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SLOPE INSTABILITY HAZARD EVALUATION AND LANDSLIDE SITES MONITORING IN THE WESTERN FLYSCH CARPATHIANS (CZECH REPUBLIC)

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Abstract. The extreme rainfalls in July 1997 triggered slope movements recorded particularly in the flysch-type rocks in the northeastern Czech Republic. The Mesozoic and Tertiary complexes of the West Carpathian Flysch Belt are characteristic by mountain and highland relief of mainly erosion and structurally-denudation nature. The special research project is running now to summarise and evaluate as much information as possible on the physiographic settings and initiation mechanisms of landslide phenomena in the model areas. However, each landslide locality has its own specific features, which apart from the natural prerequisites include also factors caused by human activities.
The focus was to establish geometry, mechanics and possible development of several different typical slope failures. These sites differ in surface topography, slope, lithological and tectonic settings resulting in different morphology and dynamics of moving mass. For recognising the landslide architecture, geomorphic mapping, core drilling and geophysical methods were used. The dating was based on ^{14}C method, palynology, palaeomagnetic and archaeological methods.
The registration of landslides is being processed in digital format, the extensive landslide localities are studied in detail. After the analysis of all the available records from the landslides areas, district area maps in a scale of 1:10,000 are made. The areas are classified in categories by degree of landslide danger and intensity of its occurrence. Maps of stability conditions provide primary basis for graphically simple prognostic maps of landslide susceptibility, sometimes called also landslide hazard maps. Evaluation of stability, morphometric, geological and hydrogeological conditions provides means to define borderlines of quasi-homogeneous zones of certain specific level of landslide hazard. Regional authorities take steps to implement the landslide hazard maps in the regional and town planning.

Key words: landslides, geohazards, risk evaluation, lithology, geomorphology, Western Carpathians.

Abstrakt. W lipcu 1997 roku obfite deszcze spowodowały ruchy zboczowe, zwłaszcza utworów fliszowych, w północno-wschodnich Czechach. Kompleksy mezozoiczne i trzeciorzędowe Zachodnich Karpat fliszowych charakteryzują się wysoczyznami i rzeźbą górską, głównie o charakterze erozyjnym i strukturalno-denudacyjnym. Obecnie jest realizowany projekt badawczy, podsumowujący dotychczasowe obserwacje, mający na celu ocenę wpływu morfologii i mechanizmów uruchamiających zjawiska osuwiskowe na obszarach modelowych. Każde lokalne osuwisko, poza oddziaływaniami przyrodniczymi, było także poddane działalności ludzkiej.
Do badań wykorzystano kartografię geomorfologiczną, wiercenia rdzeniowe oraz badania geofizyczne. Wiek osuwisk określono na podstawie datowania metodą ^{14}C oraz badaniami palinologicznymi, paleomagnetycznymi i archeologicznymi. W wyniku przeprowadzonych badań ustalono geometrię, mechanizmy oraz możliwy rozwój różnego typu osunięć zboczy.
Rejestrację osuwisk prowadzono elektronicznie, duże tereny osuwiskowe dokładnie badano, a wyniki tych badań nanoszono na mapy w skali 1:10 000. Obszary te zostały sklasyfikowane w zależności od stopnia zagrożenia oraz intensywności występowania osuwisk. Mapy prezentujące warunki stabilności terenu stanowią podstawę do tworzenia map zagrożeń osuwiskami. Ocena stabilności terenu, morfologii, warunków geologicznych i hydrogeologicznych pozwala na wyznaczanie quasi-jednorodnych stref o określonym stopniu zagrożenia osuwiskami. Mapy takie wykorzystują władze administracyjne przy tworzeniu planów regionalnych i miejskich.

Słowa kluczowe: osuwiska, geozagrożenia, ocena zagrożeń, litologia, geomorfologia, Zachodnie Karpaty.

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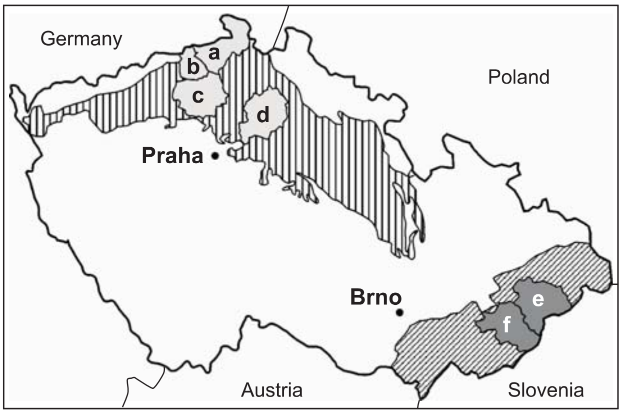
INTRODUCTION

Occurrence of numerous landslides and their reactivations, following high total precipitation, are known since long ago. During the last centuries, hundreds of people died in huge landslides triggered by heavy rainfalls in the Czech Republic. Naturally, the best historically documented landslide calamities are known primarily from densely populated areas (Praha and its vicinity, Western and Northern Bohemia). The extreme rainfalls in July 1997 triggered slope movements recorded particularly in the flysch-type sediments of the Western Carpathians (WCF) and sediments of the Bohemian Cretaceous Basin with Tertiary volcanic intrusions and pyroclastic rocks.

Landslides reaching several kilometres occur in the region of the WCF. The first scientifically documented landslide in this region occurred in Hoššálková in 1919. The landslide destroyed six houses and a small lake came into existence at a point where the landslide front dammed a brook. Actual danger from the slope movements in the WCF was recognised in the course of extensive building of water dams. The constructions of water reservoirs called for a geological research of unusual extent.

The basic registration of slope failures was made in the Czech Republic in the 1956–1962 period. The list, which is being permanently up-dated, is a part of the Slope Failures Register within the activity of the geological survey (CGS-Geofond Praha). The model landslide areas distribution map is shown in the Figure 1.



District areas with number of the landslides:

<500 >500

the Bohemian Cretaceous Basin and Neoidic volcanic intrusions

flysch Western Carpathians

the Bohemian Massif platform

Fig. 1. Schematic geological map of the Czech Republic with marked the most jeopardised district areas to geodynamic phenomena

a — Děčín, b — Ústí nad Labem, c — Litoměřice, d — Mladá Boleslav, e — Vsetín, f — Zlín

BASIC GEOGRAPHICAL FEATURES OF THE LANDSCAPE IN THE MODEL VSETÍN DISTRICT AREA

Origin and development of slope movements in the investigated area are determined by a complex interaction between extreme climatological situations, morphology of the terrain and human activities. Triggering mechanism — an extreme precipitation events, sudden fast thawing of snow cover or human impacts. Rainfalls in July 1997 caused catastrophic flooding followed by the origin of landslides in the eastern part of the Czech Republic, particularly in the Vsetín district.

The district area covers 1,143 km^2 with population of 148,227 inhabitants on 31 December 1999. In the model area, a great number of slope deformations came into existence with pronounced destructive effects. The area of Vsetín district consists of highland up to mountain relief. The highest point of the district — Čertův mlýn — reaches the altitude of 1,206 m. The altitude of the main rivers valley floors varies from 300 m up to 450 m. The relative relief of the investigated area thus reaches 350–700 m. The river network of the area consists of deep incised valleys of Vsetínská Bečva and Rožnovská Bečva rivers.

The area of mountains with frequent occurrence of slope deformations is characterised by cold and wet summers (average temperature for July is 15–16°C), precipitation amounts to 850–1000 mm during the vegetation period. The winter periods are long, mild (average temperature of January is minus 3–4°C), the number of days with frost is 140–160, snow cover is present for 100–120 days.

GEOLOGICAL, PETROLOGICAL AND GEOMORPHOLOGICAL DATA

The WCF complexes are formed by alternating layers of claystones and sandstones of the Mesozoic and Tertiary age. Flysch Belt is an allochthonous nappe system thrusted during the Palaeogene and Miocene tectogenesis over the West European plate. Other suitable materials for gravitational movements are superficial loamy-stone, loamy-clay, loamy-sand or debris sediments as well as thick unconsolidated residual mantles of weathered flysch rocks.

The flysch sediments can be classified into several lithological complexes, based on engineering geological criteria. The conglomerate and "wild flysch" complexes cover a limited area in the Vsetín district. The dominantly sandstone and typically rhythmic flysch lithological complexes build most of the area and host majority of the dangerous landslides. The sandstones can be petrologically classified as poorly sorted arenaceous sediments, more accurately — as quartz-arenites, feldspathic arenites, lithic arenites and the respective types of wackes (sandstones with 15–75% of matrix). The volume density of the sandstones range from 2.33 to 2.64 g/cm^{-3}, the porosity varies from five to 12% in fresh rocks, and over 12% in the weathered ones.

The dominantly claystone complexes are widespread but the landslides situated on this lithology are less common and of smaller size. The type of the cement controls mainly the weathering resistance of the rudaceous (conglomerate) and arenaceous sediments. The most common carbonate and clay-marly cements are easily weathering when exposed to exogenic agents. Thick-bedded sandstones usually weather as deeply as 20 m.

The degree of cementation and lithification is not strictly controlled by the sediment age. The infiltration of the meteoric water is limited to shallow depths due to steeper slopes and lower permeability of the surface layer built by clay-loamy colluvial sediments. The groundwater migrates along the fissure systems, which form a dense but shortly-reach network. The overall tectonic deformation is considerable in the WCF and detailed folding and faulting predispose the landslide planes. Examples of the areally extensive landslides are documented with structure following the syncline cores — joint systems in combination with bedding planes.

LANDSLIDE CLASSIFICATION AND CHARACTERISTICS

The statistical interpretation utilised the basic data of about 200 landslides with detailed documentation from the 1997 and 1998 years. All of them were partly or entirely active after the extreme rainfall in July 1997. The following conclusions result from the statistical analysis:

- — in 40% of cases, the older landslide areas were activated, especially in the extensive landslide areas;
- — human impacts (undercuts, linear construction works, e.g. pipelines, terrain modifications) conditioned the development of landslides in 6.5% of cases, only;
- — lateral fluvial erosion caused landslide in 10% of cases;
- — lithological changes and elements of geological structure (bedding, faults and joint systems) conditioned the origin of landslide in 14% of cases, mainly the deep-seated surface of rupture;
- — landslides were not associated to the higher extent with particular lithostratigraphical units, because 84% of landslide cases were seated in colluvial cover and only in 16% of cases, the bedrock was also displaced.

The landslides were classified into three categories, according to their dimensions:

- — no cases exceeded 100 m (62%);
- — at least one case laid in the interval of 100–500 m (30%);
- — at least one case exceeded 500 m (8%).

The particular landslides types were classified into three basic groups: falls, flows and slides. Slides were a down slope soil or rock mass movements occurring predominantly along a rupture surface or along a relatively thin zone of intense shear strain. For the majority of small landslides, which have not been surveyed to a great detail, the spread type deformations were not determined. The spread is an extension of cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material. Both types fall in our classification to one category — landslide. According to the above classification, the occurrence frequency of the particular categories is as follows:

- — falls, one case only (0.5%);
- — earth, debris or mudflows (15.5%), total frequency in combination with other types are 25%;
- — landslides (69%);
- — complex landslides (15%).

In the case of 12 landslides (6%, included in the complex landslides), the main surface of rupture occurred, according to the conducted geological and geophysical investigations, at the depth of more than 20 m and were classified as deep-seated landslides. The maximum depth of rupture surface proved by boreholes was 70 m. These types of landslides have the following characteristics: obvious morphological features (scarps, uphill facing scarps, trenches, etc.) spread over large slopes areas with high relative topography (>500 m), beginning at the foothill and running often as far or beyond the main upper ridge. They have large volumes and thickness of displaced masses and relatively slow and small displacement (Crosta, Zanchi, 2000).

Table 1

Characteristic of the area regarding stability conditions

Zone	Characteristic of the area regarding stability conditions
I	*stable areas*
I.1	flat flood plains
I.2	permanently stable slopes with very moderate gradient and flat areas above valleys
II	area where slope instability cannot be excluded
II.3	moderate slopes without verified signs of more serious failure
II.3a	moderate slopes without verified signs of more serious failure (with colluvial deposits >2 m)
II.4	steep slopes without signs of deeper failure
II.4a	steep slopes without signs of deeper failure (with colluvial deposits >2 m)
II.5	slopes deformed by superficial creep movements
III	*unstable areas*
III.6	slope deformed by landslides and block-type movements in the past time
III.7	slope deformed by present active or dormant slides, as well as by earthflows
III.8	erosion gullies of occasional as well as of permanent small flows
III.9	steep rock slopes and their toes where rockfalls may occur

Table 2

Conditions for the area to be used as construction site

Zone	Conditions for the area to be used as construction site of: residential and industrial buildings	roads	pipelines
conditionally usable areas			
II.3	suitable for not sophisticated structures, stability fauileres due to improperly designed earthwork are not excluded (cuttings, of-offs, embankments, water leakage etc.)	lay-out of the line, as well as earthwork is to be desingned with respect to slope stability	slope stability must not be inflicted with deep furrows excavated for long-distance lines
II.4	unusable for ordinary building otherwise enormous expenditures must be accepted	suitable only for local roads (e.g. forst roads)	if the lay-out cannot be changed then increased expenditures are to be accepted
II.5	if chosen as construction site increased expenditure for preventive remedy measures must be considered (e.g. for superficial or deep drainage in the area)	suitable only for local roads, otherwise increased expenditures for preventive remedy measures	ay-out of long distance lines along the dip
unsuitable areas			
III.6	unusuitable for building, acceptable only with enormous expenditures for survey, monitoring and remedy measures	construction possible only with enormously increased expenditures	unsuitable area, in case of absolute necessity lay-outalong the dip
III.7	construction has to be avoided unless stabilisation measures carried out beforhand with successful results proved by monitoring	construction possible only with enormously increased expenditures for preventive remedy measures and monitoring	entirely unsuitable area
III.8	entirely unsuitable area	unsuitable area that can be passed by abridge	unsuitable area
III.9	unsuitable area	change of the lay-out is recommended preventive remedy measures would be too expensive	without limitation under the condition of keeping the lines underground in the area of accumulation

From the total number of 200 registered landslides, in 88 cases (44%) the damage reached such an extent, that it was necessary to conduct the engineering-geological survey and geotechnical assessment. As the following step, the stabilisation and reclamation measures were carried out.

After the analysis of all available records from the landslides areas, district area maps in a scale of 1:10,000 are to provide information on hazardous areas of possible occurrence of landslide phenomena. The maps display recent and intermittent slope deformations, presently quiescent in black and recently active deformations in red colour. Fresh cuts of water flow banks and erosional trenches are also indicated. Hydrological and hydrogeological data are in blue. Green colour is used to mark damaged and endangered objects or remedied ones.

Documentation of the registered phenomena, written as well as photographic, is an implicit share of the evaluation. The areas are classified in categories by the degree of landslide danger and intensity of its occurrence. Special maps of stability conditions provide primary basis for graphically simple prognostic maps of landslide susceptibility, sometimes also called landslide hazard maps. Evaluation of input data (stability, morphometric, geological and hydrogeological conditions) provides means to define borderlines of quasi-homogeneous zones of certain specific level of landslide hazard. Colours using a signal head principle differentiate individual zones. Zone I — stable zone is expressed by green, on the other hand, the warning red has been claimed for Zone III — instability zone. Zones conditionally exploitable, i.e. zones where potential stability problems cannot be excluded, are expressed in amber (Zone II). Each zone contains subzones expressed by hatching which characterise local conditions in geology and geomorphology.

Explanations to susceptibility maps are given in tables with short definitions of conditions regarding possible use of subzones as individual construction sites. Regional authorities take steps to implement the landslide hazard maps in the regional and town planning. Characteristic regarding stability conditions of the areas and conditions for the area to be used as construction site of residential and industrial buildings, roads and/or pipelines are shown on Tables 1 and 2.

CONCLUSIONS

Landslides within the investigated area resulted into great material losses and their reclamation costs were high. The impact of land sliding is still visible on the appearance of the present day landscape and its consequences will be felt in the coming years. Landslides localised within forests, according to their size and degree of hazard to public, were reclaimed and in the recent time, they started to be planted with suitable trees (mainly by mixture of spruce, beech, ash, maple or possibly pine). Some landslide areas, especially smaller ones, have been left to natural reclamation. The situation is much more difficult as far as the landslides located on agricultural land or in the housing areas are concerned. These were the cases mainly on slopes with inclination of 5° or more. Some of them were even exempted from the agricultural land resources and are now registered as unfertile land. Other landslides are still utilised for agricultural purposes but as meadows or pastures only (slope inclination less than 5°). In such cases, the use of heavy farm machinery is restricted.

The landslides endangering housing areas and the technical infrastructure (railways, roads) were mostly remedied and their monitoring continues to increase the forecasting ability. The results of the research do not allow deciding unambiguously to what extent the studied landslides were affected by human activities. Yet, the contribution of human impact is indisputable. The numerous landslides of various sizes originated both in the forest (mainly in spruce monocultures) as well as in the grassland with dispersed woody vegetation or even with scattered settlement.

The landslides themselves had a destructive impact on the local infrastructure. These were partly restored but the risk areas witnessed the profound changes. One of many consequences of the extensive slope processes is also the change in land use in the locations of particular landslides. With respect to the possible reactivation of the slope processes, the risk areas were in most cases exempted from the agricultural land resource category or housing resource category and reclassified as forest or other category according to the progress of land reclamation. Some landslides were drained and became a subject of forestation, other have been left to the natural evolution, most of them being colonised with pioneer herbs and woods.

The unusually high number of landslides in the WCF mountains and highlands was caused by a combination of the lithological rock properties, regional topography, river network geometry and especially, by the high precipitation (up to 400 mm during several days in July 1997).

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