Engineering geological limits of the urban development of the Brno city

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Abstract: The area of the city of Brno was limited by natural conditions and from the 12th century also by human activity. The main geological structure here is north part of the Nesvačilka Graben in the surface area filled with Neogene clays of the Late Burdigalian and Langhian age. Neogene clays are fine-grained soils whose internal structure fundamentally affects their mechanical properties. These clays are significantly anisotropic, frost sensitive and susceptible to volume changes (shrinkage, swelling). In the surface parts they weather, crush and are prone to sliding. They are risky from the aspect of slope stability problems and when being exposed in construction pits. The surface of the Neogene clays on the raised blocks is located close to the surface and is mainly covered by anthropogenic fillings. Above the tectonically downslipped blocks, the surface of Neogene clays is usually below 10–15 m Quaternary sediments. At the areas of the elevated blocks and along the west edge of the Nesvačilka Graben, the clays crop out directly onto the surface or are covered by a thin layer of aeolian sediments. Human activity was proved mainly by the creation of numerous open pits for building materials, which were subsequently built up by continuous development. Many old built-up quarries are endangered until today by rockfalls. In the historical part of the city, the stability conditions were aggravated by a number of historical cellar systems and deposits up to 10 meters thick, which consist of the anthropogenic dump. The susceptibility to slope instabilities was modelled by a multivariate statistical method on the map sheet 1:25 000 Brno-sever 24-324, with an area of 115.45 km^2. The method combines input parameters (geology, land use, altitude, slope angle, aspect, relief curvature, presence of tectonic lines) and compares them with the occurrence of slope instabilities in the particular area. In addition, a layer of Neogene clays was used here, since this geological unit plays an important role in the Brno agglomeration.

Key words: Neogene clays, slope instabilities, multivariate statistical method, Czech Republic, Brno agglomeration

1. INTRODUCTION

The geological and geomorphological character of the area are the determining factors of natural conditions. Especially together with climate and hydrological conditions, they determine the basic framework for population development in the past and present. It is obvious that the conditions in Brno agglomeration were favorable, especially in the Brno basin shaped depression, and the factors present primarily from prehistory were combined with secondary loaded anthropogenic features.

An increasingly massive application of anthropogenic contribution in the transformation of the landscape's original appearance occurs from the High Middle Ages to the industrial epoch. Already at the beginning of the 12th century, there existed suburban villages in the area and in the 14th century Brno had 3 brickfields, whose open pits transformed the original relief (Flodrová, 1996). At that time, quarries for building stone, especially Jurassic limestones on Stránská skála Hill, sandstones and conglomerates of Devonian Old Red facies on Červený kopec Hill and in the rocks of Brno Massif (Mrázek, 1993) were also excavated for construction purposes.

The leading paleomorphostructure, which influences the development of the river network and slopes in the Brno agglomeration from the Tertiary to Recent period, is the buried valley of northwestern ending of Nesvačilka Graben filled with Eocene and Miocene sediments (Fig. 2; Dvořák et al., 1993). This valley has numerous paleotributaries filled with Lower Miocene to Middle Miocene sediments. The bottom of the valley was reached in Brno territory as late as in 2015 at the depth of 331.4 m by borehole 2241_B in its shallower part on the northern outskirts of Brno (Tomanová Petrová et al., 2015).

Fault-modelled slopes of grabenlike depressions and their gradual development caused the emergence of extensive slides and block slides of Neogene sediments in the Langhian stage and Quaternary period. These landslides were subsequently stabilized by filling the depression with sediments and in some places were covered by younger Quaternary deposits (loess, river gravel sand). During the extensive construction works, such as tunnels construction, these faults and block slides digging through may occur in the course of digging through, which can cause a risk to the particular constructions.

Fig. 1. Brno and its position within the Czech Republic.

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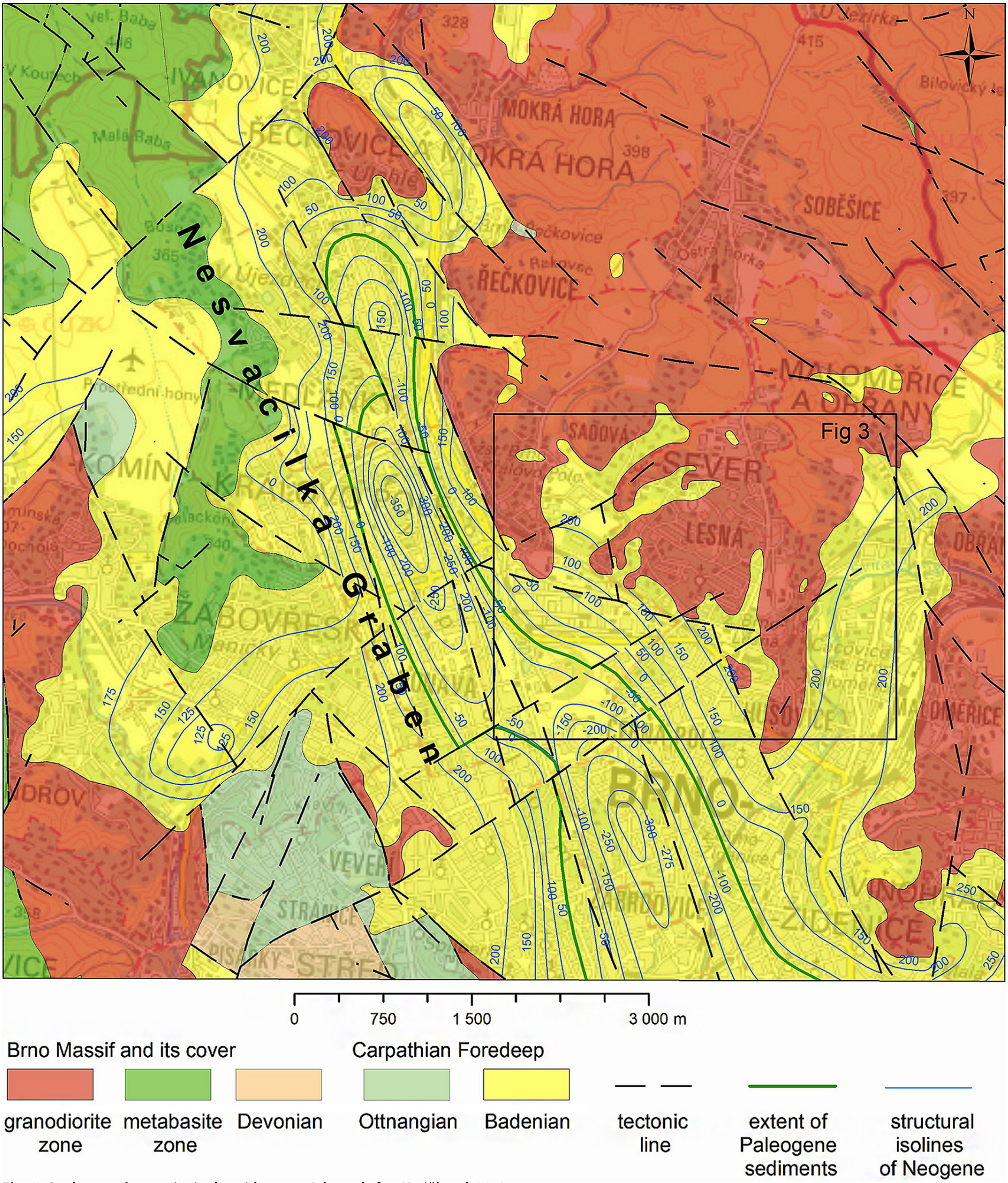

Fig. 2. Geology and tectonics in the wider area. Adapted after Krejčí et al. 2018.

2. DATA AVAILABLE FOR GEOHAZARDS ANALYSIS

Since 1858 (Doležal, 1858) plans of the city of Brno have been issued irregularly, where it is possible to observe the development of the former open pits and quarries (http://vilemwalter.cz/mapy/). Some of these open pits have been subsequently built up and are up to the present day registered as slope instabilities. These plans can be combined with the Austria-Hungarian maps of Military Survey of the 1st – 3rd phases (started from 1764–1768, finished 1918; http://oldmaps.geolab.cz/). Slope instabilities in Brno agglomeration were first recorded by engineering geological mapping of Gartner (1926) at a scale of 1:25 000. This professor of the Czech Technical University in Brno

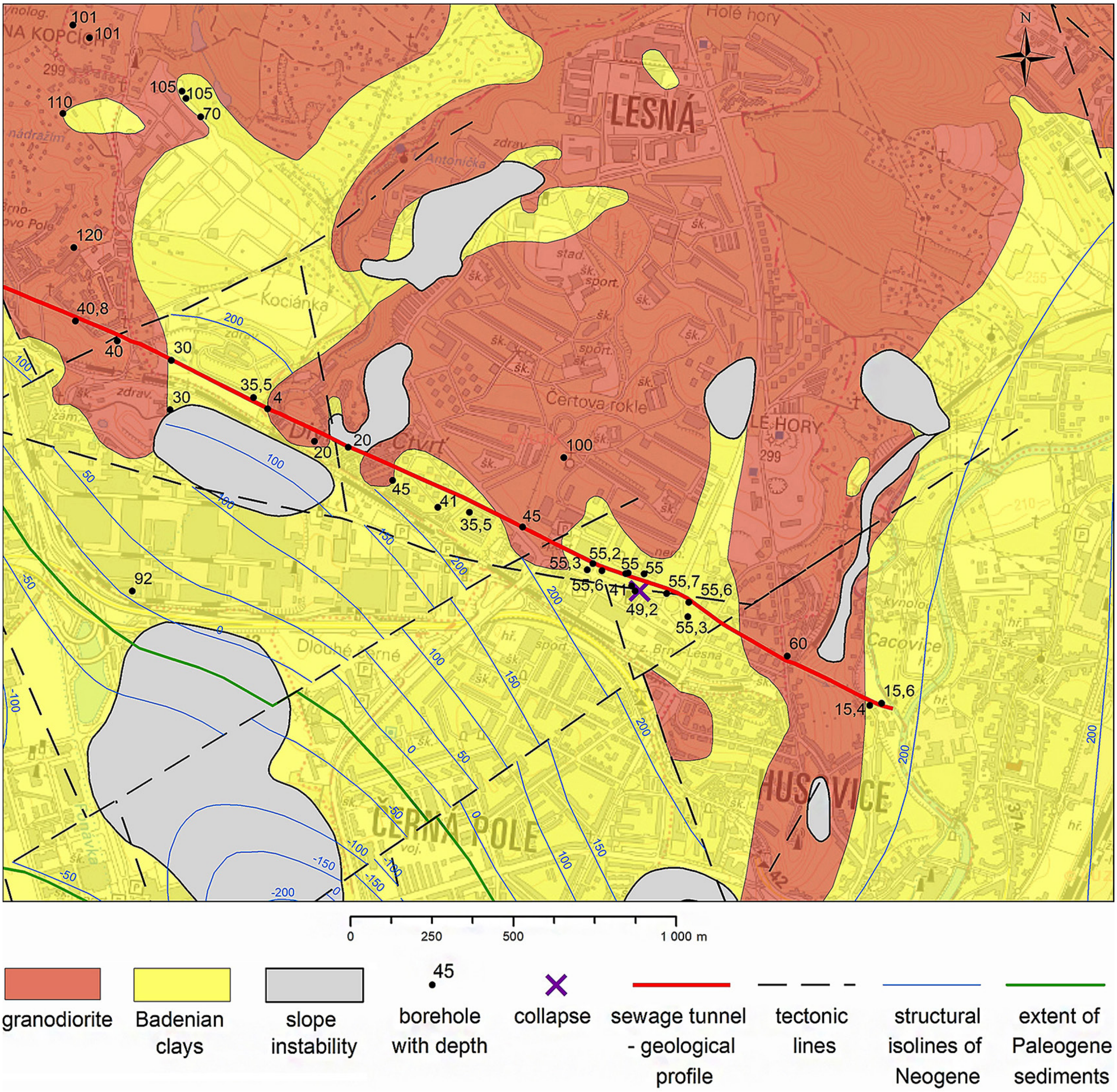

Fig. 3. Geological situation and location of the geological profile.

mapped significant landslides in Langhian clays in Medlánky area and in a zone from the Červený mlýn Mill (Figs 9, 10) along Drobného Street. This landslide area causes difficulties with the foundation engineering and damage of existing buildings to this day. Attempts have therefore been made for detailed geological and engineering-geological mapping at a scale of 1:25 000, but this has not been completed (Cicha, 1968, 1969; Papoušek, 1976). The next phase of mapping, this time without the engineering geological layer, took place a little later (Hladil, 1987; Brzobohatý, 1987; Novák, 1988; Pálenský, 1991). Comprehensive mapping of Brno agglomeration, fully digitized including the engineering geological layer, was completed in 2013 (Buriánek et al., 2013; Gilíková et al., 2011; Hanžl et al., 2011; Tomanová Petrová et al., 2013). These maps are now being prepared for publication.

On the date of 31. October 2020, a total of 237 slope instabilities were documented on the territory of Brno (Fig. 4), most of which originated on the bedrock of Langhian sediments with Quaternary cover or without it. In many cases, rockfalls were recorded on the rocks of the crystalline complex and its cover, they always concerned anthropogenically modified rock slopes or former open pits/quarries.

The excavation of mining and drilling works discovering the subsurface structure began in 1714–17, when the well at Špilberk castle was deepened to a final depth of 112 m, i.e. below the level of the Svratka River in Staré Brno cadastral territory. Exploratory wells in Brno started in the second half of the 19th century and they were the first attempts to obtain quality drinking water, especially for food-processing industry. Until then, only surface water was used. The wells then exceeded a depth of 100 m (up

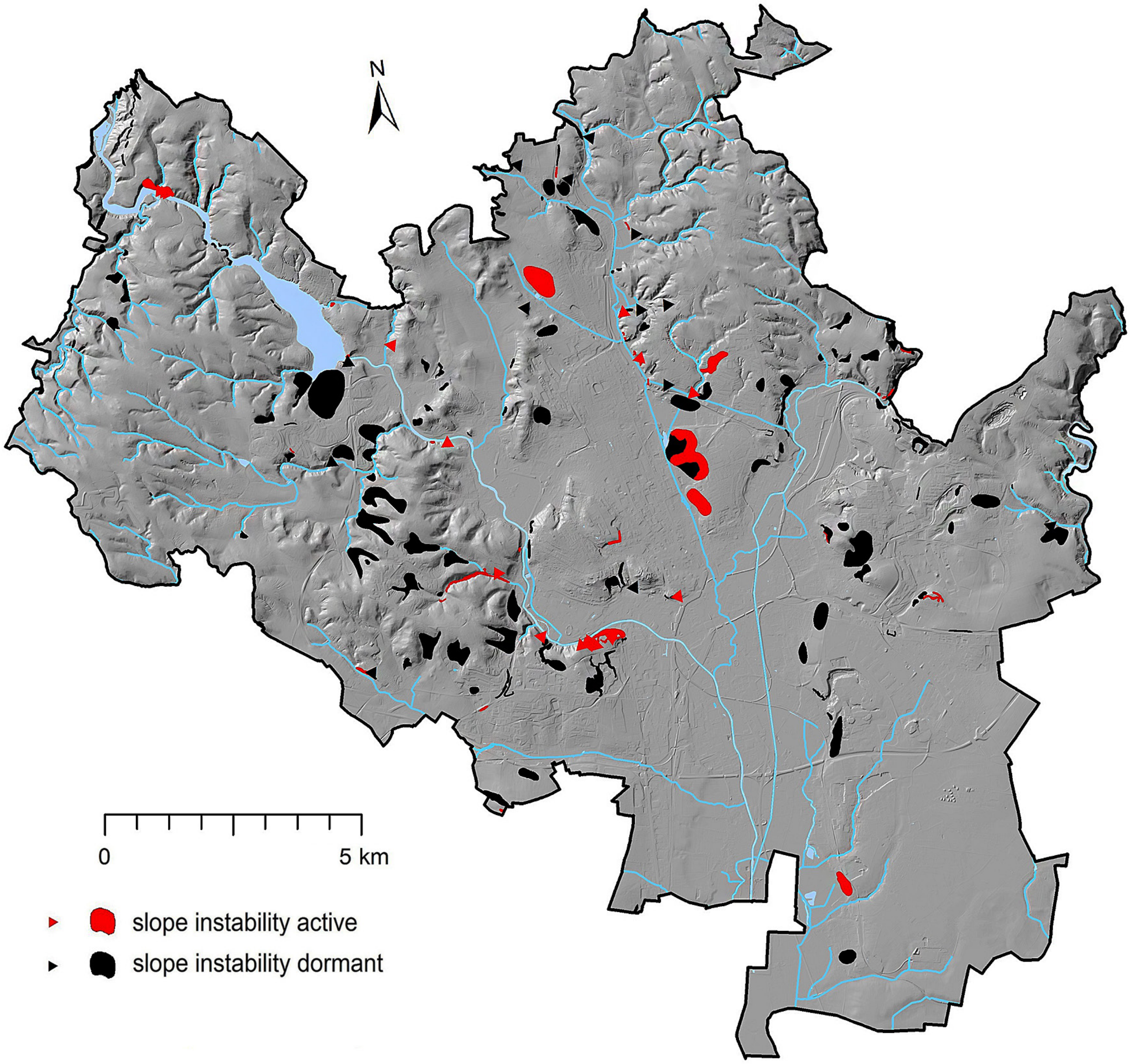

Fig. 4. Cadastral area of Brno with marked slope instabilities.

to 161 m; Rzehak, 1897). The current deepest borehole in Brno HV-110A has a depth of 711.6 m (Taraba, 1976) and was also drilled for hydrogeological purposes in Paleozoic sediments of the Moravian Karst. Deep seated water resources in Brno territory were summarized in numerous studies, especially Kouřil et al. (1978) and Kryštofová (2016), where there are also geological evaluation and descriptions of realized wells.

Knowledge of geological structure in Brno territory has significantly enriched the practice of exploration and construction works for some particular constructions types. Nowadays, we have a number of survey works from the construction of the collector network, road and railway tunnels, water supply and sewerage tunnel systems and many other constructions. Hanák and Bulgurovská (2012) summarized important final reports on these works and compiled a catalog with borehole profiles and geological sections.

As of 28 February 2020, 5 919 expert reports on survey works from the city of Brno were registered in the Czech Geological Survey – Geofond. The oldest of them have been kept on file since 1891. Older data on geological works, especially on mining of brick loam and clay, stone and sand are available in the Brno City Archive, including detailed plots of the former mining areas. Information is available since 1764 (Smutný 2012). Polák (1956) denotes the postwar situation of quarries and other open pits of nonmetaliferous raw materials in Brno. As of this year, there were a total of 100 different open pits in Brno, many of which, especially former quarries, were registered as slope instabilities. Nowadays are exploited only 2 localities in Brno, one of which is open pit for Quaternary sands and gravels exploitation (Černovice) and the other with limestone quarry (Líšeň).

3. NEOGENE CLAYS AS AN ENGINEERING–GEOLOGICAL LIMIT OF CONSTRUCTION

In the area of Brno, in terms of Neogene sediments of the Carpathian Foredeep, there can be found various clays that differ both in their age (Late Burdigalian and Langhian; in terms of www.stratigraphy.org) and in their lithological composition. In the Czech Republic formerly the Central Paratethys Neogene stratigraphy chart was used, e.g. Piller et al. 2007. Clays of Late Burdigalian age (Ottnangian stage according to Piller et al. 2007) are predominantly gray to green-gray, non-calcareous, often with silty and sandy admixture. They can have brown-red colouring also (Tomanová Petrová et al., 2018). These are limnic sediments. Clays of the Karpatian stage of the Late Burdigalian are brown-gray to gray, sporadically variegated streaked. Usually they are alternatively sandy, slightly calcareous, often bedded and of marine origin. The clays of the Langhian age (Early Badenian; Papp et al., 1978) are the most widespread and vertically spread. These are gray, gray-blue to gray-green calcareous silty clays with sand interbeds. They were deposited during the Early Badenian transgression (Hanžl et al., 2011; Buriánek et al., 2013). In the engineering-geological surveys, the age of clays is not usually subdivided and they are referred to only as Neogene, respectively they are classified as Early Badenian clays – Tegel. The term Tegel represents a common designation of unbedded calcareous clay; this term is used locally in Miocene stratigraphy (Petránek et al., 2016).

In terms of the perspective of deformation risk, the presence of expanding clay minerals of smectite and vermiculite is most important for their ability to swell and shrink. The dominant clay mineral in case of in detail studied samples from the Dobrovský road tunnel (Koubová et al., 2003) is mixed layered illite/smectite, with high expandability (75–90 % S; S = smectite). Kaolinite, discrete illite and in smaller quantities chlorite are also present. The carbonates in the clay fraction consist mainly of calcite and a very low dolomite content. Furthermore a small amount of quartz is present in the clay fraction.

The total montmorillonite content and part of the illite were converted to mixed-layered illite/smectite (montmorillonite/illite ratio (82/18) according to an average expandability of 82 % S). The content of mixed layered illite/smectite is then about 18.3 wt %, the content of discrete illite is about 4.2 wt %. More recently, the properties of these clays have been studied by Malát et al. (2016) and in the borehole 2241_B (Krejčí et al., 2018). The borehole 2241_B was drilled to understand the structural composition of the NW edge of the Nesvačilka Graben and it found Badenian clay deposits in the total thickness of up to 160 m (Tomanová Petrová et al., 2015). Such a thickness of Lower Badenian clay-silty sediments has not been available yet.

In 1960s and 1970s, large panel housing estates were built in border districts (e.g. in Bohunice, Líšeň, Bystrc or Vinohrady). Panel housing estates are a special chapter of urban development of urban and suburban house-building. The oldest of them, the Lesná housing estate, was built between 1962 and 1973 and has the character of an urban district set relatively sensitively into steep terrain with inclination to south and divided by a wooded valley.

Already during the construction of the Lesná housing estate, several completed residential buildings in Loosova and Jurkovičova streets were damaged. The main reason was the old calmed landslides, covered with a layer of loess, which did not appear in the surface terrain (Paseka, 1985). During construction of the main sewerage tunnel under this housing estate, an inrush of Neogene sediments and weathered granodiorite eluvia into the tunnel occurred, which had to be relocated afterwards (Fig. 5; Šmíd, 1987).

Extensive stability problems then arised in the Bystrc housing estate (Papoušek and Paseka, 1976) and most recently in the housing estate in Medlánky (Fig. 12; Poul et al., 2010), where landslides buried below a layer of loess occurred during construction. In these housing estates additional arrangement had to be taken both to reinforce the buildings foundations and to stabilize the landslides themselves. In the case of the Lesná housing estate, some buildings cannot be used up to this day. Another example of a large landslide are the slopes in the local urban district of Vinohrady (Fig.11). The

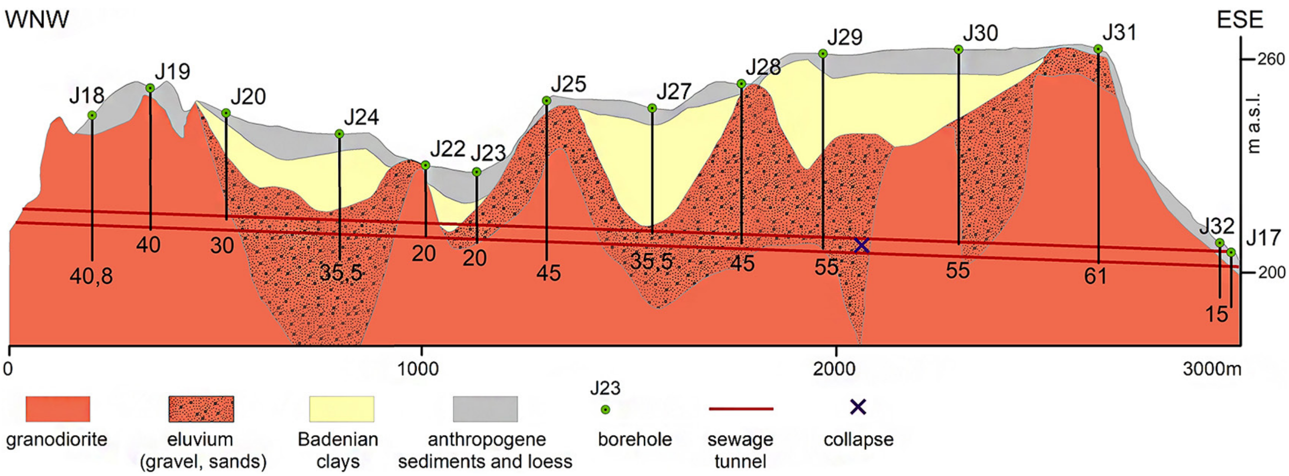

Fig. 5. Geological profile. See Fig. 3 for location.

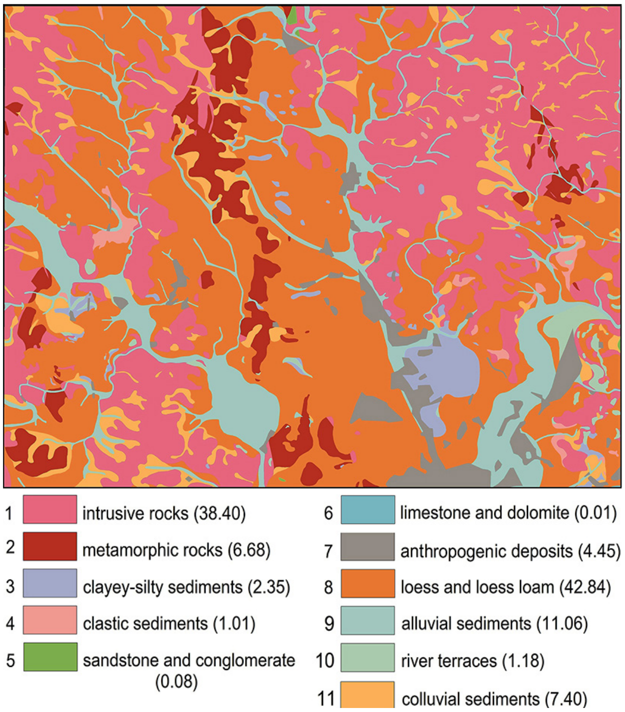

Fig. 6a. **Parametric geology map (classes 1–11). Derived from the geological map 1:25 000 according to Hanžl et al. (2009). Individual regions are defined on the basis of genetic-lithological similarity. Area (km²).**

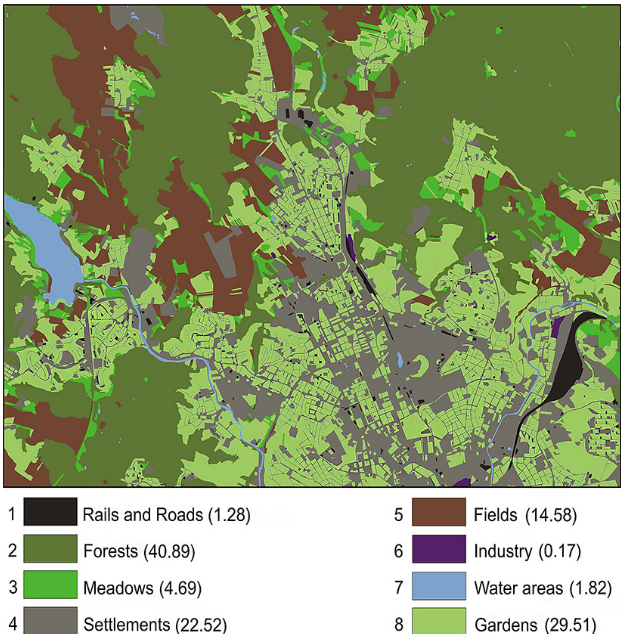

Fig. 6b. **Parametric land use map (classes 1–8). Created from digital data ZABAGED®. Planimetry and divided into different classes according to Havlín and Šikula (2017). Area (km²).**

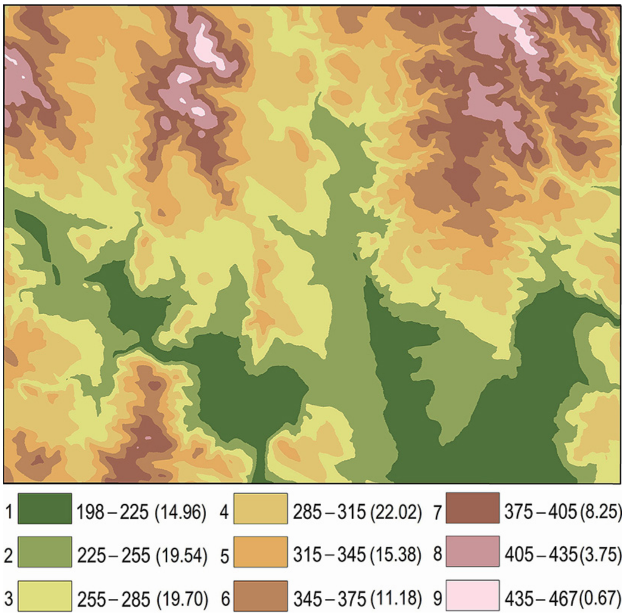

Fig. 6c. **Parametric map of altitudes (classes 1–9). Created from ZABAGED® digital data altimetry and divided into constant intervals of 30 altitude meters. The height difference between the lowest and the highest altitude is 269 m. Area (km²).**

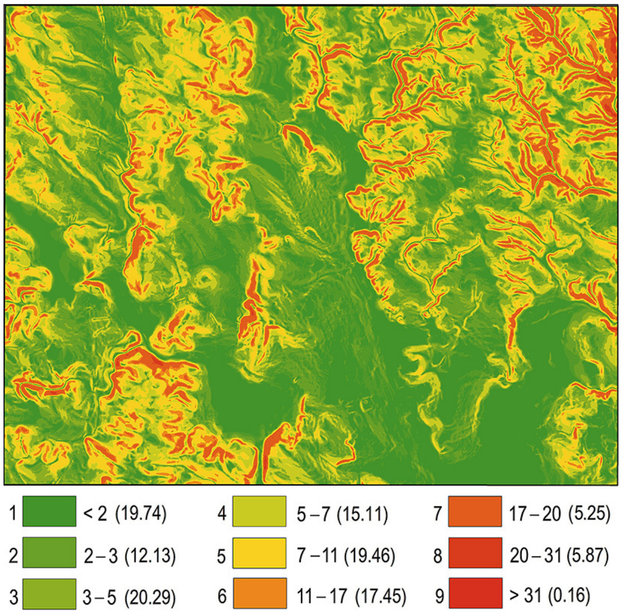

Fig. 6d. **Parametric map of slope angles (classes 1–9). Created from ZABAGED® digital data – altimetry; divided according to Hrašna (1980). Area (km²).**

last event of landslide activation of this type is known from March 2016 in the part of urban district of Bystrc (Figs 13, 14). These problems in the development are caused by the extensive presence of calcareous clays of the Lower Badenian, which within the cadastral area of Brno occupy an area of 94 km² out of a total area of 230.22 km².

Overconsolidated clays in the conditions of South Moravia form a transition between soils and solid rocks. Overconsolidation was caused by increased normal overburden pressure. After completion of sedimentation and retreat of the sea (16.5 Ma ago), consolidation was most effective (soil was not lightened by buoyancy of water). Over the next millions of years, clays were

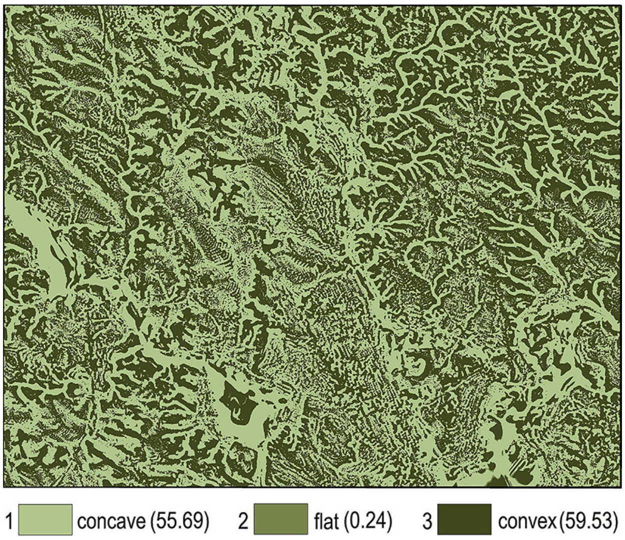

Fig. 6e. Parametric map of relief curvature (classes 1–3). Created from ZABAGED® digital data, altimetry using the Curvature extension tool in ArcGIS 10.2. Area (km²).

Fig. 6f. Parametric map of tectonic lines – constructed from geological map 1:25 000. The presence of tectonic lines is determined by the value 1 ((3,38 km²), its absence by 0 (112.07 km²).

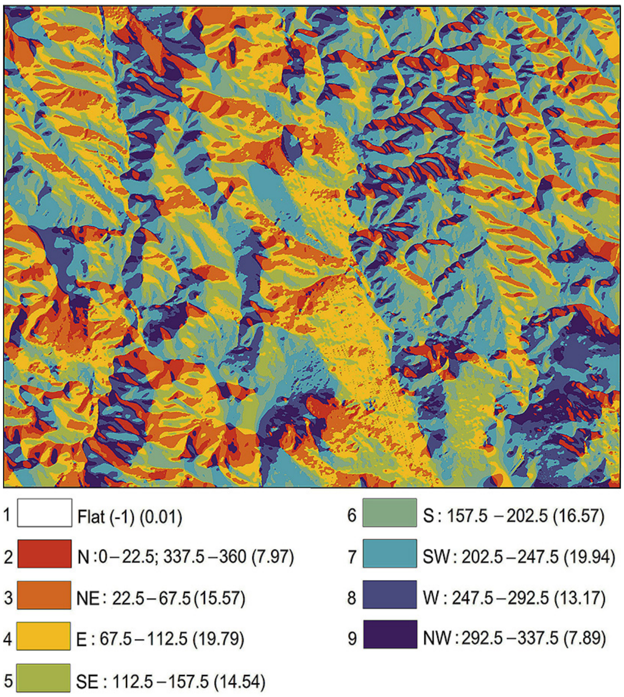

Fig. 6g. Parametric map of the aspect (classes 1–9). Created from ZABAGED® digital data – altimetry using the advanced Aspect tool in ArcGIS 10.2 and divided into classes by degrees. Area (km²).

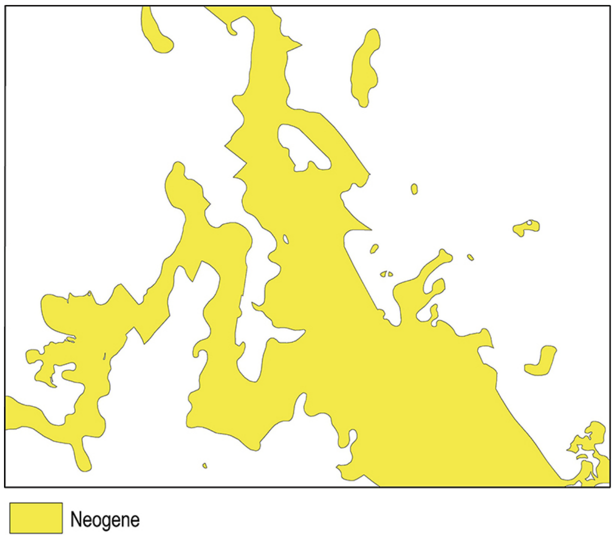

Fig. 6h. Parametric map of Neogene sediments – created from the uncovered geological map of 1:25 000. The presence of Neogene sediments is determined by the value 1 (35.37 km²), its absence by the value 0 (80.08 km²).

weathered and eroded, so increasingly deeper buried parts got to the surface.

Although the clays are characterized by firm up to rigid consistency, they are very susceptible to volume changes, slaking and sliding. Shallow slip surfaces usually develop in landslides (Šamalíková, 1982). In the surface parts clays weather and essentially change their mechanical properties. As they are often overconsolidated soils, they are tectonically (brittle) broken, complicating underground mining works (tunnels, collectors). The main unfavorable feature of clays as foundation soils is their volume instability – as the humidity increases, they swell, while during drying they shrink. Shrinkage is usually not the same under the foundations of buildings everywhere, therefore uneven subsidence of buildings occurs, leading to their failure and breaking of the walling.

4. METHODOLOGY OF STATISTICAL ASSESSMENT OF LANDSLIDE HAZARD

Landslide hazard (the probability of occurrence of potentially harmful phenomena – e.g. landslides, during a certain time period and in a particular area (Varnes et al., 1984)) can be evaluated by using several different methods. The best-known and most widely used is dividing according to Aleotti and Chowdhury, 1999, which is based on the choice of available factors. Factors entering the assessment can be evaluated qualitatively and empirically in various methods, e.g. when assessing the influence of a factor on the development of slope stability, or exactly using quantitative numerical methods. The choice of the method depends on several factors, on the size of the studied area, on the quality of the input data, on the scale and others (Petrýdesová, 2012).

In the area of interest, a multivariate statistical method was chosen to verify the influence of susceptibility to slope movements, which combines several input parameters simultaneously and compares them with the occurrence of slope instabilities in the particular area (Carrara, 1983; Pauditš, 2006; Tornyai & Dunčko, 2013; Bednarik et al., 2014, Tornyai et al., 2016; Buša et al, 2019). Input data has been prepared for the map sheet 1:25 000 Brno-North 24-324, which has an area of 115.45 km^2. In this case, there are 8 parameters that are commonly used to calculate the susceptibility (geology, land use, altitude, slope angle, aspect, relief curvature, presence of tectonic lines and occurrence of slope instabilities) and a layer of Neogene was additionally used (Figs. 6a-h). The importance of each parameter is determined by its frequency and repetition of the parameter class in several combinations within UCU (*unique condition units*). In addition, the multivariate analysis also partly takes into account interactions between individual input factors (Pauditš, 2006).

The dataset ZABAGED – ZM 10, planimetric components and altimetry – 3D contour lines were used for data preparation. The Fundamental Base of Geographic Data of the Czech Republic (ZABAGED®) is a digital vector geographic model of the territory of the Czech Republic which is administered by Land Survey Office in the public interest. To recognize the landslide structures, we used geomorphological mapping and LiDAR-based digital elevation model (DMR 5G, State Administration of Land Surveying and Cadastre) interpretation. This data was provided under a license agreement between the State Administration of Land Surveying and Cadastre and the Ministry of the Environment in 2015. Software ArcGIS 10.2 and its extensions 3D Analyst and Spatial Analyst were used for processing the data.

Parametric map of slope instabilities – created by digitization of mapped area. Only slope instabilities, which are plotted by polygon, were used for the analysis, which means that at least one of their dimensions exceeds 50 m (Fig. 7). Ground instability data is openly available from https://mapy.geology.cz/svahove_nestability/ operated by Czech Geological Survey, Prague. The presence of slope instability is determined by the value 1, its absence by the value 0.

Each parametric map was converted into raster form and subsequently reclassified. The cell size was selected to be 10 × 10 m, which corresponds to 1310 × 1073 cells over the entire area (115.45 km^2).

5. RESULTS

Combining reclassified parametric maps, quasi-homogeneous units (UCUs) were defined, with all combinations of parameter

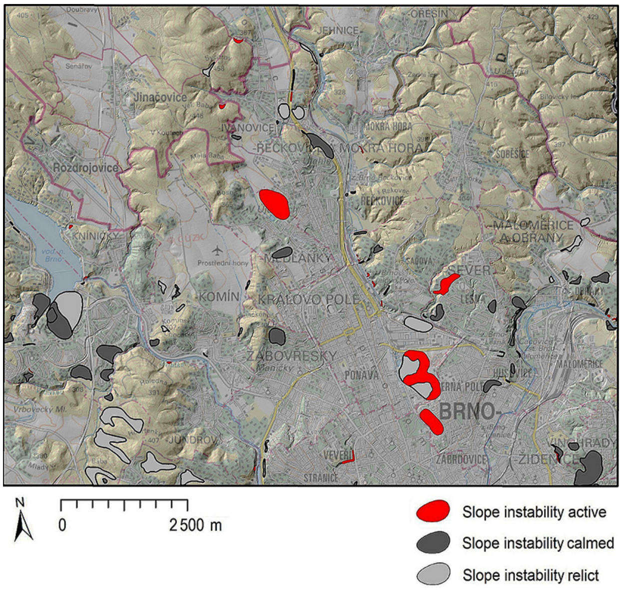

Fig. 7. Cut out from the Register of Slope Instabilities of the area of interest; the data were used to create the Parametric map of slope instabilities.

values that occur in the area of interest. These were subsequently compared with a layer of slope instabilities and the rate of susceptibility of the area to slope movements was determined by statistical procedures. The rate ranges between 0 and 1, where 0 means a stable area and a value of 1 an area most susceptible to slope instabilities.

The resulting interval must be reclassified into several classes. There are several classification methods, for example Natural breaks, Equal area, Equal interval, Standard deviation, Quantile Jenks natural breaks, etc. For visual representation, the data were divided into five classes using the quantile method. This classification divides the elements regardless of the values into individual groups evenly, which in the model area showed the best match with the occurrence of slope instabilities (Fig. 8):

1. very low rate of susceptibility to slope instabilities – value 0 (dark green colour in the map);
2. low rate of susceptibility to slope instabilities – interval of values 0 to 0.0118 (light green colour in the map);
3. medium rate of susceptibility to slope instabilities – interval of values 0.0118 to 0.0353 (yellow colour in the map);
4. high rate of susceptibility to slope instabilities – interval of values 0.0353 to 0.1255 (orange colour in the map);
5. very high rate of susceptibility to slope instabilities – interval of values 0.1255 to 1 (red colour in the map).

Of the total area of the territory of interest, the largest part is in the category with a very low rate of susceptibility to slope instabilities (67 %), low rate is represented by 12 %, medium rate 8 %, high 7 % and the smallest area – 6 % – occupies the highest rate of susceptibility to slope instabilities. Individual classes with areas and percentage are listed in the Table 1:

The prognosis map of landslide hazard compiled by the multivariate method was then verified to evaluate its informative value. To verify the success, the simplest method of verification was used – namely maps, or raster overlapping of registered slope

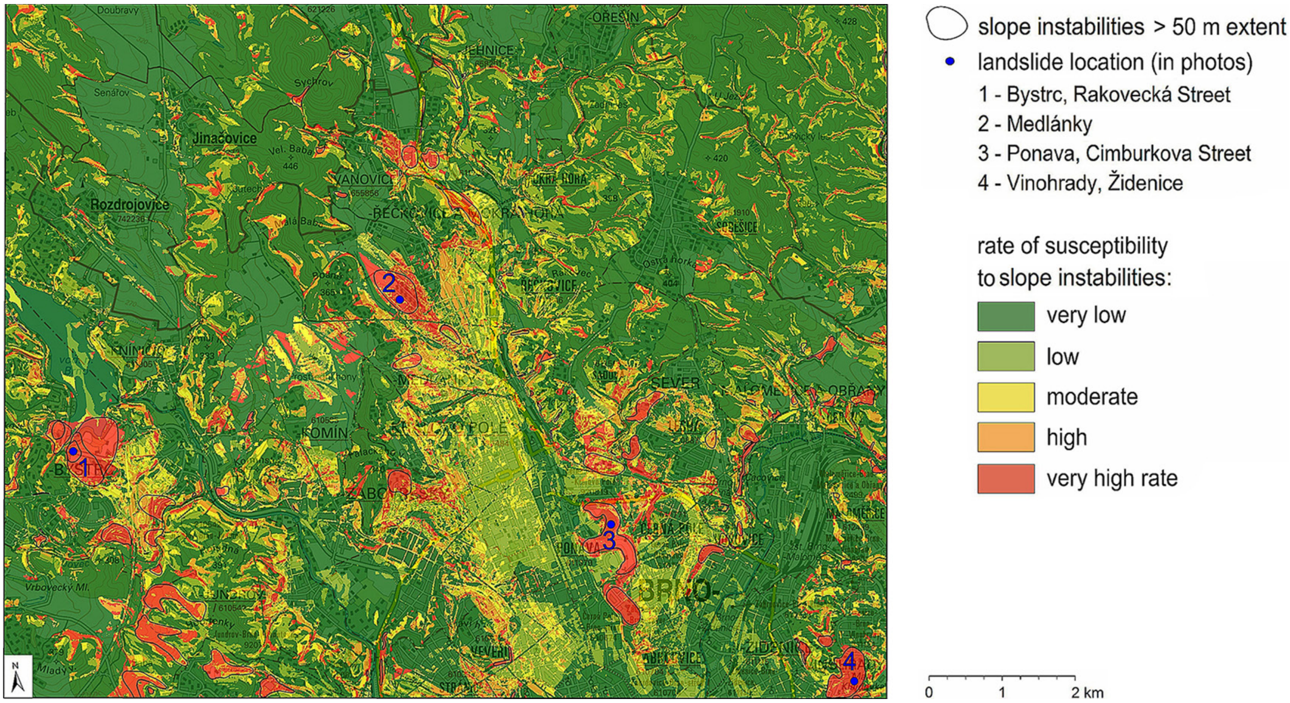

Fig. 8. Final map of susceptibility to slope instabilities 1:25 000, sheet 24-324 Brno-sever with indication of locations where results were verified.

Table 1. Individual classes with area range and percentage extents.

Class of the landslides susceptibility	Extent of the area in km^2	Extent of the area in %
1	77.7505	67
2	13.7457	12
3	8.8315	8
4	7.8792	7
5	7.2434	6

deformations with prognosis map (Bednarik et al., 2014). This verification resulted in a success rate of 93.015 %, thus proving the correctness of the selected method for assessment the landslide hazard in the particular territory.

Four localities were selected and analyzed in more detail. Their location is indicated in the final map (Fig. 8):

1. Location Ponava, Cimburkova Street (Figs. 9, 10) – landslide behind Tesco department store with a total area of 29.75 ha, currently stabilized (Fig. 10). In the 4th and 5th class of

Fig. 9. Ponava, Cimburkova Street, landslide behind Tesco department store during its construction.

Fig. 10. Ponava, Cimburkova Street, landslide behind Tesco department store after its stabilization in 2004.

Fig. 13. Bystrc, Rakovecká Street, landslide reactivated in March 2016. Heavily damaged road.

Fig. 11. Vinohrady, Židenice, view of the main scarp of the landslide.

Fig. 14. Bystrc, Rakovecká Street, landslide reactivated in March 2016. Sliding in a meadow under the road.

Fig. 12. Medlánky, view of the main scarp of the landslide with anchored pile wall. The landslide reactivated during the construction of the housing estate in 2005.

susceptibility there are 29.35 ha, which is 98.65% of the total area of the site.

2. Location Vinohrady, Židenice (Fig. 11) – landslide with a total area of 25.63 ha. In the 4th and 5th class of susceptibility there are 25.4 ha, which is 99.1 % of the total area of the site.

3. Location Medlánky (Fig. 12) – landslide with a total area of 23.25 ha. Activation occurred during the construction of the housing estate in 2002. In the 4th and 5th class of susceptibility there are 22.71 ha, which is 97.67 % of the total area of the site.

4. Location Bystrc, Rakovecká Street – landslide with a total area of 49.22 ha was reactivated in March 2016 (Figs 13, 14). In the 4th and 5th class of susceptibility there are 48.17 ha, which is 97.86 % of the total area of the site.

6. CONCLUSION

Our work contributed to the analysis of engineering geological conditions of construction in the city of Brno. The analysis of the former spontaneous development of the city with its negative consequences, manifested in damage to particular buildings and their complexes (especially prefabricated housing estates), had the effect of stricter conditions for land-use planning. It is mainly a compulsory implementation of engineering geological survey prior to the construction of particular building objects.

The key geological factor in the area of interest is the layer of Neogene sediments with an extent of 35.37 km^2, which represents 30.63 % of the city´s total area. These considerably unstable sediments cause increased instability problems, which have been proved in statistical analysis. Of the total area under assessment, 13 % are in classes 4 and 5 of landslide hazard, which is also 46.02 % of the area of Neogene sediments, from which it is evident that the Neogene contributes significantly to the susceptibility to slope movements.

The results of statistical analysis also show that the greatest instability of the area is caused by a combination of the following parameters:

- presence of sensitive clays;
- geology: colluvial and aeolian sediments, anthropogenic sediments (historical waste disposals, dump piles and excavationts from old exploitation, wild landfills). A total of 61 slope instabilities are related to previous mining activities;
- land use: agricultural land fund, built-up area, forest;
- altitude: 225 to 285 m above sea level;
- inclination of slopes: 5° – 17°.

The aspect, relief curvature and presence of tectonic lines did not play a significant role in the analysis result.

The multivariate statistical method will be further used to assess the susceptibility to slope instabilities throughout the Brno city, which covers an area of 230 km^2 and where the values of the input parametric layers are analogous to the selected area of interest.

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