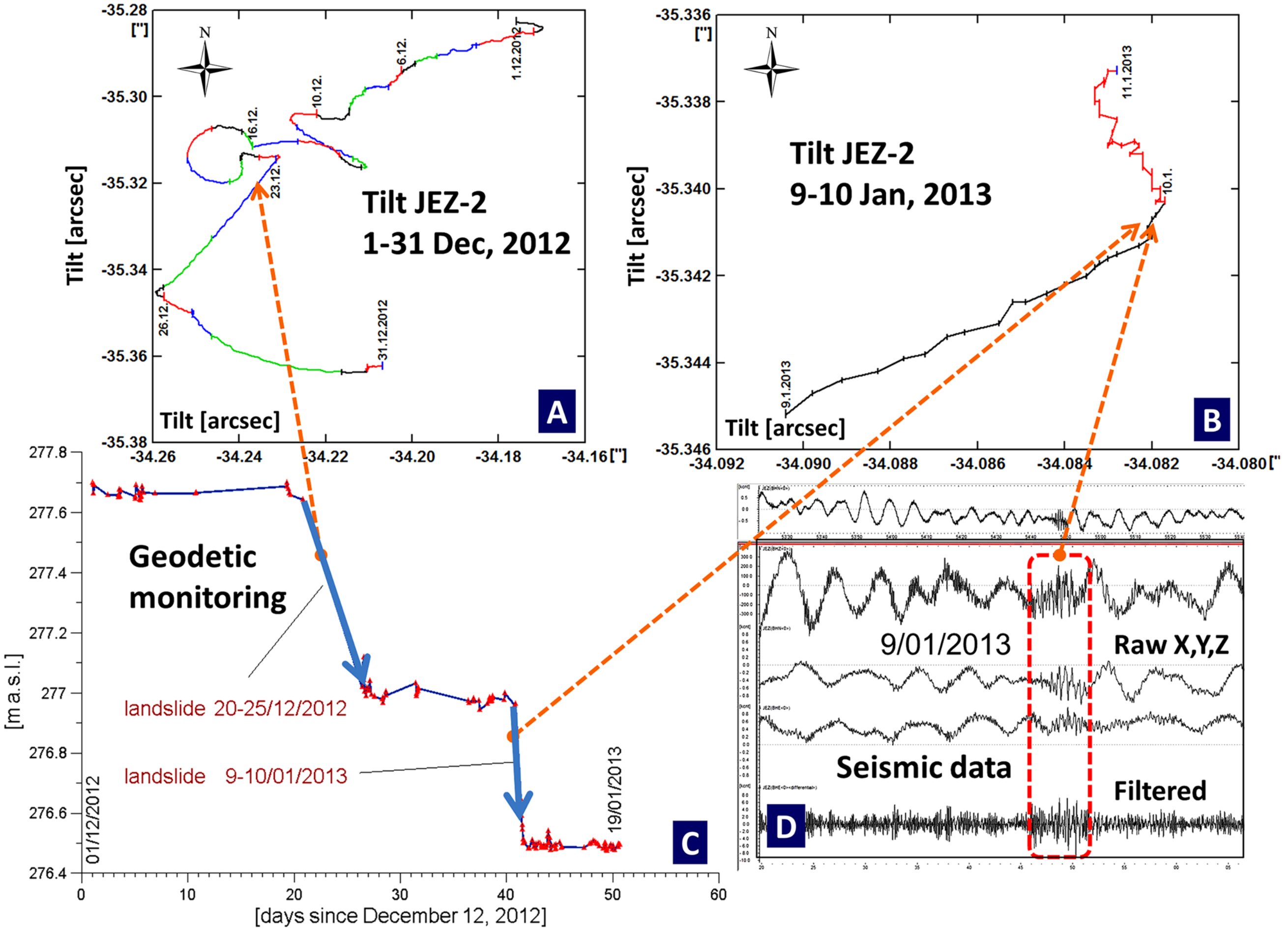

Fig. 6 Complex observations reflecting landslide events at the fault zone. Geodetic monitoring by an automated total station (**C**) clearly show vertical down-slips of the benchmark. Both events were indicated by tilt changes (**A, B**) as well as seismological disturbance (**D**)

5–9 December (before the landslide) the GWL in well JZ212 exhibited the fastest increase of the year (16 cm/5 days). Hydrological modelling and observations performed in France by (Longuevergne et al. 2009) confirm what we claim in this paper about the impact of groundwater saturation of a rock mass on tilt measurements.

The second landslide occurred at the end of 9 January 2013, when the tilt trajectory changed slightly from NEE to NNE before, and to NNW after the landslide, which also caused a disturbance in the seismological signal, see Fig. 6.

This example demonstrates that such complex observations may indicate geodynamic activity (e.g., landsliding) on a fault zone in relation to anthropogenic (mining) and exogenic (groundwater level changes, climatological phenomena, surface displacement) processes.

The interannual difference in levelling trends of points 6–13 may also be explained by the stress relaxation during winter/spring periods. The crystalline-castle block may be simply understood as a rock wedge inserted between the mass of the mountains (from the NW) and an Arboretum support pillar (from the SE), and is characterised by long-term uplift (points 7–13) accompanied by tilting into the valley of Šramnice Stream (SW azimuth). However, when the sediments of the Arboretum support pillar move in the ESE azimuth, subsequent stress relaxation leads to an ESE tilt change of the crystalline-castle block and its temporary subsidence, as shown by points 6–13.

In general, the crystalline-castle block has uplifted by up to 3.4 mm (and 2.8 mm on average) since 1985, which may be interpreted as an elastic uplift (described also by Kalvoda et al. (1990) and was proven during precise surface levelling in the 1980s and 1990s (Kalvoda et al. 1994). This elastic uplift resulted from an enormous mass unloading of basin sediments during mining (approximately 3300 mil. tons (Krejčí et al. 2014)) according to these studies. Precise surface levelling stopped in 1989 (spring monitoring) and, therefore, these results cannot clarify the interpretation of levelling results from the gallery. Other hypotheses may explain the uplift of the crystalline-castle block by endogenous tectonic uplift,

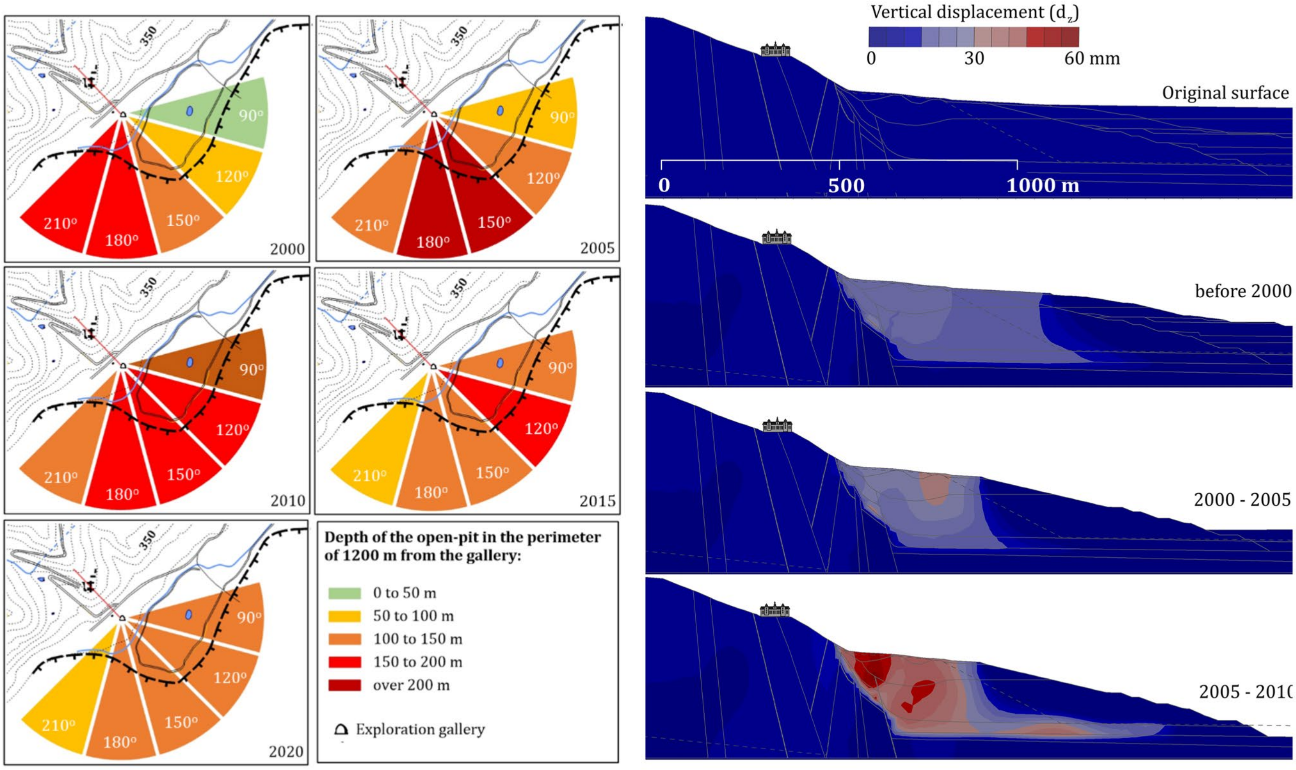

Fig. 7 **Left** An idealised diagram of open-pit depth progression between 2000 and 2020. **Right** FEM calculated cumulative vertical deformations in different stages of open-pit mining, from terrain unaffected by mining (top) to the maximum extent (depth) of the open pit (bottom)

which influenced the whole range of the Krušné hory Mts. Therefore, we assume that we will observe a long-term endogenous lift (tectonic or elastic), which is seasonally influenced by factors that have their origin in the exogenous movements of the Arboretum supporting pillar.

Levelling points 14 to 18 at the end of the gallery are placed first in a transitional zone, where the blocks of solid rocks are twisted and scattered (G^x3), and finally in the solid crystalline rock mass (G^x2). While the points in the transitional zone (G^x3) show lingering uplift (on average 1.2 mm

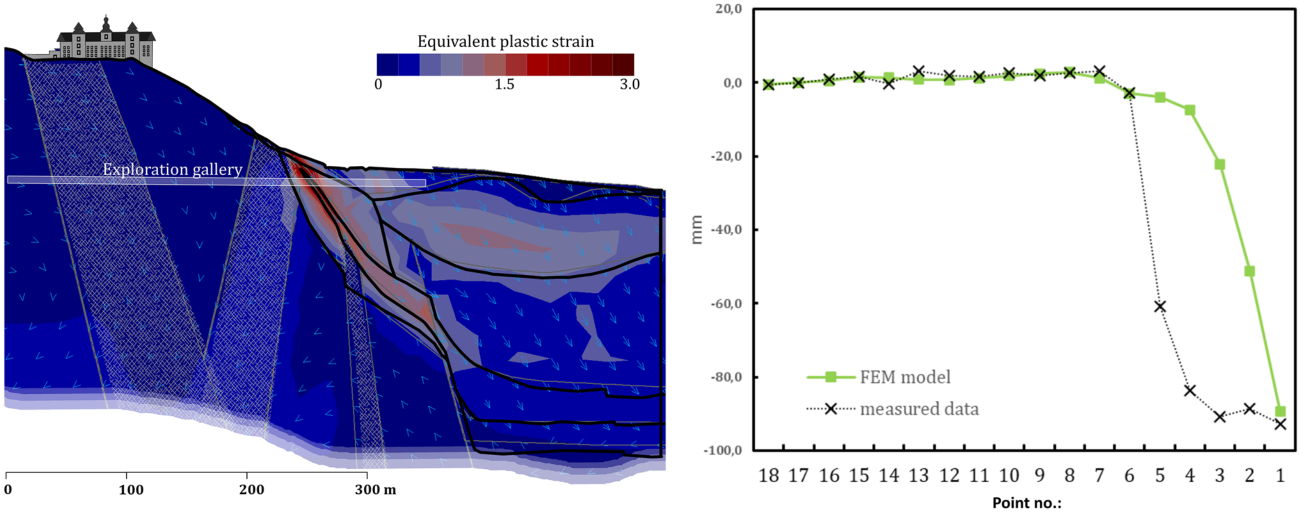

Fig. 8 **Left–**Equivalent plastic strain in the variant of the maximum extent of the open-pit (with an indication of the main geological strata according to Fig. 2. **Right–**comparison of measured (1980–2010) and FEM calculated cumulative vertical deformations

Table 1 Main geotechnical parameters (Cohesion, Phi, Young's modulus. and Poisson's ratio) utilised in the FEM analysis. The data are based on a statistically robust set of results obtained directly from the modelled site (Muhldorf et al. 1981; Vanneschi et al. 2018)

Material	Phi (^{o})	Cohesion (kPa)	Young's modulus (MPa)	Poisson's ratio
Quaternary sed. (Q)	27	5	500	0.2
Soft Miocene clays (M^1)	15	19	40	0.4
Miocene claystones (M^2)	16	38	350	0.25
Coal seam (C)	40	50	250	0.16
Neogene sediments (N)	35	150	1.400	0.2
Crystalline rock mass:				
- kaolinised (G^x1)	25	60	200	0.25
- solid (G^x2)	42	1.000	4.500	0.1
- transitional zone (G^x3)	30	1.000	1.300	0.15
- transitional zone (G^x3)	26	550	900	0.2

since 1985), the solid crystalline rock mass (G^x2) does not show any significant deformations (0.1 and -0.4 mm since 1985). Also, tilts at JEZ-1 are four-times slower compared to JEZ-2 and without any evidence of exogenous influences. The tilt trajectory is quite smooth with the WSW azimuth (into the tectonically predisposed valley of Šramnice Stream) and the 1995 and 2010 changes had a regional endogenous character (Košťák et al. 2011). JEZ-1 reflects both local and regional endogenous geodynamic phenomena, but there is no evidence of mining-induced movements, which is in accordance with the levelling results. That is probably caused by the existence of the Arboretum support pillar (Mejzlík and Mencl 1989) to the S, SE, and E of the gallery entrance, as this pillar supports the hazardous slope with the gallery and Jezeří Castle (Kalvoda et al. 1994) and eliminates stress–strain changes deep in the rock mass. In addition, the stress change in the rock mass may have been only slowly accommodating the mass redistribution in the mine Table 1.

Conclusions

This article summarises and interprets the results of long-term monitoring performed in the Jezeří exploration gallery for almost four decades. The subject of the monitoring is the rock mass including the Krušné hory fault (which is part of the European Cenozoic Rift System). The specifics of this area are extensive surface coal mining in the immediate vicinity of the fault zone. The European cultural monument Jezeří Castle is located in the lower part of the fault slope and, therefore, possible movements of the slope, whether of endogenous, exogenous, or anthropogenic origin, would pose a significant risk.

The principal results are summarised as follows:

- Comparing in situ measurements to a large-scale 2D numerical model, which was based on robust local-geotechnical-database, allowed for a better understanding of the movement mechanics of the entire rock mass due to an extensive excavation and local landsliding.
- Monitoring results reflect the basic lithological and structural settings of the geological environment–annual subsidence (avg. –1.3 mm^{-yr}) of the entry section of the gallery (drilled in the basin sediments) and less progressive uplift of the rear part of the gallery (drilled in the fault zone and crystalline rock mass) accompanied by its SW tilting.
- Subsidence of the entry section of the gallery is interpreted as a long-term gravitational creep of plastic soils, which was significantly accelerated by deepening of the open pit mine (until 2010), as its average annual subsidence rates (–2.4 mm^{-yr}) were five-times higher than in the following period between 2011 and 2020 (–0.5 mm^{-yr}), when the backfilling of the open pit began. The observed tilts in the JEZ-2 station also slowed down threefold during the same period. The movement dynamics have a strict seasonal variability with typical winter/spring displacement acceleration and tilt azimuth changes reflecting landsliding activity in the gallery surroundings.
- From the long-term observations, the uplift accompanied by SW tilting was confirmed in the crystalline block of the fault zone including Jezeří Castle. These geodynamic phenomena have the character of elastic uplift combined with tectonic uplift, and their rates were accelerated up to four times by the mining activities in a long-term perspective, and up to ten times by single landslide events during short seasonal periods.
- In the solid crystalline rock at the very end of gallery (behind the fault zone), the movement rates are up to three-times slower and without any signs of exogenous or anthropogenic influences.
- The proper hazard management is documented by geotechnical works in 1980s and by long-term monitoring, which were incorporated into mining plans. In some cases, the geodetic and tilt data exhibited a precursory character to landslides.

- The Arboretum stabilisation pillar has been left under the most endangered part of the slope (below Jezeří Castle). This fact appeared to be a successful strategy because it slowed down the crystalline block inclination.

This paper demonstrates that surface mining is possible even in the geologically, geomorphologically and environmentally complicated and sensitive settings of tectonically active graben structures, like in our case in Central Europe. Even though the surface mining is in its final stages (the mine will be closed in 2024), multidisciplinary monitoring will be important in the future, especially because it is planned to flood the excavated open pit with 270 million tons of water to create a recreation zone.

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