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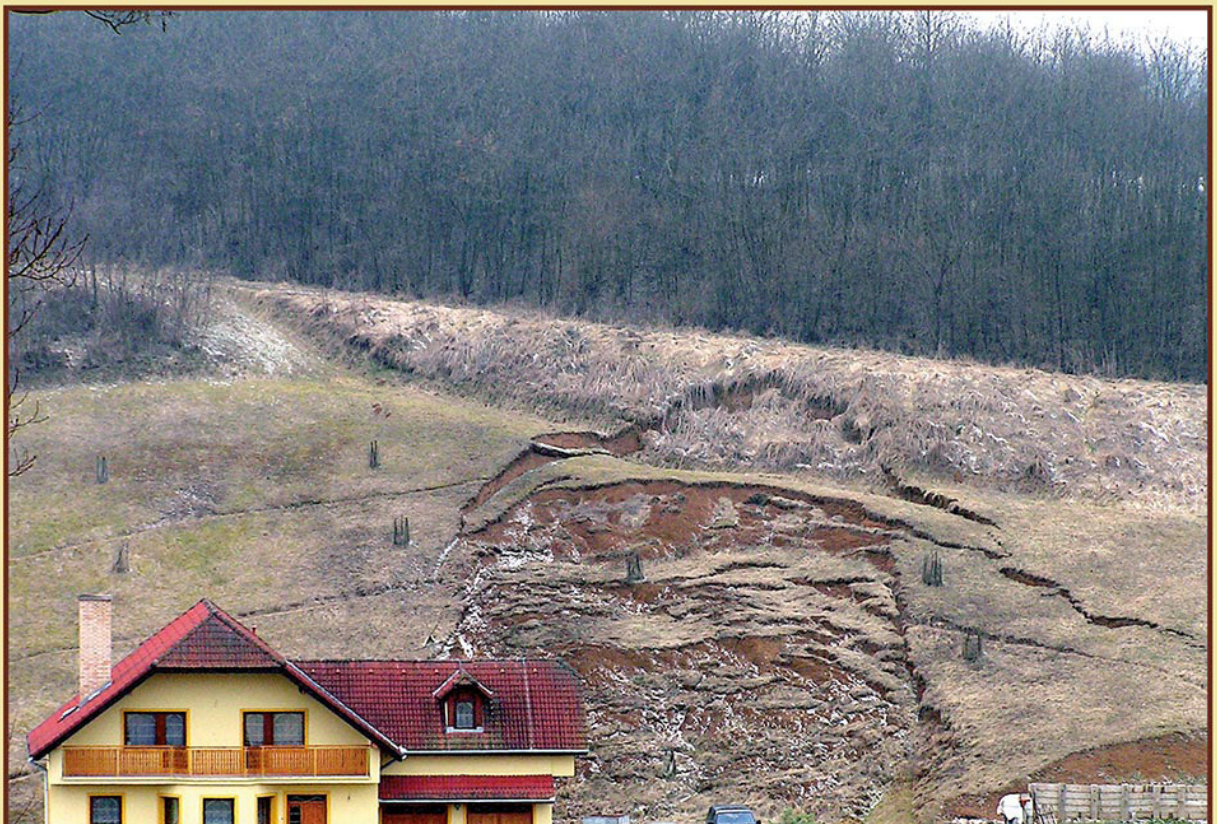
Slope Failures in Slovakia
Recent Research and Perspectives



State Geological Institute of Dionýz Štúr, Bratislava

1/2014

Contents

SLOVAK GEOLOGICAL MAGAZINE

Periodical journal of the State Geological Institute of Dionýz Štúr is a biyearly presenting the results of investigation and researches in wide range of topics:

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Cover: Landslide of 2011 in Lipovany Village (photo P. Liščák).

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Preface

Slope deformations represent the most dangerous exogenous geodynamic phenomenon in the Slovak Western Carpathians, posing a threat to humans and their property and to natural environment.

More than 30 years have passed since the publication of the well known monograph of Arnold Nemčok, "Landslides in the Slovak Carpathians, 1982". By the date of the issuance of the book, 9194 slope failures had been registered, covering about 1,500 square kilometres, representing about 3% of the entire territory of Slovakia. The publication contains several tens of cross-sections and map schematics of landslides, more than hundred photographs, corresponding explanations and the text, which became a timeless source of knowledge concerning the slope failures distribution in the regional geological, geomorphological and engineering geological conditions of Slovakia. In addition to the above assets, the monograph has become the textbook for the next generations of engineering geologists, who continued in the work of their teachers, founders of the prominent school of Czechoslovak "landslide" geologists.

Since the date of the issue of the "Landslides in the Slovak Carpathians", a third stage of slope failures inventory was launched and was completed in 1991 and the number of slope failures registered in Geofond rose to 15,000. However, in the process of inventory covering different periods, performed by different organizations and authors, the map documents often lacked correlation and acceptance of the results of previous surveys and inventories. This resulted in numerous confusing multiple registrations of the same slope deformations, at the same time with different interpretation of their borders and characteristics, including the slope deformation type and activity. As a consequence a demand emerged to create a consolidated database of slope deformations at uniform scale of 1:50,000, using modern computer technology. That is how the important project of "Atlas of Stability of Slopes in SR at 1:50,000 scale" began, covering a period from 1997 till 2006. Although it was based upon the previous inventory, nevertheless the number of the identified landslides increased significantly to 21,190 representing 5.25% of the area of Slovakia. Additional further benefit was an estimate of the land areas susceptible to slope deformation.

The Atlas's database has enabled us to identify the landslide hazard and risk using to-date methods of slope failures assessment and prognosis, both at nation-wide as well as regional and site-related scales. However due too small scale of 1:50,000 and related incompatibility of the selected topography ZM 50 with the topography of larger scales, the Atlas has also limitations for purposes of spatial planning; thus a transition into topographically accurate spatial database based on larger scale has become the challenge which is currently being solved in cooperation with IT specialists.

The year 2010 was nicknamed as the Year of Landslides. Due to the extreme climate events of spring of that year, hundreds of newly-generated landslides, along with catastrophic floods, wraught damage, mainly in Eastern Slovakia. Those with the greatest socio-economic relevance (Nižná Myšľa, Kapušany, Nižná Hutka and the others) have been incorporated into the file of sites which are monitored in the scope of Partial Monitoring System of Geological Hazards. These to-date encompass 49 monitored sites of all essential types of slope failures across Slovakia. At the sites of Okoličné and Veľká Čausa Early Warning Systems have been established based on data acquired through long-term observations of groundwater regime and kinematic activity. Naturally, large engineering structures such as nuclear power plants, water works, and major communication have developed their own monitoring networks, including regular observations of landslides and artificial slopes.

The monograph is arranged into 8 articles with the aim to provide a review of recent slope deformation research in Slovakia. The authors of the monograph believe that the book offers to public in Slovakia and abroad the essence of the major achievements in the study of landslides since the Handlová Landslide of 1960/1961.

The authors take this opportunity to congratulate the founder of the Department of Engineering Geology and Hydrogeology at the Faculty of Natural Sciences, Comenius University, **Prof. Ing. Milan Matula, DrSc.** on the occasion of his 90th birthday. Happy Birthday, Professor Matula, good health and many blessed and successful years to come!

Branislav Žec and *Pavel Liščák*

LIST OF ACRONYMS

CGO Prague	Central Geological Office, Prague
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DoGNR MoE	Division of Geology and Natural Resources of the Ministry of Environment
EG	Engineering Geology, engineering geological
EPSG	European Petroleum Survey Group
FCE STU	Faculty of Civil Engineering, Slovak University of Technology
FNS CU	Faculty of Natural Sciences, Comenius University
GeoIS	Geological Information System
GIS	Geographic Information System
GKÚ SR	Institute of Geodesy and Cartography
GLONASS	Global Navigation Satellite System (*In Russian: Globalnaya Navigacionnaya Sputnikovaya Sistema*)
GNSS	Global Navigation Satellite System
GPL	General Public Licence
GPS	Global Positioning System
GSD	Ground Sampling Distance
GSM	Global System for Mobile Communications (*originally Groupe Spécial Mobile*)
GWTL	Groundwater Table Level
HDB	Horizontal Drainage Borehole
IT	Information Technology
KNC/KNE	Real Estate Cadastre (*parcels C and E, Slovak Cadastre*)
LC	Lithological Complex
MSUE	Main Scarps of the Upper Edges
MoE	Ministry of Environment of the Slovak Republic
PMSGF	Partial Monitoring System of Geological Factors of the Environment
PPP	Public-Private Partnership
SD	Slope deformation
S/GIDŠ	State / Geological Institute of Dionýz Štúr
SHMI	Slovak Hydrometeorological Institute
S-JTSK S-JTSK	Krovak East North (*System of Uniform Trigonometric Cadastral Network*)
SQL	Structured Query Language
SR	Slovak Republic
SRID	Spatial Reference IDentifier
UCU	Unique Condition Unit
UTM	Universal Transverse Mercator
WMS	Web Map Service
WR	Water Reservoir
ZB GIS	Primary Base of Geographic Information System
ZM 10, ZM 25, ZM 50	Basic map at scale 1:10,000, or 25,000, or 50,000

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1. History of Systematic Research of Slope Failures in Slovakia

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Abstract. Due to much dissected morphology and complicated geological setting the territory of the Slovak Republic is affected by abundant slope deformations that cause significant harm the whole society. The origin and evolution of slope deformations may be natural, but very often they result from human activities, especially construction activities. The increasing number of landslide accidents in the previous century resulted in a necessity of a systematic study of this phenomenon with the goal of their registration, knowledge of the causes and progressive elimination of adverse consequences. In the article the authors present a brief overview of the history of the study of slope movements in Slovakia, demonstrating the crucial importance of the catastrophic Handlová Landslide from the break of 1960/61 for further systematic research of slope deformations; they outline the main results of the study in the last fifty years and indicate the current issues of the slope deformations research at present.

Keywords: slope failure, landslide inventory, landslide mapping, landslide monitoring, susceptibility to landslides, landslide hazard/risk assessment

1.1. Introduction

The incidence of slope deformations in Slovakia is conditioned by several specific features - the existence of geological structures favourable for generation of slope movements, complicated hydrogeological and climatic conditions, as well as continued height differentiation of individual mountains, depressions and lowlands due to rapid neotectonic movements. The summary effect of all these factors has led to violation of vast territories by landslides, which are activated primarily during the periods of rainfall anomalies. However, in view of the increasing number and range of technical interventions in the natural surroundings, the number of human-induced slope movements started to increase significantly, or many of the dormant ones have been reactivated. The assessment of the stability problems of the territory became a part of the preparation of any major construction in the first half of the last century. However, after the disastrous Handlová Landslide by 1960/61 not only professional and lay public but also the responsible national authorities realized that the stability assessment of the area was an essential part of spatial plans and technical development projects in rural areas. Thus the foundations for a systematic study of slope movements were created, which was coordinated by state administration bodies - Slovak Geological Office, later the Division of Geology and Natural Resources of the Ministry of Environment of the Slovak Republic (hereinafter DoGNR MoE). After several stages of registration of slope deformations the attention was gradually focused on selected areas, prone to slope deformations and important for the development of urbanization of Slovakia. For these territories purpose stability maps were created and methods and methodologies of the stability condition developed, as well as forecasting of future scenarios. At the same time in this period new unexpected landslides of emergency nature were promptly investigated and stabilized. Undoubtedly, a culmination of this extensive systematic research in the slope deformations represents the Atlas of Slope Stability Maps SR at 1:50,000, which was compiled between 1997 and 2006. The Atlas presents the completion of slope movements' inventory in Slovakia as a source material that can be used as a basis for advanced research of this issue using modern methods and addressing current social demands. Currently, the focus shifts into landslides vulnerability assessment of area and forecasting their occurrence using a set of evaluation methods for landslide hazard and risk, monitoring methods of selected slope movements sites with the transition to the creation of early warning systems, as well as new procedures for emergency rehabilitation of sliding slopes. Accounting for a dynamics of the phenomenon under consideration the information summarized in the Atlas are not fixed and extreme weather events (rainfall anomalies in 2010) have generated a considerable number of new slope deformations with consequent reassessment of a degree of susceptibility of certain areas to slope deformations.

The history of slope movements' evaluation in Slovakia is in several respects illustrative and instructive example of the development of modern society views on the optimal ways of our coexistence with these adverse geodynamic phenomena and the gradual elimination of the adverse consequences.

1.2. The onset of slope movements issues solution (till 1960)

In the period before the emergence of engineering geology and the early years of its formation as a separate discipline (in the first half of the last century) is hardly possible to speak about systematic research of slope movements. The phenomenon of slope failures, however, was known for more skilled science disciplines and important areas, affected by these phenomena, were reported in several geological, as well as geomorphological maps, compiled in this period. The most attention, however, elicited by the stability of slopes disturbance due to inappropriate interventions in the geological environment in the construction of technical works - particularly the implementation of cut-offs, as indispensable components of the transport and hydraulic structures. Virtually every expert opinion from this period, addressing a feasibility of selected building works, there is mention of the presence of slope failures and the possibility of their initiating by the construction work (Wagner, et al., 2000).

From the preserved extensive studies already since 1920 solutions of landslide problems are known in the construction of the railway network, interconnecting Slovakia with Bohemia. The proposed routes passed a complicated geological environment and specialized map of landslide area was an important tool in the design of their definitive location (Kettner & Záruba, 1922 in Malgot & Baliak, 1999). The knowledge of the stability problems was refined at the implementation of other large-scale railway projects, road constructions, crossing the Flysch Zone (Záruba & Myslivec, 1942), but also in the preparation of other railway lines designed in complicated geological conditions of the Western Carpathians. In addition to transportation network, the issue of slope movements was very timely in preparation of major hydraulic structures. Well-known are stability assessments in the preparation of the Upper Váh cascade in the section between Krpeľany and Lipovec (Záruba, 1954, Záruba & Mencl, 1958). Principles of geological survey methodology for the construction of dams in the area of the Carpathian Flysch, including the assessment of the stability problems, summed up Záruba (1957).

As already mentioned, the solution of stability problems in this period was largely tied to specific tasks of safeguarding the stability of slopes in concrete structures, or locations with manifestations of slope failures. Certain generalized dimension within the study of slope movements represents their record in basic geological and geomorphological maps. However, it is only a spatial location of mapped slope deformations, without learning their patterns of formation and development. Nevertheless, it can be stated that through scientific erudition and ability to synthesize knowledge brought by several important leaders of emerging Czechoslovak Landslide School - mainly Academician Q. Záruba and Prof. V. Mencl, in this time stage significant pioneering work came out, often with a strong element of synthesizing, which became the foundation for future systematic research of slope movements in Slovakia.

1.3. Handlová Catastrophic Landslide (December 1960 – May 1961)

The Handlová catastrophic landslide was active from 11/12/1960 till 30/5/ 1961. In the head area the landslide started with 80 to 110 m wide earth flow, with tributary slide they joined to a huge landslide with a width in the accumulation area of 1200 m (Fig. 1.1, Baliak & Stríček, 2012). The thickness of the slip materials in the head area was 7 m, in the accumulation zone up to 30 m; total cubic capacity of slide reached about 20 million m^3 (Záruba & Mencl, 1969).

The landslide movement had the greatest intensity from 22/12/1960 till 20/01/1961, when the movement rate reached up to 6.3 meters for 24 hours. Horizontal displacements of the mass in the central part of the landslide reached 240 m, in the accumulation part 22 m.

The consequences of the landslide were catastrophic – 150 residential homes were destroyed along with a section of the State Road 1/50 of the length of 2 km, branch Handlová water-line and several lines of high voltage (Nemčok, 1982). The Handlová Landslide is still considered the greatest natural disaster in Slovakia, induced by slope movement (Baliak & Stríček, 2012).

The Handlová Landslide was initiated by rainfall anomaly in the period from June to December, 1960. However, as shown by the results of the survey, the origin and evolution of the landslide was predestined by specific geomorphological, geological and hydrogeological conditions suitable for the formation of slope movement. Actual rainfall anomaly represented only the immediate impulse for kinematic activation of landslide masses, which occurred in stability equilibrium state.

The development and consequences of the catastrophic Handlová Landslide meant undeniable landmark in the perception of the importance of slope movements and the need of their study not only by professional and lay circles, but also by competent bodies of the state administration. The landslide has demonstrated the fact that natural disasters so large in scale may arise in our latitudes, and even without the adverse impact of human activity. The related damages have vividly illustrated the danger for the population and the overall development of the regions that stems from activating slope movements in areas prone to landslides.

In addition to extensive research of the slide area, as well as the establishment of an “anti-landslide station” in Handlová providing continuous monitoring of the landslide area, perhaps the most important consequence of the Handlová Landslide disaster has become the beginning of systematic research of slope deformations in the former Czechoslovakia. Engineering geological specialists focus preferentially concentrated to slope failures inventory throughout the country with emphasis on investment perspective areas. This attitude was based on the assumption that new landslides preferentially generate in areas that are already affected by slope failures. The concept of regional distribution of slope deformations allows in further to analyze the patterns of their formation and evolution, and derive other facts leading to the understanding of the phenomenon, its forecasting and timely adoption of the necessary stabilization measures. Thus, since the early sixties the systematic study of slope movements has become a component of purposeful research coordinated by central state administration body (initially Slovak Geological Office, later DoGNR MoE of the Slovak Republic).

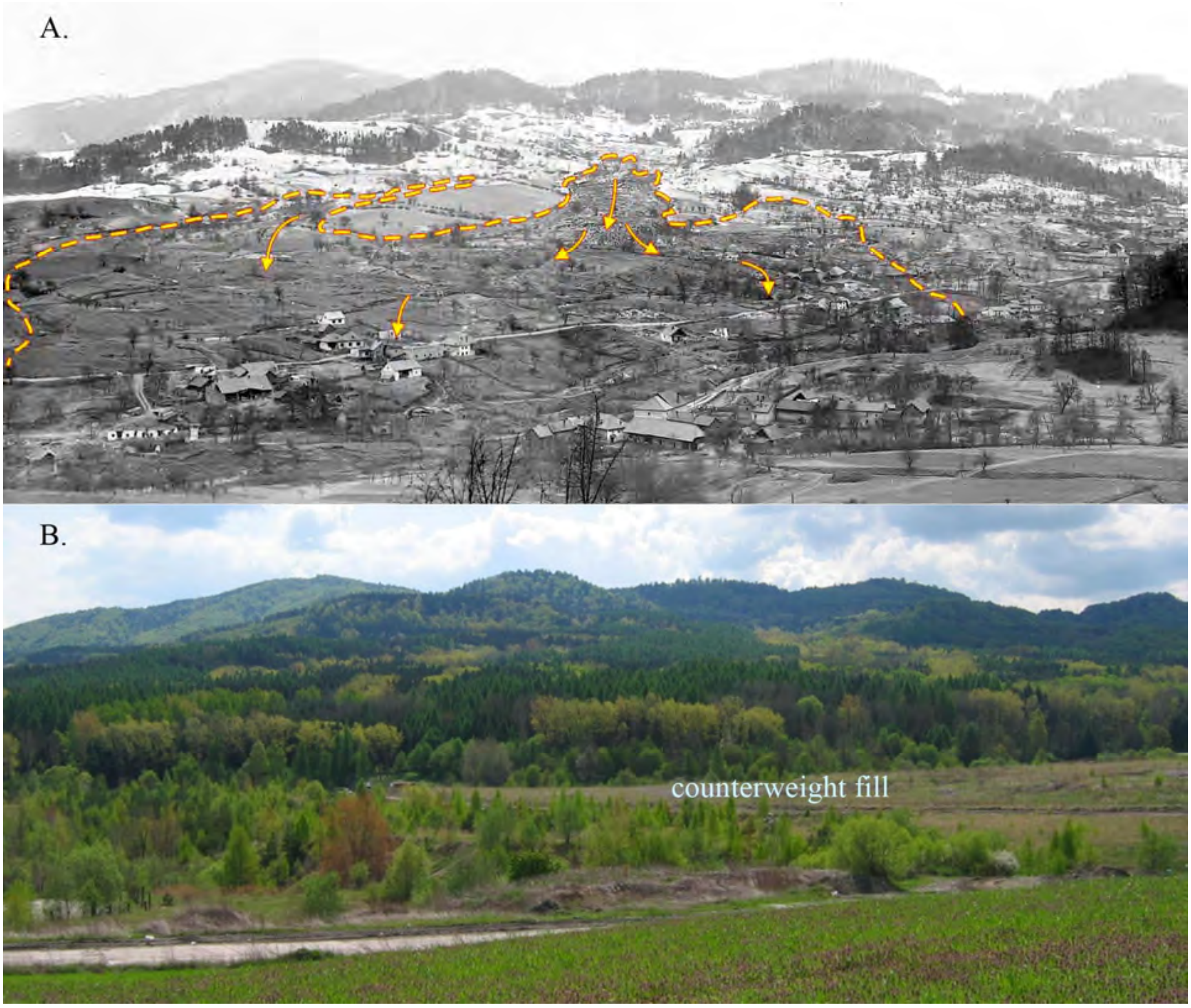

Fig. 1.1 View of the Handlová Landslide. A - photo of 1961; B - recent photo, corrective measure - counterweight fill

1.4. Systematic research into slope deformations (since 1961)

Analysis of the causes of the Handlová Landslide has shown that in certain geological structures, in case of synergy of several factors, formation or reactivation of slope movements can occur with difficult to control development and with serious consequences for the entire affected area. Growing evidence from other sites of slope movements indicated the fact that the slope failures in Slovakia mostly occur in certain geological environments (particularly the areas of the Carpathian Flysch and the Neo-volcanic mountains). Increasingly the aforementioned assumption has been confirmed that new landslides occur, or are activated in most cases at the places which were hit by these movements in the past.

In view of the above, at drafting of the systematic research of slope deformations, as their primary objective appeared nationwide registration. Consistent inventory, made since the beginning of the sixties of the last century, has allowed at the same time to identify the areas with the most likely occurrence of slope movements and to avoid in time these territories when designing major investment plans. Already that time experience did indicate that the stabilization of active landslides is much more difficult and costly than preventive measures (including warnings when designing technical works). Registered landslides were systematically imposed in the registry, located in Geofond in Prague and in Bratislava.

In parallel with the continued registration of slope movements, the selected areas of Slovakia were analysed in terms of their vulnerability to landslides (usually at scales of 1:25,000 and 1:10,000) and gradually upgraded maps of susceptibility to landslides were created, adopting progressive methodological procedures. As completion of this relatively long inventory the Atlas of Slope Stability Maps SR at 1: 50,000 (1997-2006) can be considered, in the scope of which the earlier stages of registration of slope movements were processed and the territory of Slovakia was validated according to a probability of slope movements generation.

Of course, even over a long period of registration, purpose mapping and research of slope deformations unexpected slope failures originated in different parts of the territory of Slovakia, often with very unfavourable development and emergencies had to be declared and immediately solved by appropriate measures – from the optimal methods of engineering survey, over stability calculations to the design of correction of affected slopes. In an effort to avoid such unexpected cases, systematic monitoring of selected, from social point of view the major sites started in the early nineties with a vision of future operationalization and verification of early warning systems for the areas of slope movements of major socio-economic importance.

1.4.1. Inventory of slope deformations

The inventory of slope movements was carried out in several stages, during which the method of individual slope deformation registering (use record sheets) was updated. The ways of slope movements' inventory was described in the work by Kováčik & Suchánková (1993).

In the **first stage of registration** (1961-1963), implemented by a number of scientific and university institutions of that-time Czechoslovakia, there were registered about 5,000 slope deformations at scale 1:25,000 (Matula et al., 1963). Thanks to the observed data it was possible to develop large-scale regional studies on the occurrence of slope movements in Slovakia and to identify their relation to geomorphological and geological conditions. It was also possible after registration at this stage to identify the areas with the greatest risk of slope movements; these areas were further studied in more detail. The inventory sheets of the first phase of registration of slope failures were stored in Geofond Bratislava, or Geofond Prague. The results of the registration files were processed both in the final report, and also in the first general maps at a scale of 1:1,000,000, expressing the density and distribution of slope failures in the territory of former Czechoslovakia.

Although the register of landslides (the map-sheet layout at scale 1:25,000) was continuously complemented on the data from the reports on engineering geological survey, it barely contained information on landslides, violating the areas outside the construction plans (i.e. cropland, pastures, meadows). Therefore, in the years 1974 to 1978 the **second stage of registration** was initiated, mainly focused on high mountains. This stage was conducted by the Department of Geotechnical Engineering Faculty of Engineering of the Slovak Technical University (Nemčok et al., 1980). The results of this phase of registering significantly enriched the knowledge of occurrence patterns of the slope deformations in the Western Carpathians and were used also in the creation of a new classification of slope movements (Nemčok et al., 1974). Total number of registered slope movements at the end of this phase increased to about 10,000, whereas the methodology of slope deformations registering has been upgraded in order to enable the use of computer technology.

The **third stage of registration** of slope failures ran from 1981 to 1991 and was carried out by workers of the Department of Engineering Geology GIDŠ in Bratislava. Nationwide study had regional character and its goal was to know in more detail the regularities of the origin and evolution of slope deformations and complement their existing registry. Important aspect of this stage of registration of slope failures was the selection of suitable sites and socio-economically significant slope movements to launch their long-term monitoring in Slovakia (Modlitba & Klukanová, 1996). In the third stage of registration there were recorded about 5,000 new slope deformations, bringing the total number of slope failures registered in Slovakia in the late eighties to less than about 15,000.

1.4.2. Research and survey of selected areas of slope deformations occurrence

The evaluation of selected areas of occurrence of slope deformations usually followed after their registration or often both activities were conducted in parallel. Perhaps the only difference in the registration and evaluation of slope deformations was the fact that the registration was of typically regional character study and its primary aim was to record the incidence and nature of slope deformations within a given geographical or geological formation. When evaluating slope deformations of selected areas basic maps of slope failures were drawn up usually at scales of 1:25,000 and 1:10,000 (this scale is often called the study area level - areal level). Selection of areas for such evaluations was carried out by central government body (recently DoGNR MoE). The selection was based on the general knowledge on the extension of slope failures, but also on the intentions of urbanization development of Slovakia. In the method of processing the latest research in the evaluation of slope stability was applied, along with progressive cartographic techniques to express the area susceptibility to landslides, forecasting stability condition etc.

Several areas prone to slope deformations were processed – the most famous areas should be mentioned, for example, Handlová Basin (Malgot et al., 1973), Liptov Basin (Mahr et al., 1984), Blh-Pokoradza Plateau (Demian et al., 1990), Orava Basin (Vrábeľ et al., 2000) and several others.

Within each of the treated areas representative sites of active landslides were selected, which were further studied in detail, including stability analysis, scenarios

Fig. 1.2 View of the Kraľovany Rockslide (Photo by Žilka, April 2014)

and proposals for remedial measures. In the past, the locations of these representative provided a basis for new exploration methods (e.g., a set of methods applied at pilot areas Turany, Okoličné and others in the seventies – Fussgänger et al., 1976), or they served for trial applications of new remediation methods (e.g. testing of drainage gravel walls in the brickyard Sučany, etc.). Gradual trend of further processing of further socio-economically important areas continued in the territory stability assessments in the scope of maps of environmental geofactors at scale 1: 50,000.

In parallel with centrally managed research and exploration of slope failures, on the basis of government-departmental requests purpose maps of territorial stability were processed in line with the forthcoming significant investment plans - known is extensive slide area between Hlohovec and Sereď in connection with the Váh Waterworks project (Otepka 1983) and a number of stability studies in connection with the construction of roads (Kopecký et. al., 1997).

It can therefore be concluded that systematic research of slope movements since the beginning of the sixties carried out at the regional (registration) and district levels (research and exploration of selected landslide areas). At the same time the data obtained were complemented on the results of surveys of local emergency landslides.

1.4.3. Survey of emergency landslides

For a long period covering about 35 years, despite extensive activities aimed at the study of slope deformations and prevention of their adverse consequences a number of unexpected emergency slope movements have been generated that needed to be addressed urgently, including proposals for immediate and long-term optimal remediation.

Apart from a repeated Handlová Landslide activations of 1960/1961 (most of them were recorded between 1966 and 1970 - Kuchár, 1996 and in 1999 and 2000 - Ingár & Wagner, 2004), perhaps the most attention in a wide professional and general public received catastrophic earth flow in Ľubietová in the spring months of 1977. The landslide originated without the impact of human activities and the main cause of its formation was precipitation anomaly at the beginning of 1977. The landslide movement destroyed four houses, began to move through a stream threatening the damming and flooding the valley and the village Ľubietová (Nemčok, 1982). Another significant rainfall anomaly in the national scope was recorded in the spring of 1995 and caused a number of reactivations of older landslide areas, especially in the Handlová Basin (Veľká and Malá Čausa, Bojnice), as well as in Nová Baňa (Fussgänger et al., 1996). The vast majority of landslide movements from the period of the seventies and eighties, however, were initiated by human activities, especially the construction activities. In connection with the construction of housing estates were observed extensive slope movements in Handlová (Morovnianske sídlisko settlement in the years 1974 to 1977), in Košice (settlement Dargovských hrdinov in the seventies), Zvolen (complex Zlatý Potok in 1974) and other cities (Nemčok, 1982). The mass movements significantly affected traffic on the railways - the most famous accident of slope failure was rock collapse at Podbiel in 1975 (Slivovský, 1977), slope deformation at Kriváň Village or slumping slopes rail notch at the Veľký Krtíš (Slivovský, 1979), and many existing, or newly-built sections of roads (especially the roads crossing the Flysch Zone). With the activation of landslide movements encountered the implementers of major water projects in Slovakia – Liptovská Mara, Domaša, Nová Bystrica etc. (Kopecký et al., 2014).

1.5. Atlas of Slope Stability (1997- 2006)

It is understandable that a relatively long period since 1961 would require a more detailed description of all the activities that were carried out in the study of slope failures - whether in terms of research issues, quality improvement of methodologies solutions, as well as surveys of specific demanding sites and their corrective measures proposals. Despite the diversity of issues solved certain unifying element throughout the period mentioned was felt resulting in an attempt to register the greatest number as possible of slope failures in our area and gradually shift to modern methods of their assessment, including the assessment of area susceptibility to landslides and stability forecasting. Therefore, the Atlas of Slope Stability Maps SR at 1:50,000 (Šimeková & Martinčeková, 2006) can be considered as final output of this time-extensive stage, which in the period 1997-2006 was compiled by a team of top experts on landslide issues from various institutes. The nature of the output documents of the Atlas (digital processing of the results in GIS) illustrates a comprehensive development, which has been reached in the study of slope failures in Slovakia.

The main objective of the Atlas work of was to process all existing information on the occurrence of slope deformations in Slovakia from previous registration and mapping, and present them in a modern and accessible way to the general public. The main archival source was stored in the Landslides Registry in Geofond. Contradictory data and less investigated areas were verified by field mapping. The main outputs of the Atlas were slope stability zoning maps at a scale of 1:50,000, covering the entire territory of Slovakia (total 132 sheets of maps - Fig. 2.1, Šimeková et al., 2014). The zoning map depicts unstable, potentially unstable and stable areas along with all slope deformations registered in the territory of the sheet. Each slope deformation is labelled and processed in a data sheet, containing 28 items of basic information.

Complex processing of data in the Atlas enabled to perform a set of statistical evaluations on the territory of Slovakia disturbed by slope failures. Prior to the Atlas, based on the data from three stages of the registration there had been estimated that slope deformation affected 3.06% of the territory of the Slovak Republic, after completing data in the Atlas were recorded all-in-all 21,190 slope deformations, covering the area of 257,591.2 ha, representing 5.25% of the territory SR (Kopecký et al, 2008). The way of data processing in GIS has allowed to derive a number of other important information about the violation of the territory of Slovakia slope failures. The summary of these findings is presented in detail in the contribution Šimeková et al., (2014) of this monograph. It can be concluded that the Atlas represents a worthy comprehensive work summarising many years research into slope movements (since 1961) in Slovakia. Although it was finalized in 2006, the GIS database allows its constant update and to make use of stored data in follow-up studies and analyzes. The dynamics of this phenomenon, as well as the development of methods of assessment and forecasting of slope deformations caused that even in recent years (since 2006) there have been significant changes in certain parts of the territory, as well as methods of evaluation.

1.6. To-date trends of the slope movements research after 2006

The Atlas along with the GIS database of all recorded slope deformations does not represent only the completion of an extensive study phase slope deformations in Slovakia since 1961, but it serves as well as input for continued research on this issue. Thanks to the significant progress in methodology and research methods and increasing demand, the registration and mapping of the phenomenon provide only essential basis for solving current issues of the active protection of the territory and society from the adverse effects of the slope movements. The focus has been shifted into slope movements monitoring and development of early warning systems; regional studies aspire to improve methods of landslide hazard and risk assessment. In particular, the newly emerging catastrophic landslides have become a challenge in developing progressive methods and techniques of rehabilitation of the slope movements.

Despite the undeniable progress in research it is not possible to avoid the impact of extreme natural (climatic) events. For instance, the climate extremes occurred during May and June 2010 and more than 500 new slope deformations significantly changed the map of slope deformations distribution in the Eastern Slovakia.

1.6.1. Monitoring of slope movements

Monitoring of slope movements was an element of engineering works in unstable areas in the past, but usually it was applied during implementation and after remediation to verify effectiveness and functionality of corrective measures. Such monitoring was perceived as only a short-term process and after leaving the site the survey organization terminated its operation (maximum after about one year). This was usually associated with not only termination of periodic measurements, but also maintenance of rehabilitation objects was stopped. Renewed interest in the functioning of remediation facilities was usually associated with recurrent activation of slope movements. The above practice was experienced in most major slope movements in Slovakia in the second half of the last century. The exceptions to the common practice represented only demanding construction works, located in a potentially unstable environment. These included major hydraulic structures (sufficiently illustrative example is Liptovská Mara Waterwork, where monitoring of the so-called Veľká Mara landslide has been implemented. The landslide is located near the right-hand abutment of the dam and the monitoring has been performed continuously since the execution of the works, i.e. since 1975 - Kopecký & Magula, 2005). The next objects with implemented monitoring have been selected sections of line structures, permanently threatened by landslides.

A qualitative change in the nature of monitoring occurred in 1993 with the launch of the project of "Partial Monitoring System of Geological Factors of the Environment" (hereinafter PMSGF), which is coordinated by SGIDŠ. Among subsystems of relevant geological hazards the prominent role plays the subsystem Landslides and Slope Deformations (Klukanová, 2002).

The landslides and other slope deformations are monitored at several locations covering all types of slope movements, occurring on the territory of Slovakia. The selection of monitored sites is not fixed and is adjusted according to the needs of society as a whole. Significant newly created slope movements are supplemented to the monitored sites, and in those slope failures with diminishing importance the frequency of monitoring measurements has been either reduced, or they had been abandoned. In 2009 30 sites from Slovakia (most of them in the area of the Handlová Basin) were observed, in 2014 (after "landslide" year 2010) the number of sites increased to 49.

The adopted monitoring methods are based on the common practice of engineering survey and adjusted to different types of slope movements. The monitoring of typical landslide character is performed by measuring displacements of observation points by convenient geodetic methods - terrestrial or by satellite (GNSS), measurements of shifts in the zone of shear plane (currently almost exclusively by measuring the deformation by precision inclinometer), measurements of stress state (by the method of pulse electromagnetic emissions in boreholes) and the observation of the main slide-forming factors (measuring ground water table level and its temperature, the yield of drainage facilities and measurements of total rainfall). The symptoms of slope movements of rock fall character are monitored by dilatometric and photogrammetric measurements of observed points shifts, along with measurements slide-forming factors (the number of frost days, precipitation totals) and repeated measurements of changes in the morphology of the rock wall (Jánová, 1997). Finally, monitoring of creep movement is performed by measuring displacements of rock blocks using optical-mechanical dilatometer. Monitoring methods evolve, improve and refine. The last decade is characterized by the trend towards continuous observation methods (automatic level gauges for measuring groundwater table level regime, continuous inclinometer, Wagner et al., 2010).

The long-term monitoring period (in most cases more than 10 years) enables an accumulation of rich data sets (Iglárová et al., 2012) of observed changes in individual parameters. This extensive data base from the monitoring results constitutes the basis for the transition to a higher degree of stability assessment of the state of the observed sites. It justifies a localization and objective setting of early warning and forecasting of the stability state at different boundary conditions of influencing factors.

The creation of early warning systems against adverse geological factors meets the basic nation-wide requirements, namely the timely prevention of adverse impact of geological hazards on community development and quality of life.

In solution of the project of "PMSGF" significant progress in developing early warning systems for landslide movements has been reached by installation of automatic gauges with adjustable critical groundwater table levels and remote data transmission at the major landslide locations Veľká Čausa and Okoličné in 2005 (Wagner et al., 2006). However, the formation of early warning systems based solely on changes of groundwater table level can be often insufficient and refinement is necessary to obtain sufficiently detailed data on physical activity of landslide masses. Such information can provide records of continuous inclinometer, properly installed in the depth of the active landslide slip surface. Comparison of records of automatic level gauges and continuous inclinometers, located in the most active parts of the landslide in the Veľká Čausa (Ondrejka et al., 2011) has allowed to define a direct correlation between the groundwater table regime and the magnitude of deformation. Therefore, a long-term reliable operation of the early warning system is based on continuous observation of changes in the groundwater table level and definition of the limit levels, corresponding to certain values of kinematic activity of landslide masses.

It can be concluded that the application of modern monitoring methods and optimum focusing of monitoring, aiming in the implementation of different types of early warning systems is presently one of the major challenges of current research into slope deformations.

A true “hot issue” is the rockslide Kraľovany in northern Slovakia, which has been activated in the active limestone and dolomite quarry in spring 2013, and become one of the most spectacular slope failures in the modern history of Slovakia, both in terms of the dimensions as well as the risk to society (Fig. 1.2). The slide masses reaching a volume of more than 2 million m^3 pose a risk for recent infrastructure and lives and property of inhabitants and visitors to the site. Moreover, a route of the most important transportation artery – motorway D1 - has been designed in the very place of the accumulation zone of the rockslide. In addition to classical exploration of the a monitoring was implemented at the site involving on terrestrial survey and GNSS methods, land-based and aerial photogrammetry and laser scanning (Liščák et al., 2014).

1.6.2. Landslide Hazard and Risk Mapping

Terms *hazard* and *risk* were for the first time used in the UK and US literature and they responded to the interest of insurance companies. A term *landslide hazard* was introduced in 1984, when Varnes for the first time defined landslide hazard as a probability of occurrence of potentially harmful landslide phenomenon with certain intensity in time and space. An ability of a system to respond to outer impact by change in own state is defined as *susceptibility* (Petro et al., 2008).

Any activity carried out in jeopardized environment is closely connected with risk, which can be expressed as a probability of occurrence of an event with potentially harmful consequences in form of loss and damage to natural environment, constructions, life and property (Ondrášik, Gajdoš, 2001). In other words risk is a product of hazard and vulnerability (Fig. 1.3).

The postulates in the landslide hazard assessment according to Varnes (1984) and Hutchinson (1995, in Aleotti, Chowdhury, 1999) are as follows:

1. With a great probability the landslides will occur in the same geological geomorphological, hydrogeological and climatic condition as in the past.
2. The main conditions of sliding are controlled by identifiable physical factors.
3. The hazard level can be assessed in advance.
4. All the types of slope deformations can be identified and classified.

Recently there are plenty of methods, which assess the landslide hazard; they can be roughly classified into five groups (Carrara et al., 1992):

- geomorphological hazard mapping;
- analysis of landslide inventories;
- heuristic or index based methods;

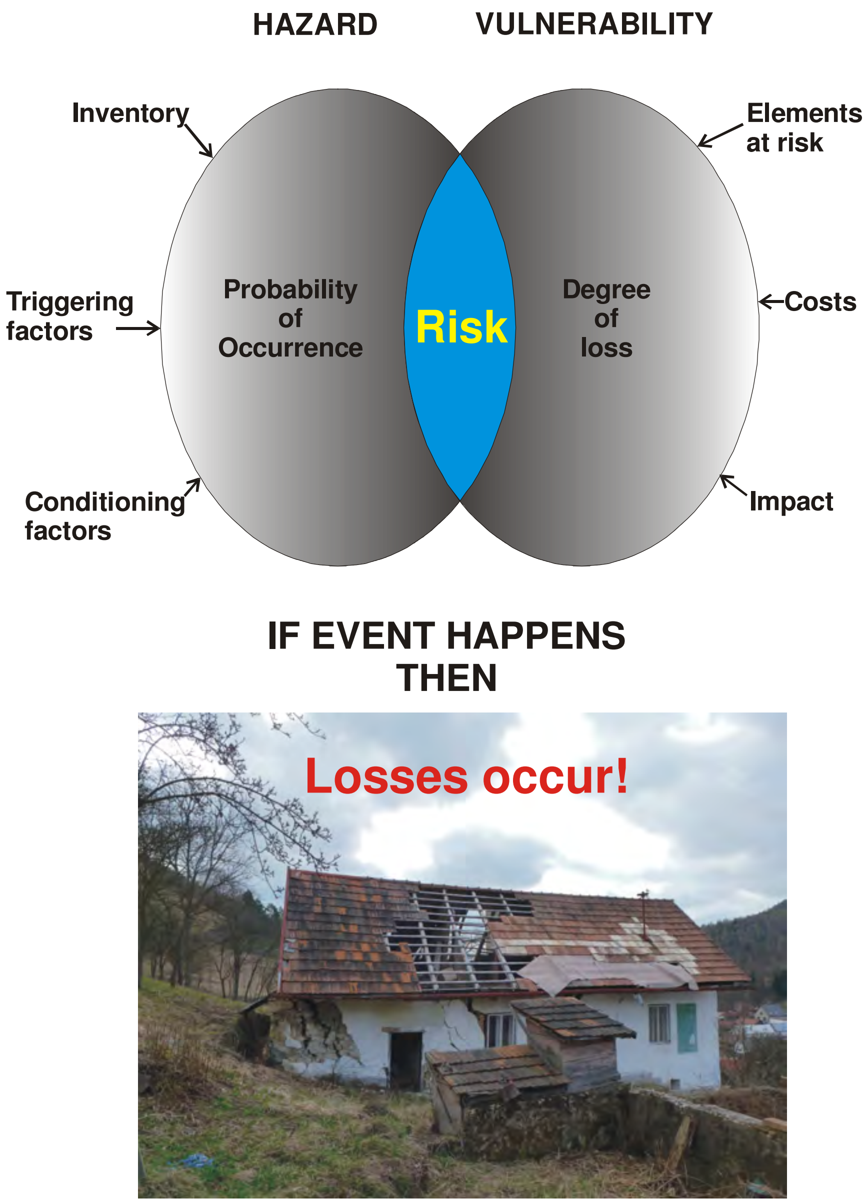

Fig. 1.3 Graphic depiction of the landslide risk assessment methodology (modified according to Alexander, 2002, in Petrýdesová, 2012). Photo of destroyed house in the Červený Kameň village, Liščák, 2013

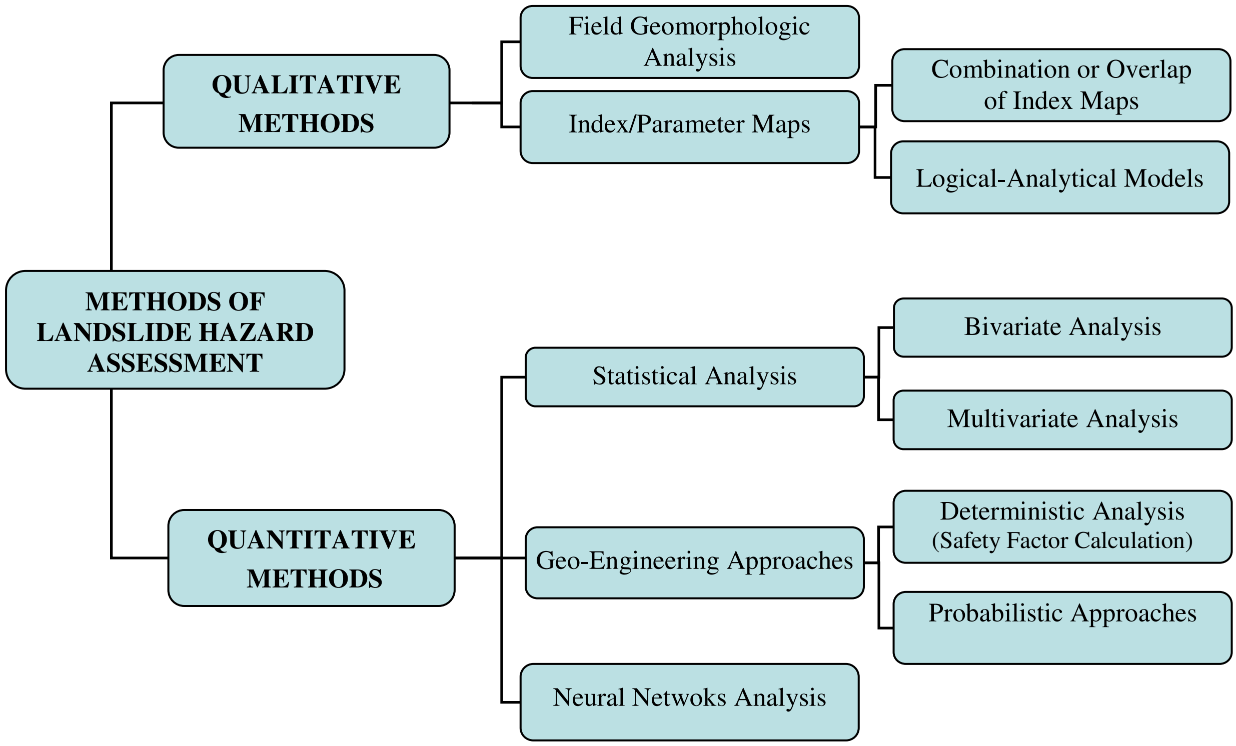

Fig. 1.4 Overview of the methods of landslide hazard assessment (in Petrýdesová, 2012, modified after Aleotti, Chowdhury, 1999)

- functional, statistically based models;
- geotechnical or physically based models.

The outcomes of the qualitative methods are discussed in brief in the subchapter 1.5 and in detail in Šimeková et al., 2014.

Among the quantitative methods of the landslide hazard assessment the in-depth studies statistical analyses have been widely used in Slovakia, followed by geo-engineering approaches. Neural networks analysis is about to be applied in the near future at selected sites of Slovakia.

In Slovakia the statistical analyses are relatively known and widely used methods, by which several territories were studied. They have started to be developed since 60ies of the previous century. One of the first works of the landslide hazard assessment by weighting of the relevant components of the environment was the research by Vlčko et al. (1980). A huge step forward in the landslide hazard assessment was reached thanks to application of GIS tools at the break of millennia. Among the first works of quantitative assessment, which also involved methodology of statistical processing in GIS along with resulting prognoses belong the following works: Bednarik (2001, 2007, 2008); Pauditš, Bednarik (2002, 2006); Jurko (2003); Pauditš (2005); Pauditš, Vlčko, Jurko (2005); Bednarik et al. (2005). The first GIS-based regional estimation of landslide hazard in Slovakia, using bivariate analysis, was compiled in 2010 (Bednarik, Liščák). The to-date trends of statistical methods used in GIS-based landslide hazard assessment are discussed in detail in contribution Pauditš et al. (2014).

Deterministic approach in the landslide hazard assessment is used for local or site-specific analyses under provision that sufficient data on geological, geotechnical and hydrogeological conditions (Kralovičová et al., 2014). The application of GIS in deterministic approach enables a simulation of multiple scenarios, based on a hypothesis of triggering factors variability. In the Slovak conditions for the first time this method was applied by Jelínek (2005), who analysed the Ľubietová Landslide and modelled the maps of landslide hazard for two scenarios of groundwater table level depth. The next GIS-based deterministic study of the landslide hazard provided Jelínek and Wagner (2007) for the case study area Veľká Čausa. In her PhD. Thesis Petrýdesová (2012) applied the deterministic stability assessment of shallow landslides in regional scale for the area between Hlohovec and Sereď towns. The entry data were retrieved and validated using three interpolation methods - Inverse Distance Weighting, Kriging and Spline.

The to-date trends of deterministic methods used in GIS-based landslide hazard assessment of the Chmiňany Landslide area are analysed in detail in the contribution by Kralovičová et al. (2014).

The pioneer work in the landslide risk assessment is the Thesis of Bednarik (2007), in which the author processed the territory of extensive landslide area of the Nitrianska pahorkatina Upland on the left bank of the river Váh between the towns of Hlohovec and Sereď.

1.6.3. 2010 – Year of Landslides

Within the last two decades, there occurred several landslides throughout Slovakia: in 1995 – Veľká Čausa, Diviaky nad N., Bojnice; in 1998 – Handlová, Kunešovská cesta; in 2006 – Poriadie, Podkozince, Bukovec, Čadca, Svrčinovec, Povina, Prosiek, Mojtín. However, in the year 2010 the slope deformations were so numerous, that since than the engineering geological community termed this year the "**Year of Landslides**". In May/June 2010, we experienced an unprecedented generation of slope failures, which has been undoubtedly subject to extremely high rainfall in the month of May, in many places exceeding long term means 4 to 5 times. Particularly affected were mainly the territories of Eastern Slovakia (Košice and Prešov regions). Along with flooding, slope failures brought a great damage to several tens of municipalities of the affected regions. In many of them the "State of Emergency" was proclaimed. The worst situation was in Nižná Myšľa, Kapušany, Prešov - Pod Wilec Hôrkou and Horárska, Nižná a Vyšná Hutka, Vyšný Čaj, Varhaňovce, etc.

Soon afterwards, by the mid of June the Government addressed the Slovak Geological Institute of Dionýz Štúr to carry out an inventory of landslides in order to get figures on the scale of damage. The field work started on June 17, 2010 and was closed in September 2010, resulting in inventory of 551 slope failures covering 2.88277 km^2. In principle, the methodology consisted of the following successive steps in the field survey followed by the analysis of the results (Liščák et al., 2010):

Field section:

a) Identification of slope deformations in the field;

b) The levelling of slope deformations using a GPS device – this methodology was used for the first time in the landslide inventory practice in Slovakia;

c) Detailed photo documentation of the landslide body and damaged, or threatened infrastructure;

d) Completion of the special-purpose data sheet.

Besides the inventory work, the engineering geologists provide the administration bodies in the municipalities and the civilians the advice on the immediate counter-landslide measures. This activity helped in many sites to alleviate the situation and to save the property of population. Despite this prompt reaction of the Ministry of Environment and SGIDŠ staff, the landslides induced damage was immense. 136 housing estates were intensely disturbed, 38 of them were destroyed, and further 11 were abandoned. More than 400 houses occurred in the state of a permanent threat. Tab. 1.1 brings figures on the damage/threat on the transportation network.

The GIS database, besides the obligatory characteristics of slope failures contains also their division into 4 categories according their socio-economic relevance. This classification provides the Ministry of Environment an essential tool for aiming engineering geological surveys and corrective measures into the most endangered sites. All-in-all, 58 slope failures at 36 sites were selected for engineering geological surveys, which were realized in extremely short time period of about 3 winter months on the break of 2010/2011. Based on the data retrieved from the surveys corrective measures were implemented on the most significant sites in 2011-2012 (the first stage of remediation), the second stage is planned for the summer 2014. In addition to the landslides of 2010, SGIDŠ workers registered in the following years numerous new landslides, for instance in 2011, 21 from the 36 registered occurred in the territories, classified by "Atlas" (Šimeková et al., 2006) as stabile (Petro et al., 2011). Some of them were even declared emergency landslides (Fig. 1.5, Dananaj et al., 2012, Ondrejka et al., 2012).

Table 1.1 Damaged and threatened communications of Košice and Prešov regions

		Roads 1st class (m)		Roads 2nd and 3rd class and local roads (m)		Railways (m)	
	District	Damaged	Threatened	Damaged	Threatened	Damaged	Threatened
801	Gelnica	0	0	48	53	0	45
806	Košice - surrounding	0	0	477	2,234	0	78
802	Košice I	0	0	0	52	0	0
808	Rožňava	0	0	0	0	0	0
810	Spišská Nová Ves	0	0	111	494	0	23
Region	Košice in total	0	0	636	2,833	0	146
	District	Damaged	Threatened	Damaged	Threatened	Damaged	Threatened
701	Bardejov	0	0	237	2,074	0	55
702	Humenné	0	0	101	997	0	0
703	Kežmarok	0	0	110	1,072	0	67
704	Levoča	0	0	185	436	0	0
705	Medzilaborce	0	0	25	44	0	0
706	Poprad	27	138	33	92	0	0
707	Prešov	0	61	992	2,733	0	30
708	Sabinov	0	0	297	1,921	0	0
709	Snina	0	0	14	14	0	0
710	Stará Ľubovňa	0	97	578	1,532	0	66
711	Stropkov	0	0	527	2,448	0	0
712	Svidník	0	0	270	1,074	0	0
713	Vranov nad Topľou	0	0	200	280	0	0
Region	Prešov in total	27	296	3,569	14,717	0	218

Fig. 1.5 Configuration of stabilization-drainage ribs at the site Krupina

1.6.4. Challenges in Landslides Mitigation

Due to extreme climate events, but also due to human interference into the sensitive slopes in the period of 2010 -2014 more than 600 new slope deformations were included in the Slovakia landslide database. Given the continuing trend of increasing number of new (or reactivated) slope deformations, as well as the existence of yet (from a geological point of view) unexplored or only partially repaired emergency landslides, it will be necessary to take measures to prevent the reactivation of landslides, or their permanent rehabilitation in case of emergency. Moreover, this fact is also reflected in enhanced awareness of the lay public on landslide issues, which are recently quite frequently covered by Slovak media.

Ongoing impact of climate change in the SR increases the incidence of local extreme rainfall, which in specific areas significantly contribute to the mobilization of landslides in territories that were considered safe; - Banka, Piešťany, 2014. Evaluation of areas at landslide risk by enhanced statistical and determination methods and the implementation of adaptation measures allowing, for example, effective removal water from slope, or its detention in secure areas, shall reduce the risk of damage to property and lives of the residents. These ambitious plans have been reflected in the strategic policy document of the MoE "The Prevention and Management of Landslide Risk" (2014-2020), which shall address the following main activities in order to reduce landslide risk:

- Identification, engineering geological mapping and inventory of slope deformations (facilitating methods of remote sensing and "scaleless" record of slope deformations in the field);
- Systematic slope deformations database update and compilation of maps of landslide hazard and risk-scale (based on accurate topographic documents, for instance ZBGIS);
- Engineering geological exploration of slope deformations (besides the classical drilling wider use of enhanced geophysical methods);
- Remediation of slope deformations (state-of-the-art technology);
- Monitoring of slope deformations (continuous collection of data, implementation of remote sensing, early warning systems development at sites of the highest socio-economic relevance).
- A particular focus will be in prevention, survey and remediation of emergency landslides directly related to excessive rainfall, meeting the following principles:
- Projects will be implemented in line with the "The Prevention and Management of Landslide Risk" programme;
- Preferential support will receive the projects aimed at addressing landslides with a higher socio-economic landslide risk (R-value);
- The most favoured projects shall aim at the landslides threatening higher population.

1.7. Conclusions

Slope movements are the most important geohazards that threaten the territory of Slovakia. A process of understanding of this phenomenon in recent decades passed several development stages, reflecting the current state of knowledge, but also the degree of development of society and its demands to eliminate this unfavourable phenomenon. While in the first half of the twentieth century the assessment of slope stability issues was associated predominantly with human intervention into the natural environment during construction and many that-time experts had adopted opinion that in our natural conditions there was no risk of mass movements of larger scale, following the disastrous Handlová Landslide of the years 1960/1961 the perception of the issue of slope movements has changed significantly. The concern about possible occurrence of slope movements of analogous extent in other parts of the territory of Slovakia and their accompanying adverse consequences has encouraged systematic research of slope deformations, starting from their inventory and mapping of the most vulnerable areas. This long-time purposeful activity resulted in the creation of the Atlas of Slope Stability Maps at a Scale of 1:50,000 for the whole territory of the Slovak Republic in 2006. At the same time these decades witnessed significantly advanced level of knowledge in a broad range of disciplines related to slope deformations research. The abrupt launch of computing technologies in virtually all fields of human activity and the associated development of information technology initiated new methodologies of area stability evaluation with a gradual transition to the compilation of maps of the landslide hazard and risk. Increasing importance began to take purposeful prevention of the adverse effects of slope movements - in the forefront with monitoring of vulnerable territories and gradual creation of early warning systems for landslides. Significant progress has been made also in the development of remediation techniques and technologies. In addition, the whole society awareness towards landslides has been changed. Activities of prognostic and preventive nature and the principles of optimum population "coexistence" with landslides have been favoured increasingly in order to avoid intensive remediation of already incurred slope movements.

Despite the undeniable progress, the methods and methodologies of research and exploration of slope deformations and quantity of the corrective measures we are still experiencing activation, or creation of slope movements, especially in relation to extreme rainfall events. An example of the last period was the climatic anomaly of May and June 2010 - the year of landslides, which caused the activation of a large number of slope movements. It should be emphasized, however, that developments in the knowledge of slope deformations in recent decades have positively reflected in such extreme situations - new landslides were recorded on existing and functional databases, they are plotted in cartographic documents of area susceptibility to landslides, specifying the thresholds of monitored factors and in necessary cases the new landslides are stabilized based on optimal remediation methods. The current situation is certainly not comparable with the state of the Handlová Landslide period when systematic research and exploration slope deformations started.

The history research of slope movements in Slovakia is a vivid example of the development of knowledge of a phenomenon of the professional, but also society-wide perspective. The authors of the contribution have attempted to outline the objectives of essential stages of this long process. Their goal was not only to preserve vital information about the history of the systematic study of slope deformations, but to illustrate a set of lessons learned to optimize solutions of the current issues.

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2. Atlas of Slope Stability Maps of the Slovak Republic at Scale 1:50,000 – Its Results and Use in Practice

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Abstract. The article presents the main results of the geological project "Atlas of Slope Stability Maps SR at 1:50,000", consisting of maps, inventory sheets (passports) of slope deformations and the final report. The work provides accessibility to detailed regional analysis of slope deformations in Slovakia related to the territorial units of engineering geological regions and areas, geomorphological units and territorial administrative units (districts and regions). The article evaluates practical use of the Atlas and also indicates shortcomings, reflected especially in efforts to transform the area slope deformations shown in the Atlas of the topographic groundwork scale 1:50,000 to detailed scales (1:10,000 and more detailed).

***Key words*:** Atlas of Slope Stability Maps of the Slovak Republic at 1:50,000, slope deformation, inventory of slope deformations.

2.1. Introduction

In the years 1997-2006 in Slovakia the geological project titled "Atlas of Slope Stability Maps SR at 1:50,000" (the Atlas, Šimeková, Martinčeková et al., 2006) was being completed. The project was funded by the Ministry of the Environment, the contractor company was INGEO-ighp Žilina, in cooperation with the Department of Geotechnics SF STU Bratislava, GEOKONZULT Košice, SGIDŠ Bratislava and the Department of Engineering Geology of FNS CU, Bratislava.

The objectives of the project were:

1. Registration of all slope deformation identified from archival materials and field mapping during the project solution at scale 1:50,000, according to an uniform methodology.
2. Creation of data sheet (passport) of each slope deformation, comprising a total of 28 columns with data on territorial integration, exploration, slope deformation characteristics, endangered objects and reasons for generation of slide and existence/absence of remedial measures.
3. Outlining the areas susceptible to slope movement generation in each map sheet.
4. Processing of supplementary maps of small scale to each map sheet (Layout of registered slope deformations, Regional engineering geological division of the territory, Geomorphological division of the territory, Regional engineering geological investigation).
5. Digitization of maps in GIS.
6. Submission of final report.

The methodology was tailor-made and adjusted for the purposes of the project in cooperation among the Principal Investigator, experts from the Faculty of Civil Engineering, Slovak University of Technology, Bratislava (†Assoc. Prof. Malgot, Prof. Baliak) and other professionals involved in the project solution. The final adjustment was based on the knowledge gained from the simultaneous compilation of the pilot map sheets.

The final processing of the geological task resulted in brand new analysis of the occurrence and frequency of slope deformations, and their essential attributes according to geomorphological, engineering geological and administrative division of the territory of the Slovak Republic, as well as the entire territory of the Slovak Republic.

2.2. Groundwork documents for the compilation of the Atlas of Slope Stability Maps SR at scale 1:50,000

The compilation of the Atlas had been preceded by several geological projects focused on, among others, the mapping and registration of landslides and other slope deformations, which represented the input materials for documentation of slope deformations and development of their databases in the Atlas. These included the following documents:

- Results of previous inventories of landslides carried out in three stages (Tab. 2. 1), which were processed in the Landslides register of Geofond.
- Thematic engineering geological maps of scales 1:10,000, 1:25,000, 1:50,000 (multipurpose maps of engineering geological conditions, engineering geological zoning maps, special maps of slope deformations and territory susceptibility to landsliding).
- Geological maps of scales 1:50,000, 1:25,000.
- Passportization of slope deformations in relation to road and rail network and major routes of pipelines of Central Slovakia Region and selected districts of the East Slovakia Region.
- Map documents with data on slope deformations, developed in the scope of geological exploration tasks

Tab. 2.1 Stages of previous inventory of slope deformations

Inventory stage	Period	Provider	Output document	Territory
1st	1962-1964	GIDŠ Bratislava, FCE STU Bratislava, FNS CU Bratislava, ÚÚG Prague	Depiction of landslide contours in map 1:25,000; description on punch cards	Endangered areas along communications and in the vicinity of municipalities
2nd	1974-1978	Department of Geotechnics FCE STU Bratislava	Depiction of landslide contours in map 1:25,000; Monograph (Nemčok, 1982)	High mountain areas, selected areas in flysch and volcanic regions and intramountain depressions
3rd	1981-1988	GIDŠ Bratislava	Depiction of landslide contours in map 1:10,000; inventory sheets designed for computer processing	Flysch regions, volcanic mountains, intramountain depressions

for civil engineering structures, for evaluation and optimal selection of alternative sites and routes.

- Results of engineering surveys of investigated landslides.

In the process of inventory covering different periods, performed by different organizations and authors, the map documents often lacked correlation and acceptance of the results of previous surveys and inventories. This resulted in numerous ambiguous multiple registration of the same slope deformations, at the same time with different interpretation of their borders and characteristics, including the slope deformation type and activity.

The goal of the Atlas was processing and synthesis of existing data obtained from source documents, coherent assessment of disturbed areas, validation of insufficient or contradictory data on slope deformations taken from archival materials. Approximate reconnaissance of unexplored territory in order to detect dangerous slope deformations, posing a threat to the population and existing engineering works was carried out. The project didn't solve a more detailed mapping of unexplored areas nationwide.

2.3. Brief presentation of the Atlas of Slope Stability Maps of the SR at scale 1:50,000

2.3.1. Slope stability zoning maps

Slope stability zoning maps are the most significant results of the project. They were compiled separately for each map of the layout 1:50,000 (in total 132 map sheets) and then "welded" (Fig. 2.1, Fig. 2.2). In order to make the results accessible for the public the slope deformations have been visualized on the map server SGIDŠ (http://mapserver. geology.sk/ zosuvy/).

Each slope failure in the map is marked with digit and contours or point mark (slope deformations of less than 50 m). Estimated slope deformations activity is expressed in color and type of slope failures shows hatch (Fig. 2.3). A simplified classification by Nemčok - Pašek - Rybář (1974) was adopted.

Components of each map sheet 1: 50,000 are also additional maps at scale 1:250,000 (Fig. 2.2), which in transparent manner indicate a complementary information – location of map sheet in the Slovak Republic map layout, distribution of registered slope failures in the respective map sheet, territory geomorphological subdivision, regional engineering geological division of the territory and existing engineering geological maps of regional character.

Territory susceptibility to slope movements generation is expressed in maps dividing the territory into three color-coded zones using heuristic method:

- Zone of unstable area (red area)
- Zone of potentially unstable area (yellow area)
- Zone of stable area (green area).

The main zoning criterion is the stability of slopes defined as the resistance of the geological environment on slopes to form a gravitational deformation, or territory susceptibility to the development of slope deformations.

2.3.2. Inventory sheets (passports) of slope deformations

For each slope deformation registered in the Atlas, an inventory sheet so called passport was drawn. The passport provides more-detailed information about the respective slope deformation (Fig. 2.4). Source information on a slope deformation was retrieved from the old inventories (Baliak et al., 2014) of landslides stored in Geofond. For those slope deformations, which were not registered in the Geofond, or the information in the registry was inadequate or questionable, the data were obtained by study of other existing archival materials and additional field mapping.

The passport of a slope failure includes: serial number of slope failure (column 1), territory administrative division (district, geomorphological unit, engineering geological region, columns 2-4), data on exploration and visualization scale (columns 5-8), slope deformation description (columns 9-14), slope failure dimensions (columns 15-18), endangered objects (columns 19-25), causes of slope failure generation (columns 26-27) and corrective measures (column 28).

Statistical processing of an extensive set of data contained in individual passports of slope deformations provided groundwork for comprehensive analysis of the project results.

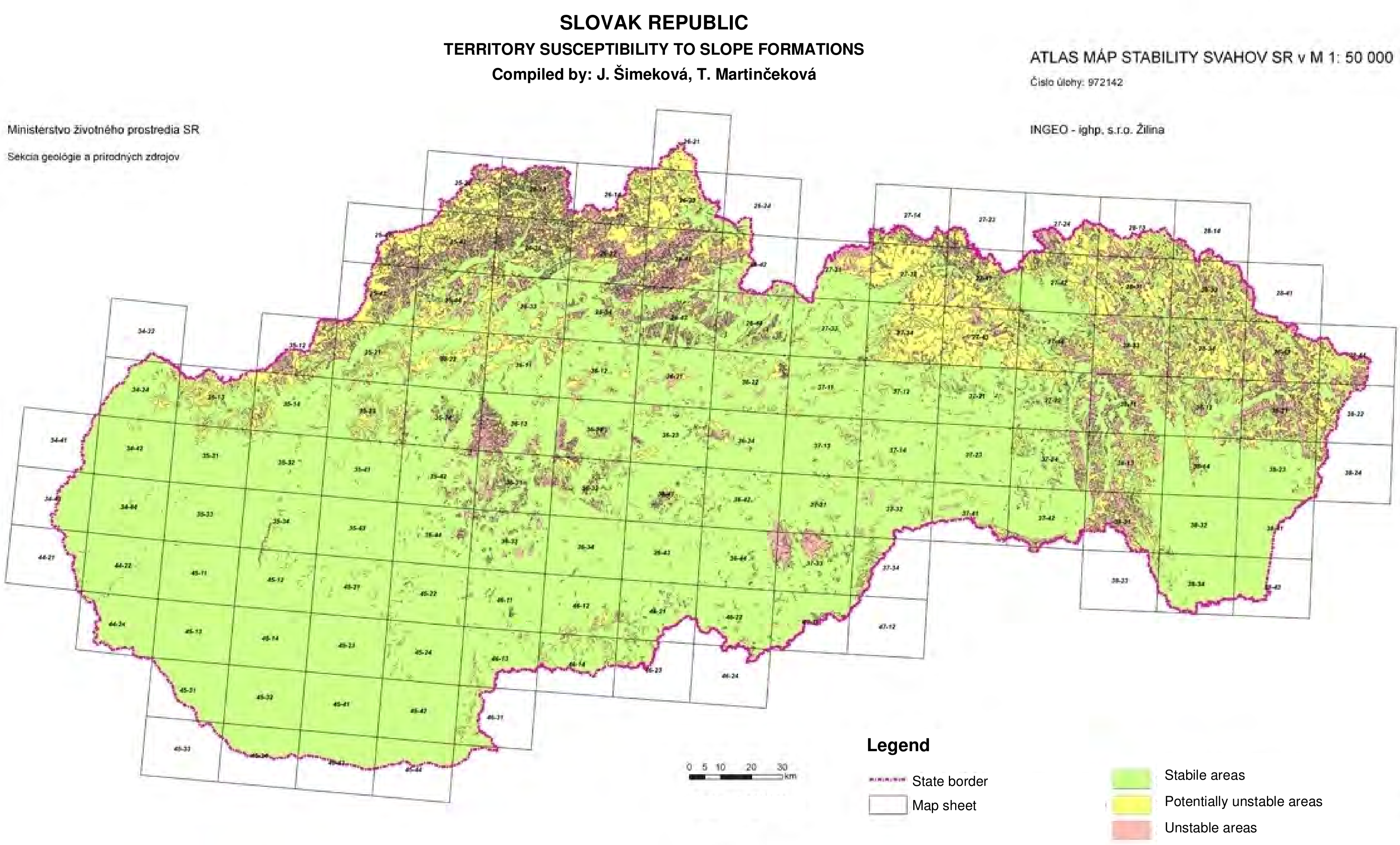

Fig. 2.1 Landslide susceptibility map of the SR with depiction of map sheet layout at scale 1:50,000 (The map is available in Slovak at the Map Server of SGIDŠ)

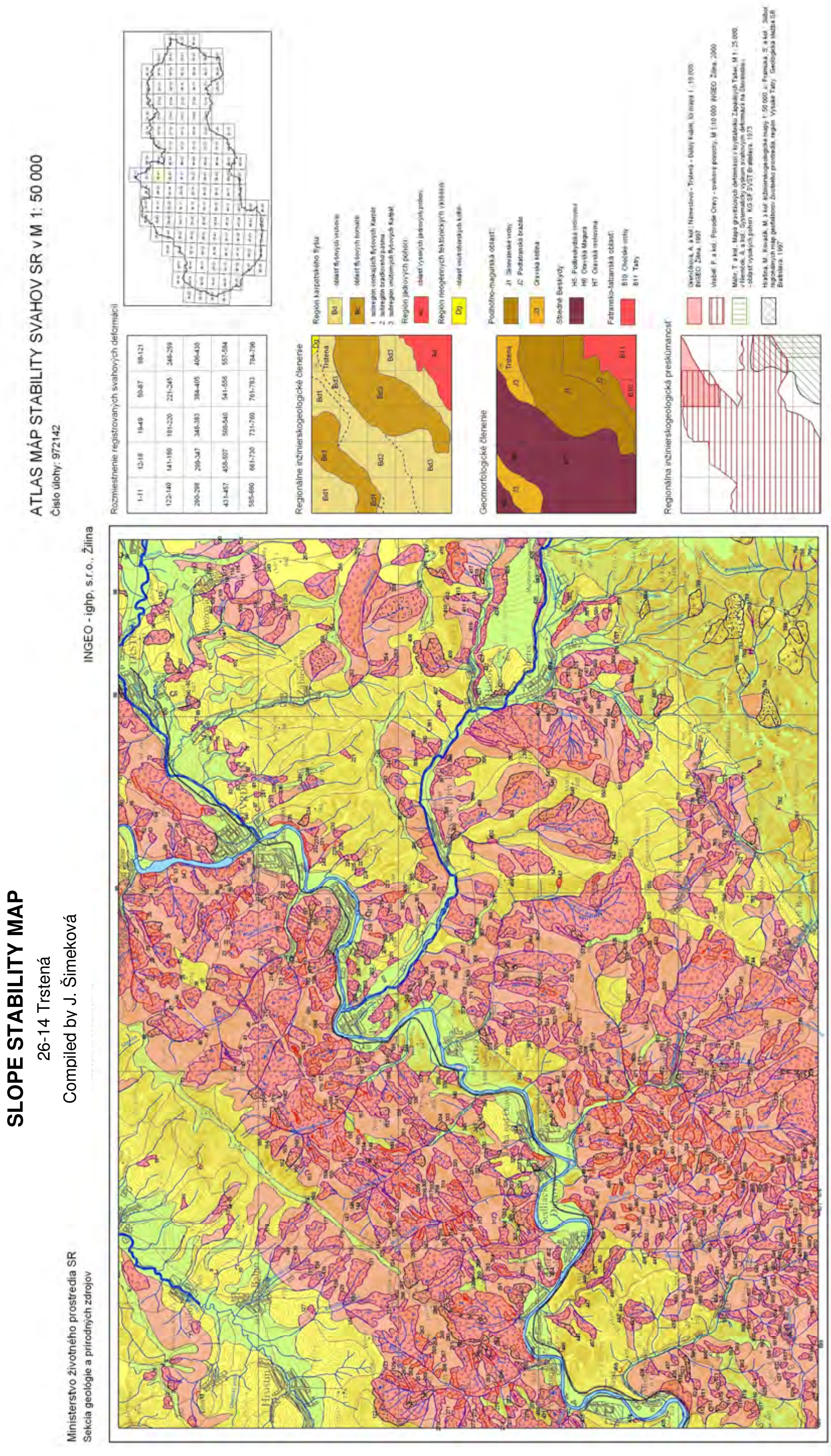

Fig. 2.2 Example of slope stability zoning map, map sheet 26-41 Trstená (to the right are complementary maps of small scale)

Fig. 2.3 Detail of the map sheet 26-41 Trstená

2.3.3. Statistical processing of data on slope deformations registered in the Atlas

2.3.3.1. Slope deformations occurrence

In the scope of the Atlas of Slope Stability Maps SR at 1:50,000, **21,190 slope deformations** were registered by the end of the project in 2006. Of the total number of slope deformations registered in the Atlas:

- 13,012 (61.4%) slope deformations were retrieved from archival documents without their field validation;
- Due to nonconformity of archival documents, 6,076 (28.7%) slope deformations were validated in the field (determination of the type, extent, activity, additional data on the endangered objects, etc.);
- 2,102 (9.9%) slope deformations were discovered and registered in the scope of the field work. Most of them were randomly identified during field reconnaissance of the archived landslides, in rare cases they were detected by targeted mapping of the territories with potential threats to infrastructure based on various indications, e.g. topographic studies.

The number of registered slope deformations gives only indication of the overall territory of Slovakia affected by slope failures. The actual number of slope deformations is significantly higher. Due to the output scale maps 1:50,000 it was often necessary to combine complex and interlinked slope deformations in intensively disturbed areas. Thus, such clusters of individual failures were recorded under one label.

Fair idea of the territory of Slovakia affected by slope failures gives Table 2.2; the final figure of the Atlas equals to 257,591.2 ha, representing **5.25% of the total land area of the Slovak Republic**. For comparison, in the scope of the former registration, which preceded the compilation of the Atlas, there were estimated 9,194 slope deformations in Slovakia affecting 3.06% of the total territory (Nemčok, 1982).

From the data in Tab. 2.2, which outlines the land-use of affected areas (built-up areas, playgrounds, cemeteries), it indicates that agricultural and forest lands are disturbed about equally (50.6% and 46.7%). The share of the other lands amounts to mere 2.7%. Some areas of agricultural land disturbed by slope failures have been abandoned because of difficult farming conditions, and are now overgrown with wild grassy, bushy or forest stands. This is confirmed by the results of the analysis by Liščák et al., (2009), according to which directly affected by slope failures are 120,855 ha of the forest stands (the analysis was based on Corine Land Cover 2000 input data).

Tab. 2.2 Acreage of area disturbed by slope failures (Šimeková, Martinčeková et al., 2006)

Acreage	Acreage in total	Acreage of slope failures	Disturbance by slope failures [%]	
	[ha]	[ha]	vs acreage in total	vs land use
Slovak Republic	4,903,347	257,591.2	5.25	-
Agricultural land use	2,436,876	130,289.9	2.66	50.6
Forest land use	2,004,100	120,243.3	2.45	46.7
Other land use	462,371	7,058.1	0.14	2.7

				Investigation Level										Acreage				Endangered objects							Causes		
																		Roads			Buildings		Eng. Netw.				
Label	District	Geomorphologic unit	Engineering geological area	Geofond - Landslides register (Nr.)	Geofond - report (Nr.)	Present state	Scale	Slope failure type	Activity	Bedrock	Geological complex	Hydrogeol. cond.	Slope angle (°)	In total (ha)	Agricultural land (ha)	Forest (ha)	Other landuse (ha)	Motorway and Ist class (m)	II. and III. class (m)	Railway (m)	Housing estates (number)	Others (number)	Above ground (m)	Underground (m)	Natural	Anthropogenic	Corrective measures
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
267	DK	H6	Bc1	-	83646	-	B	Z	P	Pg	ZF	S	13	1,2		1,2									KE		N
268	DK	H6	Bc1	x	83646	-	B	Z	A	Pg	ZF	P	17	3,5	1,5	2,0									WE		N
269	DK	H6	Bc1	-	83646+	-	B	Z	P	Pg	ZF	P	12	3,5		3,5			200				150		KE		K
270	DK	H6	Bc1	56372	83646	-	B	Z	P	Pg	ZF	P	13	24,2	4,0	20,2			300						KE		N
				54385	58280+				A	Pg	Z	Z	13	4,4		4,4									K		N
271	DK	H7	Bd1	54385	83646	-	B	Z	P	Pg	ZF	P	13	10,0	3,0	7,0									KE		N
					46025+				A	Pg	Z	Z	14	5,2	2,0	3,2									KE		N
272	DK	H7	Bd1	54385	83646+	-	B	Z	P	Pg	ZF	Z	11	11,7		11,7									KE		N
273	DK	H7	Bd2	54384	83646+	-	B	Z	P	K	ZF	Z	13	7,6		7,6									KE		N
274	DK	H7	Bd2	54384	83646+	-	B	Z	P	KJ	ZS	P	12	13,3		13,3									KE		N
275	DK	H7	Bd2	-	83646	-	B	Z	P	JPg	ZF	Z	18	9,9		9,9									KE		N
									A	Pg	Z	Z	11	2,3		2,3									KE		N
276	DK	H7	Bd2	-	83646	-	B	Z	P	K	ZF	P	15	5,4		5,4									KE		N
								P	A	K	Z	P	13	0,8		0,8									KW		N
277	DK	H7	Bd2	54383	83646	-	B	Z	P	Pg	ZF	Z	18	5,1		5,1									KE		N
					46025				A	Pg	Z	Z	13	1,6		1,6									KE		N
					58280			P	P	Pg	ZF	Z	17	2,0		2,0									KE		N
278	DK	H7	Bd2	54382	83646	-	B	Z	P	Pg	ZF	Z	15	11,5	3,0	8,5									KE		N
					46025+				A	Pg	Z	Z	16	0,9		0,9									KE		N
279	DK	H7	Bd2	54378	83646+	-	B	Z	P	K	F	P	15	56,2		56,2									KE		N
280	DK	H7	Bd2	-	83646	-	B	B	S	Pg	F	S		21,4	6,4	15,0									P		N
281	DK	H7	Bd1	54417	83646	-	B	Z	P	Pg	F	P	11	66,0	46,0	20,0			550		7	1	900		WE		N
					58280+				A	Pg	Z	P	13	12,8	4,4	8,3	0,1		45						KW	GM	N
282	DK	H7	Bd2	51943	83646	-	B	L	P	Pg	F	P	17	7,4		7,4									PW		N
				54393	58280			Z	P	PgK	F	P	11	55,5	15,6	39,9			650		6	1			EW		N

Fig. 2.4 Passport of slope deformations 267-282 from the map sheet 26-412 Trstená

The sloping agricultural land areas are the most affected by landslides, or by their combinations with other types of slope deformations (about 90%). In the devastation of the forest land landslides are the most abundant (67.4%), but also important (32.6%) are slope deformations of the creep, fall and flow types. Other areas, particularly built-up areas (2.7%), are particularly susceptible to landslides. The areas above the tree line are dominantly susceptible to failures of the creep, fall and flow types.

Of the total number of registered slope deformations (21,190 units) 90.15% are landslides; other types of slope deformations account for less than 10%. In terms of the assessment of disturbed areas acreage (Fig. 2.5), which is more representative than the above account, the share of landslides is also significantly higher (78.12%) than block fields (15.31%) and other types of slope failures, including the combined ones (total 6.57%).

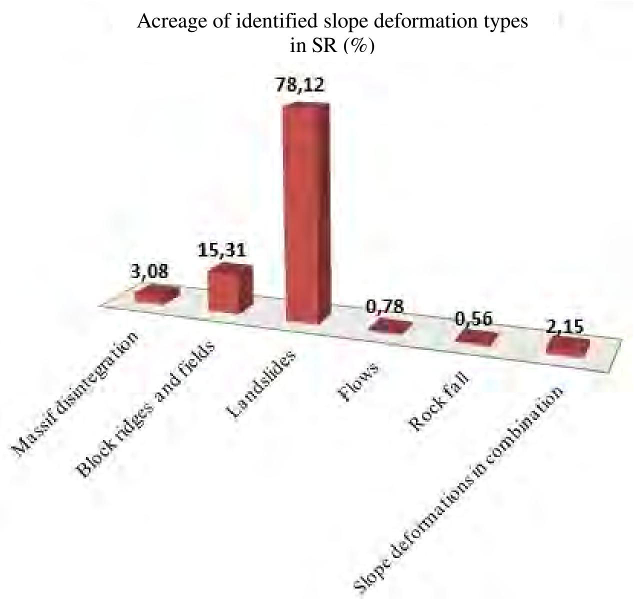

Fig. 2.5 Proportion of slope deformation types

Statistical analysis of the occurrence of slope deformations in relation to the bedrock (geological formations) showed that the most affected are the Paleogene strata representing 60.1%, Neogene - 18.7%, Cretaceous - 9.9%, Paleozoic - 4.2% and Triassic - 2.3%. The remaining 4.8% goes to other geological complexes. The occurrence of various types of deformation is often specific to a particular bedrock, or a combination of geological complexes, for example, disintegrating massif - Paleozoic (75.0%), block ridges - Neogene volcanites (68.0%), block fields – Neogene volcanites (61.2%), landslides - Paleogene (65.9%), debris flows - Paleozoic (55.6%), rock fall – Neogene volcanites (40.7%). For creep deformations of the block movements group, besides Neogene volcanites, typical is a combination of several complexes which are generally characterized by a favorable structure of rock complexes differing in strength properties. Most often combinations are: Triassic - Cretaceous, Neogene - Paleogene, less Jurassic - Cretaceous and Jurassic - Triassic.

The average angles of the slope deformation types are as follows: disintegrating massif - 26.7°, block fields - 15.2°, landslides - 13.3°, debris flows - 25.2°, rock fall - 27.6°. On the steepest slopes disintegrating massifs, flows and rock falls are frequently present. Artificial slopes affected by slope failures have an average slope of 21°. The landslides, which make up 90% of all slope deformations, have a mean inclination of 13.3°; to be more accurate 65.5% of landslides are formed on slopes of 7° to 17° (Kopecký et al., 2008).

2.3.3.2. Slope deformation distribution in the enginee ring geological regions and areas

The evolution and forms of slope movements have their own characteristics depending on the geological setting and geomorphological evolution. For the purpose of this assessment an engineering geological division of the territory of Slovakia according to Matula (Matula, Pašek, 1986) was adopted in the Atlas, which takes into account the criteria of geological structures uniformity and macro-relief. This division was later modified and updated by the authors Hrašna, Klukanová in the Atlas of Landscape SR (2002). The territory of Slovakia is divided into 4 engineering geological regions and 8 engineering geological areas as follows:

1. **A** – Region of Core Mountains:
   - **Aa** – Area of High Core Mountains
   - **Ab** – Area of Core Highlands
2. **B** – Region of Carpathian Flysch:
   - **Bc** – Area of Flysch Highlands
   - **Bd** – Area of Flysch Uplands
3. **C** – Region of Neogene Volcanites:
   - **Ce** – Area of Volcanic Highlands
   - **Cf** – Area of Volcanic Uplands
4. **D** – Region of Neotectonic Depressions:
   - **Dg** – Area of Inner-Carpathian Depressions
   - **Dh** – Area of Inner-Carpathian Lowlands

The Region of Carpathian Flysch (B) is dominated by various types of landslides. In the Region of Core Mountains (A) occur most frequently creep deformations of a character of massifs disintegration. In the Region of Neogene volcanites (C) deformations of block type are significant and in the Region of Neoectonic Depressions (D) landslides prevail over block deformations (Tables 2.3, 2.4, Figs. 2.6, 2.7).

In summary presentation of slope deformations acreage in various engineering geological areas (Tab. 2.5) the most disturbed is the Area of Flysch Uplands followed by areas of Volcanic Highlands and Flysch Highlands. In relation to the total area of the Slovak Republic the first place is occupied by the Area of Flysch Uplands followed by the areas of Volcanic Highlands and Inner-Carpathian Depressions.

2.3.3.3. Slope deformations distribution in territorial-administrative units (regions)

In terms of territorial-administrative division of the Slovak Republic (8 regions, 79 districts) relatively high-

Tab. 2.3 Occurrence of the main types of slope deformations in the engineering geological regions and areas of Slovakia

EG Region	EG Area	Massif disintegration	Block ridges and fields	Landslides	Flows	Rock fall	Slope deformations in combination	Total EG Area	Total EG Region
		[ha]	[ha]	[ha]	[ha]	[ha]	[ha]	[ha]	[ha]
A	Aa	6,355.5	2,726.7	5,291.1	862.9	975.0	1,442.2	17,653.4	23,741.9
	Ab	1,301.1	579.5	3,934.1	9.8	75.5	188.6	6,088.5	
B	Bc	134.8	2,266.8	24,732.2	153.8	9.1	231.8	27,528.5	138,169.7
	Bd	25.3	2,150.4	105,956.2	568.7	1.3	1,939.3	110,641.2	
C	Ce	61.0	19,085.4	17,737.7	263.1	373.3	1,045.6	38,566.1	52,214.3
	Cf		10,311.4	3,167.3	14.7	13.2	14.6	13,648.2	
D	Dg	50.6	2,207.0	33,449.7	97.5	3.9	538.8	36,347.5	43,465.5
	Dh		113.1	6,969.7	35.2			7,118.0	
IN TOTAL		7,928.3	39,440.3	201,238.0	2,005.7	1,451.3	5,527.9	257,591.4	257,591.4

Tab. 2.4 Frequency and acreage of main types of slope deformations in the engineering geological regions of Slovakia

EG Region	Massif disintegration		Block ridges and fields		Landslides		Flows		Rock fall		Slope deformations in combination		TOTAL	
	No	area [ha]	No	area [ha]	No	area [ha]	No	area [ha]	No	area [ha]	No	area [ha]	No	area [ha]
A	114	7,656.6	88	3,306.2	1,260	9,225.2	672	872.7	84	1,050.5	41	1,630.8	2,259	23,741.9
B	5	160.1	147	4,417.2	12,624	130,688.4	156	722.5	4	10.4	28	2,171.1	12,964	138,169.7
C	6	61.0	518	29,396.8	1,708	20,905.0	46	277.8	61	386.5	22	1,187.2	2,361	52,214.3
D	3	50.6	51	2,320.1	3,513	40,419.4	34	132.7	3	3.9	4	538.8	3,608	43,465.5
TOTAL	128	7,928.3	804	39,440.3	19,105	201,238.0	908	2,005.7	152	1,451.3	95	5,527.9	21,192	257,591.4

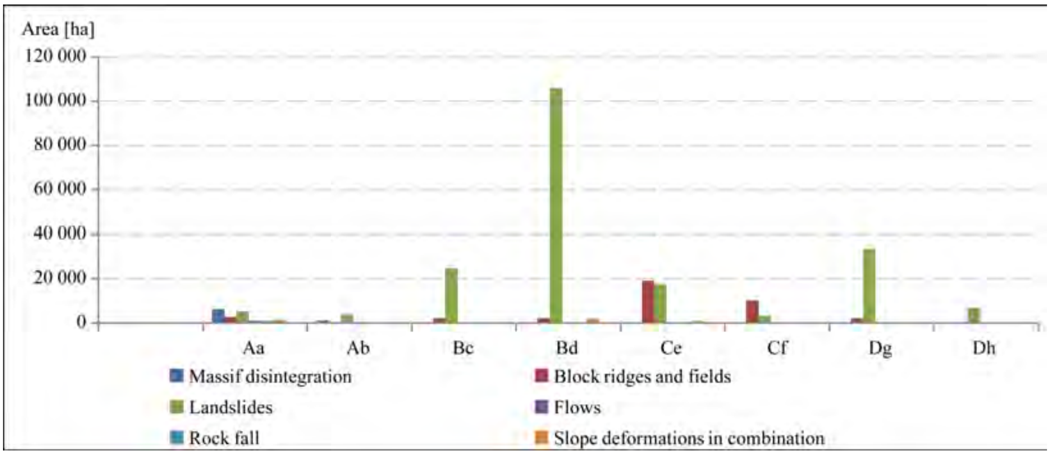

Fig. 2.6 Diagram of acreage of the main types of slope deformations in the engineering geological regions and areas of Slovakia

Tab. 2.5 Summary disturbance of engineering geological areas of Slovakia

EG Area	Share of EG Area in the area of SR	Acreage of EG Area disturbed by slope deformations		Share of slope deformations of EG Area in the area of SR	Share of slope deformations of EG Area to disturbed area of SR
	%	[km^2]	%	%	%
Aa	7.70	176.53	4.79	0.36	6.85
Ab	17.90	60.89	0,71	0.12	2.36
Bc	5.40	275.28	10,58	0.56	10.69
Bd	15.30	1,106.41	15.13	2.26	42.95
Ce	6.90	385.66	11.78	0.79	14.97
Cf	4.00	136.48	7.19	0.28	5.30
Dg	14.40	363.48	5.27	0.74	14.11
Dh	28.40	71.18	0.52	0.15	2.76
TOTAL	100.00	2,575.91		5.25	100.00

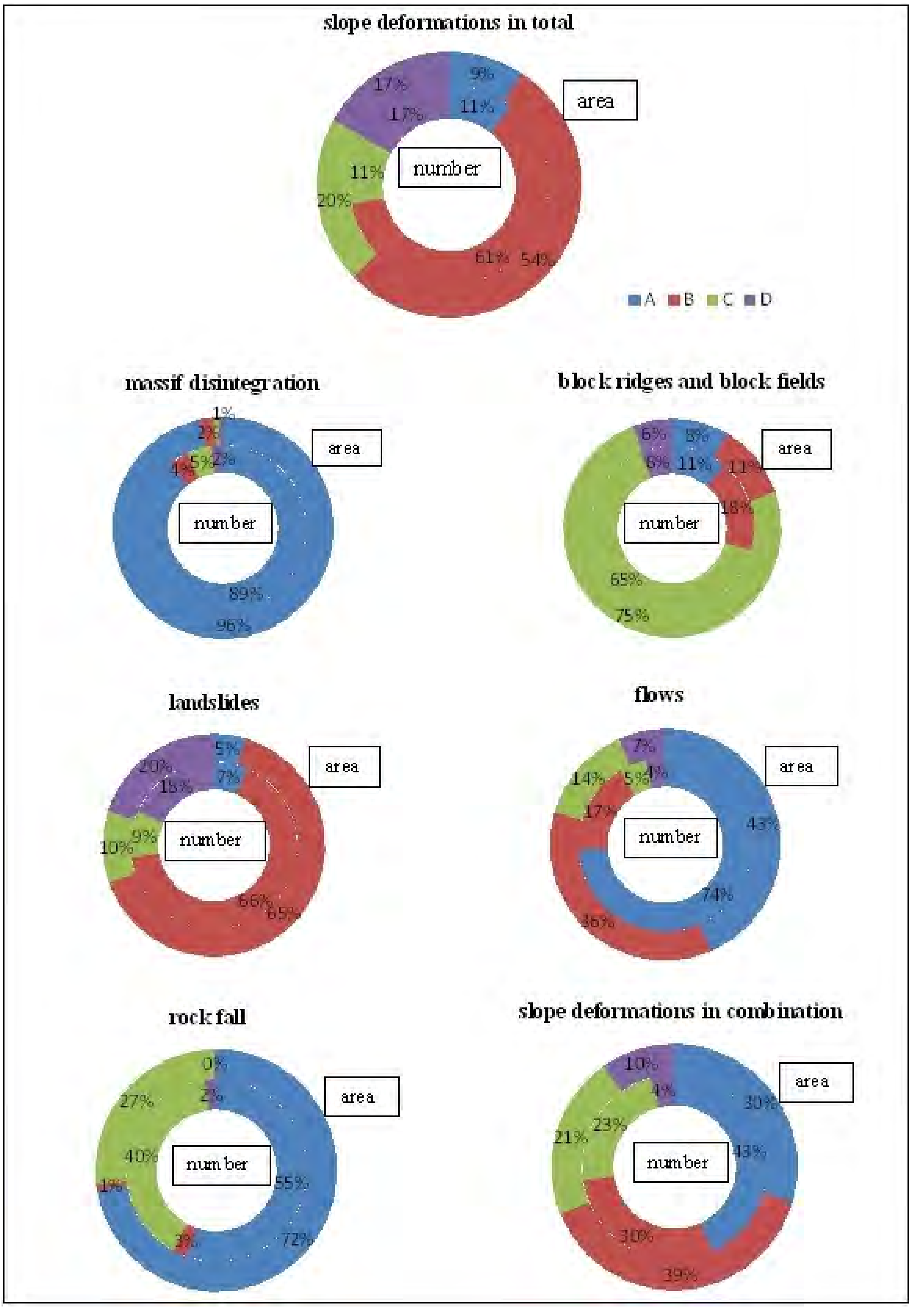

*Fig. 2.7 Frequency and acreage of the main types of slope deformations in the engineering geological regions of Slovakia in %. **Legend**: A - Region of Core Mountains, **B** - Region of Carpathian Flysch, **C** - Region of Neogene Volcanites, **D** - Region of Neotectonic Depressions*

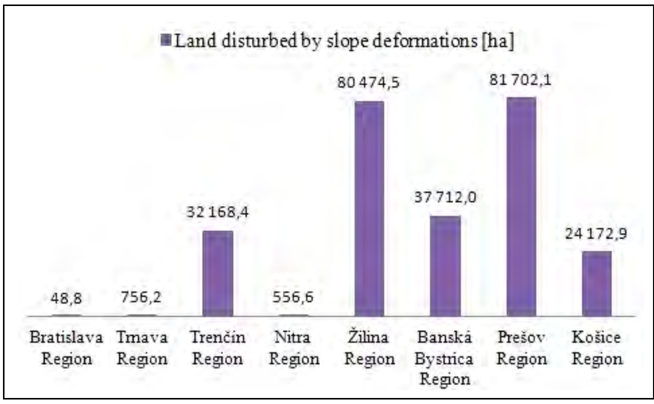

Fig. 2.8 Acreage of slope deformations in the regions of the Slovak Republic

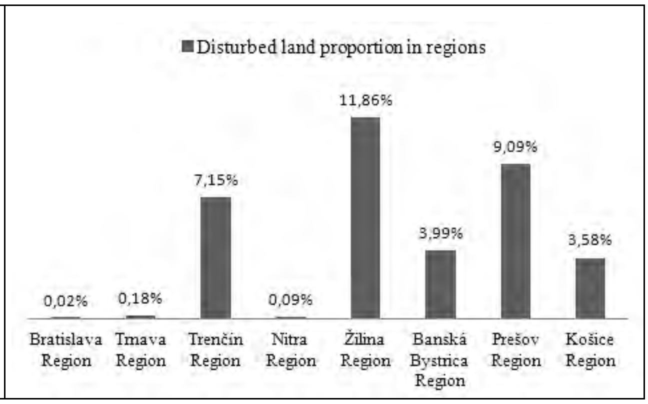

Fig. 2.9 Disturbance of the regions of the Slovak Republic by slope deformations in %

est disturbance by slope failures is documented in the Prešov region followed by Žilina and Banská Bystrica regions (Fig. 2.8).

In terms of percentage disturbance to the total area of the region, Žilina is the most affected region followed by Prešov and Trenčín regions (Fig. 2.9).

Bratislava, Nitra and Trnava regions are less affected by slope failures.

2.3.3.4. Threat for buildings and other objects

The high disturbance of the SR territory by landslides also implies a high extent of the threat to buildings and other structures (Tab. 2.6). The given data have to be considered as guidelines. In common, they were denominated from the basic topographic maps of scale 1:10,000, with the last update 10 to 20 years prior to the Atlas issuance. In numerical terms in the table are included the objects which had been damaged or set out of operation, as well as the objects that were stabilized by remediation works (during the construction of an object or as a result its emergency state).

Tab. 2.6 Objects jeopardized by slope deformations (Šimeková, Martinčeková et al, 2006)

Type of object	Extent
Buildings (housing estates and other buildings)	27,920 objects
Other structures (water-supply tanks, cemeteries, playgrounds, bridges and others)	600 objects
Sites with more than 50 objects endangered*	168 sites
Motorways and roads of the Ist class	98 816 m
Roads of the IInd and IIIrd classes	571,408 m
Railway	67,210 m
Above-ground engineering networks	1,116,056 m
Gas pipelines	101,180 m
Oil pipelines	3,500 m
Water pipelines	290,925 m

**endangered municipalities, urban suburbs, recreation and garden areas, which are fully or partially located in the territories affected by slope deformations*

The most frequently threatened other buildings include water-supply tanks (38.5%) and cemeteries (32%). Degree of threat to objects is dependent on several factors, but mainly on the type and activity of slope failure, its extent and depth course, relative position of an object threatened to a slope deformation, etc.

2.4. Application of the results of the Atlas of Slope Stability Maps SR at scale 1:50,000 in practice

Given that Atlas is the first complete digital map depicting slope deformation throughout the territory of the Slovak Republic, freely available on the Internet through the map server SGIDŠ (http:// mapserver.geology.sk/ zosuvy/), it has been often used for various purposes. During almost one decade of its use there have been identified a number of shortcomings and examples of its misuse for the purposes of which the map scale and the related generalization of landslide areas has not been intended. The insufficient scale of the Atlas is evident especially in experiments, or efforts extrapolating the landslide area in the Atlas into documents of larger scales, e.g. in the development of spatial plans and the evaluation of specific building sites.

The deficiencies of the Atlas of Slope Stability Maps SR at 1:50,000 can be divided into several groups.

1. Deficiencies arising from the scale:

- generalization and distortion of mapped boundaries of slope deformations during the transformation of the detailed documentation for the scale 1:50,000 (Fig. 2.10a, b, c, d);
- joining together (welding) of composite disturbed areas and landslides directly interlinked or lying in close proximity and their registration as single slope failure (one label) (Fig. 2.10e, f);
- visualisation of smaller slope deformations (with dimensions <250 m) only by icons (e.g., Fig. 2.10e, f - landslide Nr 216);
- inequalities (distortion) among topographic documents of different scales.

2. Deficiencies arising from the lack of nation-wide mapping:

- we can not exclude the existence of previously unregistered slope deformations, even in relatively stable areas (green areas in the zoning map).

3. Deficiencies arising from the aging of map documents (completion in 2006):

- there is no systematic update of the status on newly registered, newly formed and reactivated slope deformations (e.g. in 2010 after massive activation of landslides, especially in eastern Slovakia, SGIDŠ registered 551 new active slope failures using precise GNSS measurements (Liščák et al. 2010).

4. Deficiencies resulting from inaccuracies of the source documents:

Objective errors:

- field mapping performed only by validating the facts with available topographic document of appropriate scale (usually 1:10,000), without accurate registration of contours and morphological elements of slope deformations by modern geodetic GPS devices;
- inaccurate or outdated topographical maps used in the course of mapping work;
- slope deformations without significant morphological manifestations facilitating their unambiguous identification and delineation (disguised by secondary modeling through erosion-denudation and weathering processes or anthropogenic activity - agriculture, construction activities);
- vegetation cover during the field mapping (dense vegetation, growing wild and lush vegetation, incapacitating especially in summer and spring seasons motion of mapping staff and veiled morphological shapes of slope deformations);

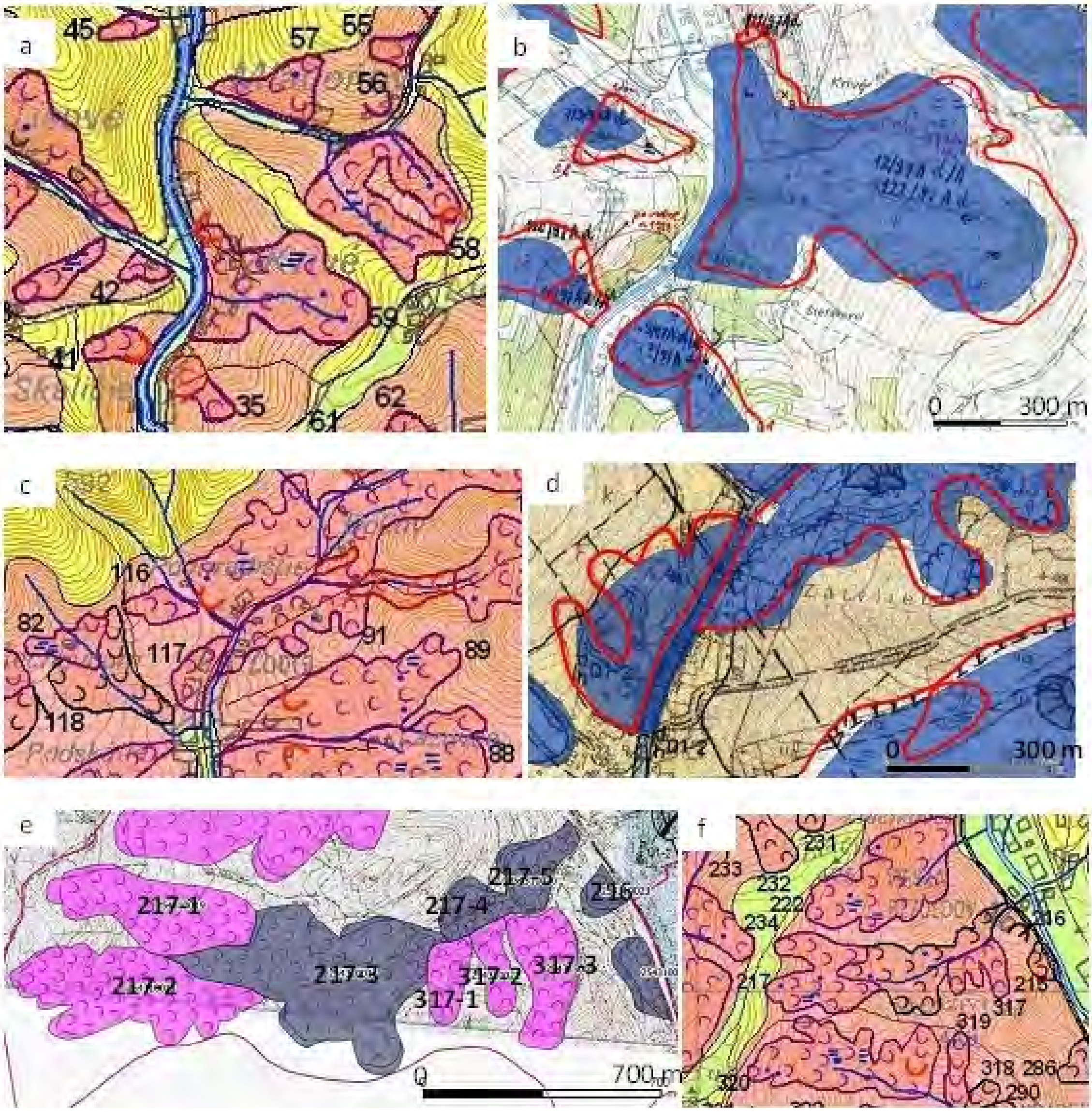

Fig. 2.10 Depiction of deficiencies of the Slope Stability Atlas SR 1:50,000 due to map scale
Explanations: a, c, f - detail from Atlas' zoning map; b, d - detail from working groundwork map Atlas' at scale 1:10,000, with highlighted landslides boundaries (red line) and area in colour, representing landslides areas transformed from Atlas into opography ZM 10; e - complex sliding area with 8 partial landslides (217 - 1 to 5, 317 - 1 to 3) mapped on topography at scale 1:10,000 and f - its final depiction in the Atlas at scale 1:50,000 (landslides 217 and 317)

- inaccessibility of the terrain in terms of build-up land or other land use (fenced private facilities, military facilities, etc.).

Subjective errors:

- inaccurate mapping and incorrect information due to lack of experience and knowledge of the mapping geologist;
- inaccurate and incorrect mapping information due to inconsistency of the mapping geologists;
- subjective approach of a mapping geologist in harder identifiable slope failures;
- miscalculation of distance.

Despite the above outlined shortages the Atlas of Slope Stability Maps SR at scale 1:50,000 has many advantages and benefits:

- The Atlas of Slope Stability Maps of the SR is a single clear map series, processed in digital form in a GIS environment, showing the occurrence of slope deformations, distinguished by type and activity throughout the territory of the Slovak Republic. This work can be continuously updated, refined and used in practice.
- For each slope failure registered in the Atlas a passport (database) of a slope failure was drawn with its detailed characteristics, territorial-administrative affiliation, level of investigation, figures on geometric characteristics and objects at risk, and eventual corrective measures, which form the basis of extensive statistical file.
- The data on level of investigation listed in passports of slope failures include a link to the source map documents provided they are available. Most of these documents are available at Geofond SGIDŠ Bratislava. Previous multiple registrations of the same landslide area led to a variety of records with different interpretations. Provided, they were not validated in the scope of the

Atlas field work, the most preferred records were those with a more detailed scale mapping and actual time-date).

- Compilation of the Atlas supplemented existing Landslides Register of Geofond on new slope deformations. Contradictory data on slope deformations produced during the previous multiple registrations were eliminated.
- Newly registered, validated in the field and spatially corrected slope deformations of the Atlas were plotted on the primary working topographic maps at scale 1:10,000.
- All figures in the passports (acreage of slope deformation, the extent of endangered objects) were derived from existing documents or detailed working maps of the input documentation of the Atlas.

As was already mentioned the usefulness of the output maps of the Atlas is partially limited due to the used scale 1:50,000. The Atlas is suitable for the following applications:

- As a primary source of information on the occurrence of landslides in the area of interest in various geological projects and land use planning;
- For the indicative assessment of major investment plans, for example, assessment of variant communications routes, water works and other constructions (in the stage of engineering geological study and preliminary engineering geological survey);
- As basis for assessing the suitability of the construction area for structures foundation, or other land use on a wider scale and its optimization;
- For designing engineering works at the stages of technical study, environmental impact assessment and documentation of building plan.

The Atlas is conditionally suitable only as a primary source of information - study of more detailed documents, or the assessment of the territory by a professional geologist is necessary. The input map should not be superior to specific approach of the professional geologist in the territory assessed:

- For the formulation of the statements of the Ministry of Environment of the SR in compilation of land-use planning documentation from the viewpoint of geological hazards;
- For the creation of spatial plans in medium and small scales;
- For physical and legal entities when buying land;
- For building committees of local authorities in building proceedings and issuing a building permit;
- For the need of insurance companies in terms of property insurance.

2.5. Conclusions

The Atlas of Slope Stability Maps of the SR at 1:50,000 presents an overview of digital map developed by unified methodology for the whole territory of the Slovak Republic. In the scope of this work there were registered 21,190 slope deformation of the total area of 257,591.2 ha, which constitutes 5.25% of the total area of Slovakia.

The majority of the registered slope deformations belong to the group of potential sliding activity. In some regions of Slovakia (mainly the flysch areas of north-western and eastern Slovakia - Region of Carpathian Flysch, but also in the territories made of volcanic rocks in the central and eastern part of Slovakia - Region of Neogene Volcanites) the share of affected land is often greater than 10%. In terms of territorial-administrative division of Slovakia, dominantly affected are the Žilina and Prešov regions. This aspect is reflected in the high number of endangered objects, number of emergency situations due to activation of slope movements and considerable financial resources expended for corrective measures.

The Atlas provides a wide range of uses, however, with certain limitations. The most important issues are too small scale 1:50,000 and related incompatibility of the used topography ZM-50 with topography of larger scales, causing relatively large distortions in the transformation of slope deformations boundaries from the Atlas into more detailed map documents.

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3. Landslide Inventory in Detailed Scale: Current State and Future Approaches

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Abstract. Accounting for annually recorded slope stability problems, but especially after the massive occurrence of landslides and debris flows in 2010, public and government interest has increased to identify sites with registered potentially dangerous slope failures. There have been efforts to include them consistently in the development of spatial plans and in the selection of building plots.

This aspect has also been reflected at the last amendments of the Geological Law No. 569/2007 Coll., in which requirement is set out of expression of the Ministry of Environment SR in a form of an statement to geological hazards and exploitation in the territory with adverse engineering geological conditions. From the above facts follows acute necessity of registration and inventory of landslides and a reassessment of their existing register with more detailed spatial accuracy meeting the requirements of spatial planning and the current trend in formation of detailed digital topographical documents (Primary Base of Geographic Information System), orthophotomaps, maps of real estate cadastre). Recently, there are at hand also technical possibilities of the so-called databases with spatial extensions, which are especially convenient for the purposes of slope deformations inventory.

Keywords: landslide inventory • very accurate digitization • spatial database/database with spatial extension • detailed topographic maps • Primary Base of Geographic Information System • cadastral maps • orthophotomaps • landslide hazard maps • open-source software

3.1. Introduction

Slope deformations in Slovakia occupy ca 5.25% of the total land area (Šimeková & Martinčeková, et al., 2006) and thus constitute a phenomenon that significantly influences the condition and efficient land use. They act as a constant threat, where structures are placed within a reach of a slope deformation without adequate measures. Potential landslides repeatedly cause damage to land, linear and other construction objects, engineering networks, as well as agricultural and forest soils.

In recent years, largely due to extreme climatic events, but also due to the influence of anthropogenic interventions, numerous landslides and earth flows were mobilized that have required declarations of emergency situations in the various municipalities across Slovakia (Liščák et al., 2010). For their stabilization considerable funds were allocated. Part of the emergency landslides resulted from the unconscious, but unfortunately sometimes wilful disregard of landslide susceptible areas already in the development of spatial plans, selection of building plots and construction of residential, economic and other objects by private entities without engineering survey, which inter alia, assesses stability conditions.

At present the landslide hazard and risk in some regions of Slovakia is also increasing due to amplified construction activity shifted from flat and slightly sloping hillsides and territories to more exposed areas. This trend is particularly evident in the villages of the mountainous regions of Slovakia. This is caused by a lack of suitable building land in flat areas, but also by often targeted location of buildings on the slopes due to the attractiveness of the environment (terrain with panoramic views, privacy, cleaner environment ...).

The inventory of landslides in the Slovak Republic has been carried out more or less systematically since the 60ies of the 20th century. Particular impetus for a systematic inventory gave disastrous landslide in Handlová, active at the turn of 1960/61, which inflicted enormous economic damage. Following the Handlová landslide a landslide register was established aiming on inventory of slope deformations across Slovakia. The Landslides Register of the Slovak Republic is administered by the Geofond Department of the State Geological Institute of Dionýz Štúr (SGIDŠ). Currently the Geofond registers about 18 000 slope deformations in Slovakia.

From 1997 to 2006 the Atlas of Slope Stability Maps of Slovakia at scale 1:50,000 was compiled representing a concise digital base map (the Atlas, Šimeková et al., 2014), which has processed using an unified methodology all previously mapped and registered slope deformations, including the development of a database in the form of passport of a slope failure. The passports provide a review of the relevant territorial affiliation of slope deformations, their stage of exploration, dimensions, engineering geological characteristics, constructions and other objects at risk, causes of their generation and eventual remediation.

Despite the fact that the Atlas of Slope Stability Maps today still represents the most comprehensive mapping and inventory work in the Slovak Republic, it demonstrates acute deficiencies in terms of time requirements. A particular challenge is poor positional accuracy of the applied scale of 1:50,000, in particular a positional incompatibility of obsolete topographic document (accessible in digital form as the state map series SVM-50) with the actual detailed topographic groundwork (e.g. orthophotomaps). The differences in positional superposition are often in the tens of meters. Slope deformations plotted and digitized into such incompatible (and inaccurate) topography can not be used as an input into the creation of detailed spatial plans and also, for example, in the evaluation and creation of landslide hazard maps in detailed scale according to today's requirements (Pauditš et al., 2014).

Currently, or in the near future national base map series ZB GIS shall be available to the public (Michalík, 2010; →http://www.geoportal.sk/sk/udaje/udaje-zbgis/). This detailed and very precise topographic document is compatible with other commonly used detailed map groundwork, including maps of the land register (KNC/KNE), accurate orthophotomap (Šrámková, 2004) and previously used maps at scales of 1:10,000 and 1:25,000 (state map works). In the future, ZB GIS map series will be likely binding as a digital topographic basis for all map scales ("scale-less"), so it is essential to customize also a database of slope deformations to these developments.

Based on the above, the Department of Engineering Geology SGIDŠ in cooperation with Landslide Register of Geofond, has begun in 2012 to build a GIS database of slope deformations in the fine-scale topography compatible with ZB GIS. This database will gradually integrate slope deformations of the older registers and various map data adapted to the scale and ZB GIS (working and terrain 1:10,000 maps of the Atlas, detailed maps available from the register of slope deformations of Geofond, fine-scale maps of the different projects kept in Geofond Archive) along with slope deformations mapped using precise GPS/GNSS devices, registered since 2010 (Liščák et al., 2010; Ondrejka et al., 2011).

The goal of this database is the reassessment of all previously registered slope deformations in Slovakia and their plotting into a detailed scale. The database will be continually updated and accessible to the public via information system GeoIS (→http://mapserver.geology.sk/zosuvy).

3.2. History of landslide inventory in Slovakia

The beginnings of compiling the Register of slope deformations (the Landslides Register) are associated with the catastrophic Handlová landslide in 1960, when 150 homes were destroyed along with 2 km long stretch of State Road 1/50, Southeast branch of the Handlová water pipeline, several lines of high voltage, etc.

The cases of the Handlová landslide and several others have shown that stabilization of active slope deformations is far more expensive than preventive measures. Another important finding has been the fact that the slope movements are recurrent in the areas of old landslides, mainly.

In the light of the above the next logical step in the research into slope deformations was their inventory; this effort divided into three stages covering a period of 1961-1991 has contributed to the development of a prominent school of Czechoslovak engineering geologists dealing with landslides around Nemčok and co. (for instance, Nemčok 1982). The history of landslides inventory is discussed in detail in the paper by Baliak et al. (2014).

3.2.1. Register of slope deformations in Geofond

The first massive mapping of landslides took place in the years 1961-1963 (based on the Resolution of the CSSR government), and focused mainly in the investment-important areas. The result was a final report to the General map at a scale of 1:1,000,000.

From 1965 maps with delineated landslides and area registration cards started to be submitted to Geofond. The records were stored on punch cards and drawn into maps at scale 1:25,000. The results of this phase of registration are stored in Geofond Bratislava, or in Geofond Prague.

The Landslides Register began to be used in practice in 1975 and especially for the needs of expression for capital investments in terms of landslide exploration.

In 1980 the reconstruction of the Register started. Old inventory cards have been restated to inventory passports. This approach was based mainly on internal work by Dr. Milan Špůrek of 1976, entitled "Guidelines for the registration of landslides and other dangerous slope deformations". Further on, the landslides and other dangerous geodynamic phenomena were plotted into maps at scale 1:25,000 according to agreed established rules. The new data sheet was extended to 80 data items, mostly numeric ones. For the purpose of phenomenon registering there were created several new coders and defined mandatory and optional items. These were particularly the localization phenomenon (map, map scale, etc.), basic data such as date of formation, grade of investigation, etc.

Important period in the development of the Register represent mainly 90ies, which were primarily linked to the development of information technology and especially graphics programs and database systems. Since 1990, the maps of scale 1: 25,000 have been graphically processed, simultaneously with the creation of the first digital maps and outputs from the Register. In 2002, the digitization methodology was prepared for the project Atlas of Slope Stability Maps SR at Scale of 1:50,000 (Šimeková & Martinčeková, et al., 2006) in order to build an information system in ArcView GIS 2.3. The Geofond participated in the project and was in charge of digital maps processing. All further changes in the Register were associated mainly with the development of database programs. In 2005, the Landslides Register was transformed from a dBase to Oracle database. The Register's considerable reconstruction occurred in 2010, when the change was related to the re-development of GIS and especially with the creation of geodatabases (ESRI platform system), which managed to combine the non-graphical data with the graphical ones.

While the Register's database was continually updated on new records, the Atlas of Slope Stability Maps has remained closed. Therefore, there appeared acute need to connect data in appropriate way. The problem arose when analyzing the Atlas, where imperfections were found in data integrity between adjacent map sheets – it often happened that the boundaries of graphical objects were incompatible. Although the task was solved in GIS the record sheets were separated from digital maps and data were not compatible in some cases.

A detailed analysis of various Register entries and Atlas of Slope Stability Maps as well as other incremental projects has led to a creation of common structure of the new database. Currently it consists of 84 fields, which are divided into larger groups like geology (geological formation, geological structure, ...), hydrogeology (hydrogeological conditions of the slope, ...), slope geometry (mean angle, slope aspect, ...), localization of the phenomenon, the basic data, the extent of the phenomenon and others (Tab. 3.2). For coded fields, there were created new coders or the original ones were amended (mostly by merging different values of the sources).

The database contains also an indication of the source data, which is very important for data displaying. The Register was drawn into the maps at scale 1:25,000, while the Atlas of Slope Stability Maps is based on scale 1:50,000. Currently into the Register enter various projects, which have been obligatory submitted to Geofond they are also mapped at different scales. This paper presents a new spatial oriented database, which is based on the scale of 1:10,000. The Register's geodatabase at scale 1:50,000 currently contain 17,879 graphical entities retrieved from different scales.

3.2.2. Atlas of Slope Stability Maps SR at scale 1:50,000

The Atlas of Slope Stability Maps SR at 1:50,000 (Atlas) covers the whole territory of Slovakia and contains entities from various archival sources, processed in digital form, of all previously registered and newly mapped slope deformations in topographic scale 1:50,000. Thanks to its complexity and accessibility (the work is freely available on the SGIDŠ website) the Atlas offers a wide range of uses; however they are limited in several respects. The essential limitations are the general display scale and the positional incompatibility of the used topography with current detailed topographic documents. The Atlas's results and shortcomings are in more detail discussed by Šimeková et al. (2014).

3.3. The objective of landslides inventory at detailed scale

In view of the aforementioned shortcomings of existing practices in the registration and inventory of slope deformations in the Slovak Republic the SGIDŠ acceded to the systematic creation of a detailed database that should integrate graphic (or geographic) interpretation of slope deformations in the form of graphical entities in the map along with attribute data referred to in respective passports. This integration is implicitly provided by GIS technology in the so-called spatial databases.

Geographical location of slope deformation is plotted as detailed as possible, a necessary condition for positional accuracy to allow to identify individual parcels of the cadastre, where a slope deformation is present. This means that the smallest usable cartographic scale for inserting graphical entities in the database is 1:10,000 (or 1:25,000). Limit for the largest scale is not given, slope deformation is thus possible to display in a very detailed cadastre maps (KNC/KNE) and in geodetic site plans at a scale of 1:500. It follows that in the future it will be possible to visualize a slope deformation with respect to each specific building, of course, on sufficiently precise topographic documents.

The main objective of such detailed geographic database is to provide materials for:

- producing detailed land use plans,
- landslide risk assessment for specific parcels and property,
- basis for insurance companies, etc,
- producing detailed maps of landslide susceptibility, landslide hazard and risk.

Accounting for ZB GIS topography, to which detailed GIS database will be positionally adapted in the future, the landslides would be possible to display on maps of smaller scales (1:50,000 to 1:100,000), without loss of positional accuracy. This is made possible by the fact that the ZB GIS map series is referred to as "scale-less", that means, the current position of each object in the GIS system is constant; only the density of the visualized elements is modified relative to a given scale (contours step, for example).

In developing land use plans and detailed planning documentation each municipality will be able to take into account on the basis of spatially accurate GIS database published on the Internet, actual incidence of slope failures registered in a given area of interest, not only indicatively, as it was previously. Individual municipalities will have a real opportunity to include the occurrence of slope deformations and potentially dangerous territory in their spatial development concepts. Similarly, the database can also serve for insurance companies when assessing the possible future risk of landslide events within the conclusion of insurance contracts. The database will enable to direct potential customers and construction companies and developers in the future selection of building plots for the location of their property.

In addition to precise plotting of geographic location on the map the detailed database will be also beneficial in terms of improved attribute part of the database. Tabular data are designed as optimal synthesis of data used so far: passports in the Geofond registers, attribute data of the Atlas and attributes arising from new technological approaches to mapping and registration of landslides (e.g. GPS accuracy - position and altitude, the exact time during the mapping, an indication of the date when the slope deformation evolved, etc.). The aim is to provide to the public mapping services through the Internet, the most relevant and up-to-date information about the registered slope deformations and these data will be constantly updated.

Special emphasis was put in compiling a database meeting the requirements for issuing landslide hazard maps in detailed scale, because in recent years often in the formation of these maps computerized statistical methods are utilized. Spatial database as an index map of landslides is a necessary input variable in the compilation of the landslide hazard mapping by statistical methods in GIS environment (Pauditš and Bednarik, 2002; Pauditš, 2006; Bednarik, 2007). With this so-called binary (0/1) variable all input parametric maps are being compared in the process of calculating the weights of bivariate analysis and also the variable when compared with the quasi-homogeneous units in multivariate analysis. For this purpose, individual landslides in the database are recorded not only as sole surface entities, but also as linear entities – head scarps extended to the edges of transportation areas as well as transverse and longitudinal cracks in the landslides bodies. Such interpretation of a binary variable better reflects the area in which landslide occurred and allows to eliminate systematic error in evaluation of the areas that were affected by accumulation part of a landslide (Bednarik and Pauditš, 2010). These areas may be in terms of landslide susceptibility de facto stable – e.g. areas of alluvial plains with mild to zero slope grade.

3.4. Methodology of the database creation and its technical aspects

As was mentioned above, accounting for the deficiencies of the Atlas, in particular the positional uncertainty and incompatibilities arising from the use of digital topography SVM 50 (Špaček, 1999), we proceeded to the creation of the GIS database of slope deformations of fine-scale compatible with maps, or ZB GIS.

The database is the spatial one, this means that in addition to attribute data (mostly text, numerical and Boolean) in tables are stored graphic (or geographic) data, representing the geometry of the individual entities. The geometry storage directly in a relational database table is provided by the means of a so-called spatial extension, which writes the geometry into a database table using a coded sequence of alphanumeric characters. In addition to geographic coordinates of entities vertices, the character sequence contains also SRID (Spatial Reference IDentifier) that gives the exact way to set up cartographic projection of given table/coverage in GIS software. The database software used is PostgreSQL with PostGIS spatial extension, distributed via Internet under free GPL license (→http://postgis.org/).

The database runs on server, which allows concurrent access to multiple users in real time, and it is available also for editing (not read-only). The server environment technically solves potential conflicts that may occur due to concurrent inserting or updating. The database can be accessed from various common programs (Excel, Access, Internet browser, etc.). The graphical data visualization and direct editing allow GIS programs, e.g. Quantum GIS (→http://www.cigis.org) and MapInfo Professional (from version 10.0 and higher →http://www.mapinfo. com).

In the main table in the database, which is also the bearer of extensive information on each recorded landslide (passports), the geometry of slope deformations is plotted in the form of polygons - the outlines of bodies of each slope deformation, including the accumulation parts. Head scarps, transportation and accumulation parts of landslides in these polygon entities are not separated in this table. Information on detachment-transportation parts of a landslide stores another table, where landslides are recorded in the form of lines of main scarps of the upper edges (MSUE), or head- transportation parts (Fig. 3.1), what is needed in terms of methodology of slope deformations entry in the statistical evaluation of landslide hazard (Clerici, 2002; Süzen and Doyuran, 2004). This table is linked to the main polygon table using SQL by 1:1 relationship.

In a special "cosmetic" database Schema, various hatch patterns and auxiliary graphic elements are stored, that are necessary for common landslide plotting and visualization. Both polygons (hatch patterns of sliding direction at main scarp surface) and lines (prescribed hatch of motion direction of landslides and earth flows, lower edges of the main scarps and others) are stored.

Each of these types of entities is stored in a separate database table, or for each category of graphical entities shown in Fig. 3.1, the separate database table (GIS layer) is established. Overview of GIS database table of slope deformations is shown in Tab. 3.1. The list of attributes (passport items), assigned to the main polygon table is taken mainly from the Atlas (Šimeková and Martinčeková, et al., 2006) and the Geofond Register, along with other useful technical aspects arising from the GPS records measurements and field mapping (e.g. GPS accuracy class record, average and lowest accuracy of GPS record, area and perimeter of a slope deformation, date and time of mapping (data collection), or date and time of digitizing, etc.).

The number of attributes is not yet final and will be amended in respond to emerging requirements, together with complementing database entries. Estimated finite number of attribute fields in the data sheet (passports) of the database is more than 150. Current overview of attributes (as of December 2013) is reported in Tab. 3.2.

Main advantages of the slope deformations inventory in the form of a spatial database with client/server architecture are:

- the possibility of concurrent access for inserting or updating graphical features and/or attribute data simultaneously for multiple users with possibility to set the user access rights to each user separately;

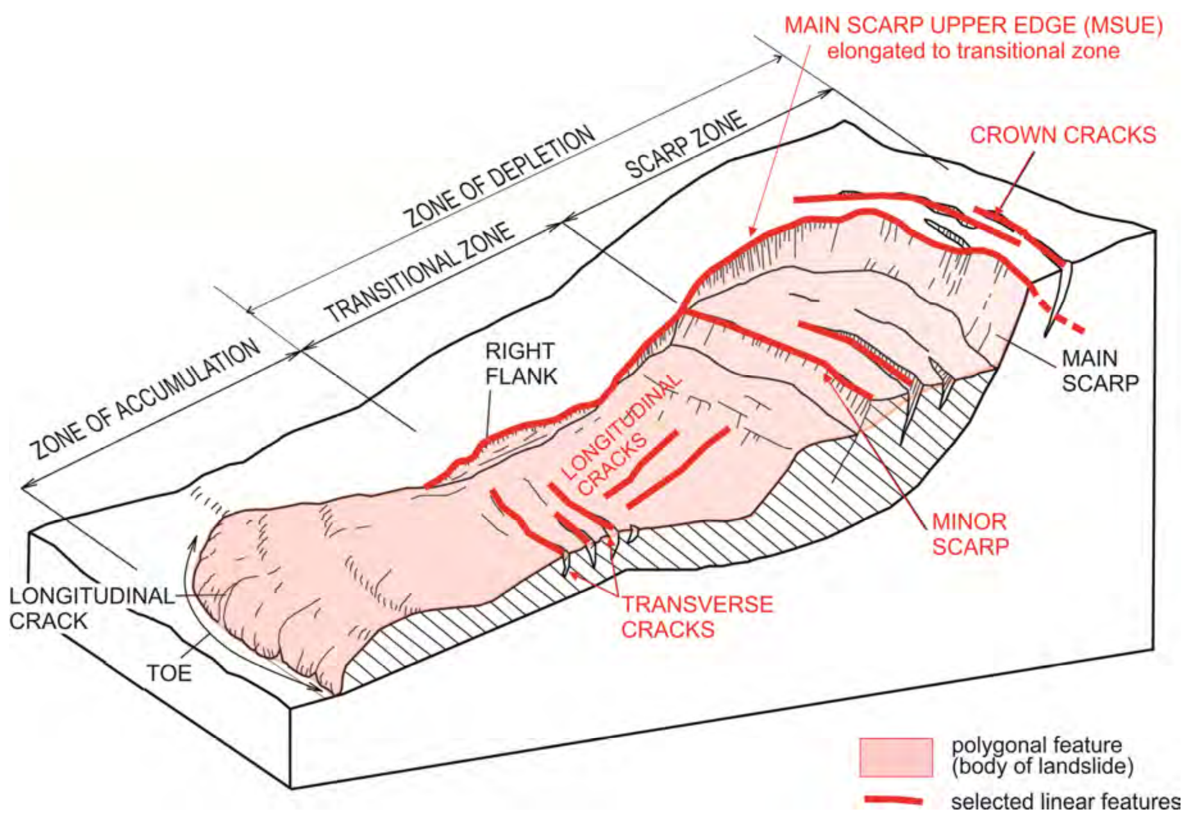

Fig. 3.1 Schematic presentation of the landslide elements, recorded into the database: polygon entities are stored in the main table gm10_zosuvy_poly, selected linear entities are stored in table gm10_ zosuvy_odlucne_hrany (Tab. 3.1)

Tab. 3.1 List of database tables

Table name	Description
gm10_zosuvy_ poly (polygon)	Outlines of landslide bodies (polygons) including accumulation parts, (main database GIS layer with attributes / passports of landslides).
gm10_zosuvy_odlucne_hrany (line)	Lines of main scarps and transportation parts, transversal and longitudinal crevasses in landslides.
srafy_ line (line)	Line hatch of slope deformations (in terms of Directive MoE SR. 3/99-3).
srafy_poly (polygon)	Polygon hatch (filled) of slope deformations (in terms of Directive MoE SR. 3/99-3).
kodovnik_sraf	Codes of hatch needed to adjust colour and attributes in printed maps of slope deforma-tions.
mapinfo_mapcatalog	Auxiliary table for MapInfo communication with PostGIS database.
zm10_listoklad (polygon)	Map-sheet layout ZM 10 (1:10,000).
sm5_listoklad (polygon)	Layout of orthophotomaps, or map-sheets SM 5000 (1:5,000).
zm10_vodne_toky (line)	Water streams lines at scale 1:10,000 (derived from ZB GIS and topographic documents).
gps_trasy_gpx2d (line)	Rough field data: GPX and KML file type (Garmin devices, smart-phones, etc.).
gps_trasy_ssf3d (line)	Rough field data: SSF (3D) file type (Trimble devices).

- the possibility of using different software platforms to access and edit the database (GIS programs, MS Excel, MS Access, WEB browsers, etc..);
- the possibility of rapid selection using SQL standards, based on specified criteria according to recorded attributes;
- possibility of full SQL selection on the basis of geographical criteria and spatial functions (distances, overlaps, areas, etc..), in combination with selection on table attributes (e.g.: "select all earth flows exceeding an area of 5 ha within 200 m buffer zone from the nearest river in the village Zbora which threaten 1st class roads", etc…).

3.4.1. Digitization of field maps

The field maps, usually processed within the Atlas (Šimeková & Martinčeková, et al., 2006), are processed primarily on the basis of ZM 10 at a scale of 1:10,000. The slope deformations mapped in the field were plotted directly into topographic documents of a scale 1:10,000 or into copies of working field maps from previous surveys and mapping works. Reference to the source is recorded in the attribute table of slope deformation (Tab. 3.2).

Tab. 3.2 Attributes (database fields) of the slope deformation main table (as of 2013)

Field /Attribute name	Data type	Description
registracne_cislo	integer	Label of a registered landslide in database created in the scope of the Landslides inventory 2010 (Liščák et al., 2010).
ku_nazov	varchar(75)	Name of cadastre, in which landslide is situated, or its head scarp in the case of several cadastre areas affected by a landslide.
datum_mapovania	date	Date of landslide mapping.
cas_mapovania	varchar(75)	Start and end time of landslide mapping.
minut_zaznamu	integer	The duration of GPS record (in minutes) of landslide outline mapping.
kvalita	double precision	Assessment of landslide mapping quality and accuracy: 1 - GPS measurement with the highest possible accuracy (up to 2 m), 2 - GPS measurement with accuracy 2-7 m, 3 - GPS measurement with accuracy 7-25 m, 4 - point GPS measurement with accuracy up to 5 m, 5 - point GPS measurement with accuracy up to 25 m, 6 - landslides plotted into the map 1:10,000 without GPS record, 7 - landslides plotted into the map 1:25,000 without GPS record.
hoz_avg	double precision	Mean horizontal accuracy of GPS record.
hoz_worst	double precision	Worst horizontal accuracy of GPS set of records.
rcvr_type	varchar(50)	Type of the applied GPS receiver.
kategoria_sev	varchar(5)	Socio-economic classification of the risk induced by sliding: R1 - low risk, R2 - moderate risk, R3 - high risk, R4 - very high risk, potential threat to lives and property (Liščák et al., 2010).
plocha	double precision	Area of landslide in ha.
obvod	double precision	Perimeter of landslide (outer line) in m.
idsrf	varchar(75)	Code of the geological basement of landslide corresponding to unified database legend GeoIS (SGIDŠ, 2006, (→http://mapserver.geology.sk/gm50js|
priemerny_sklon_svahu	double precision	Mean slope angle within landslide body (accumulation part included).
azimut	double precision	Mean aspect of landslide (azimuth, starting with N).
svetova_strana	varchar(5)	Symbol of aspect quadrant of landslide.
haz_dial	Boolean	Information on risk for a motorway (1 - true, 0 - false).
haz_cesta	Boolean	Information on risk for other roads (1 - true, 0 - false).
haz_zeleznica	Boolean	Information on risk for railway (1 - true, 0 - false).
haz_budova	Boolean	Information on risk for buildings (1 - true, 0 - false).
pricina_antropog	Boolean	Information, on the either anthropogenic factors (1) or natural factors (0) of landsliding.
sanacia_navrh	Boolean	Information, whether landslide is proposed for remediation (1 - true, 0 - false).
sanacia_real	varchar(75)	Year(s) of remediation (several years are separated by comma).
poznamka	memo	Notes to landslide.
geom	geometry (polygon, 100100)	PostGIS geometry (100100 is SRID/EPSG code of cartographic projection JTSK 03/ Krovak East-North with binding transformation key GKU for SR).
zaznamenal	varchar(125)	Name of geologist, who inserted record into the database (responsible for record correctness).
row_id	serial (primary key)	The record identifier.
stupen_aktivity	varchar(75)	Activity (active, potential, stabilized).
lokalita	varchar(175)	Designation of slope deformation.
mapovali	varchar(175)	Mapping geologists' names.
atlas_ss	integer	Registration number in Atlas (Šimeková & Martinčeková, et al., 2006), code of linking to attribute table in the Atlas database.
geofond	varchar(75)	Registration number in Geofond Register.
geomorfologia	varchar(25)	Index of geomorphological unit (in terms of regional division SR).
ig_stavba_svahu	integer(5)	Engineering geological characteristic of slope, expressed by index.
regionalna_ig_rajonizacia	varchar(175)	Regional engineering geological division, expressed by index.

ig_rajony	varchar(25)	Index of engineering geological zone.
hg_pomery	varchar(175)	Hydrogeological conditions of landslide.
vztahy_toky_nadrze	varchar(175)	Code of relation to streams and reservoirs.
pramene	integer	Presence and number of springs.
vyska_max	double precision	Maximum altitude within landslide body (derived from DMR).
vyska_min	double precision	Minimum altitude within landslide body (derived from DMR).
typ_sd	varchar(75)	Type of slope deformation.

The source maps ZM 10 with plotted slope failures are geo-referenced to the coordinate system S-JTSK (Krovak East-North), on the basis of the corners of map sheets, using a GKÚ binding transformation key for the SR territory (Droščák, 2011). The achieved accuracy (RMS error) including the error of transformation WGS84/ETRS89 - JTSK ranges from 30 cm to 2 m (60 cm on average).

Digitization of slope deformations in GIS environment runs directly on the basis of ZBGIS (Fig. 3.3), which can be downloaded or directly linked from Geoportal GKÚ SR via WMS technology (→https://zbgisws.skgeodesy.sk/zbgis_wms_featureinfo/service.svc/get), in order to adapt to its topographical features that should achieve in this map series proclaimed sub-meter accuracy. Morphology of a landslide must be digitized by an expert - a geologist with respect to key elements of topographic maps, especially water streams and relief represented by contour lines and/or hill-shading.

3.4.2. Slope deformations recently mapped and registered in the field

In addition to the base ZB GIS, or ZM 10, in the scope of the digitization of graphical entities in a GIS environment base orthophotos are also used with a resolution and accuracy of 1.5 m (IACS project; Šrámková, 2004), available to SGIDŠ from the entire territory of Slovakia. It is also possible to use freely disseminated satellite and aerial imagery from Google database, however, their positional accuracy varies considerably, due to the inconsistencies of resources used (error in documents of Digital Globe Company on Google Earth may reach for the territory of the Slovak Republic +/-25 m, while documents from the companies Eurosense/Geodis Slovakia achieve sub-meter accuracy. The orthophotos provide accurate information on the direct threat to civil engineering works: buildings, roads and railways, relevant for their record into table (passport) of a slope failure.

For technically flawless digitizing of polygon contours of slope deformations it is also necessary to respect the topological correctness on the joint of graphical entities, mainly due to further correct processing using GIS spatial analysis. The above mentioned GIS software allows so-called "topological editing" (avoid overlay, intersection). The topological correction can also be additionally made directly in database environment PostGIS.

Further technological progress in the inventory of slope failures has been made in connection with an excessive activation of slope deformations in 2010. The SGIDŠ geologists promptly made registration of 551 active slope deformations in the territory of Eastern Slovakia (Liščák et al., 2010). For the first time in the history of systematic inventory of slope failures and other geological objects in the Slovak territory they applied very precise, "scale-less" survey of slope failures and their morphological features using GNSS technology (Fig. 3.2; output on example of the Chmeľnica Village, Fig. 3.4). A component of the research was also compiling of a detailed database of registered slope deformations and their classification in terms of socio-economic significance.

Since 2010 the Department of Engineering Geology SGIDŠ has carried out all terrain mapping and registration of new slope deformations using precise GPS of GIS category (Trimble GeoXT 2005) with an option of signal refinement from the EGNOS device and use the DGPS corrections. Under ideal conditions, these devices can achieve sub-meter accuracy of a record (Ondrejka et al., 2011). Individual line and area features of slope failures are recorded and distinguished on the ground (head scarp, accumulation part, cracks, etc., Fig. 3.2).

This way recorded field data are processed within the so-called postprocessing and various subjective corrections in GIS programs and stored in a spatial database on PostGIS server. In the attribute table the details of the achieved positional accuracy are recorded (maximum error, average error, time of recording, device type, etc.) and the resulting quality grade 1-7 according to the following rules:

1. Landslides surveyed geodetically or with GPS devices of GIS categories (e.g. Trimble GeoXT) with the highest achievable accuracy (within 2 meters), or very accurate products of airborne survey (photogrammetry, laser scanning);
2. Landslides surveyed with GPS devices with an accuracy of 2-7 meters (equipment of GIS category or navigation devices and smartphones/tablets with GPS + GLONASS signal in the open air);
3. GPS measurements with an accuracy of 7-25 meters (GPS navigation devices and smartphones with restricted signal reception (due to forest vegetation, high-rise buildings); GPS devices without GLONASS reception, navigation devices in cars, etc.);
4. Spot GPS measurements with accuracy within 5 m;
5. Spot GPS measurements with accuracy within 25 m;

6. Landslides plotted into the map 1:10,000 without GPS survey, or orthophotomaps 1:5,000.

7. Landslides plotted into the map 1:25,000 without GPS survey.

The database stores these original field records without any adjustments in specific tables (gps_trasy_gpx2d, gps_trasy_ssfSd, Tab. 3.1) in separate database Schema.

Fig. 3.2 GPS recording of landslide main scarp in Spišské Vlachy village, during the field survey and mapping of new activated landslide after rapid rainfall event in June of 2010.

Fig. 3.3 View of graphic and attribute form of detailed database of landslides visualised on ZB GIS groundwork.

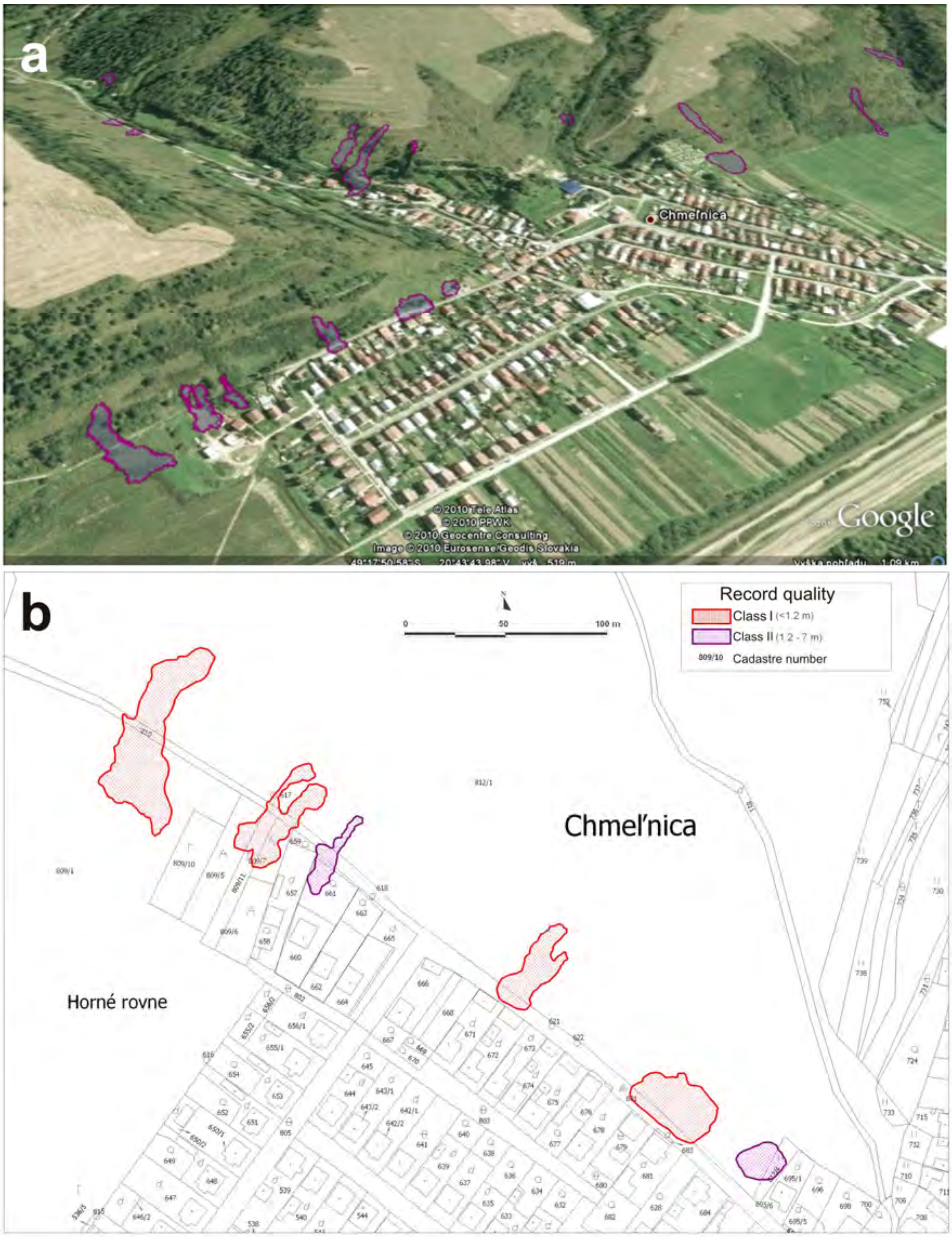

Fig. 3.4 Visualization of detailed landslide mapping on topographic groundwork: a) orthophotomap (Google Earth, 2010); b) KNC cadastre map.

5. Conclusions

The results of systematic mapping and registration of slope deformations, as one of the riskiest geological factors in Slovakia were completed in 2006 in a comprehensive map series "Atlas of Slope Stability Maps SR at Scale 1:50,000" (Šimeková & Martinčeková, et al., 2006, see also paper by Šimeková et al. 2014), assessing by unified methodology the whole territory of Slovakia. Despite the unquestionable importance of this work its practical use has revealed certain deficiencies derived mainly from general scale but also from its gradual "aging" (maps are not systematically complemented on emergency and other activated landslides or other newly registered slope deformations) and therefore they find limited use in engineering projects and spatial plans documents.

The above deficiencies of the Atlas can be eliminated by:

1. Building a GIS database of slope deformations in the fine-scale compatible with ZB GIS topographic basements. This database will gradually integrate slope deformations:

- registered in the Atlas, whereas the polygons of slope deformations are digitized from the working and terrain maps of scale 1:10,000 of the Atlas's initial documentation, as well as from various engineering geological maps of detailed scales, or other documents;
- new slope deformations registered within the geological projects after 2006, i.e. after the completion of the Atlas;
- slope deformations registered by SGIDŠ geologists in their expert visits to emergency landslides reported to MoE by local authorities or directly by the citizens.

2. New projects aimed at creating the landslide hazard maps in detailed scale based on reassessment of older relevant maps and a new field mapping, using new computer technology and software, oriented to the area with the greatest landslides risk.

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4. Landslide Hazard Assessment Using Spatial Statistical Methods

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Abstract: The paper presents several commonly used statistical methods: bivariate analysis with weighting factor and multivariate conditional analysis with regard to the landslide hazard assessment within GIS environment. Complete methodology from selection of input factors, data collection and preparation of parametric maps as well as compilation of landslide hazard map is proposed. Finally, evaluation, advantages or disadvantages of both applied methods are compared in case study area nearby Hlohovec and Sereď (Slovak Republic) in detailed map scale.

Keywords: landslide hazard • landslide susceptibility map • spatial statistics • bivariate analysis with weighting • multivariate conditional analysis • parametric maps • Geographic Information Systems (GIS) • Hlohovec – Sereď area

4.1. Introduction and terminology

In the present time landslides pose a significant environmental threat with their unfavourable socio-economic impact in many regions of the world, including Slovakia. Therefore, the interest of many researchers is mainly focused on the defining factors of slope movements and making prognoses of landslides occurrence in the future with high probability. This effort has led to the development of many methods of landslide hazard assessment and prognosis. Among them, the quantitative methods have an important position, which includes also the statistical methods presented in this paper (Aleotti & Chowdhury, 1999). They are based on relation between relevant factors affecting the slope stability and registered slope deformations, with subsequent statistical processing.

Statistical methods have been gradually developed since the 70ies, when there were published a lot of papers presenting many different approaches to solve the above topic. A detailed overview of the methods from this period is contained in the studies of authors van Westen, 1993; Carrara et al., 1991.

In the natural sciences, which are mainly engaged in the examination of objects and phenomena, the real geographical space is closely related the use of geoinformation systems (GIS). The wider use of GIS technology in natural science disciplines has been started from the first half of the 90ies in connection with available personal computers. Thanks to use of available technology, which is needed for processing large statistical data files, development of statistical methods in the landslide hazard assessment was significantly shifted both in theory and in practice.

With respect to the fact that the statistical prognosis of the landslides occurrence is based on the assessment of the similarity of a set of conditions in the affected area, it followed the assumption that landslides will occur in the future under the same conditions as occurred in the past and occur at present. According to this assumption, the steps of assessment are: the detailed landslide inventory; the mapping of factors (parameters) associated with the landslides occurrence; the classification of set of factors, regarding a degree of landslide susceptibility in the area based on the statistical relation to the registered slope deformations; and the final synthesis and compilation of the resulting prognosis map.

The final prognosis maps divide the area into a defined number of landslide susceptibility zones. From these maps it is possible to determine critical areas, where occurrence of slope deformations can be expected in future, assuming the presence of appropriate trigger events. In Slovakia, three zones are defined: stable areas, conditionally stable and unstable areas in terms of methodology by Kováčik (1996) and Directive of MoE SR (1999). These maps were compiled predominantly in traditional way (empirical engineering geological and geotechnical approaches), but at present they could be significantly improved using statistical methods within GIS environment.

In the presented case-study the area between the Hlohovec and Sereď cities in western part of Slovakia was chosen. The area is intensively affected by the active landslides and has been continuously monitored since 1997 by the State Geological Survey (SGIDŠ, Iglárová et al., 2011).

4.1.1. Basic terms

Herein used terminology is based on the most commonly used terms, mainly from studies: Carrara (1983, 1988); van Westen (1993); van Westen et al. (1993) and Aleotti & Chowdhury (1999). The terminology of engineering geology, geological hazards and risks follows the study of Varnes (1984), the landslides classification (in the Slovak Republic) is according to Nemčok, Pašek and

Rybář (Nemčok et al., 1974) and Matula (1995), Ondrášik & Gajdoš (2001), Drdoš (1992), Minár & Tremboš (1994).

In this paper the *landslide susceptibility* term depends on the context and can be optionally replaced with the term *landslide hazard*.

In the scope of the landslide hazard assessment we can estimate the areas of the occurrence, the time and the intensity of this phenomenon with various degree of probability. The place of the occurrence can be predicted with a high probability based on the analysis of relevant factors by conventional models with low uncertainty. The models are based on the implementation of the spatial distribution of those factors, which are relevant to the occurrence of slope failures. The term *slope stability conditions* includes various external and internal factors that affect the stability of slopes, e.g. lithology, physico-mechanical properties of the rock environment, character of geological structures and setting, georelief (slope dip, slope length, aspect), hydrogeological conditions (rainfall and groundwater level), land cover, etc.

Most of the mentioned conditions and factors of slope movements can be quantified; i.e. expressed in numerical form (absolute or relative/semi-quantitative). Numerically expressed factor of slope deformations is called *index* or *parameter.*

Trigger factors directly cause landsliding in unfavourable conditions, for example by increasing the active forces acting on the slope (external causes), or reducing the shear strength of rocks inside the slope (internal causes). They are usually unexpected events that cannot be predicted by conventional deterministic models: e.g. earthquake, rapid rainfall, increasing of slope angle caused by lateral erosion during the storms and floods, various influences of anthropogenic activities (surcharge on slope with artificial fills, undercutting the slope toes, etc.). Trigger factors and events are not included in the presented methodology.

For solving of presented problems within GIS environment it is necessary to define each input parameter in a spatial form as *parametric map* (often termed as "index map"). The parametric map in digital form (vector or raster) represents a data coverage (theme) with polygon topology. In terms of vector graphics each polygon is given by a set of nodes (vertices) of border line, where the nodes are defined by pairs of coordinates (X, Y) in two-dimensional geographic space. For the methodology used in the present paper the raster format is more appropriate and recommended, which is the standard for using map algebra.

4.1.2. Review and progress of statistical method*s* in the landslide hazard assessment

Among the statistical methods, two groups of methods are the most important: bivariate and multivariate analyses. In the case of *bivariate analysis* each input parameter is compared separately with landslides inventory map. The advantage of the bivariate analysis is the possibility to weight each input parameter, calculated on the basis of the landslides density within each class of parameter. Weights for each input parameters are reflected in the final compilations of resulting maps.

The *multivariate analysis* considers mutual combination of several (or all) input parameters simultaneously with the landslide inventory map. The quasi-homogeneous *unique condition units (UCUs)* are created by combination of classes within each input parametric map. In this case the weights of individual parameters are not accepted, because the importance of each parameter is determined by its frequency and repeating the class of parameter in combinations within the UCU. The multivariate analysis also partially reflects the interaction and influences among different input factors.

The first case studies of statistical approach to landslide hazard assessment were published by Carrara (1983, 1988) and Carrara et al. (1990, 1991). Later on, several authors continued in this research, innovating and applying the issue of quantitative landslide hazard assessment using GIS in many areas (Atkinson & Massari, 1998; Guzzetti et al., 1999; Gupta & Joshi, 1990; Jäger & Wieczorek, 1994, etc.). The summary report of methodology of GIS application in the landslide hazard analysis is in the works of Carrara et al. (1995) and van Westen (1993). Van Westen (1993) discussed in detail basic principles of different approaches using bivariate (or univariate) analysis, as well as the multivariate analysis. Authors implemented the theoretical principles into the sophisticated program GISSIZ which practical manual was the second part of the publication (van Westen et al., 1993).

From practical point of view the following studies are notable: Irigaray & Chacón (1996); Clerici (2002); Süzen & Doyuran (2004); Joshi et al. (1997). Comprehensive summary of the landslide hazard assessment, short description and classification scheme of mostly used methods (including statistical methods) is presented in the work by Aleotti & Chowdhury (1999).

In Slovakia, except of a pioneer work by Vlčko et al. (1980), the application of exact quantitative methods of landslide hazard assessment was not systematically solved until early the turn of millennia. Since 2001 to 2012, several progressive works and studies as well as scientific publications dealing with the practical application of statistical methods in landslide hazard assessment have been created.

In the initial period, the studies were focused more in the theoretical principles of statistical methods and their practical application in selected areas predominantly in the scale 1:50,000 (Pauditš & Bednarik, 2002; Bednarik et al., 2005; Jurko et al., 2005; Pauditš et al., 2005, etc.). Later, the case studies and practical applications were focused in the landslide hazard maps creation in smaller areas in more detailed scales (Bednarik, 2007; Magulová, 2009; Petrýdesová, 2012).

At present, the attention is focused in specific theoretical and practical aspects of these methods (Bednarik & Pauditš, 2010) as well as a comprehensive assessment of larger areal units, including transboundary areas (Bednarik & Liščák, 2010; Holec et al., 2013).

The attention deserves a project titled "Engineering Geological Mapping of Slope Deformations in the Most Vulnerable Areas of the Flysch Zone" (Grman et al., 2011), in which the landslide hazard map of the north-west and north-eastern part of Slovakia with an area of 4,042.23 km^2, at a scale of 1:10,000 was created.

4.1.3. Terminology and principles of the raster data model and map algebra

Generally, the Geographic Information Systems (GIS) have been considered as a special type of IT systems where the most data have been fixed to spatially localized objects, phenomena or events (according to Clarke, 1999). One of the basic advantages of using GIS is the modelling and analysis of dynamic spatial processes by set of numerical and statistical methods (Tuček, 1998; Hofierka, 2003). In the case of raster data model the basic unit is presented by grid cell. Set of cells represents a regular numeric matrix in two-dimensional space (*grid).* Each cell of raster is defined by a pair of coordinates in real two-dimensional geographic space and at least by one numeric attribute - quantifier, which represents the basic entry for mathematical operations.

The relation between the numerical values of cells in the grid can be continuous or discrete. In the case of continuous values smooth transitions exist between the neighbouring grid cells (e.g. continuously changed values of altitudes). Conversely, discrete data field has crisp boundaries between differently classified areas, without smooth transitions (it is not possible to present it in the form of isolines). The change in grid topology from continuous to discrete allows a *reclassification* process, by definition of intervals. On the other side, the *interpolation* process allows for calculating the empty space between the discrete input data (points or lines). In case of entry into the statistical analysis it is better to use the reclassified data fields (for example the slope angle divided into six intervals, the aspect into four quadrants, etc.).

The most frequently used analytical tool for processing of raster maps is *map algebra.* It provides the opportunities for manipulation of numeric values in the grid cells as elements of arithmetic expressions and functions. Programming procedures and calculations within the map algebra could be usually run using short scripts in command line environment. In the present paper utilization of map algebra environment of the *open source GIS GRASS* is recommended – the r.mapcalc package (Shapiro & Westervelt, 1992). In the past, the GRASS GIS environment was used in predicting landslide hazard and the creation of landslide susceptibility maps by Gupta & Joshi (1990); Jäger & Wieczorek (1994); Clerici (2002) and others. Statistical analyses were realized in GRASS system (r.stats package) connected with statistical software *R-statistical language* (Bivand, 2000).

4.2. Methodology overview

Methodical approach of landslide hazard maps creation by statistical methods in the Slovak Republic has been published repeatedly since 2002 and practically verified by several case studies. Development of the coherent methodology at the present time depends mainly on the relatively dynamic implementation of GIS technologies to geological practice. This trend is likely to influence also a development of related legislation, not only in Slovakia but also worldwide.

The methodology of statistical assessment and prognosis of landslide hazard is based on the appropriate selection of slope stability factors and their evaluation resting in a comparison with the occurrence of slope deformations in the study area. Based on the above, potential occurrence of landslides in future is expected in the same conditions as in the past, respectively at present. Set of factors, statistically assessed in GIS environment by comparison with the spatial distribution of registered landslides has been applied using the extrapolation to the field units in the whole assessed area, where it is also assumed the possibility of occurrence of slope deformations in analogical favourable conditions. A new prognostic map dividing the study area into the zones with different degrees of landslide susceptibility was created. The zones classified according to the statistical approach can be applied only in the area where the statistical assessment has been done, so the extrapolation has not a general application. Terrain units cannot be classified by the same way as in other areas where the conditions of landslide susceptibility can be different.

Based on the above, the main thesis and goals of this paper are:

- selection of the appropriate statistical methods for creating of landslide hazard map with regard to the implementation within GIS environment;
- proposal of methodology with respect to optimal possibilities of practical applications: data collection, statistical processing, final compilation of the resulting maps;
- practical verification of weighting calculations with subsequent determination of the relevance of various input parameters in the model area;
- practical application of the proposed methodology in the model area between Hlohovec and Sereď, creation of landslide hazard map of detailed scale (compatible with ZB GIS; Michalík, 2010), including all necessary attributes resulting from existing directives (Kováčik, 1996; Directive MoE SR, 1999);
- proposal of the most appropriate method for the practical use in future (with respect to data sources and data availability, legislation, geological conditions, landscape-ecological and urban aspects, etc.).

The progress of the works can be summarized as follows (Fig. 4.1):

Engineering geological mapping and landslides registration are required for statistical analysis and application of all mentioned methods. The landslides can be obtained from different types of data archives, maps or remote sensing images, etc. The field verification and supplementary mapping focused on the accurate position of entities is necessary.

Mapping of input parameters. Different natural and anthropogenic factors influencing the slope stability represent important input variables in the statistical analysis. Selection of the input factors is specific for each study area and widely depends on the individual assessment of conditions and professional experience of researcher. For example, the slope aspect more markedly influences the soil moisture in coastal areas with predominant winds in one direction (usually from the seaside), as in the inland where the wind direction does not influence so much. The weight of each factor in specific area can be exactly determined using methodology by Vlčko et al. (1980).

Implementation into GIS environment. Each input factor has to be quantified prior to entering the GIS and spatially expressed in the form of index map. At present sense of words, index map represents a system whose each component is represented by quantified parameter class.

Statistical analysis consists of comparing the index maps with landslides inventory map in GIS environment based on exact rules and statistical methods. In the presented study, the bivariate analysis with application of weighting of variables and conditional multivariate analysis were used. The result of the analysis represents the reclassification of input parameters according to susceptibility to landslides based on frequency of landslide occurrence in each parameter class.

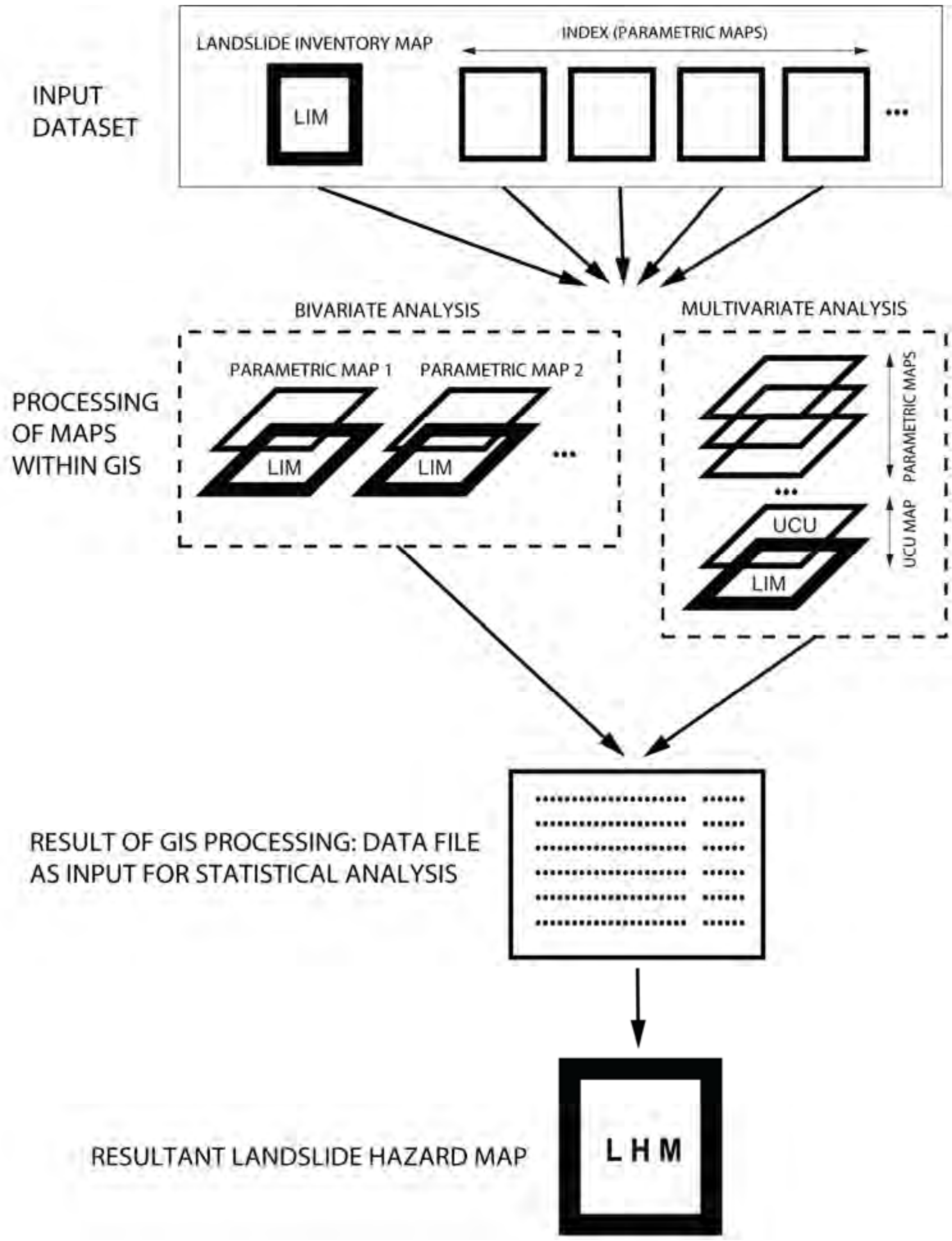


Fig. 4.1 Landslide hazard assessment schematic flowchart.

Compilation of the prognosis map is the final step of the whole methodology process. The distribution process and determination of the finite number of the zones in the map represents a creative and highly responsible part in terms of the final results, which depends on the individual approach of the investigator and used procedure.

4.2.1. Preparation of index maps

Technology of raster based GIS and map algebra assumes a precise preparation of the input index maps, often created by the conversion of primary vector data layers into raster format, which creates a basis for all statistical and mathematical operations.

Each index map in the GIS environment represents the spatial distribution of the parameter that enters into the statistical analysis. For the correct work with these maps in GIS environment, it is necessary to fulfil certain technical requirements. The basic requirement of each parametric map is its *positional accuracy*. Parametric maps are often derived from multiple sources: different thematic maps in various cartographic documents, digital vector maps in various projections, remote sensing data, satellite images, etc. Positional accuracy of such sources is often variable and results mainly from scale, method and precision of scanning and georeferencing.

In the Slovak Republic in the GIS environment most commonly used coordinate system is S-JTSK in Křovak cartographic reference. Despite the fact that its accuracy is being currently reevaluated, it is still officially supported coordinate system and most digital data (including topographic groundwork) are available within this system. For this reason, the cartographic data transformations among different coordinate systems are often necessary (e.g. from S-JTSK to UTM). This is usually connected with minor or major loss of positional accuracy.

In the former Czechoslovakia before the 1989, some public cartographic maps were deliberately distorted and deformed for strategic reasons. These distortions were strongly reflected mainly in the maps of small and medium scales. Later they were partially transferred also into digital map series (e.g. SVM 50 - seamless vector map 1:50,000) distributed by GKÚ SR, which currently cannot be considered as spatially accurate. Since 1989, all published map layers should contain correct positioning (in relation to the S-JTSK and its known position errors). Currently, the actual digital maps (e.g. ZB GIS; Michalík, 2010) have solved the problem of positional accuracy in detailed scales (so called "scaleless" map series).

Many thematic maps, which contain important information source for the input index maps were processed in the past and currently exist only in printed form. Therefore, for their entry into the GIS their digitization is needed. This includes for example: set of geological maps at a scale of 1:50,000, issued in SGIDŠ until the year 1992; synoptical engineering geological map of Slovakia from 1989 (PIGMAS, Matula et al., 1989) and many authors´ original manuscripts plotted on different topographic and elevation layouts. Some of these maps cannot be georeferenced with required precision and subsequently digitized, therefore, they are not considered as positionally accurate.

Despite the mentioned facts, for the correct subsequent processing the positional alignment of all input maps with topographic layouts (and also with each other) is necessary. Statistical methods require indispensable geographic accuracy and *correct superposition* of all input parametric maps. For mutual “superpositioning” of the digital maps derived from various sources serve different transformation algorithms (linear and polynomial transformation, *rubber-sheeting*), which are commonly implemented in GIS systems (e.g. the ADJUST in ESRI/ArcInfo™, i.rectify command in GRASS GIS, etc.).

Another important step, which is needed for conversion of vector layers into raster parametric maps, is the *topological correction,* which involves error corrections of polygon topology generated during digitization process and subsequent map editing. Among standard errors belong: snapping error and overshooting of lines to fitting point, missing fitting point, unclosed polygon, etc. Without correction of these seemingly minor technical errors the conversion to raster format would not be possible, which is the final stage of technical preparation of parametric maps. For topological correction, the BUILD and CLEAN commands are standard-used.

After the conversion to raster format, it is also necessary to adjust all input parametric maps in terms of the geometry of grid. This means that each parametric map must have the same grid geometry (same number of cells of the same size) within the assessed area; otherwise the results of statistical analyses could be highly distorted and unreliable. GRASS GIS system defines uniform geometry for all parametric maps already within the definition of the system variables (LOCATION/MAPSET) and these are fixed to all index maps of the same project.

The cell size is chosen based on the required precision and scale, eventually also depending on the required quality of the printed output. In general, for the data derived from maps of medium and large scales the cell size 10 x 10 m is adequate; more detailed grid with smaller cells takes inappropriate requirements on computing performance, but usually doesn’t give higher information value in results.

In the model area in the present paper, the uniform defined grid of square cells of cell size 5 m is used, which in the whole area (89.40 km^2) represent 1,720 x 3,430 cells.

Index maps originally obtained or generated in raster form: e.g. DEM and its derived morphometric parameters (slope angle, curvature, etc.) primarily represent the distribution of input factor in form of a continuous grid. Therefore, they must be transformed into grids with discrete values separated by crisp boundary. Conversion process of continuous values into discrete intervals is called *reclassification*. Rules for the reclassification of various parametric maps may be different; mostly they are not based on exact procedures, but on the author's opinion and character of given input parameter in the assessed area.

The objective of the first reclassification of parametric maps is to get the minimum number of categories (classes) in each parametric map, in order to obtain the minimum number of final quasi-homogeneous units (UCUs) in combination with each other in the case of multivariate analysis. Either the maps without primary reclassification or maps with a large number of classes (e.g. the original geological map with many units) are used, the number of final UCUs in multivariate analysis will be enormous (nonsensical proportions in principle) and very difficult for final processing. On the other side, in the case of bivariate analysis, the weighting process containing determination of correlation coefficient is preferable to work with a lot of data contained in original non-reclassified parametric maps.

4.3. Bivariate analysis with determination of the weight of input parameters

In the case of bivariate analysis each parametric map is statistically compared with landslide inventory map separately. In simplified term, it is a comparison of two input parameters where one (the landslide inventory map) presents a dichotomous variable as the binary map with numeric values: 1 (TRUE) or 0 (FALSE). The result is a table containing a double combination, in which one of the numbers is a class in the parametric map and the second number (0 or 1) means the presence or absence of the landslide in given category.

Having in mind that the landslides map is usually expressed in the form of sequences of grid cells representing a scarp zone of landslide as the line, the number of landslides cells in each class of parameter is decisive. The result of combination is to determine a total number of cells with and without landslide scarps in each class of parameters.

The next step is the calculation of *density* within each class of parametric maps. The density represents a number of cells contained in the area with landslides in each class in proportion to the total number of cells in the parameter's class.

The density calculation is in principle relatively simple, while the landslide inventory map is expressed by dichotomy form of binary grid (0/1). Provided the landslides in parametric map are presented in the form of scarp lines (main scarp upper edge - MSUE; Clerici, 2002), the number of cells can be converted to the length of scarp (e.g. based on the ratio of the basic cell size and the diagonal; Jurko, 2003) and intensity of landslide activity in the study area was expressed by total length of MSUE (in meters)/1 km^2 of area of the parameter class. In the case of presentation of landslides entities as raster polygons, the number of cells has to be converted to total area (in m^2) and intensity was expressed as the percentage or per mille (Bednarik & Pauditš, 2010).

These calculations are obviously loaded with systematic errors, resulting from the approximation of cell size, but generally the cell size doesn't significantly influence accuracy and reliability of the calculation result of density value. For instance, for the 5 x 5 km area, the difference in accuracy with cell size 10 x 10 m and 2 x 2 m is of order of tenths of a percent.

This way obtained density generally expresses a frequency of landslide events in the parameter class. For example, by comparing the lithology factor with landslides inventory map it can be found that statistically most affected areas per basic area unit fall within flysch formation with a predominance of clayey soils, etc.

This indicates that usually the output maps have been highly influenced by the inaccuracies and errors during the preparation process of parametric maps, especially by differences in positional accuracy and mutual superposition. Results from non-coincident, spatially inaccurate and geometrically different maps cannot be considered as representative and may be misleading.

Based on the calculated density of the landslide occurrence, each parametric map can be secondarily reclassified, where newly assigned numeric value (replacing the first one) represents statistically determined landslide susceptibility separately for each parameter class (see Tab. 4.1). The reclassified parametric map is created, in which the highest numerical value represents the class most susceptible to sliding and on the other hand, the class with the lowest numerical value presents the lowest landslide susceptibility hazard.

Tab. 4.1: Example of secondary reclassification of input parametric maps with assignment of weighted classes' values (by Bednarik, 2001: Pauditš & Bednarik, 2002).

	Lithology	Slope	Elevation
Primary classes	1 2 3 4 5 6 7 8 9 10 11	12 3 4 5 6	12 3 4 5 6
Secondary reclassified classes	4 11 9 1 1 2 3 3 10 8 1	5 6 4 3 2 1	6 5 4 3 2 1

An outcome of the bivariate analysis is the final map of landslide hazard resulting from the weighted summation of all secondary reclassified parametric maps. Prior to the final summation it is necessary to determine the weight of each input parameter.

Another necessary step prior to the final summary is the equalisation of the number of classes in each input parametric map according to the parametric map with the largest number of classes (parameter z/m_i - equation 4.1). If this equalisation is not applied before the final summation, parametric maps with fewer classes would enter into the summary with distorted (undervalued) values, and therefore partially depreciate the weight of each parameter.

The equation for the final summation in the bivariate statistical analysis for the calculation of the weighting parameter as a whole is as follows:

$$y = \sum_{i=1}^{n} C * \frac{z}{m_i} * W_i \quad (4.1)$$

y – value contained in final landslide hazard map;
i – the number of the input parametric maps (1, 2…..n);
z – the number of categories in the parametric map with the highest number of categories;
m_i – the number of categories in the relevant parametric map;
C – the value of class in secondary reclassified parametric map;
W_i – the weight of the input parameter.

The result of such summation is a continuous interval of values limited by the equalised summary of the lowest and highest values in each of the parametric maps in the whole study area.

Finally, the interval of values should be divided into a final number of classes, representing the zones of landslide hazard map. Current Directive of the Ministry of Environment of Slovak Republic issued to produce the landslide susceptibility maps (Kováčik, 1996; Directive MoE SR, 1999) indentifies three degrees (zones) of stability of the area: zone of the unstable areas, zone of the conditionally unstable areas and zone of the stable areas. The ranges (intervals) are advisable to be selected based on either an equitable distribution of the result to three equal parts, or more exact methods application (Pauditš et al., 2005; Pauditš, 2006). In other cases, a five level scale could be used: low, moderate, medium, high and very high susceptibility, which describes zoning area in more detail (Bednarik & Liščák, 2010; Holec et al., 2013; Petrýdesová, 2012).

4.3.1 Determination of weight of the input parameters

The weight of each input parameter indicates its relevance in the landslide hazard analysis. It determines the degree of correlation of values in the parametric map data with a constant value of 1 (TRUE), representing the occurrence of landslides. If the degree is high, it can be stated clearly that the parameter has a significant impact on the formation and distribution of slope deformations within the study area.

The principle of weighting determines the possibility to use the weight of input parameter value in the bivariate analysis only when the weighted value enters into the final summation of the secondary reclassified parametric maps. In the case of the multivariate analysis the weighting of values in that sense of word cannot be used, because when compared with the landslide inventory, all parametric maps enter simultaneously. Nevertheless, the weight of a parameter is possible to determine as a partial result of multivariate analysis – matrix of values combination of the all input parametric maps, based on the analysis of frequency and probability distributions by any standard statistical processes (Student's t-test, χ^2 test, etc.). This way obtained weight can be used only in the process of the bivariate analysis.

The methods of determination of the weight of input parameters could be various: as a whole, including all classes (Vlčko et al., 1980) or individual for each class (category) within the parametric map (van Westen, 1993; Donati & Turrini, 2002; Süzen & Doyuran, 2004). Each of the methods has some specifics and different usability in a given area. For example, in areas, where the dependence of the occurrence of landslide on certain factor, which lacks any category having some impact on the landslide occurrence, has been observed (e.g. northern quadrant of aspect), the low weight of such parameter as whole could be set falsely, whereas all the remaining classes didn't show significant statistical correlation. Therefore it is necessary to apply always such a weighting method, which takes into account the specificities of the study area and also the character values within input parameter maps. There is recommended to calculate the weight of each parameter separately for specific monitored area, or to use a subjective weighting method for each area.

In order to obtain the most exact result of calculating the weighting parameter it is necessary to work with the maximum input data set. Therefore, it is preferable to calculate the weight parameter prior to primary reclassification of parameters into classes. For example, if the weight for slope angle factor is calculated (using any method), it is better to use the original input floating point values (calculated with step of 1°), and not just a small number of classes after the reclassification. Similarly, it is necessary to follow the same way in all cases where the original grid exists in the form of continuous (floating point) data field.

In this paper, the determination of the weight parameter as a whole based on the value of entropy and information coefficient has been used. Practical approach, especially within the GIS environment, the exact method of determining the relevance and calculating the weight of individual input parameters was suggested by Vlčko et al. (1980). The present approach is based on the principle of the bivariate analysis, which determines the intensity of slope deformations occurrence (p_{ij}) in the individual classes of input parameters. Within the model area between Hlohovec and Sereď cities, 6 parameters were used: lithology, digital elevation model, slope angle, curvature of the relief, distance to stream and current land use. The way of determining the weight parameter as a whole is based on the determination of entropy (H_j) and maximum entropy (H_{jmax}) of the system according to the following equations:

$$H_j = -\sum_{i=1}^{Sj} \left[p_{ij} * \log_2(p_{ij}) \right] \quad (4.2)$$

H_j – entropy;
S_j – number of components in system – classes in parametric map (j = 1... n);
p_{ij} – probability of the landslide occurrence in class of parameter (i = 1 ... S_j).

$$H_{j\max} = \log_2 * S_j \quad (4.3)$$

$H_{j\,max}$ – maximum entropy;
S_j – number of classes in the parametric map, j = 1... n.

The information coefficient I_j is defined according to equation, for j = 1, 2… n:

$$I_j = \frac{H_{j\max} - H_j}{H_{j\max}} \qquad (4.4)$$

The result will be in range [0, 1]. When the closer is a result to 1, the more destabilizes the input parameter the system. The weight of the parameter W_i is the product of the information coefficient I_j and the average probability p_j (represents the real probability values for each classes of all parameters), for $j = 1, 2 \ldots n$:

$$W_i = I_j * p_j \qquad (4.5)$$

Calculated weight value of each parameter can be entered into the equation (4.1) as the value W_i for the determination of the resulting categories of landslide susceptibility in the bivariate analysis.

4.4. Conditional analysis

Multivariate analysis, in broad terms, is based on a comparison of the input parameters simultaneously as independent variables with landslides inventory map. The landslide inventory map (dichotomous variable) does not take into account only the value 1 (TRUE), but also the value 0 (FALSE), which is equally important informative value.

In the case of *conditional analysis* (Carrara et al., 1995; Chung et al., 1995; Clerici, 2002), the extensive table containing all combinations of the classes in all input parametric maps, which are in mutual superposition, has been obtained by mutual simultaneous combination of all input parameters. The combination of all classes in parametric maps creates new areal elements in interim map, which represents quasi-homogeneous units, so-called Unique *Condition Units* – UCU (Clerici, 2002). For instance, if the class 6 (10° – 15°) is superimposed on the map of slope angle, class 4 (Pleistocene terraces) in the map of lithology and class 3 (forest) in the map of land use, the resulting quasi-homogeneous unit will consist of combination [4.6.3], etc.

When comparing with landslide inventory map in this combination [4.6.3] the main scarp edges attain a total length XY m ([6.4.3.1]) and combination without landslides occupies a total area of the XY m^2 ([6.4.3.0]). The final table includes the same number of records (rows) as the total number of mutual combinations of all classes contained in the all input parametric maps, landslide inventory map included. This number may reach the order of several thousands.

Neither secondary reclassification nor weighting of parameters is necessary before entering the multivariate analysis. In this case, the weight of parameter (or class of parameter) is determined on the basis of certain value repeating in each parametric map. Frequency of repeating values in matrices of categories can be determined exactly by known statistical methods (e.g. χ^2). However, for the conditional multivariate analysis (Clerici, 2002) determination of weight (in above mentioned sense of word) is not substantiated.

As in the case of bivariate analysis, the final combination with landslides existence (value 1 in the landslide inventory map) has been set according to calculated intensity occurrence as a ratio between the number of UCU cells with landslides and the total area of UCUs. Results ordered in the upper rows of the table represent combinations of classes of the input parametric maps, which we may consider in terms of landslide susceptibility as the most dangerous.

In the position of the last rows are UCUs that contain a very small number of cells of the scarps. These can be caused by systematic errors during the parametric maps creation. Determination of the number of "error" cells must be done empirically, individually for each project, based on the quality of source data.

In the case of using a larger number of input parameters the UCUs may be affected by landslides in a very high share (up 100%), although their area is negligible (often 1 or 2 cells from several millions).Value of the intensity of landslides in such UCU is very high and moves such UCU to the highest ranking position in the statistical susceptibility assessment. Such cases cannot be avoided, but for example the UCU where the total number of grid cells is less than 50 can be ignored in the process of assessment.

Process of final categorization area to a specified number of zones can be based on the following principles (Jurko, 2003):

- calculation of the mean intensity of landslides (M_d - *mean density*) in the study area within the UCU, which is affected by landslides (MSUE value 1 in the landslide inventory map) based on the ratio of the total number of cells in a given area and the summary number of cells of the scarp zones. The average intensity of affected UCUs represents the mean value of the middle interval calculated in ‰:

$$M_d = \frac{N_{pix} MSUE}{N_{pix} total} * 1000 \qquad (4.6)$$

- the searched range of the interval of the landslides occurrence intensities in each combination (C_i - class interval) can be determined from the equation:

$$C_i = \frac{M_d * 2}{N_{inrervals}} \qquad (4.7)$$

- subsequently, total number of combinations in the areas affected by slope deformations were divided into a specified number of zones on the basis of the calculated interval range: 0 – C_i; (C_i +1) – (C_i * 2); [(C_i * 2) + 1] – (C_i * 3); ...etc. In the present paper, where the value of M_d = 3.307, the following five intervals were defined: **1.** 0 – 1.322, **2.** 1.322 – 2.646, **3.** 2.646 – 3.966, **4.** 3.966 – 5.288, **5.** >5.288 corresponding to 5 degrees of landslide hazard.

For the final classification of all existing combinations (UCU) into final landslide hazard zones (degrees), program in map algebra environment can be used (shell script; Clerici, 2002; Bednarik et al., 2005), or a spatial database environment with the use of SQL language. In the case of using the SQL relational database an extensive table, which contains the coordinates of the grid cells (or spatial extension), combinations values and new assigned categories of landslide susceptibility are processed. Number of rows (records in the table) can increase to millions, depending on the size of the reference area and raster resolution (cell size).

Processing of such amount of data is quite time-consuming and requires the high performance computing, even with the current availability of IT. Other technical way is to export an extensive table to an external database, allowing processing of spatial data in real geographic coordinates (e.g. PostGIS spatial database). Operations of exports and backward reloading the result into the GIS system are also time-consuming.

4.5. Compilation of resulting hazard map

In terms of methodology based on the “Directive of the Ministry of Environment of Slovak Republic” issued to compilation of the geofactors maps is the final map entitled: “Map of relative susceptibility of region to landsliding” prepared by the compilation of the following topics:

- coloured area zonation (zones and subzones);
- lithology (the class of lithological units shown by hatching);
- borderlines of landslide bodies;
- deformations caused by the undermining;
- elements of water erosion;
- tectonic features;
- hydrological and hydrogeological conditions;
- topographic groundwork.

Area zonation in final map is highlighted in coloured zones using the standard “semaphore” scale presenting the zone of stable areas (green), conditionally stable areas (yellow) and unstable areas (red). For better visualization, the colours can be highlighted using the hill-shade effect, as the map will have more “plastic” character and allows better orientation in map with respect to morphology.

Schematic lithology in the map is represented by transparent hatches, overlaying the basic colour zones. Hatches identify the typology of Pre-Quaternary rocks and Quaternary cover. Lithological classes are formed by merging classes of the original geological, respectively engineering geological maps and their number can be varied.

Special item in the map legend are *geodynamic phenomena*, which are divided into active (red), temporarily stabilized (purple) and stabilized (black). Slope deformations are classified into 6 groups: A. falling and toppling, B. earth flows, C. landslides in soils, D. creep deformations of rocks, E. block fields and rifts, F. creep deformation of soils (slope deposits). In each group more types of slope deformations are selected marked by individual symbols. Tectonic faults are shown in the form of lines different for Pre-Quaternary and for neotectonic active failures. Elements of water erosion (rills, gullies, etc.) are represented by red line entities.

4.6. Input index maps

The six input parameters have been evaluated in the present case study Hlohovec – Sereď, specifically: lithology, DEM, slope angle, curvature of the relief, distance to stream and current land use. DEM, slope angle and curvature of relief are the geomorphological factors. Each input parameter enters the statistical analyses in the form of raster index map, which technical preparation requires a precise approach (see above).

The positional accuracy of maps is adapted to binding topographic groundwork in the Slovak Republic - ZB GIS (Primary Base of Geographic Information Systems), applicable to a scale 1:10,000 and higher (up to detailed cadastral maps).

4.6.1. Lithology

In the term of presented methodology, the factor of geology converted into the index map of lithological units, has been considered as one of the most important assessed factors. Besides the character of lithology, in the landslide susceptibility assessment there has to be taken into account a structural characteristic of rock environment as a complex unit. Spatial distribution of lithological types significantly controls the formation and evolution of slope deformations in the study area. The main factors influencing the slope stability are engineering geological properties of rocks: physical properties (bulk density, permeability) and strength characteristics expressed by cohesion and angle of internal friction.

The map of lithological units in assessed area was primarily derived from digital geological map at 1:50,000 scale (Káčer et al., 2005), which has been subsequently modified and adjusted to 1:10,000 topography, mainly water streams in alluvial basins and valleys. The original 20 lithological units contained in the source geological map were reduced to 9 classes (primary reclassification) based on the similarity of the engineering geological properties (Fig. 4.2, Tab. 4.2). The largest spatial distribution in the selected area occupy the aeolian sediments represented by loess and loess loam (class 7), which are distributed in more than 46% of the whole area.

4.6.2. Geomorphology

Morphological parameters of georelief (slope angle and curvature of the relief) present secondary derivative obtained from digital elevation model (DEM) created in ArcGIS environment using the interpolation tool (Topo to Raster), that interpolates a hydrologically correct raster surface from point, line and polygon data. As an input data source for DEM creation the contour lines from 1:10,000 scaled topographic maps were used which have been geo-referenced to S-JTSK coordinate system. The final raster of DEM (cell size 5 x 5 m) represents a matrix of associated values of altitude with floating point, which was reclassified to integer values (discrete intervals) - *hypsographic levels*. Digital elevation model was reclassified into five classes and their spatial distribution is given in Fig. 4.2 and Tab. 4.3. The differences in altitudes are relatively small, only 180 m, and a bit more than 45% of the study area falls within the second class ranging from 140 to 180 m a. s. l.

Tab. 4.2 List of reclassified lithological units with ID number contained in origin geological map.

Class	Description
1	anthropogenic and organic-fluvial sediments (3, 38)
2	Holocene fluvial sediments (1, 24, 25)
3	Holocene proluvial sediments (26)
4	Pleistocene terraces (4, 5, 11, 28)
5	slope sediments (18, 20, 40)
6	outwash sediments (14, 124)
7	eolian sediments - loess and loess loam (16, 681)
8	Neogene sediments - predominantly gravels (22, 1721)
9	Neogene sediments - predominantly clays (23)

Slope angle belongs to the most important geomorphological factors, which significantly influences the slope stability. Each slope has a threshold value of slope angle, beyond which the slope begins to be unstable. In the digital form, the slope angle grid represents a matrix of values of angles in degrees. In the present study, the values of slope angle derived from DEM were reclassified into 9 classes (Tab. 4.3, Fig. 4.2) in terms of the methodology LANDEP (Miklós & Izakovičová, 1997). Tab. 4.3 shows that in the studied area dominates first class of very flat slopes (slope angle is less than 2°) which occupies more than 33% of the whole area. This class is characterized by the alluvial plain of the river Váh and the area isn't prone to sliding. Nevertheless, this class is relatively important in relation to accumulation zones of landslides. The areas, where the landslides are more frequent, take more than 53% (classes 5 and 6). Slopes with the angle value over the 17° (classes 7, 8, 9) occupy very small part - only 1.12% of the assessed area.

Curvature of the relief is the another geomorphologic factor derived from DEM. Curvature factor substantially affects the dynamics of the surface water flow over the relief (acceleration, convergence and divergence) and often is used in assessment of the vulnerability of areas to surface water erosion (Hofierka, 2003). Within GIS environment is possible to calculate several types of curvature (profile, tangential, mean, etc.). The most widely used type of curvature which was applied in this study is combination of curvature - combination of profile and plan form curvature. While the profile curvature affects the flow acceleration (influences on erosion and deposition), the plan curvature influences convergence and divergence of flow. Considering both kinds of curvatures together allows to understand more accurately the flow across a surface (www.esri.com, 2014). The resulting raster map of curvature of the relief (Fig. 4.2) was reclassified into three classes according to Pauditš (2005) and Bednarik (2007): convex (positive values), concave (negative values) and linear (values close to 0 – inflection points). During the reclassification process the following intervals were used (Pauditš, 2005): less than -0.00025 (concave forms); from -0.00025 to 0.00025 (linear forms) and values more than 0.00025 (convex form). The concave and convex relief forms were relatively evenly distributed in the assessed area with a slight predominance of convex forms (Tab. 4.3).

4.6.3. Distance to streams

Lateral erosion of stream may affect the stability of slopes undercutting the landslide toe, reducing the passive forces acting contra the sliding. At the same time the vicinity of a stream leads to increased water saturation of the rock environment.

The distance from the streams determined in the GIS environment can be realized using various distance analyses. The simplest way is to determine the two-dimensional space using Euclidean distance based on the straight-line distance. The Euclidean distance output raster contains the measured distance from every cell to the nearest source - streams. The distances are measured as the crow flies (Euclidean distance) in the projection units of the raster, such as feet or meters, and are computed from cell centre to cell centre.

The map is represented by grid distance of landslides from streams and rills. As a basis for compilation of parametric map distances to streams, detailed vector map of the river network was used. The final raster map was reclassified into 8 classes. In Tab. 4.3 the interval of the distance distribution area of streams is listed, as well as the spatial distribution of individual classes and cumulative expression of the distance area.

The highest percentage occupies the area remote from streams in range of 500 to 1,000 m (27.5 km^2). As already mentioned the largest influence on the formation and activation of landslides has the lateral erosion of streams and then the most important is the area closest to streams. All-in-all, within 250 m from streams is almost 25% of the study area, from which only 3% is up to 50 m.

4.6.4. Landcover

The parameter expresses the current land use, with focus on the character of the *vegetation cover*. The vegetation cover affects the slope stability mainly in terms of retention of rainfall, different ability of evapotranspiration and also the distribution and depth range of the root system. The state of vegetation cover also affects the resistance against erosion, which also partially affects the slope stability. The question of the vegetation cover and slope stability is thoroughly reviewed in the study of Greenway (1987).

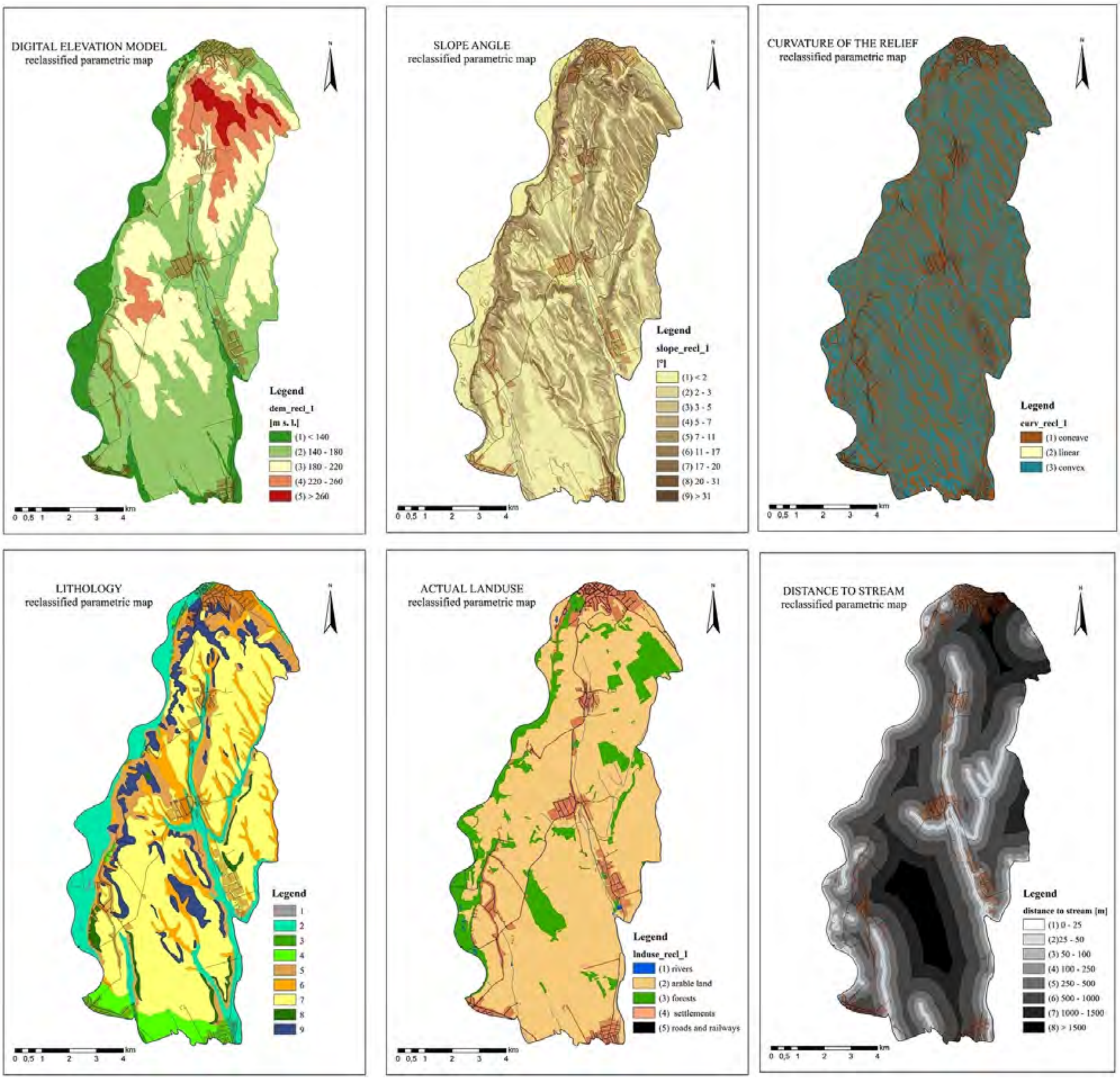


Fig. 4.2 Reclassified input parametric maps.

The map of actual land use was compiled from topographic raster images (scale 1: 10,000) provided by GKÚ in Bratislava. The map of current land use was divided into polygon features representing the elements of landscape structure and converted to raster format with cell size 5 x 5 m (Fig. 4.2). Spatial distribution of current land use classes is shown in Tab. 4.3. The case study area between Hlohovec and Sereď cities is predominantly exploited for agricultural purposes and therefore the most share represent the arable lands; up to 77.5% of the territory. Slope deformations, however, pose the greatest threat to the existing settlement and infrastructure, which together occupy 8.19% of the total assessed area.

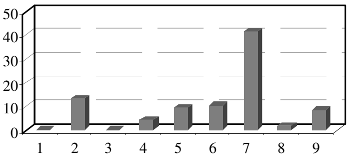
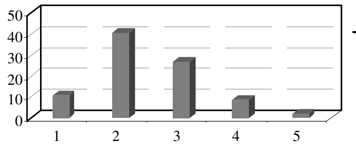
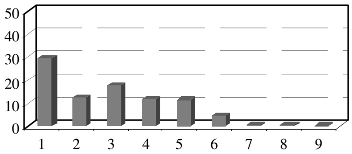
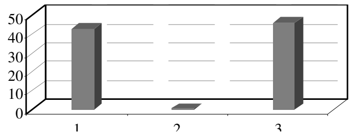
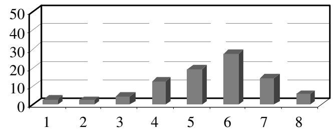
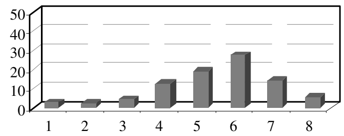
4.6.5. Landslide inventory map

The landslide inventory map (Fig. 4.3) represents the most important input variable in statistical processing of landslide hazard analysis, which is compared with all parametric maps. It is presented as raster map containing dichotomous variable in binary grid form (0/1).

Within this study the interpretation of landslides in the form of lines presenting the main scarp zones (MSUE) was applied (Clerici, 2002; Bednarik & Pauditš, 2010). Using this form the landslide inventory is better interpreted as the entry of the entire landslide bodies including the accumulation zones. If the accumulation zones were included into the analysis, which often interfere to stable parts (e.g. alluvial plain), the final results would be significantly distorted and unreliable (Bednarik & Pauditš, 2010).

Overall, the slope deformations cover the area of 5.98 km^2 (597.98 ha) of the total area 89.4 km^2, so it constitutes 6.68% of the whole assessed area. However, the main scarp zones occupy markedly smaller part of the area, only 0.29 km^2 (0.32% of total area). The landslide occurrence in individual classes of input parameters is processed and presented in the following sections.

Tab. 4.3 Spatial distribution of input parameters.

Factor	Class	Description	Spatial distribution of classes		
			area S_t [km^2]	area S_t [%]	graphic visualization
lithology	1	anthropogenic and organic-fluvial sediments	0.1413	0,158	
	2	Holocene fluvial sediments	13,282	14,856	
	3	Holocene proluvial sediments	0,170	0,190	
	4	Pleistocene terraces	4,286	4,794	
	5	slope sediments	9,553	10,685	
	6	outwash sediments	10,240	11,453	
	7	eolian sediments - loess and loess loam	41,622	46,555	
	8	Neogene sediments - predominantly gravels	1,644	1,838	
	9	Neogene sediments - predominantly clays	8,467	9,471	
digital elevation model [m s. l.]	1	< 140	10,777	12,054	
	2	140 - 180	40,487	45,286	
	3	180 - 220	27,176	30,397	
	4	220 - 260	8,718	9,751	
	5	> 260	2,247	2,513	
slope angle [°]	1	< 2	29,636	33,148	
	2	2 – 3	12,502	13,984	
	3	3 – 5	17,747	19,851	
	4	5 – 7	11,644	13,024	
	5	7 – 11	11,470	12,830	
	6	11 – 17	4,658	5,210	
	7	17 – 20	0,739	0,827	
	8	20 – 31	0,799	0,893	
	9	> 31	0,209	0,234	
curvature	1	concave	42,928	48,015	
	2	linear	0,213	0,238	
	3	convex	46,264	51,747	
Euclidean distance to stream [m]	1	0 - 25	2,746	3,072	
	2	25 - 50	2,329	2,605	
	3	50 - 100	4,539	5,076	
	4	100 - 250	12,854	14,378	
	5	250 - 500	19,303	21,590	
	6	500 - 1000	27,508	30,769	
	7	1000 - 1500	14,342	16,041	
	8	> 1500	5,783	6,469	
actual land use	1	river network	0,132	0,147	
	2	arable land	69,369	77,591	
	3	forests	12,574	14,064	
	4	settlements	6,405	7,165	
	5	road and railway network	0,924	1,033	

4.7. Results

4.7.1. Bivariate analysis with weighted parameter as a whole

In terms of the methodology presented above, the all input parametric maps were analysed separately by statistical comparison with the landslides inventory map: lithology vs. landslides; slope angle vs. landslides, etc. Fig. 4.4 and Tab. 4.4 show the spatial distribution of landslides within classes of each parametric map. The mutual comparison resulted in the following findings:

- The landslides were the most abundant in slope sediments and Neogene clay sediments, where almost 70% of all scarp zones fall. These lithological units covered 20% of the whole assessed area. The Neogene sediments of clay character are generally considered as the sediments susceptible to sliding and to activation of slope deformations and landslide spatial distribution in study area has confirmed this definitely. More than 25% of the landslides were in the outwash sediments and aeolian sediments which covered almost 60% of study area.
- The occurrence of slope deformations is not significantly influenced by altitude and they are mostly concentrated in lower elevations (up to 220 m). This is mainly due to action of streams affecting the slope stability by lateral erosion in the past. Most of the landslides - 70% are in the class within the interval 140-180 m a. s. l. which occupies more than 45% of the whole area. Above 220 m a. s. l. (12% of the area) occur only less than 9% of all registered landslides.
- From a statistical comparison with the map of slope angle results that the most critical slopes are in the interval from 7° to 17°, where 53% of all landslides are located. Maximum occurrence, equalling to 28.6%, is in the 6th class with an interval of 11° to 17°. According to the classification by Hrašna (1980, in Matula et al., 1983) the landslides occurrence is concentrated in the class of gentle slopes with moderate slope angle (5° to 17°) where more than 61% of landslides are recorded. Steep slopes (>17°) occupy only 1.9% of the area but there are recorded up to 32.2% of the all scarp zones within this class.
- Although the relief curvature specifically affects the flow of masses on relief, spatial distribution of landslides occurrence in the concave and convex forms of curvature is nearly the same. Slightly prevalent are the convex forms of relief.
- The landslides occurrence depending on the distance to streams has been documented mainly in a range from 250 to 1,000 m, where 62% of the landslides are situated. The landslide occurrence in such a relatively

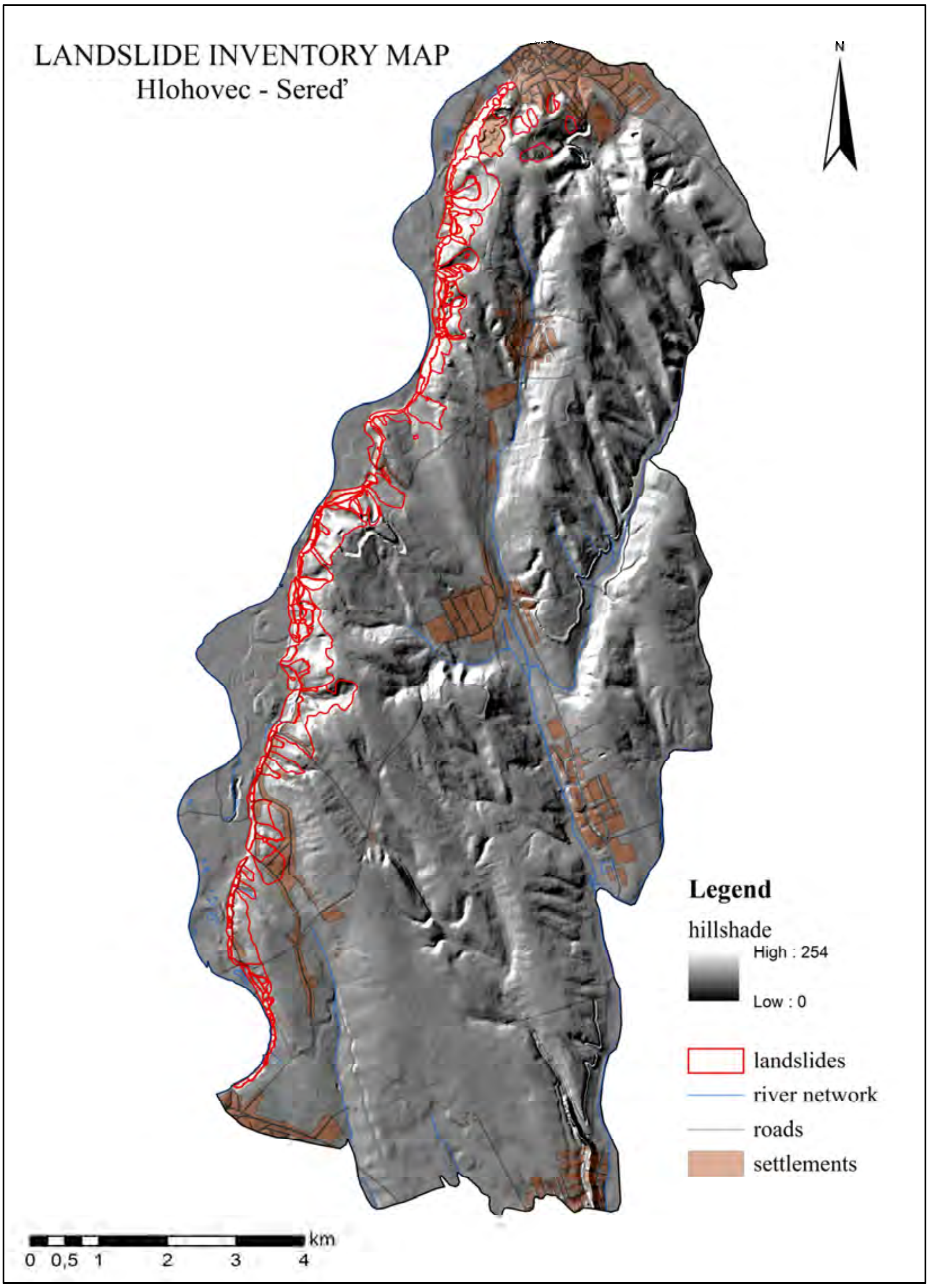


Fig.4.3 Landslide inventory map.

large distance from the stream is given by the width of the alluvial plain of the river Váh. Locally this width has been reduced (depending on the meandering of the river Váh) and within the distance 250 m occur 37% of the landslides.

- The study region is exploited mainly for the agricultural activities. The arable land together with forests occupies more than 90% of the study area and the landslides predominantly exist in these classes – 96%. Even though landslides affect also the settlements, roads and railways in relatively high percentage - 4%.

Based on the landslide density comparison, new numerical values for each class of parameter were assigned (secondary reclassification). The highest numerical value is given to class which is the most susceptible to landslides and the lowest value represents the class with the least tendency to sliding.

Subsequently the weight of each parameter was calculated according to the above mentioned methodology by Vlčko et al. (1980). The results are presented in Tab. 4.4, where the values of calculated weights (W_i) are shown and subsequently the partial results, sorted by the descen-

Tab. 4.4 Spatial distribution of classes, landslide occurrence within classes and partial calculations determining the weight of input parameters.

Input factor	Class	Spatial distribution of classes		Spatial distribution of landslides within the classes		p_{ij}	(p_{ij})	H_j	$H_{j\,(max)}$	$H_{j(max)}$-H_j	$avgp_{ij}$	I_j	W_i	recl_2
		S_t [km^2]	S_t [%]	S_z [km^2]	S_z [%]									
slope angle	1	29.636	33.148	0.003	1.015	0.0001	0.0006	2.117	3.170	1.053	0.020	0.332	0.006584	**1**
	2	12.502	13.984	0.003	0.930	0.0002	0.0012							**2**
	3	17.747	19.851	0.013	4.278	0.0007	0.0040							**3**
	4	11.644	13.024	0.023	7.913	0.0020	0.0113							**4**
	5	11.470	12.830	0.074	24.882	0.0064	0.0360							**5**
	6	4.658	5.210	0.085	28.686	0.0182	0.1021							**6**
	7	0.739	0.827	0.029	9.900	0.0396	0.2220							**8**
	8	0.799	0.893	0.058	19.699	0.0729	0.4089							**9**
	9	0.209	0.234	0.008	2.697	0.0382	0.2140							**7**
actual land use	1	0.132	0.147	0.000	0.000	0.000	0.000	1.355	2.322	0.967	0.004	0.417	0.001723	**0**
	2	69.369	77.591	0.106	35.974	0.002	0.074							**3**
	3	12.574	14.064	0.177	59.976	0.014	0.682							**5**
	4	6.405	7.165	0.009	2.891	0.001	0.065							**2**
	5	0.924	1.033	0.003	1.158	0.004	0.179							**4**
lithology	1	0.141	0.158	0.000	0.000	0.000	0.000	1.980	3.170	1.189	0.003	0.375	0.001293	**0**
	2	13.282	14.856	0.000	0.000	0.000	0.000							**0**
	3	0.170	0.190	0.000	0.000	0.000	0.000							**0**
	4	4.286	4.794	0.012	4.202	0.003	0.094							**6**
	5	9.553	10.685	0.152	51.319	0.016	0.512							**9**
	6	10.240	11.453	0.038	12.893	0.004	0.120							**7**
	7	41.622	46.555	0.037	12.597	0.001	0.029							**4**
	8	1.644	1.838	0.002	0.668	0.001	0.039							**5**
	9	8.467	9.471	0.054	18.321	0.006	0.206							**8**
distance to stream	1	2.746	3.072	0.001	0.499	0.001	0.024	2.341	3.000	0.659	0.003	0.220	0.000609	**3**
	2	2.329	2.605	0.005	1.666	0.002	0.095							**4**
	3	4.539	5.076	0.022	7.567	0.005	0.222							**6**
	4	12.854	14.378	0.082	27.866	0.006	0.289							**8**
	5	19.303	21.590	0.096	32.322	0.005	0.223							**7**
	6	27.508	30.769	0.089	30.081	0.003	0.146							**5**
	7	14.342	16.041	0.000	0.000	0.000	0.000							**0**
	8	5.783	6.469	0.000	0.000	0.000	0.000							**0**
curvature	1	42.928	48.015	0.127	42.780	0.003	0.431	1.173	1.585	0.412	0.002	0.260	0.000592	**2**
	2	0.213	0.238	0.000	0.017	0.000	0.034							**1**
	3	46.264	51.747	0.169	57.203	0.004	0.535							**3**
DEM	1	10.777	12.054	0.036	12.242	0.0034	0.3105	1.691	2.322	0.631	0.002	0.272	0.000588	**4**
	2	40.487	45.286	0.208	70.477	0.0051	0.4758							**5**
	3	27.176	30.397	0.046	15.413	0.0017	0.1550							**3**
	4	8.718	9.751	0.006	1.868	0.0006	0.0586							**2**
	5	2.247	2.513	0.000	0.000	0.0000	0.0000							**0**

ding weight value. The most significant effect on the formation and activation of slope deformations in the assessed area have the slope angle, actual land use and geological conditions.

The result of bivariate statistical analysis is the Landslide hazard map (Fig. 4.5) outgoing from the weighted summation of secondary reclassified maps. In GIS the equation (4.1) has the following form (4.8):

y = "dem_recl_2" * 1.8 * 0.000588312 + "slope_recl_2" * 1 * 0.006583607 + "curv_recl_2" * 3 * 0.000591835 + "gl_recl_2" * 1 * 0.001292551 + "vvt_recl_2" * 1.125 * 0.000608825 + "lnduse_recl_2" * 1.8 * 0.001723118 (4.8)

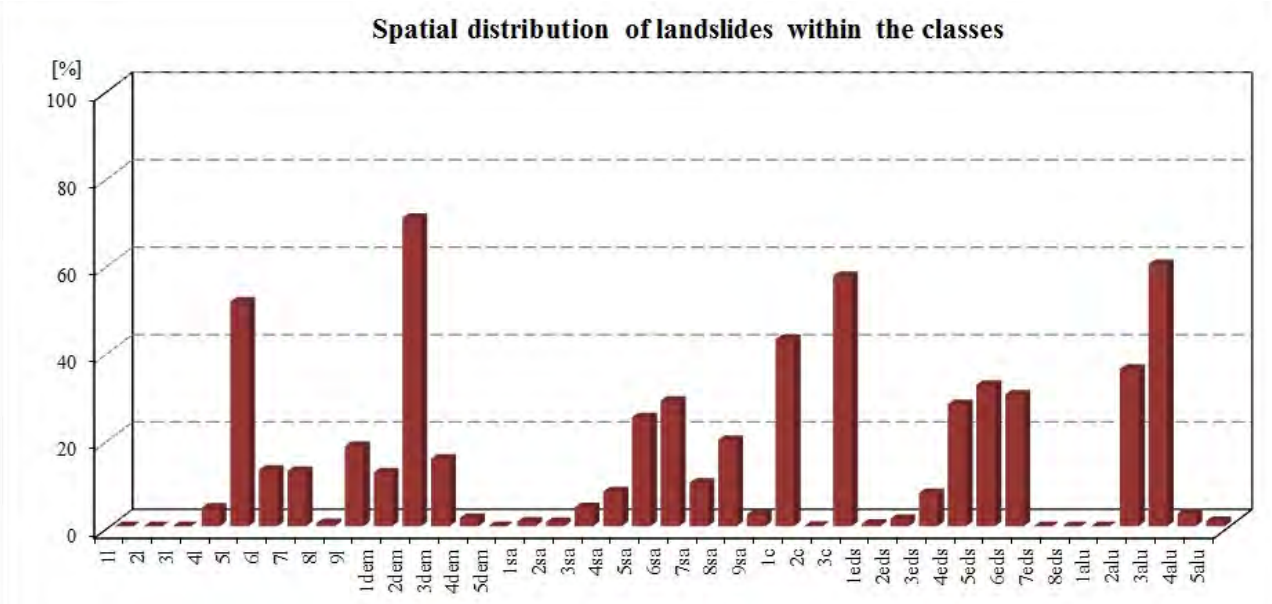


Fig. 4.4 Graphical view of spatial distribution of landslides within the classes, where: 1l - 9l means classes in lithological parametric map; 1dem - 5dem means classes in map of digital elevation model; 1sa – 9sa are classes in parametric map of slope angle; 1c - 3c means curvature of relief; 1eds - 7eds are classes of Euclidean distance to stream and 1alu - 5alu are classes of actual land use.

The result of the summation is a continuous interval of values <0.0146497; 0.102494>, which represents different degrees of landslide hazard. Generally, the final landslide hazard can be reclassified using various methods into three or five conventional classes. The final map was classified based on the method of "*Natural breaks – Jenks"* implemented in GIS into 5 classes with the following intervals:

1. Very low degree <0.014649742; 0.03807494>;
2. Low degree <0.03807494; 0.048754074>;
3. Moderate degree <0.048754074; 0.059777696>;
4. High degree <0.059777696; 0.075968641> ;
5. Very high degree <0.075968641; 0.102494232>.

The natural breaks classes are based on natural grouping inherent in the data and normal Gauss distribution according the mean values. The features are divided into classes whose thresholds are set according to relatively biggest difference in the data values (www.esri.com, 2014).

Spatial distribution of the landslide hazard classes is shown in Tab. 4.5. Very high degree of landslide susceptibility covered almost 3% and together with the class of high degree they occupy almost 17% of the assessed area. From simple verification, which consisted of comparing the areas of existing landslides and classes of very high and high degree of the landslide hazard (Tab. 4.5) was calculated, that in these two classes exist more than 90% of the landslides.

4.7.2. Multivariate conditional analysis

As already mentioned, the principle of conditional analysis is based on the simultaneous comparison of all input parameters as independent variables with a landslide inventory map. The output of the analysis of statistical processing in GIS environment represents the 6,648 possible combinations of input parameters, the quasi-homogenous units (UCUs). After the statistical comparison with landslides, 655 of UCUs were affected by landslides and the rest 5,993 combinations, the landslides have not been present.

Tab 4.6 shows an example of the output of the statistical combinations. The numbers within the first column represent the classes of input parameters in the following order: lithology – actual land use – distance to stream – curvature of relief – slope angle – digital elevation model. The second column of the table contains the number of cells (count) of the UCUs (N_{pix}) and in the third column are the cells of the UCUs containing the landslides N_{pix}(MSUE). The fourth column represents the density of the landslides (D) for each UCU calculated based on the ratio of the UCU count containing landslides and count of the total number of cells expressed in per mille (‰).

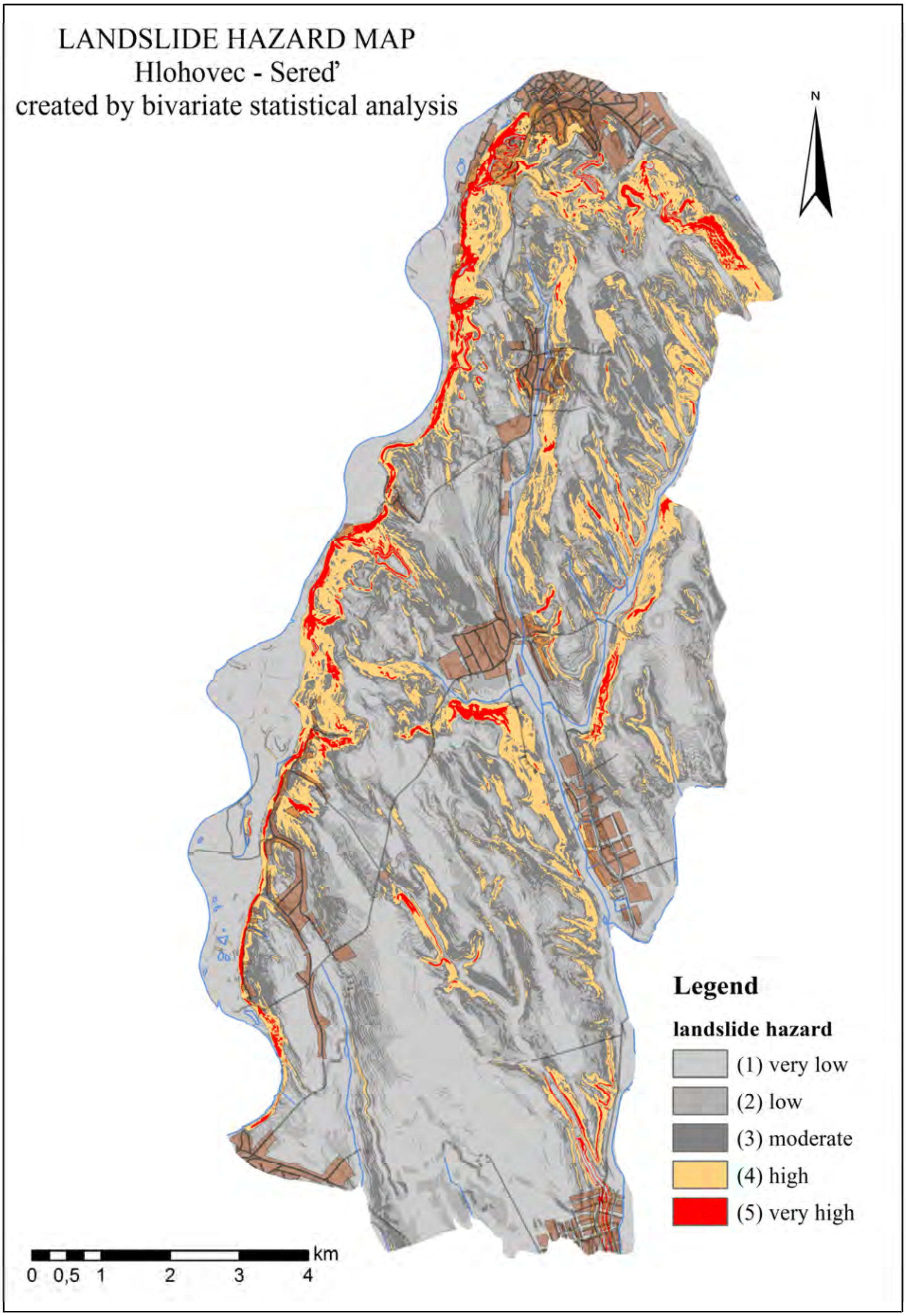


Fig. 4.5 Landslide susceptibility map created by bivariate statistical analysis.

The last column (susc.5) gives the degree of landslide susceptibility of the individual UCU. The comparison of the count of the UCUs with landslides in the whole study area and count of these MSUEs which are only contained within the 5th class of the landslide hazard, are given in Tab. 4.7.

Based on the Tab. 4.6 and Tab. 4.7 the following facts have resulted. The landslides occur mainly in the formation of slope sediments where there were recorded 231 combinations with landslides (from the overall 655) and the second class with the relative high frequency of landslides is linked to the class of the Neogene clay deposits. It means that these categories are mostly affected by sliding, which is in accord with the results of the bivariate analysis. The classes of the Holocene fluvial and proluvial sediments (2 and 3) are not influenced by landslides.

The second place in the first column belongs to the actual land use. Regarding the agriculture exploitation of the study region the most affected areas are the forests and arable land.

Tab. 4.5 Spatial distribution of classes of the landslide hazard and spatial distribution of landslides within the landslide hazard classes.

Class	Landslide hazard degree	Spatial distribution of classes		Spatial distribution of landslides within the classes [%]
		[km^2]	[%]	
1	very low	30.83	34.48	0.74
2	low	23.39	26.16	2.544
3	moderate	20.02	22.39	6.334
4	**high**	**12.74**	**14.25**	**31.25**
5	**very high**	**2.44**	**2.72**	**59.14**

Tab. 4.6 An example of multivariate statistical analysis results.

UCU	N_{pix}	N_{pix}(MSUE)	D	susc. 5
9.3.3.3.6.2	39	25	641.03	5
5.3.5.1.9.2	191	48	251.31	5
9.3.5.3.5.3	780	12	15.38	5
5.2.6.1.5.2	2884	38	13.18	4
9.2.6.1.5.3	7301	94	12.87	4
9.4.5.1.6.2	196	2	10.20	4
5.2.6.1.6.3	2486	25	10.06	4
9.3.4.1.5.2	101	1	9.90	3
9.2.6.3.5.4	4563	45	9.86	3
5.2.6.3.6.4	411	4	9.73	3
7.2.6.3.3.2	18982	76	4.00	2
9.2.5.1.2.3	259	1	3.86	2
9.3.3.3.8.2	261	1	3.83	2
9.2.6.3.4.4	1836	6	3.27	1
5.2.6.3.3.3	7645	24	3.14	1
9.2.6.1.2.4	340	1	2.94	1
5.2.6.1.1.3	2055	1	0	1
9.2.5.1.3.2	2634	1	0	1
9.2.5.1.5.2	2762	1	0	1

Tab. 4.7 The comparison of the count of the UCUs with landslides in the whole area and count of the UCUs with landslides contained only within the 5th class of the landslide hazard.

Parameter	Class	Count N_{pix}(MSUE)	Count N_{pix}(MSUE) in 5th class of landslide hazard
lithology	1	0	0
	2	0	0
	3	0	0
	4	57	52
	5	**231**	**171**
	6	144	122
	7	84	55
	8	13	6
	9	126	75
land use	1	0	0
	2	209	85
	3	**354**	**315**
	4	56	47
	5	36	34
distance to stream	1	23	23
	2	43	41
	3	83	76
	4	133	108
	5	**209**	**146**
	6	164	87
	7	0	0
	8	0	0
curvature	1	**351**	208
	2	2	2
	3	302	**271**
slope angle	1	18	9
	2	23	8
	3	50	22
	4	86	45
	5	**154**	111
	6	143	**116**
	7	86	81
	8	74	70
	9	21	19
DEM	1	148	140
	2	**394**	**298**
	3	86	39
	4	27	4
	5	0	0

Another important factor influencing the slope stability is the slope angle. From statistical combination results that the dominating are the slopes with angles from 7° to 17°, predominantly in combination with lithological classes 5 and 9. These results are very similar to those of the bivariate analysis. The final map (Fig. 4.6) was divided into 5 classes with the following intervals:

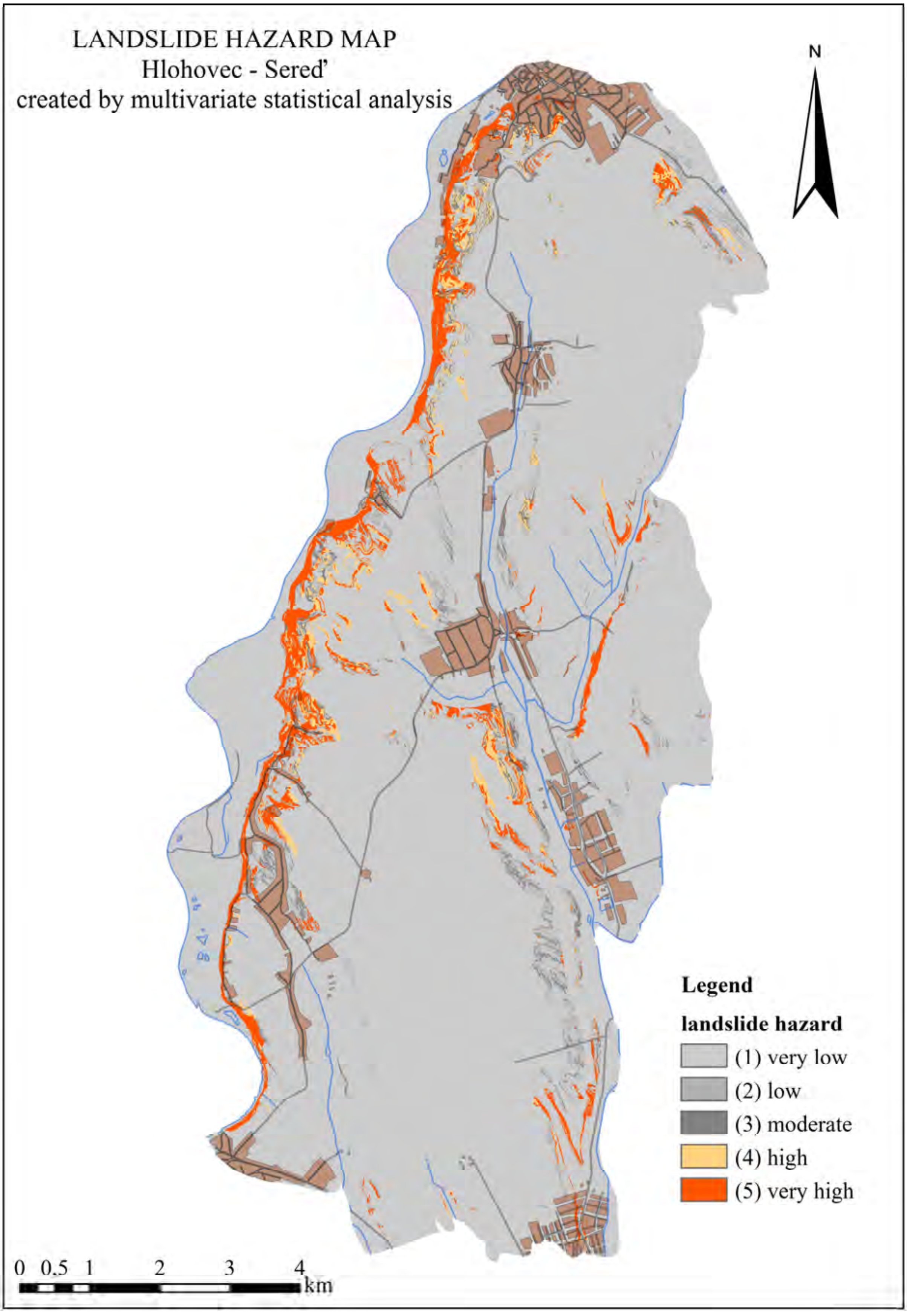


Fig. 4.6 Landslide hazard map created by multivariate conditional statistical analysis.

1. Very low degree <0.0; 1.322 >;
2. Low degree <1.322; 2.646>;
3. Moderate degree <2.646; 3.966>;
4. High degree <3.966; 5.288> ;
5. Very high degree > 5.288.

The average intensity of the landslide occurrence M_d in the study area is 3.307‰ and based on the equation 4.7 the class interval C_i is 1.322. Due to elimination of random and technical errors the first interval was assigned to the UCUs without registered landslides – very low degree (5 993 UCUs). Spatial distribution of the landslide hazard classes is given in Tab. 4.8 along with the comparison of the areas of the existing landslides and classes of very high and high degree of the landslide hazard. In these two classes are almost 90% of the existing landslides.

Tab. 4.8 Spatial distribution of classes in the landslide hazard and spatial distribution of landslides within the landslide hazard classes.

Class	Landslide susceptibility degree	Spatial distribution of classes		Spatial distribution of landslides within the classes [%]
		[km^2]	[%]	
1	very low	80.85	90.43	3.66
2	low	2.52	2.81	3.97
3	moderate	1.05	1.17	2.98
4	**high**	**1.50**	**1.68**	**5.91**
5	**very high**	**3.49**	**3.90**	**83.48**

4.7.3. Comparison of the results of multivariate and bivariate analyses

From the results of both used statistical analyses (multivariate conditional and bivariate) the most unfavourable conditions of slope movements have been identified. The landslides occur mostly in the slope and Neogene clays sediments in forests and arable land with slope angle 7°-17° at an altitude 140-180 m a. s. l. The comprehensive assessment of the most and the least susceptibility categories of each parameter of study area is given in Tab. 4.9.

The most stable areas are in the Holocene fluvial and proluvial sediments which are situated close to streams (alluvial planes). Although the least susceptible categories of parameters distance to streams and digital elevation model are just in the areas where these lithological units are absent, this has been confirmed by the interpretation of the landslide geometry which entered to the process of statistical assessment. To the process of susceptibility assessment only the main scarp zones of landslides have been considered. There were not assessed the whole landslide bodies, because their accumulation parts interfere with these areas, which are stable in term of landslides activation; otherwise the results would be distorted.

Comparison of the spatial distribution of the landslide hazard classes created by different statistical methods is shown in Tab. 4.10 where the spatial distribution of landslides within the classes is also presented. Differences in the values represent various approaches in the used methodologies; any of them does not vary so much to identify result as diametrically different. The most reliable is considered the result of conditional multivariate analysis.

Within the verification process, the very high and high levels of landslide hazard are compared with the registered landslides. According to this assumption it can be stated that the difference between the multivariate and bivariate statistical analyses is only 1%. In the case of multivariate statistical analysis the 5th class is almost 25% higher than the 5th class of the bivariate analysis. First three classes are evenly distributed in both cases.

4.8. Discussion

All the mentioned procedures are time-consuming. In order to achieve the highest quality and most accurate results, the most time should be paid to preparation of the input parameter maps. This phase is the most sensitive to generate errors in the whole process, because these kinds of errors would be transmitted to the next steps of the assessment and negatively affect the result. Reliability of the results depends mainly on the precise approach to the preparation of input data.

4.8.1. Results comparison obtained from presented statistical methods

Based on the results obtained from both presented statistical methods it can be concluded that the mutual comparison shows a small advantage of multivariate conditional method compared to bivariate analysis with the application of weights, where some corrections are necessary and they are affected by high subjectivity and experience of the researcher.

Preference of conditional multivariate analysis rests in the principle of simultaneous use of all input parameters. The method works primarily with larger data set (more complex data file) and reflects the interactions between input parameters more sensitively. It is also more appropriate, because it better reflects the degree of influence of the main factors on the landslide hazard (geological setting, lithology, morphometric parameters). The map created by the multivariate analysis divides the area in more detail and the borders between zones are more sensitive to local spatial changes in natural conditions of the area, as in the case of the bivariate analysis. The sensitivity threshold follows from the character of the multivariate analysis (working with a quantity and variability of mutual combinations of parametric maps), but also depends on the precise approach to the final susceptibility zoning.

Another advantage of the multivariate method is relatively less-demanding on technical and time-consuming computers operations. The exception is the final reclassification into five susceptibility zones associated with the operation in relational databases and subsequent backward import of the result into the GIS environment. The intensity of operations depends on size of processed area that is directly proportional to the number of cells in the

Tab. 4.9 The assessment of the most and the least susceptible classes of each parameter.

Input parameter	The most susceptible category	The least susceptible category
slope angle	5, 6 (7°-17°)	1, 2 (< 2°)
actual land use	2, 3 (arable land; forests)	1 (rivers)
lithology	5, 9 (slope sediments; Neogene clays)	1, 2, 3 (anthropogenic; Holocene sediments)
distance to stream	5 (250-500 m)	7, 8 (>1000 m)
curvature	1 (concave)	2 (linear)
DEM	2 (140-180 m a. s. l.)	5 (> 260 m a. s. l.)

Tab. 4.10 The comparison of results of multivariate and bivariate analysis.

Class	Landslide hazard degree	Spatial distribution of classes		Spatial distribution of landslides within the classes	
		bivariate analysis [%]	multivariate analysis [%]	bivariate analysis [%]	multivariate analysis [%]
1	very low	34.48	90.44	0.74	3.66
2	low	26.16	2.81	2.54	3.97
3	moderate	22.39	1.17	6.33	2.98
4	**high**	**14.25**	**1.68**	**31.25**	**5.91**
5	**very high**	**2.72**	**3.90**	**59.14**	**83.48**

area, which determines number of records in a database table. These time-consuming operations are not automatic, the interactive input of a project researcher is not required, and therefore the process is less prone to the creating of random errors, in contrast to the lengthy and laborious calculation of the weights by the bivariate analysis.

In the case of the bivariate analysis the major problem is the calculation of weights. The paper presents a method based on the degree of entropy of the system, represented by the parametric map, where the components of the system are represented by calculated value of intensity of landslide occurrence in each class of parametric maps. Despite complying with the methodology, the result does not sufficiently reflect objective reality and the susceptibility map compiled by the bivariate analysis without subsequent subjective modification of weights is not possible to recommend in future.

For future processing with statistical methods for landslide susceptibility assessment in GIS environment, we recommend the use of *conditional multivariate analysis*. This sophisticated methodology could be also binding in the future and included in the wording of the amended Directive for the compilation of landslide susceptibility maps of the Slovak Republic, as one of the possible and useful exact methods of the landslide hazard assessment.

4.8.2. Comparison of the presented methodology with existing empirical approaches

Regarding the assessment of principal advantages (or disadvantages) of statistical methods of the landslide hazard analysis using GIS compared to commonly used empirical methods, the following facts can be clearly stated:

- advantage of quantitative statistical approaches compared to the geotechnical model, for example, based on the analysis on physico-mechanical properties, is better availability of input data. Their obtaining is not so technically and financially demanding as for the required amount of physical parameters; this fact exactly favours the use of statistical methods in wide areas in regional scales;
- providing that the all of the above mentioned principles and rules will be adopted, the statistical methods allow for more complex results in GIS. This way, in the landslide hazard analysis those exact parameters could be included that have not been assessed only visually and empirically within standard approach (e.g. slope angle), respectively they have not been rated at all (average rainfall, slope length, etc.);
- vulnerability of both statistical methods is mainly in the accuracy of the input data: maps of varying quality from different sources, scales and coordinate systems, transformation and correlation issues, and as already mentioned a subjective approach to the precision within the preparation of parametric maps; all of these items highly influence the final results;
- despite the comprehensive approach to the data preparation, the mentioned processes are susceptible to the random and systematic errors generated mainly due to their complexity;
- the possibility of a subjective approach of these methods shall be limited to the selection of input parameters, selection rules for the first reclassification of parametric maps, selection of statistical methods and finally, the control and correction of partial results (especially in bivariate analysis), compared to the classical heuristic method, where the individual approach and expertise of researcher has been applied more significantly especially within the compilation of final maps.

4.8.3. Evaluation of the usability of presented methods and perspective of its utilization in future

The perspectives of the use of the presented methods for predicting landslide hazard are quite promising. In Slovakia, the creation of landslide susceptibility maps at a scale of 1:50,000 is part of the set of "Maps of the Environmental Geofactors" (Directive of MoE SR, 1999). After a successful pilot project of detailed landslide mapping and landslide hazard assessment at detailed scale realized in the Flysch Formation (Grman et al., 2011) real assumption of the project extension to the other part of Slovakia is arising. Therefore, it is necessary to prepare the binding methodology for creating these maps supported by the use of modern information technologies based on GIS.

Currently, the use of GIS technology has been more intensely applied in geological practice in Slovakia. Legislative and technical aspects of the use of GIS are regulated mainly by several directives of INSPIRE, as well as outdated Directive of MoE SR published in 2000, which obliges the researchers of geo-environmental projects to submit the resultant data in digital form in the GIS format.

4.9. Conclusions

In the paper the compilation of the landslide hazard map using statistical methods in GIS and implementation of these methods in the model area Hlohovec - Sereď is presented. Two, in the world most widely used quantitative statistical methods are used: the bivariate method using the weights of input variables and the multivariate conditional analysis. The weighting method takes into account the weights of input parameters as a whole based on the entropy of the system where individual components are represented by parameter classes (categories).

Statistical approaches are based on the assumption that landslides will occur preferably under the same conditions, as they occurred in the past and at present. The processed results are based on a statistical comparison of input parameter maps, representing relevant input factors, with a landslides inventory map.

Based on the evaluation of methodology and results obtained in the present study, the application of the conditional multivariate analysis has been recommended for the future reference and for its implementation in the binding methodology. The advantages are mainly in considering the interactions between input factors; a lower degree of subjectivity (as well as lower susceptibility to generation of random errors) in the assessment of input factors, working with the complex data sets and a higher sensitivity of the final map to local changes in conditions in the study area. Despite the possibility of the weighting of each input parameter in the process of bivariate analysis (compared with multivariate analysis) the disadvantages represent mainly the impossibility of interactions correction between input parameters and their calculated weights as well as improper modification of partial results. On the other hand, the possibility of correction of partial results allows better application of individual approach and the researcher's expertise.

Presented methods are conceptually simple; but their application is quite complicated and requires a lot of experience, especially with the use of computer technology and geo-informatics. Compared with previously used empirical processes, the applied methods are more exact and generally less burdened by subjective approach.

Application of the present methodology and techniques in the landslide hazard assessment in standard practice is promising. However, some improvements are necessary, especially in to current legislation, which should respond to the implementation of geoinformation technologies in professional practice.

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5. A Large-Scale Landslide Hazard Assessment within the Flysch Formation in the Slovak Republic

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Abstract. The article presents the main results of the project "Engineering geological mapping of slope deformations in the most vulnerable areas within the Flysch Formation at a scale 1:10,000", consisting of three kinds of maps, data sheets (passports) of slope deformations and final report. The focus is on the methodology for the creation of landslide hazard maps and assessment of landslide hazard in the restricted area of Flysch Zone in the northern and northeastern part of Slovakia. The selected area is characterized by a high density of slope failures; it is periodically affected also by floods accompanied with the activation of slope deformations, particularly landslides and earth flows, due to impact of adverse climatic conditions.

***Key words*:** landslides, landslide hazard, Flysch Formation, Slovakia

5.1. Introduction

During the years 2005-2011 geological project "Engineering geological mapping of slope deformations in the most vulnerable areas within the Flysch Formation at a scale 1:10,000“ was realized in Slovakia, ordered by the Ministry of Environment SR (MoE) (Grman et al., 2011). The project was solved by team of researchers from the following organizations: GEO Slovakia, Ltd., Košice, GEOTREND, Ltd., Žilina, Faculty of Natural Sciences, Comenius University in Bratislava, Slovak University of Technology in Bratislava, Technical University in Košice and SGIDŠ in Bratislava. The project was generated by the society-wide necessity in the context of increased negative consequences of repeated activation of slope deformations.

The main outputs are defined below:

- Specialized engineering geological map at scale 1:10,000
- Map of documentary points at scale 1:10,000
- Landslide hazard map at scale 1:10,000
- Data sheets (passports) of slope deformations.

This article is focused primarily on the landslide hazard maps that are pioneering work by their mapping scope and used methodology. In the area studied they represent a significant update of Atlas of Slope Stability of Slovakia at a Scale 1:50,000 (Šimeková et al., 2006) and also compensate deficiencies of "Atlas", resulting from used scale and follow the experience in creating maps of the landslide hazard in smaller scales (Liščák et al., 2009, Bednarik & Liščák, 2010).

The landslide hazard presents probability of occurrence of the landslide phenomenon within the space. The output of the project are prognosing landslide hazard maps, which now represent a suitable basis for spatial planning, or solution of the current slope stability situation. They have a recommendatory character and are intended to bring the investor, designer, statics to a decision what extent, type and method of engineering geological investigation is needed for a specific site (line, ground and underground) in terms of the occurrence of slope deformations. The incidence of geodynamic phenomena, in this paper mainly slope deformations, significantly affects and changes the view of the implementation of the engineering works. Landslide hazard maps generated on large scales (1:10,000 and larger) can significantly reduce direct and indirect damages resulting from landslide hazard.

5.2. Delimitation of the mapped area

The territory assessed covers an area of 4,042.23 square kilometres, in other terms, 17 map sheets at scale 1:50,000, or on 285 map sheets at scale 1:10,000.

The area is divided into western (Žilina Region) and eastern parts (Prešov Region) (Fig. 5.1), representing whole or partial cadastres of 50 municipalities in five districts of the Žilina Region (13 municipalities partially), 310 municipalities in 11 districts in the Prešov Region (of which 66 villages partially).

For map compilation predominantly area belonging to the Flysch Zone was chosen, in which the geological, hydrological and morphological conditions create favourable conditions for the slope deformations occurrence. In most districts of the area of interest the share of the registered slope deformations exceeds 10 % (Šimeková et al., 2014).

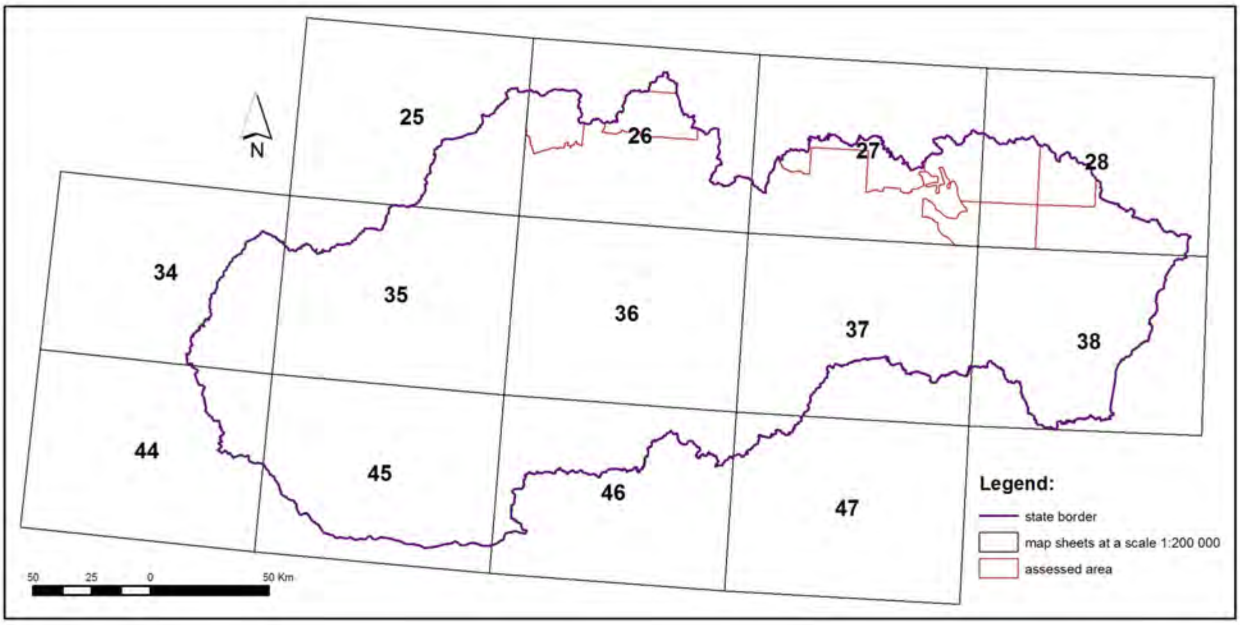

Fig. 5.1 General overview of the assessed area

According to engineering geological regional division of Slovakia (Matula & Pašek, 1986) the mapped area belongs mainly to the region of the Carpathian Flysch (areas of Flysch Uplands and Flysch Highlands), only in the eastern parts the study area extends into the region of Neogene Tectonic Depressions (Area of Intermountain Depressions) and to the region of Neogene Volcanics.

In the region of the Carpathian Flysch due differentiated tectonic conditions it is possible to distinguish:

- Sub-region of Outer Flysch Carpathians,
- Sub-region of Klippen Belt,
- Sub-region of Innner Flysch Carpathians.

5.3. The methodology of compilation of specialized engineering geological map

Specialized engineering geological map represented a fundamental starting basis for the compilation of the landslide hazard map. It is also self-use map with versatile application in the field of geology, building constructions and urban planning. The maps were constructed on the basis of archive data processing, re-compilation of existing maps and field mapping.

Specialized engineering geological map on topographic base at a scale 1:10,000 shows: rock environment, geodynamic phenomena, hydrogeological data, hydrological data and tectonic conditions.

Within the geological environment are displayed:

- Quaternary lithological complexes with thickness more than 1 m,
- Pre-Quaternary lithological complexes exposed at the surface (Quaternary cover less than 1 m).

Information on the rock environment are shown as coloured areas and the corresponding numerical indexes expressing the genesis and representing lithological types.

Basic lithological types represented within the assigned formations and complexes are generally reviewed in Tab. 5.1.

On the geological setting of the area predominantly rocks of the Flysch Formation are participating, in the area of the Klippen Belt the rocks of variegated Sandstone-Marlstone-Limestone Formation are abundant, and in comparison with the Flysch Formation are lithologically more heterogeneous, as well as from engineering geological properties points of view, and partly also Neovolcanites Formation is involved. The Pre-Quaternary rocks are irregularly distributed across the mapping area and incoherently covered by Quaternary sediments.

Among the geodynamic phenomena are shown:

- slope deformations,
- erosion-accumulation phenomena.

Depending on the size, the slope deformations as resulting forms of slope movements, are shown spatial or point objects. By line colour and the marks inside slide polygon, or by mark colour (for point plotted slope deformations) activity of slope deformation is distinguished. The type of slope failure is differentiated by marks within the area of slope deformations, or by pictogram (in the case of small-size failures).

Within the mapping area in accordance with the classification of slope movements in Slovakia (Nemčok, 1982) committed basic groups and types of slope deformations were used (Tab. 5.2).

The most common type of slope movement in the study area is sliding. In flysch environment, there occur slip movements along a flat (planar) or complex (rotary-planar) slip surface. The slip surface of landslides tends to be mostly predisposed to interface among weathered and sound Pre-Quaternary, mainly flysch rocks, or to the boundary of the Quaternary slope sediments and basement rock. In deep landslides in their bodies

Tab. 5.1 Rock environment within the study area

Period	Formation	Lithological complex		Index within map	Basic lithotypes
Quaternary	Quaternary cover	anthropogenous		**1**	deposits, landfills
		slope sediments		**2**	clays, silts, debris
		proluvial	valley	**3**	gravels, clays, silts, debris
			terrace	**4**	gravels, clays, silts
		fluvial	alluvial	**5**	gravels, clays, silts, sands
			terrace	**6**	gravels, clays, silts
		glacifluvial		**7**	gravels, clays, sands
		organogenous		**8**	clays, sands
		organic		**9**	peat
		chemogenous		**10**	foamstones
Neogene	Neovolcanites	tuff		**11**	tuffs, conglomerates, sandstones
		extrusive andesites		**12**	andesites
		effusive andesites		**13**	andesites
	Molasse	siltstones-claystones		**14**	claystones, siltstones, sandstones, conglomerates
		siltstones-sandstones			
		sandstones-conglomerates			
Paleogene	Flysch	Flysch sandstones-conglomerates		**15**	sandstones, claystones, conglomerates, breccias
		Flysch with predominance of claystones		**16**	claystones, sandstones, siltstones
Paleogene-Cretaceous		Flysch with predominance of sand-stones		**17**	sandstones, claystones, conglomerates
Paleogene		claystones		**18**	claystones
Paleogene-Cretaceous	Variegated sandstone-marlstone-limestone	Flysch marlstones-limestones		**19**	marlstones, claystones, sandstones, limestones, conglomerates
Cretaceous-Jurassic		limestones		**20**	limestones, sandstones
Jurassic				**21**	limestones, radiolarites
Triassic				**22**	limestones, dolomites

Tab. 5.2 Classification of slope deformation within the study area

Basic groups of slope deformations	Types of slope deformation	Slope deformation activity
Deep creep	- block deformations (block fields, block ridges)	stabilized, dormant
Surface creep	- surface creep movements of Quaternary sediments	dormant, active
Sliding	- different types - erosive slides	dormant, stabilized, active
Flowing	- flows - streams	dormant, stabilized, active
Falling	- debris cones, scree cones - stone seas	stabilized, dormant

there are also numerous individualized rock blocks, which are mostly characterized by a lower degree of disintegration.

A particular type of landslide, which often occurs in the area, but generally has smaller dimensions, is a waterside slump. This type is formed by sliding of bank of a watercourse or water reservoir into the bed, due to lateral erosion of a stream, or due to abrasion. Depending on their size, the accumulations of these landslides are usually transported by water flow immediately after the sliding. Deep creep deformations with character of block fields (block landslides) are concentrated in areas with a prevalence of Flysch sandstones overlying claystone formations, or formations with predominance of claystone with favourable bedding, or tectonic conditions. Quaternary slope sediments or colluvial-eluvial soils are affected by flows, mainly. Within the mapping area numerous earth and debris flows have been recorded. Special form of flow-type slope movement are ravines. These are usually of a small area, or linear, caused by abrupt erosion, torrential rainwater, or by intensive oversaturation of surface layers. Being soaked, a loss of strength starts in top layers (grass surface, topsoil) up to the depth usually 0.3-0.5 m, occasionally up to 1 m. They are frequent on the banks of watercourses, as a result of a sudden drop in water table level.

The group of falls within the mapping area includes the shedding of fragments of rocks that are gradually accumulated at the foot of rock walls and cliffs. The loose debris and fallen rocks combined with saltation and sliding down the slope form on its foot or directly below the rock walls different morphological forms - scree cones, debris cones, stone fields. Their occurrence in the mapping area is rare, they are significantly concentrated only in the Klippen Belt area, particularly in the geomorphological unit of Pieniny.

The slope failures (landslides of various stages of activity) in the territory occur mostly in the environment of deluvial complex and Flysch complex with a predominance of clays. The share of slope deformations atop identified lithological complexes is presented in the Tab. 5.3. Part of landslides extends over two, occasionally three lithological complexes simultaneously, which is also valid in terms of the depth of the reach of many landslides. The Quaternary soils and underlying Pre-Quaternary basement affected by landslide movement are characterized as sliding sediments. The slope deformations, where underlying lithological complexes are covered by original slope sediments or other Quaternary sediments with thickness greater than 1 m are included in the area of slope deformations on deluvial sediments complex, although by landsliding may be affected not only Quaternary sediments but also underlying rocks.

Tab. 5.3 Representation of lithological complexes and their disturbance by slope deformations

Formation	Lithological complex (LC)	Index within the map	Area of LC		Slope deformations (SD)			
					area	% from area of LC	% from total area of SD	% from the total area
			km^2	%	km^2	%	%	%
Quaternary cover	anthropogenous	1	0.62	0.02	0.04	5.8	0.01	0.00
	deluvial sediments	2	1,784.55	44.15	331.69	18.59	58.13	8. 21
	proluvial - Pleistocene	3	25.10	0.62	0.18	0.70	0.03	0.00
	proluvial	4	18.60	0.46	0.01	0.07	0.00	0.00
	fluvial - Pleistocene	5	362.16	8.96	2.23	0.61	0.39	0.06
	fluvial	6	54.26	1.34	2.18	4.02	0.38	0.05
	glacifluvial	7	15.79	0.39	0.13	0.83	0.02	0.00
	organogenous and organic	8, 9	0.38	0.01	0.00	0.00	0.00	0.00
	chemogenous	10	0.001	0.00	0.00	0.00	0.00	0.00
Pre-Quaternary formations	tuff	11	0.22	0.01	0.00	0.00	0.00	0.00
	andesite	12, 13	6.97	0.17	0.41	5.90	0.07	0.01
	Molasse Formation	14	4.85	0.12	0.53	10.92	0.09	0.01
	sandstones-conglomerates	15	301.13	7.45	28.40	9.43	4.98	0.70
	Flysch with predominance of claystones	16	844.24	20.89	131.95	15.63	23.12	3.26
	Flysch with predominance of sandstones	17	482.49	11.94	50.45	10.46	8.84	1.25
	claystones	18	1.81	0.04	0.09	5.10	0.02	0.00
	marlstones-limestones	19	85.49	2.12	21.07	24.65	3.69	0.52
	limestones	20-22	14.15	0.36	1.23	18.44	0.21	0.03
	Watercourses and reservoirs		39.41	0.97	0.01	0.03	0.00	0.00
	Total		4,042.22	100.0	570.59	14.12	100.0	14.12

Among the erosion phenomena on the maps are shown linear erosion on slopes (erosion gullies, potholes) and active erosion of watercourses as a line entity. On the banks of reservoirs places with an active abrasion are marked. For larger watercourses lateral erosion is more significant, in the smaller tributaries and mountain brooks with steep slopes lateral and streambed erosion are more often.

From the accumulation phenomena in the map proluvial cones are depicted.

In addition, the maps show: hydrogeological data (springs, waterlogged areas), hydrological data (watercourses, natural and artificial reservoirs), and tectonic data (observed and predicted tectonic lines and failures, bedding).

5.4. The methodology of creating landslide hazard maps

Landslide hazard assessment using statistical methods in GIS environment is based on the selection of the appropriate factors affecting the slope stability. Statistical analysis of the landslide hazard comes from the principle of actualism of geological phenomena and processes, according to which the landslides will occur in places where they have been in the past, or currently under similar conditions of activation. Selected factors affecting the genesis and development of slope movements are formulated in parametric maps and thus enter into the process of statistical evaluation using map algebra in GIS environment. According to the chosen statistical method, the comparison of parametric maps with landslide inventory map followed. The conclusions resulting from the statistical comparison were then extrapolated to the whole evaluated territory and the result is a prognostic map of hazard. Further, it is necessary to divide the landslide hazard map, based on the mathematical distribution (e.g. median, standard deviation and other), into three (low, medium, high degree of hazard) or five (very low, low, medium, high and very high degree of hazard) categories representing the degree of landslide hazard.

From the group of statistical methods for the landslide hazard assessment within GIS environment a bivariate statistical analysis was selected, which together with multivariate analysis is the most widely used method with high success rate of model (Pauditš & Bednarik, 2006).

This method presents a statistical combination of each parametric map with a map of registered landslides. Bivariate statistical analysis uses one dependent variable (landslide inventory map) and one independent variable (individual input parametric map). The result gives the total number of grid cells with landslides and without landslides in each class of input factors, calculated per unit area or percentages. The double combinations are stored in tabular form, where one of the numbers is a class in the parametric map and the second number represents the presence or absence of landslides (0 - false, 1 - true).

Based on this combination it is necessary to provide secondary reclassification for each parametric map. During this process to the existing classes within each parametric map new numerical values are assigned, representing statistically calculated probability to sliding. The highest numerical value is assigned to the class most susceptible to sliding and vice versa, a class with the lowest numerical value is the least susceptible to sliding.

Before the summing secondary reclassified parametric maps it is necessary to determine the weights of individual parameters. Here-in, weights are calculated based on entropy index according to mathematical procedure proposed by Vlčko et al. (1980).

Result of bivariate statistical analysis is a map of the landslide hazard, calculated as the weighted sum of the secondary reclassified parametric maps. The equation for the final sum has the form:

$$y = \sum_{i=1}^{n} C * W_i \qquad (5.1)$$

where:
y - the value of landslide hazard in the final map,
i - individual parametric maps,
C - class,
W_i - weight of the corresponding parameter.

The result of the weighted sum is then a continuous range of values representing the value of the landslide hazard degree in the model area. Continuous interval is necessary to interpret and divide into classes, reflecting the degree of the landslide hazard. Here-in, the five-point scale representing very low, low, medium, high and very high degree of landslide hazard was used.

5. 5. Landslide hazard assessment

5.5.1. Input parameters

Eight input factors are evaluated, which somehow affect slope stability. Each factor enters to the bivariate statistical analysis in the form of parametric map. Chosen parameters reflect the geological, climatic and hydrological conditions in the area, morphometric characteristics of the relief and current land-use.

The total processed area has an extent of 4,042.23 square kilometres, the area of registered slope deformations constitutes 570.59 km^2, thus, 14.12 % of the total area is affected by slope deformations.

Interpretation of geological conditions

Basis to obtain information about the geological setting of the study area provide specialized engineering geological maps at a scale of 1:10,000 in a vector form. These maps are one of the outputs of the project. The maps were scanned, georeferenced and then vectorized in a coordinate system S-JTSK. Parametric map in a vector form was converted to the raster format with a cell size of 10x10 m (Fig. 5.2). Legend to this parametric map is shown in tables 5.1 and 5.3.

Based on the statistical evaluation that was performed using map algebra within GIS environment, it was found a percentage of individual lithological complexes of the total area (Tab. 5.4). Index Ac represents the total area (acreage) of class expressed in km^2.

Tables 5.3 and 5.4 show that the largest area extent in the model area (1,784.55 km^2) have deluvial sediments; among the Quaternary sediments also fluvial sediments have significant representation. Paleogene Flysch sediments - classes 15, 16 and 17 occupy summary area of more than 1,600 km^2.

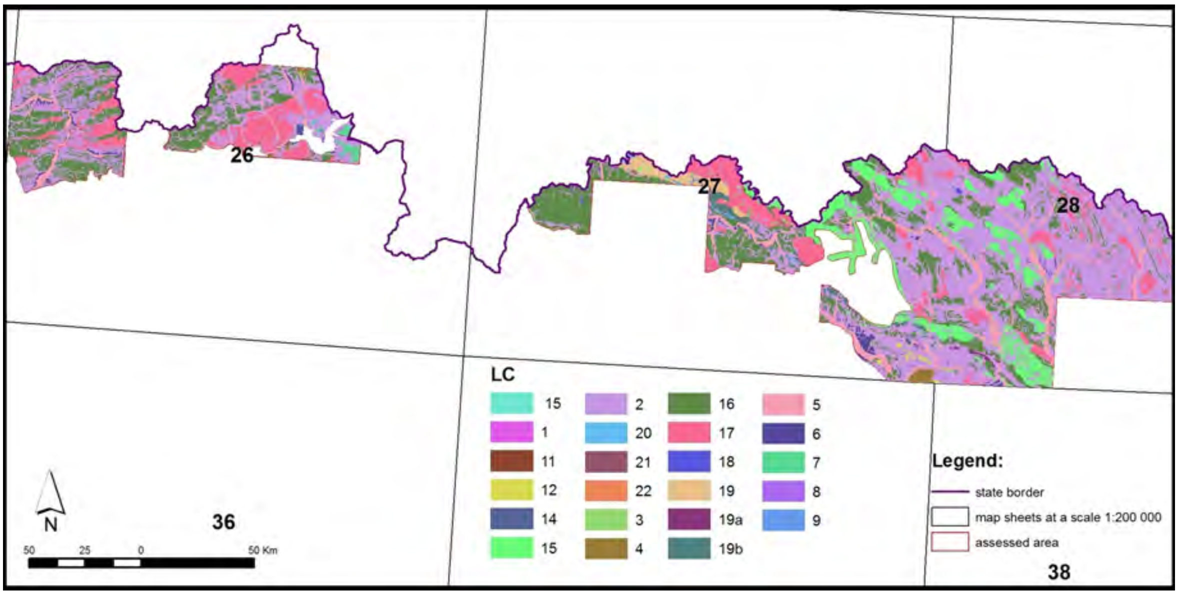

Fig. 5.2 Parametric map of engineering geological conditions in a raster form

Tab. 5.4 Spatial distribution of individual classes of lithological complexes

Class	Ac (km^2)	Class	Ac (km^2)
1	0.6204	13	0.001
2	1,784.5468	14	4.8546
3	25.1002	15	301.1265
4	18.6031	16	844.2422
5	362.1564	17	482.4918
6	54.2643	18	1.8052
7	15.7852	19	48.8389
8	0.0409	19a	4.5785
9	0.3416	19b	32.0758
10	0.001	20	9.1895
11	0.22	21	4.6789
12	6.9676	22	0.2829

Morphometric parameters of the relief

In the frame of this study following morphometric parameters were evaluated:

- hypsographic levels (levels of altitudes),
- slope angle,
- slope aspect,
- curvature of relief,
- slope length,
- contributing areas.

Morphometric parameters were derived from a digital elevation model (DEM - Fig. 5.3). The source of input data for the compilation and calculation of the DEM in the model area were contour lines and elevation points from topographic maps at a scale 1:10,000, which are distributed by Institute of Geodesy and Cartography. Areal extension of the categories is shown in Tab. 5.5.

More than 2,900 km^2 of the total area of the study area is located at altitudes 290-770 m a.s.l. (classes 2, 3 and 4). The height difference between the lowest and highest altitude represents 1,420 meters.

Tab. 5.5 Spatial distribution of reclassified DEM

Class	Interval [m a. s. l.]	Ac (km^2)
1	130-290	408.8894
2	291-450	907.917
3	451-610	1,204.765
4	611-770	813.4838
5	771-930	409.9881
6	931-1,090	183.1551
7	1,091-1,250	80.6844
8	1,251-1,410	28.0409
9	1,411-1,550	5.2991

Slope angle

Slope angle is indicated in degrees (range 0-90 degrees) or as a percentage (or per mille). Parametric map of slope angle (Fig. 5.4) is reclassified according to Hrašna (1980, in Matula et al., 1983), which is commonly used in the engineering geological mapping (Tab. 5.6). Slopes are divided into 9 categories.

Tab. 5.6 Classification of slope angle

Class	Slope angle [%]	Slope angle [°] (class)
I. Flat (with small slope angle)	< 3	< 2 (1)
	3-5	2- 3 (2)
	5-9	3-5 (3)
II. Slightly (with a moderate slope angle)	9-2	5- 7 (4)
	12-20	7- 11 (5)
	20-30	11-17 (6)
III. Steep (with a large slope angle)	30-36	17-20 (7)
	36-60	20-31 (8)
	> 60	> 31 (9)

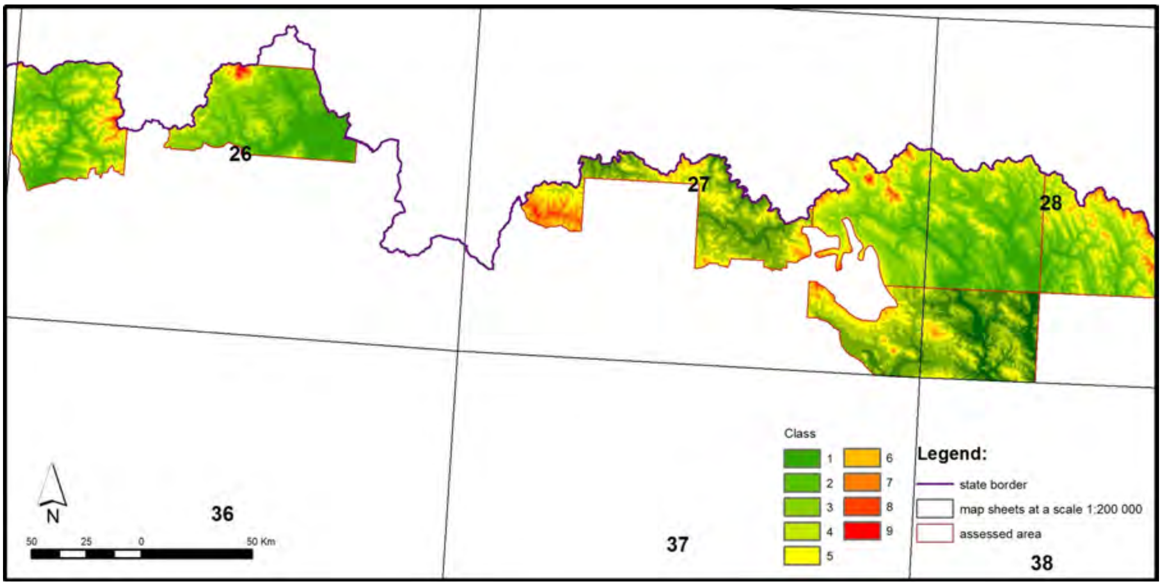

Fig. 5.3 Parametric map of digital elevation model in a raster form

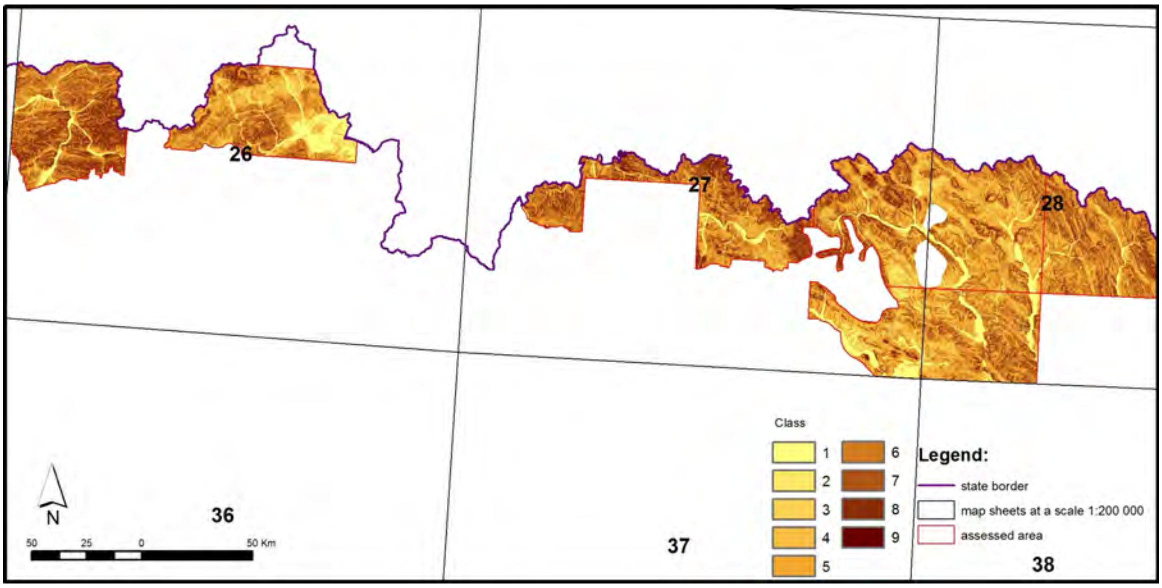

Fig. 5.4 Parametric map of slope angle in a raster form

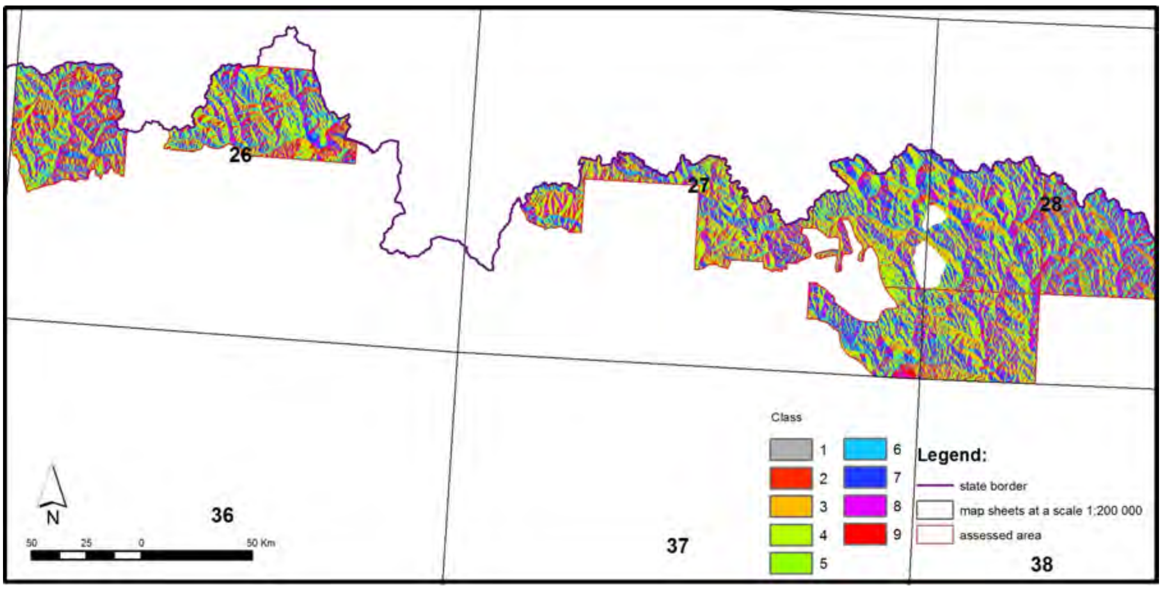

Fig. 5.5 Parametric map of slope aspect in a raster form

The total area of the reclassified categories of slope angle is shown in Tab. 5.7. The largest area have the slopes with a moderate slope angle of 11-17° (class 6) and slopes of 7-11° (class 5). Other classes are approximately equally distributed, except class 9 (steep slopes), which occupies just over 14 km^2.

Tab. 5.7 Spatial distribution of reclassified slope angles

Class	Interval	Ac (km^2)
1	< 2°	304.6084
2	2-3°	142.2787
3	3-5°	327.4622
4	5-7°	428.0142
5	7-11°	967.6527
6	11-17°	1,134.34
7	17-20°	342.5587
8	20-31°	381.1609
9	> 31°	14.147

Slope aspect

The resulting parametric map is in degrees; in raster form with cell size of 10x10 m is shown in Fig. 5.5. The slopes are reclassified into 9 categories, where category 1 presents a flat area without relation to the cardinal points (Tab. 5.8).

Within the study area slopes in terms of orientation to cardinals are approximately equally distributed. The largest spatial representation have slopes with South-West orientation - class 7.

Tab. 5.8 Spatial distribution of slope aspect

Class	Interval (°)	Ac (km^2)
1 (flat)	(-1)	34.3354
2 (N)	(0-22.5), (337.5-360)	417.0316
3 (NE)	(22.5-67.5)	565.114
4 (E)	(67.5-112.5)	549.594
5 (SE)	(112.5-157.5)	479.8359
6 (S)	(157.5-202.5)	535.2548
7 (SW)	(202.5-247.5)	651.2452
8 (W)	(247.5-292.5)	472.633
9 (NW)	(292.5-337.5)	337.1812

Curvature of the relief

The resulting curvature (Fig. 5.6) was reclassified into three categories - convex (positive values), concave (negative values) and linear (inflection field values close to 0). Tab. 5.9 presents spatial extension of the individual forms of relief curvature in the study area. Convex and concave relief forms are spread rather evenly with a slight predominance of concave forms.

Tab. 5.9 Spatial distribution of reclassified forms of relief curvature

Class	Interval	Form	Ac (km^2)
1	< -0.00025	Concave	1,427.502
2	- 0.00025 to 0.00025	Linear	1,516,017
3	> 0.00025	Convex	1,098.704

Slope length and contributing areas

To derive the slope length and contributing area parameters, flow direction of hydrologically correct digital elevation model should be calculated firstly. Direction of water flow was calculated in ArcGIS using the module "flow direction" and the output is a grid cell with the cell size 10x10 m. From it, slope lengths - using the "flow down" and using the "flow up" modulus contributing areas grids were generated in the model area. The resulting grids were reclassified into 6 classes (Figs. 5.7 and 5.8), and their area extension is shown in Tabs. 5.10 and 5.11.

Tab. 5.10 Spatial distribution of reclassified slope length

Class	Interval [m]	Ac (km^2)
1	0-100	133.0903
2	100-500	952.147
3	500-1000	1,111.89
4	1000-1500	786.299
5	1500-2000	481.8508
6	> 2000	576.9448

Tab. 5.11 Spatial distribution of reclassified contributing areas

Class	Interval [m^2]	Ac (km^2)
1	0-100	2,030.095
2	100-500	1,822.137
3	500-1,000	152.5688
4	1,000-1,500	22.0251
5	1,500-2,000	8.0694
6	> 2,000	7.3288

From the parametric maps of reclassified slope lengths is clear that they are evenly distributed throughout the model area except of class 1, which represents the slopes with a length of up to 100 m.

In contributing areas parameter classes 1 and 2 (up to 500 m^2) dominate, which correspond to the small contributing areas. Classes with a large surface area (class 6) occur in the model territory only over an area of 7.3 km^2.

The actual land-use

Parametric map of the actual land-use was vectorized from raster topographic images and is shown in Fig. 5.9. The spatial distribution of individual elements of the cur-

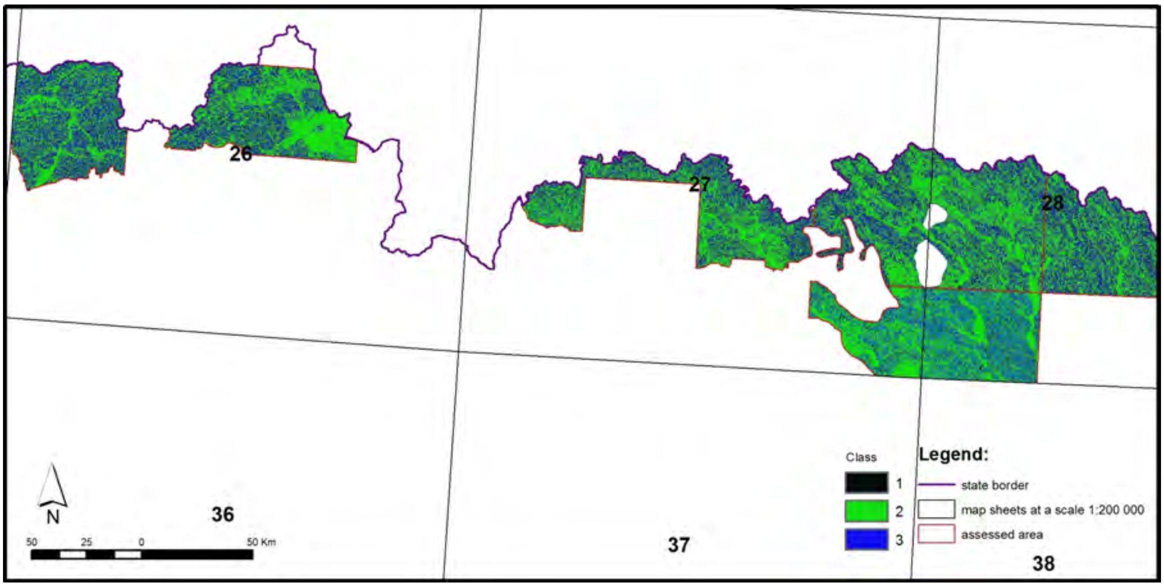

Fig. 5.6 Parametric map of relief curvature in a raster form

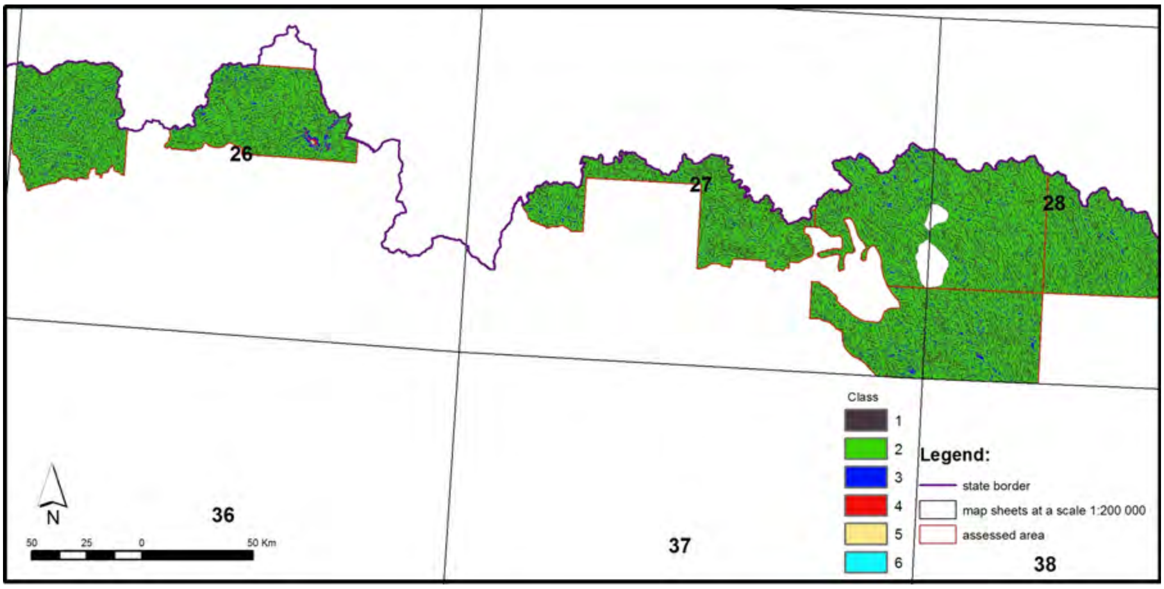

Fig. 5.7 Parametric map of slope length in a raster form

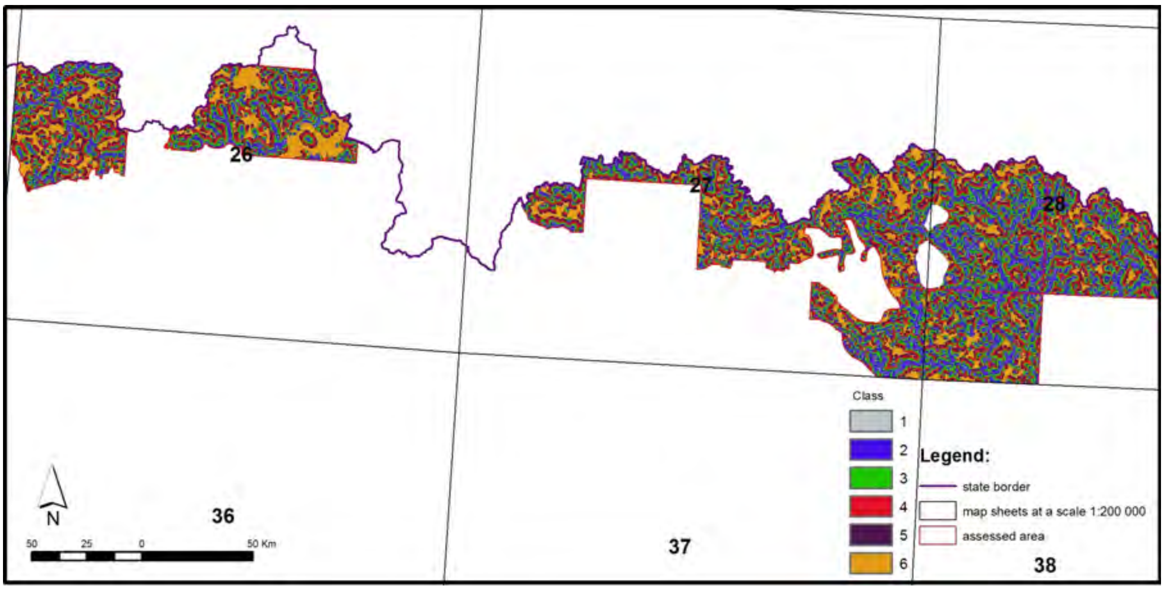

Fig. 5.8 Parametric map of contributing areas in a raster form

rent land-use (Tab. 5.12) shows that the area is mostly afforested, class 5 (2,197.2 km^2), urban environment (class 2) covers an area over 124 km^2.

Tab. 5.12 Spatial distribution of elements of actual land-use

Class	Interval	Ac (km^2)
1	Road network	28.2893
2	Settlement	124.7727
3	Pastures	491.451
4	Arable land	1,066.1914
5	Forests	2,197.181
6	Meadows and gardens	90.5386
7	Watercourse network	41.5557
8	Railway network	1.7278
9	Quarries	0.4626

Interpretation of slope deformations

As a basis of preparation of the parametric map of landslides the study areas were revised and newly registered slope deformations were assessed in the maps of engineering geological conditions, as well as 372 landslides registered within the project "Registration and evaluation of newly evolved slope failures in 2010 in Prešov and Košice regions" (Liščák et al., 2010).

As was already mentioned, the registered landslides in the study area cover an area of 570.59 km^2 of the total area 4,042.23 km^2. This means that 14.12 % of the total area is directly affected by slope failures. The resulting parametric map of landslides as entry to the bivariate statistical analysis is shown in Fig. 5.10.

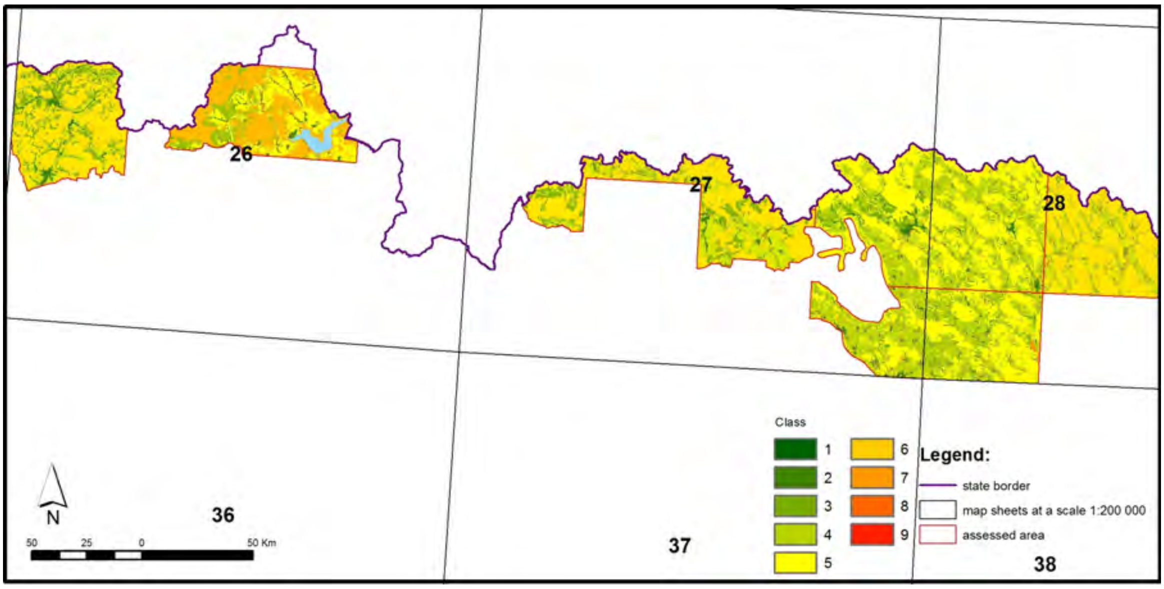

Fig. 5.9 Parametric map of actual land-use in a raster form

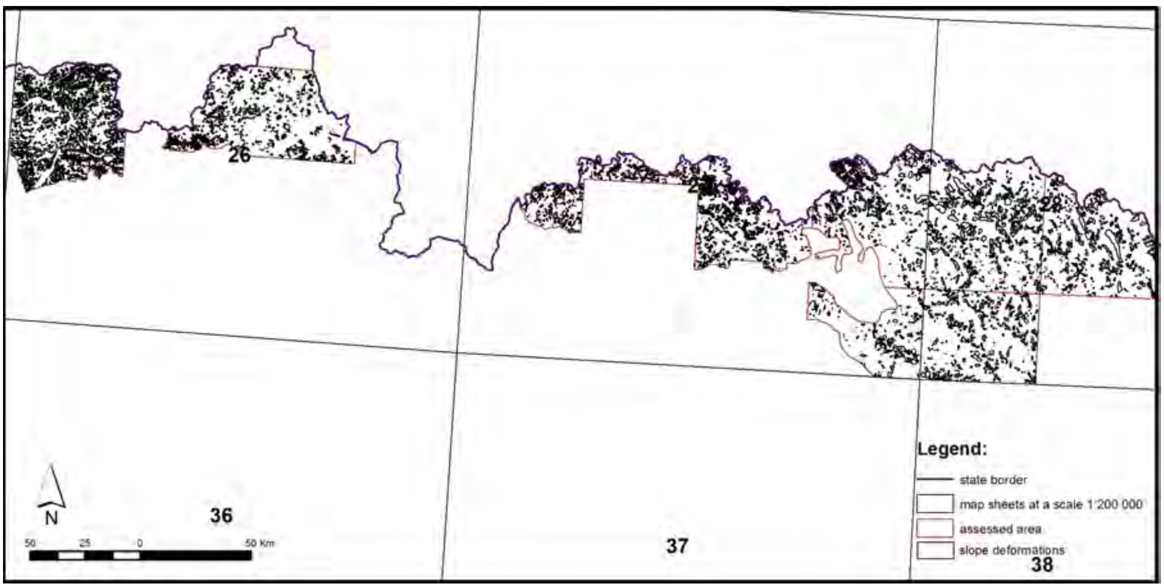

Fig. 5.10 Parametric map of slope deformations in a raster form

5.5.2. Results of bivariate statistical analysis

Table 5.13 shows the results derived from bivariate statistical analysis. Ac represents the area of classes after first reclassification; Asd is the area of landslides within the individual class of each parameter.

From the comparison of parametric map of lithological complexes with the landslide inventory parametric map follows that the most disturbed areas are built by deluvial sediments (class 2); 58% of all registered landslides can be found in this class. They are followed by class 16, Flysch with a predominance of claystones - 23%, and Flysch with a predominance of sandstones - 9% (class 17).

Most slope deformations are located at altitudes 450-610 m a. s. l. (class 3) - 31%, followed by the altitude interval 291-450 m a. s. l. with 26% (class 2) and the interval 611-770 m n. m. with 19% (class 4). The highest parts of the territory are affected by slope failures only marginally.

Almost 86% of the total area of landslides occur on slopes between 5° and 20°. The comparison shows that the most critical slopes are within the range 11° to 17° (class 6, more than 35% of landslides) and slopes within the range 7° to 11° (class 5, with more than 31% of the total area of landslides). They are classified as gentle slopes with moderate slope angle.

The slope aspects are evenly distributed in the model area, and similarly, the distribution of slope deformations in each class of slope aspect is evenly distributed, as well. This implies that the slope aspect parameter does not have a big impact on slope movements, as is evidenced also by the weight of this factor.

Tab. 5.13 Results of bivariate statistical analysis

	Class	Ac (km^2)	Asd (km^2)		Class	Ac (km^2)	Asd (km^2)		Class	Ac (km^2)	Asd (km^2)
Lithological complexes/landslides	1	0.6204	0.036	**Slope angle/landslides**	1	304.6084	1.8899	**Land-use/landslides**	5	8.069	0.7568
	2	1784.547	331.6866		2	142.2787	3.415		6	7.329	0.3624
	3	25.1002	0.1759		3	327.4622	20.7147		1	28.29	2.8498
	4	18.6031	0.0126		4	428.0142	54.6141		2	124.8	8.6659
	5	362.1564	2.2258		5	967.6527	176.5365		3	491.5	112.7914
	6	54.2643	2.1797		6	1134.34	204.9129		4	1,066	126.2962
	7	15.7852	0.1309		7	342.5587	54.7507		5	2,197	308.8293
	8	0.0409	0		8	381.1609	52.2858		6	90.54	10.9618
	9	0.3416	0		9	14.147	1.471		7	41.56	0.1369
	10	0	0	**Slope aspect/landslides**	1	34.3354	4.304		8	1.728	0.0428
	11	0.22	0		2	417.0316	60.7515		9	0.463	0.0134
	12	6.9676	0.4108		3	565.114	89.3241				
	13	0	0		4	549.594	77.5357				
	14	4.8546	0.53		5	479.8359	68.9181				
	15	301.1265	28.3958		6	535.2548	77.9717				
	16	844.2422	131.9468		7	651.2452	85.8633				
	17	482.4918	50.4527		8	472.633	61.4855				
	18	1.8052	0.0921		9	337.1812	44.4367				
	19	85.4932	21.0749	**Curvature /landslides**	1	1,427.502	282.5809				
	20	9.1895	0.7436		2	1,516.017	183.6193				
	21	4.6789	0.4844		3	1,098.704	104.3904				
	22	0.2829	0	**Slope length/landslides**	1	133.0903	13.7496				
Altitude/landslides	1	408.8894	40.7149		2	952.147	147.7797				
	2	907.917	150.5895		3	1,111.89	166.4366				
	3	1204.765	172.7775		4	786.299	112.1667				
	4	813.4838	109.626		5	481.8508	63.75				
	5	409.9881	56.45		6	576.9448	66.708				
	6	183.1551	25.4881	**Contribution area/landslides**	1	2,030.095	201.31				
	7	80.6844	10.8608		2	1,822.137	326.2965				
	8	28.0409	3.6112		3	152.5688	38.2747				
	9	5.2991	0.4726		4	22.0251	3.5902				

Comparison of parametric maps of curvature of the relief with the parametric map of landslides indicates that the slides occur more on concave relief forms (50%, class 1). To convex forms 32% of registered slope deformations are fixed. Accumulation parts of slope deformations are bound to linear forms of curvature.

Landslides are mostly located on the slopes with a length of 500-1,000 m (class 3, more than 29% of slides), as well as on the slopes with a length in the range of 100 to 500 m (class 2, more than 26% of landslides). 20% of landslides occur on slopes with a length of 1,000-1,500 m (class 4).

Most landslides occur in small contributing areas of the class 2 (up to 500 m^2, more than 57% of the total share of landslides) and in this regard class 1 is also interesting (up to 100 m^2), which encompasses 35% of landslides.

Forests are most affected by slope failures within the study area, 54% of registered deformations are in this class (class 5), 22% of slope deformations are in class 4 – arable land and 20% in pastures (class 3). More than 8 km^2 of landslides affect the built-up area (class 2). Road and rail networks are affected by slope failures in area of almost 3 km^2 (classes 7 and 8).

The evaluation of bivariate results was followed by determining the weights of individual parameters according to the methodology set out in the work by Vlčko et al. (1980). Calculated weights show that the greatest impact on the formation and development of landslides in the model area have slope angle and lithology of the area. Much lower impact have further parameters in the following order - the length of slopes, slope aspect, curvature of the relief, contributing area and hypsographic levels - altitude.

Based on the calculated probability P_{ij} and probability density (P_{ij}) each input parametric map was secondarily reclassified. To each class new numeric value was assigned (integer) for each grid cell, to represent the degree of landslide susceptibility of a given parameter class.

5.5.3. Landslide hazard map

Landslide hazard map was created based on a simple weighted sum of the multiplication of secondary reclassified parametric maps and weights of individual parameters. The equation used for the creation of landslide hazard map for the model area has the following form:

y = /slope_recl2/*0.011363 + /aspect_recl2/*0.001014 + /land-use_recl2/*0.010321 + /geology_recl2/*0.010515+ /curvat_recl2/*0.008359 + /flowleng_recl2/*0.001137 + /flowmic_recl2/*0.006903 + /dem_recl2/*0.00687 (5.2)

where:

y - represents the value of landslide hazard in the resulting map,

/slope_recl2/ - value in the each cell of grid of secondary reclassified parametric map of slope angle,

/aspect_recl2/ - value in the each cell of grid of secondary reclassified parametric map of slope aspect,

/land-use_recl2/ - value in the each cell of grid of secondary reclassified parametric map of the current land-use,

/geol_recl2/ - value in the each cell of grid of secondary reclassified parametric map of lithological complexes,

/curvat_recl2/ - value in the each cell of grid of secondary reclassified parametric map of curvature of the relief,

/flowleng_recl2/ - value in the each cell of grid of secondary reclassified parametric map of slope lengths,

/flowmic_recl2/ - value in the each cell of grid of secondary reclassified parametric map of contributing areas,

/dem_recl2/ - value in the each cell of grid of secondary reclassified parametric map of altitudes.

The result of this sum is a continuous range of values representing the varying degree of landslide hazard. The resulting landslide hazard interval was reclassified into five classes representing the degree of landslide hazard in the model area:

1. very low degree of landslide hazard,
2. low degree of landslide hazard,
3. moderate degree of landslide hazard,
4. high degree of landslide hazard,
5. very high degree of landslide hazard.

The resulting landslide hazard map is presented in Fig. 5.11. To check the degree of success of the hazard map, as the easiest way of verification a comparison with the parametric map of landslides was used. The verification compares the area of landslides which occupies a very high degree of landslide hazard (class 5) in the prognostic map. From this simple comparison came out percentage of 84.2%, which means that when exposed to a significant trigger factor over 80% assumed of slope failures can be mobilized according to the landslide hazard map.

5.6. Conclusions

Within the project frame 285 map sheets at a scale of 1:10,000 were processed in GIS. The result represents an original and unique solution not only in Slovakia. Vectorization, statistical analysis as well as visualization were carried out using the softwares ArcGIS, ESRI Ltd., which belong to the largest and most comprehensive commercial GIS softwares.

The map outputs were processed in the form of vector and raster data models in a coordinate system S-JTSK. Vector maps include also the database in the form of attribute tables. In raster models the cell size of 10 m was set out.

The main outcomes of the project are maps that cover an area of 4,042.43 km^2 (8.24% of the total area of Slovakia). The territory is almost exclusively built of the Flysch Formation with significant Quaternary cover. Three types of maps were created:

1. Specialized engineering geological map,
2. Map of documentary points,
3. Landslide hazard and flood hazard maps (flood hazard is not discussed in this paper).

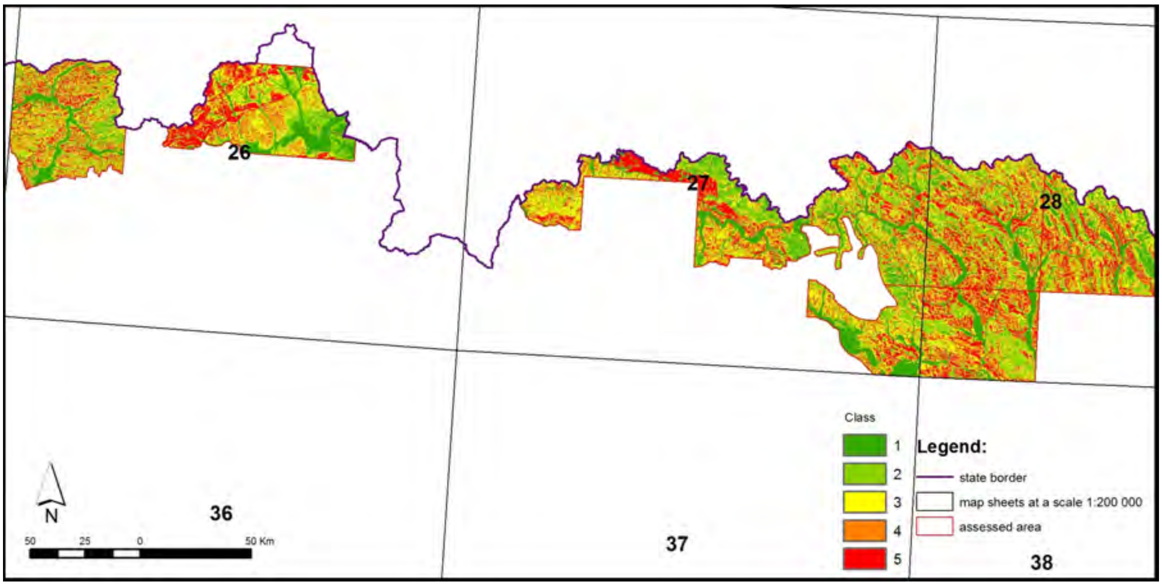

Fig. 5.11 Landslide hazard map

Specialized engineering geological map presents a base for the creation of the landslide hazard map, and provides a separate map series showing the geological setting of the area and geodynamic phenomena with emphasis on slope deformations, which significantly affect land-use. The slope deformations represented mostly by landslides in various stages of activity cover an area over 570.59 km^2; it equals to 14.12% of the total study area. This is several times higher compared to the average slope instability in Slovakia, which is 5.25% (Šimeková et al., 2014).

Landslide hazard maps currently represent a suitable basis for spatial planning. They have a recommendatory character – they enable to make qualified decisions of investors, engineers and contractors about the extent, type and method of engineering geological investigation required for the particular type of construction (lined, ground and underground) in terms of the probability of slope deformations occurrence. The occurrence of these geodynamic phenomena greatly affects and changes the view of the implementation of the works. Landslide hazard maps were generated on large scales (1:10,000) and are also suitable for design and implementation of remediation works that can largely avoid direct and indirect losses resulting from the landslide hazard.

Eight input factors, which in certain way affect the stability of slopes, are evaluated. Selected factors reflect the geological, climatic and hydrological conditions in the study area, morphometric characteristics of the relief and current land-use. In terms of calculated weights determined by the entropy (a measure of chaos in natural systems), different factors in the area have the influence on the stability of slopes in following order:

- Slope angle,
- Lithology,
- Land use.
- Much lower impact on slope stability have:
- Curvature of the relief,
- Contributing areas,
- Altitudes,
- The length of slopes,
- Slope aspect.

Landslide hazard maps are drawn in "traffic light" manner. The territory classified in the high and very high degree of landslide hazard (red colour) includes both multiple combinations of factors adversely affecting the stability of slopes, e.g. combination of unfavourable geological setting, together with the dangerous slope angle and inappropriate land-use. This should be an objective basis for the recommendation of the necessity of carrying out a comprehensive detailed engineering geological investigation focused primarily on evaluation of the stability conditions and the resulting assessment of the feasibility of a particular investment project itself, and also the feasibility of wide range of preventive remediation measures restricting the emergence of possible damage to area and constructed parts and measures providing definitive stability of the object.

The moderate degree of landslide hazard (orange colour) is a combination of two unfavourable factors, and there should be recommended at least preliminary engineering geological investigation and the consequent adequate designing and realization update – prior to a building plan implementation.

Low degree of landslide hazard (green colour) represents areas that have long been predicted as stable, in terms of the stability conditions is not necessary to carry out engineering geological investigation. This does not preclude assessment for the potential flooding area, the bearing capacity of foundation soil, aggressive rock environment and erosion.

Important component of this geological project was the development of record sheets (passports) of selected sites where there is damage or serious risk to various objects due to landslides or erosion processes. These sites were documented in detail and evaluated from the aspect of the needs and possibilities for remediation, with a proposal for necessary geological reconnaissance work preceding the actual remediation. A total of 212 passports were produced in 11 districts of Žilina and Prešov regions.

Acknowledgements:

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6. Landslide Hazard Assessment Using Deterministic Analysis - a Case Study from the Chmiňany Landslide, Eastern Slovakia

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Abstract: In Slovakia, the most frequently methods used for the landslide hazard assessment in GIS environment are statistical analyses. The aim of this paper is to present the other, physically based or deterministic method. The landslide hazard assessment in the deterministic method is performed based on the direct calculation of the factor of safety of slopes, which is determined for each grid cell contained in a raster GIS map. The deterministic method is usually applied for local or site-specific analyses where sufficient data on geological, geotechnical and hydrogeological conditions is available. In this paper, an active landslide nearby Chmiňany Village, Prešov district, Eastern Slovakia has been selected. The detailed input parameters needed for the analyses have been obtained from the engineering geological and geotechnical investigations in relation with a proposed highway construction. Taking into consideration the cause of the landslide, identified as groundwater change, two scenarios of landslide activity have been investigated: scenario of dry slope and scenario that considers the maximum groundwater table level. The results of deterministic analysis in the Chmiňany Landslide allowed to define the different activity stages within the landslide body.

Keywords: landslide hazard • deterministic method • slope stability • spatial analysis • Chmiňany Landslide • parametric maps • Geographic Information Systems (GIS) •

6.1. Introduction

Various approaches to landslide hazard assessment have been developed and published in the literature. Most noted examples can be finding in Carrara, 1988; Van Westen et al., 1993; Terlien, et al. 1995; van Westen and Terlien, 1996; Aleotti & Chowdhury, 1999; Guzzetti et al., 1999; Dai et al., 2002; Zhou et al., 2003, Carrara & Pike, 2008; Alexander, 2008 and others. Each approach can be classified into the two main categories: qualitative and quantitative, which are further classified as: inventory, heuristic, statistic, and deterministic. Each type has advantages and limitations for its application to different scale and purpose of the analysis.

In Slovakia, statistical and deterministic methods have been commonly used, following the expansion of GIS. Statistically based approaches (bivariate and multivariate conditional methods) have been mainly applied for assessing and predicting of regional landslide hazard (Pauditš & Bednarik, 2002; Bednarik et al., 2005; Jurko et al., 2005; Pauditš et al., 2005, etc.), while deterministic approaches for local or site-specific analyses where sufficient data on geological, geotechnical and hydrogeological conditions is available. An example of landslide hazard assessment for two single landslides in Ľubietová and Veľká Čausa villages can be found in Jelínek, 2005 and Jelínek & Wagner, 2007, respectively. In both cases, the susceptibility relative hazard maps were produced for two selected scenarios based on the safety factor calculation. Petrýdesová (2012) has implemented the deterministic stability assessment of shallow landslides in regional scale for the area between Hlohovec and Sereď towns. By this method, it was possible to assess the stability of the youngest generation of shallow landslides corresponding to slip surface depth up to 5 m.

In the proposed paper, the deterministic method was applied to assess stability of the Chmiňany Landslide. The landslide hazard is determined using a slope stability model, resulting in the calculation of factors of safety for two scenarios of groundwater table levels – scenario of dry slope (without the considering of groundwater influence) and scenario for maximum groundwater table level.

6.2. Basic principle of the deterministic method

The deterministic approach using geotechnical model requires several simplifications; otherwise, the method would be very complex and almost impossible to give correct results. Basic requirements for obtaining acceptable results can be summarized in the following conditions:

- detailed and sufficient input data on geotechnical, hydrogeological, and morphological parameters and their spatial and temporal variability must be guaranteed;
- the main conditions that caused landslide must be known and identified;
- correct justification of a potential failure mechanism must be known.

It is further assumed that the geological conditions are quasi-homogeneous, failure occurs as a single soil layer, which is the result of a translational slide.

The fulfilment of the complete model requirements is very difficult, and this is the reason why the deterministic approach has only limited applications. The main problems are related to the heterogeneity of the environment and subsequent spatial variability and uncertainties in material properties. In most cases of slope analysis, uncertainty is associated with geotechnical parameters (soil strength), geotechnical models, and the frequency, intensity, and duration of triggering agents (Chowdhury & Flentje, 2003). Due to difficulties regarding availability of detailed input parameters, the method is usually applied on a large scale and over small areas. To eliminate these uncertainties, conventional deterministic models must be combined with statistical and probabilistic methods, which take into consideration spatial variability of land characteristics, material properties, or sampling error.

It is further considered that the landslide material slides along a planar slip plane parallel to the surface (Anderson, Richards, 1987, in Jelínek, 2005) and each soil layer is merged into one single layer. The simple infinite slope stability model is generally used in a GIS environment. This two-dimensional model calculates the slope stability for an infinitely large slip surface. Individual pixels of the input parametric maps are considered as "homogeneous units". However, the effect of the neighbouring cells is not taken into account. The model is used for the calculation of the stability of each single cell of the resulting landslide hazard map (van Westen, 1993).

Assessment of the landslide hazard of the selected area by deterministic method is expressed as a factor of safety (FS), calculated for all the slopes and final classes of landslide hazard are divided by the degree of factor of safety. Degree of FS is given by the ratio of the summation of the passive forces (acting as the sliding-resistance force) and the active forces (acting as the sliding-disturbing force). The forces acting at any point along the potential slip surface in the infinite slope model are illustrated in Fig. 6.1. If the safety factor is greater than 1 then the slope is considered as stable, while the factor of safety lower than 1.0 indicates unstable slope and a potential failure existence. However, the limiting value has been defined differently for various land use. For the urban zones has been used the limiting value of FS 1.5, for the agricultural land use, woodland, fields and meadows the limiting value is 1.1 and for other land use it's 1.0.

There are different ways to express the safety factor within the infinite slope model (Nash, 1987; Graham, 1984; Montgomery & Dietrich, 1994). The basic stability equation (formula 1.0) according to Brunsden & Prior (1979) in van Westen (1993) allows modelling of various stability scenarios. This formula is mainly used for the stability analysis of shallow translational landslides usually with a depth of slip surface to 5 m. An important parameter defining the impact of groundwater influence to stability conditions is parameter *"m"*. The parameter *"m"* is given by a ratio of groundwater table levels above the slip surface and a depth of slip surface.

$$FS = \frac{c_{ef} + (\gamma - m\gamma_w) z \cos^2\beta \tan\varphi_{ef}}{\gamma z \sin\beta \cos\beta} \qquad (6.0)$$

Where:
c_{ef} - the effective cohesion [kPa];
φ_{ef} - the effective angle of shearing resistance [°];

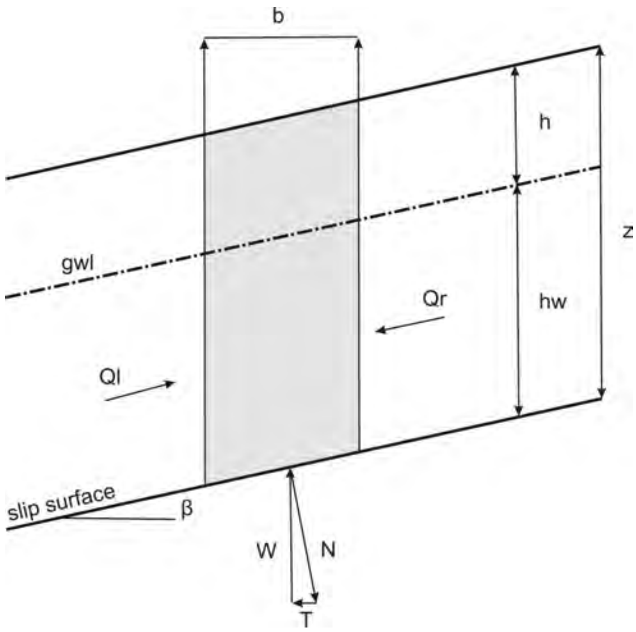

Fig. 6.1 Schematic view of the active and passive forces acting inside the slope, in an infinite slope model (in Jelínek, Wagner, 2007), where β - the slope angle [°], z - the depth of the slip surface [m], h - the depth of groundwater table [m], hw - the height of groundwater table level above the slip surface [m], b - the slice width, Ql and Qr are the side forces applied to soil column

γ - the unit weight of soil [kN.m^{-3}];
γ_w - the unit weight of water [kN.m^{-3}];
β - the slope angle [°];
z - the depth of slip surface below the terrain [m];
m-h_w/z - the ratio of the height of groundwater table level above the slip surface h_w [m] and the slip surface depth z [m].

If the pore-water pressure at the slip surface has been directly considered, then the parameter *"m"* in the equation 6.0 has been removed and replaced with parameter *"u"*, which can be calculated according to the formula 6.1 (Nash, 1987).

$$FS = \frac{c_{ef} + (\gamma.z.\cos^2\beta - \mathrm{u}) \tan\varphi_{ef}}{\gamma.z.\sin\beta.\cos\beta} \qquad (6.1)$$

$$\mathrm{u} = \gamma_w.h_w.\cos^2\beta \qquad (6.2)$$

Where:
c_{ef} - the effective cohesion [kPa];
φ_{ef} - the effective angle of shearing resistance [°];
γ - the unit weight of soil [kN.m^{-3}];
β - the slope angle [°];
z - the depth of slip surface below the terrain [m];
u - water pressure [kPa];
h_v - groundwater table level [m below terrain];

The resultant safety factors may be used for testing different scenarios of slope instability but not as absolute values. Corominas & Santacana 2003 recommended that the degree of slope instability in GIS-based approach must be considered globally, and the resultant safety factors calculated at each cell cannot be interpreted individually because they may give erroneous conclusions.

6.3. Methodology

The resulting map of landslide hazard (in our case stability maps) depends on a detailed knowledge of the studied site and on the quality of input parameters. The acquisition of these data is relatively difficult mainly in time and economic term. The data are usually obtained from engineering geological investigations, field surveys and laboratory analyses. All available data are collected, analysed and organized into a spatial database. The factors influencing the stability conditions are processed in a raster format with cell size 1 x 1 m containing the numerical values. To the process of deterministic analysis in GIS environment the parametric maps enter through the use of map algebra.

As already stated, the deterministic analysis requires the detailed input data. In case of the Chmiňany Landslide, the data were obtained from previous engineering geological investigations (Havčo et al., 2009; Lukács et al., 2012, Kopecký et al., 2013). The investigations included determination of physical and mechanical properties of soils (e.g. shear strength), the groundwater conditions, geological and morphological setting, etc. The collected data were represented as a single point (e.g. borehole); therefore the missing values were interpolated or extrapolated.

Given that the rainfalls in the Chmiňany Landslide represent an important triggering factor causing the sliding, two stability scenarios were modelled: the first scenario which does not consider the influence of the groundwater – dry scenario; and the second scenario that considers the maximum level of the groundwater obtained from the landslide monitoring. Final stability scenarios were compared and the influence of the groundwater upon slope stability determined.

Landslide hazard map created by deterministic analysis represents the different degree of stability of the area. Factor of safety was calculated for each cell of the raster map and according the final value of FS the landslide hazard map was divided into 5 classes (Tab. 6.1).

Tab.6.1 Classification of landslide hazard and stability state according to calculating of factor of safety FS

Factor of safety FS	Stability state	Landslide hazard
< 0.5	Unstable state	very high hazard
0.5-1.0		high hazard
1.0-1.25	Conditionally stable state	moderate hazard
1.25-1.5	Stable state	low hazard
>1.5		very low hazard

6.4. Selection and characteristic of study area

The Chmiňany Landslide was investigated in relation with a highway construction (D1 Fričovce – Svinia). Thus, the data obtained were sufficient for the deterministic analysis.

The investigated landslide is situated on a gentle slope south of the Chmiňany Village, near the current confluence of the Svinka River and Jakubovianka Brook. According to Nemčok, Pašek & Rybář (in Nemčok et al., 1982) classification, the landslide is classified as equidimensional landslide with size characteristics 450 x 565 m (Fig. 6.2). The landslide was reactivated due to combination of extreme rainfalls in 2010 and undercutting of the landslide toe (up to 4-5 m high) in relation to building of social houses. The other unfavourable factor was the suspension of highway construction within the PPP project when the topsoil was removed in a trace of the projected highway. The stability of landslide toe has been disturbed, which has been reflected in visible cracks situated approximately 5.0 m from the edge of the excavation.

Geological settings

According to the engineering geological zoning of Slovakia (Matula & Pašek, 1986), the Chmiňany Landslide belongs to the Region of Neogene Tectonic Depressions (Area of the Intermountain Basins). The geological structure consists of the Pre-Quaternary rocks represented predominantly by Inner-Paleogene Biely Potok Member (Gross et al., 1999). It is represented by layers consistings of claystones and sandstones alternating in different share; fewer by sandstones and conglomerates. The Quarternary sediments are represented by slope deposits, proluvial, fluvial sediments and deluvial-eluvial sediments, mainly clays and loams with various percentage of fragments. Proluvial sediments consist of varied and unsorted gravels, clays and loams with fragments and hard heads. Fluvial sediments are characterized by river plain sediments and terrace sediments - mainly gravels sporadically covered by loams and clays (Havčo et al., 2009).

Within the wider area are more than evident the mass movements and erosion leading to occurrence of slope deformations with different characteristics and size proportion. Appropriate conditions for the landslide occurrence are conditioned by relatively low permeability of Paleogene, or Pre-Quaternary claystones and weathered clayey loams. The easy-weathering Paleogene complexes form assumption conditions for the creating of thick slope deposits. The slope and Pre-quarternary deposits interface is extremely favourable for the formation of slip surfaces and often provides very useful engineering geological, geotechnical and hydrogeological conditions for activation, or reactivation of slope deformations (Havčo et al., 2009).

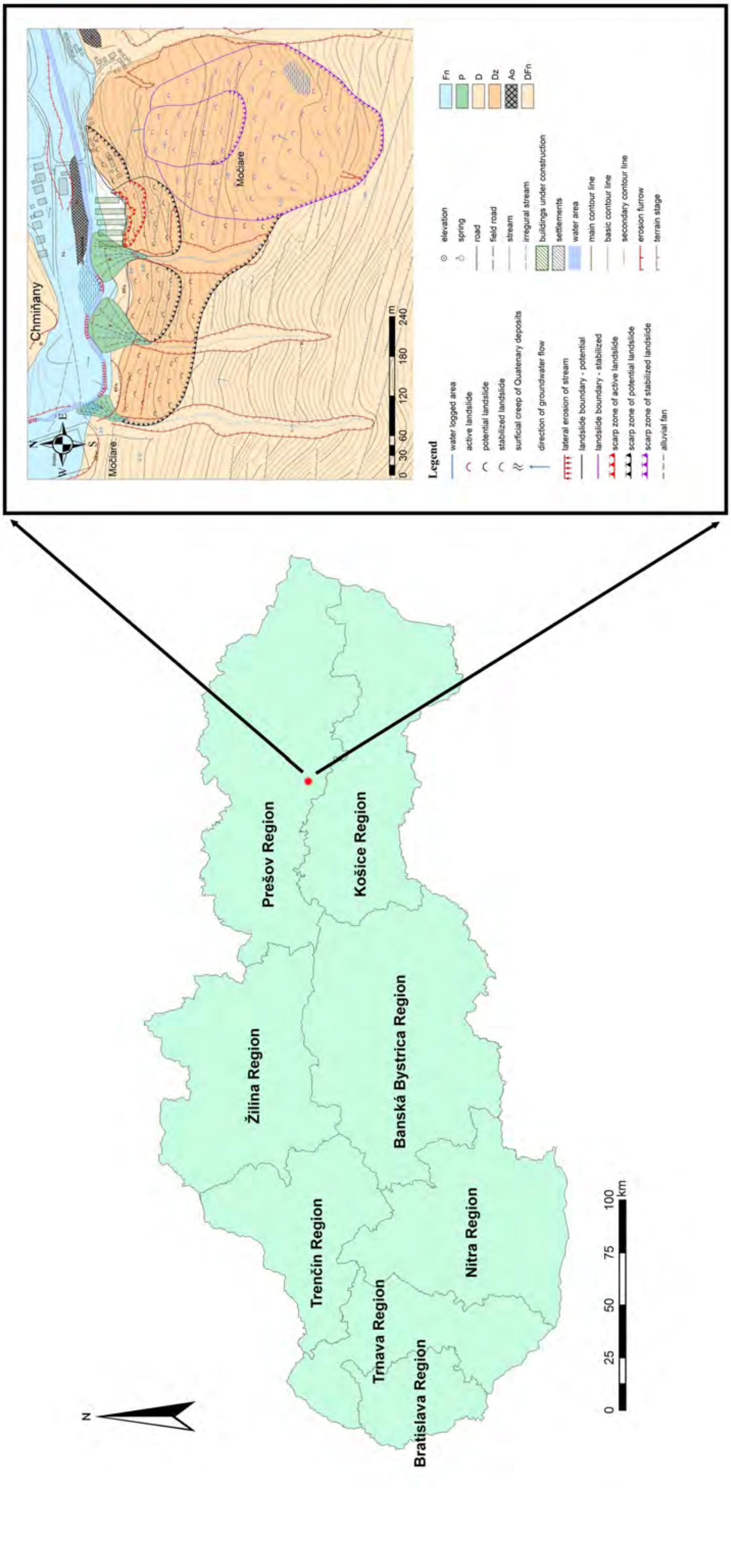

Fig. 6.2 Localization of the Chmiňany Landslide

Tab. 6.2 Basic statistical values of input parameters

	range	min	max	average	median	standard deviation
depth of slip surface z [m]	26.00	0.50	26.50	9.93	9.45	6.35
groundwater level - maximum h_{vmax} [m]	26.00	0.00	26.00	12.63	11.85	6.42
effective cohesion c_{ef} [kPa]	10.00	2.00	12.00	7.28	8.00	2.13
angle of internal friction φ_{ef} [°]	15.00	13.00	28.00	17.34	17.00	2.84
unit weight of soil γ [kN.m^{-3}]	3.00	18.00	21.00	20.68	21.00	0.84

6.5. Input parameters

The input parameter maps have been created using the method of spatial interpolation. GIS is now very powerful software that supports the hazard map creation, including interpolation/extrapolation of the original input parameters. Within the interpolation process, important are mainly density and distance of input data. Spatial distribution of monitoring objects used as an input parameter for each parametric or thematic map is illustrated on Fig. 6.3. In total, the data from 50 points (boreholes, sampling points) were used for the spatial analyses. These are summarized in Tab. 6.2.

Principle of IDW interpolation method

In the present paper the *IDW (Inverse distance weighting)* interpolated method was implemented in GIS environment. The IDW method represents the basis for several interpolation methods. It´s based on the linearly weighted combination of a set of sample points. The estimates cell values are the most intense to the value that is closest to them and this dependency decreases with increasing distance. The surface being interpolated should be that of a position-dependent variable. The basic geostatistical principle is applied - phenomena that are spatial closer together are more similar than phenomena that are more distant in space. The aim of this method is to determine the weights of data values based on the mentioned principle. The weights are determined by simple function that takes into account the distance from an unknown value - *function of inverse distance h (1/h)*. Disadvantage of the method is that it cannot calculate values higher or lower than the values of the input data. Assigned weights have been governed by a single spatial model - inverse distance modified using adequate power according to equation 6.3 (Hlásny, 2007):

$$^{*}(x_0) = \sum_{\alpha=1}^{n} \left[z(x_\alpha) \underbrace{\frac{\left(\frac{1}{h_{\alpha 0}}\right)^p}{\sum_{\alpha=1}^{n} \left(\frac{1}{h_{\alpha 0}}\right)^p}}_{\omega_\alpha} \right] \qquad (6.3)$$

ω_α - weight of value source;
$h_{\alpha 0}$ - distance from position of value point x_α, to point with estimated value in the position x_0;
p - modified exponent.

6.5.1. Slope angle

Slope angle (rate of gradient altitude) is one of the main factors influencing the stability conditions of slopes. It determines the velocity of materials flow down the slope. Each slope has certain critical value of angle; the threshold exceedance changes the stability conditions and leads to sliding. This value depends mainly on the strength characteristics of soil forming the slope – angle of internal friction (φ) and cohesion (c).

The map of slope angle was created using the ArcGIS Spatial Analyst tools. It was derived from digital elevation model (interval 1°) with cell size 1 x 1 m. Value of slope angle has been calculated as maximum rate of slope angle and distance between given cell and eight neighbouring cells, i.e. the steepest slope has been defined - maximum change of calculated z-value and neighbouring cells (ArcGIS Desktop Help, 2014).

The resulting input map (Fig. 6.3) showed the relatively wide variability of slope angle with range from 0.01° to 36°. In the central part of the landslide, particularly in the area of the projected highway, the value of slope angle is relatively high. It depends upon the slope excavation – undercutting the slope toe. In the other parts the mean value of slope angle is 9.78°.

6.5.2. Map of groundwater table level

The groundwater table level in the Chmiňany Landslide is mainly bound to the near-surface zones with high permeability and also to the zones of weathering and loosening of rocks environment – zone of disruption and sliding. The groundwater in the Quaternary sediments is bound mainly to proluvial and fluvial sediments, to a lesser degree to weathering zone - slope sediments (Havčo et al., 2009).

The hydrogeological conditions in the equation 6.1 are accounted by calculating pore water pressure *u,* for two different scenarios, dry scenario and scenario that considers the maximum groundwater table level recorded during the landslide monitoring in the following periods:

- 2008-2010 - irregular measuring intervals (Havčo et al., 2009);
- 2011-2012 - at an average 4 time per month (Lukács et al., 2012);
- since 2013 - irregular measuring intervals (Kopecký et al., 2013).

Thus spatial distribution of the maximum groundwater table levels results in the different accumulation stages of groundwater inside the landslide body. The

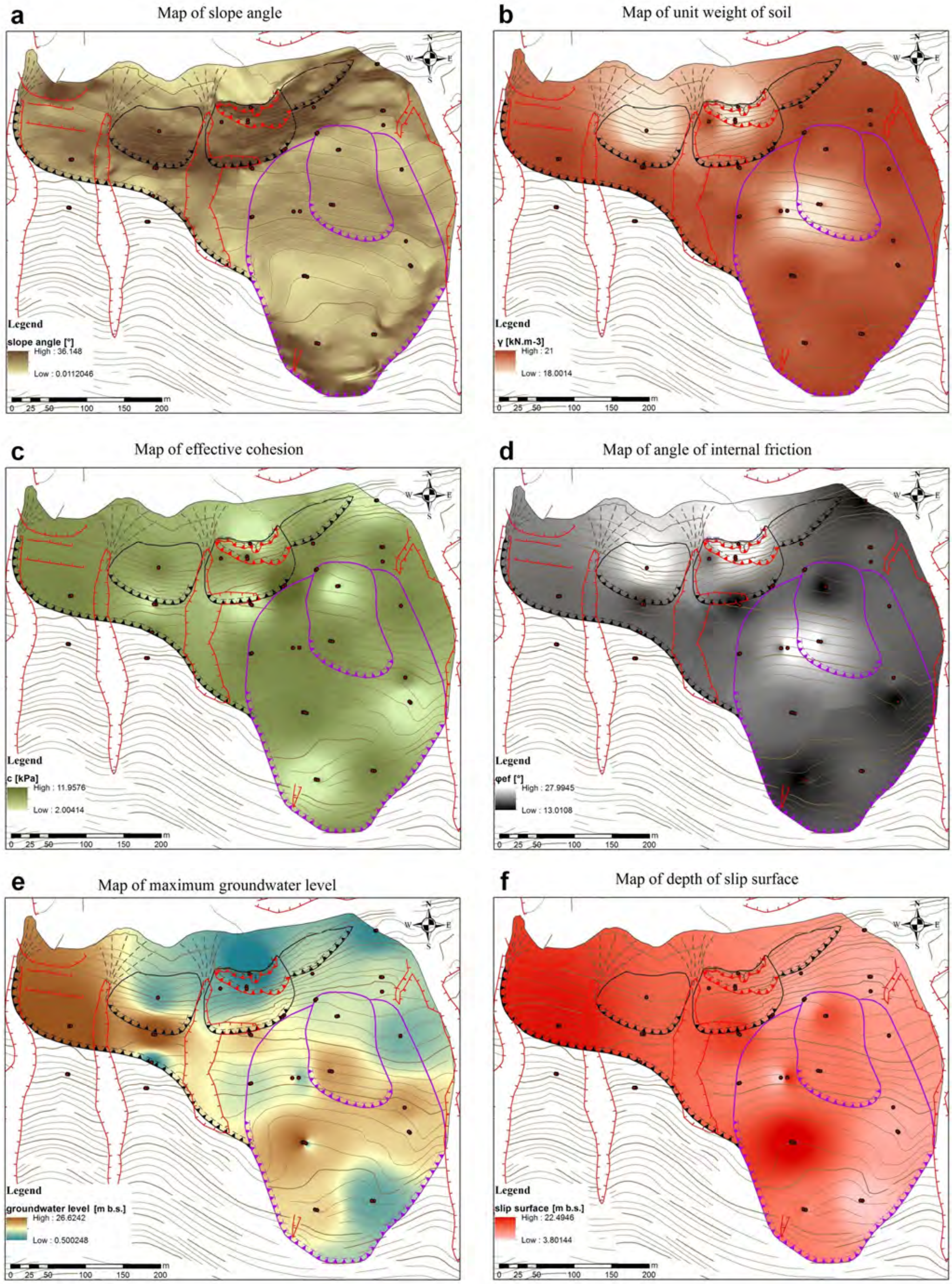

Fig. 6.3 Input parametric maps

western part is represented by block-type landslide where the groundwater table level is in depth more than 20 m. Similar situation is in the central part of the slope deformation (stabilized landslide), where the average depth of the groundwater is approximately 14 m. The higher values of the groundwater table level were measured in the boreholes situated in scarp zones of partial landslides, especially in partial landslides localized in toes of block-type landslides (North part of slope deformations).

Rainfall infiltration was localized in the area south of the landslide. Near the scarp zones of stabilized part of the landslide, depth of the groundwater was less than 7 m. The highest oscillation of the groundwater table level was measured just in the boreholes situated in this part - 13.92 m during the observation period 2008-2012 (Havčo et al., 2009).

6.5.3. Slip surface

Map of slip surface (Fig. 6.3) was created based on the data collected from the previous engineering geological investigations. The Chmiňany Landslide is a typical areal landslide which is characterized by several slip surfaces. Slip surfaces were created in deluvial clayey sediments in different depths. Three stages of slip surfaces were defined:

- 1st depth (horizon) of slip surface: 4-6 m below terrain;
- 2nd depth (horizon) of slip surface: 9-14 m below terrain;
- 3rd depth (horizon) of slip surface: 21-23 m below terrain.

Western part of the landslide is characterized by block failures where slip surfaces are localized in a depth of more than 20 m. This is defined as basal slip surface (3rd horizon). In this part the shallow slip surfaces absent. In the east part of the landslide, the all three horizons of slip surfaces were identified. In the central part, the basal slip surface was determined, which probably represents a presumed fault.

In the landslide body, three horizons of slip surfaces were determined. However, just one, generalized slip surface has been used for the analyses. If more than one slip surface has been determined in a borehole, the slip surface closest to the terrain has been used for the calculations. In case, when the slip surface was not determined in a borehole, the boundary between the Quaternary and Paleogene sediments has been accounted for instead.

6.5.4. Geotechnical parametric maps

In term of stability of slope, the geotechnical parameters of soils represent the important element of rock environment. In nature conditions the collapse of soil mass occurs in most cases by exceeding the shear strength of soils. Within the stability analysis, it is necessary to know the shear strength of soils, i.e. cohesion c [kPa] and angle of internal friction φ [°]. These parameters were obtained from the laboratory analyses of soil samples from slip surface of the landslide or numerical values were used from technical standards (such as STN 73 1001). In the study area the soil near the slip surface was classified as eluvial deposits with character of loams and clays with moderate value of shears parameters; they was classified as F6-CI/CL. Each geotechnical parametric map is shown in Fig. 6.3.

6.6. Stability models and results

The resultant landslide hazard maps represent the different degree of factor of safety within the landslide area. Because the safety factor in the final hazard map is assigned as a single value in every cell of a raster map, it is convenient to perform a reclassification of the calculated values (Jelínek & Wagner, 2007). The resultant hazards maps were reclassified into five classes safety factor: < 0.6; 0.6-1.0; 1.0-1.25; 1.25-1.5 and > 1.5. The areas where the degree of FS is less than 1.0 (classes 1 and 2) are considered as the areas with unstable conditions. Areas with intervals of ranges of FS <1.0-1.25> and <1.25-1.5> are considered as potentially unstable and the areas with the degree of FS greater than 1.5 are stable. Factor of safety calculated for each cell according to formula 1.1 and 1.2 get the following form (1.4) in a GIS environment:

FS = ("idw_c" + (("idw_gama" * "idw_sp" * (Cos("slope") * Cos("slope")) - "u") * Tan("idw_fi")) / ("idw_gama" * "idw_sp" * Sin("slope") * Cos("slope")) (6.4)

Where:

idw_c:	parametric map of effective cohesion compiled by IDW, spline and kriging method;
idw_gama:	parametric map of the unit weight of soils compiled by IDW, spline and kriging method;
idw_fi:	parametric map of effective angle of shearing resistance of soils compiled by IDW, spline and kriging method;
slope:	parametric map of slope angle
idw_sp:	parametric map of slip surface
u:	parametric map of pore water pressure calculated according to equation 6.2.

The calculated values of factor of safety are generally used for comparison of selected scenarios or to identify the unstable parts of the landslide. Due to limited number of boreholes and their spatial distribution in the Chmiňany Landslide, the most reliable values are the values closest to the measured ones. Final stability maps are illustrated on Fig. 6.4 and their comparison is listed in Tab. 6.3.

The result showed that the most unstable parts in the final maps are situated close to partial scarp zones, especially in the active part of the slope deformation. Exactly in this part where undercutting of landslide toe within the building process of social houses (Fig. 6.5) occurred. The total size of the area where the factor of safety was less than 1 (classes 1 and 2) for scenario without the influence of groundwater was approximately 0.02 km^2. When the

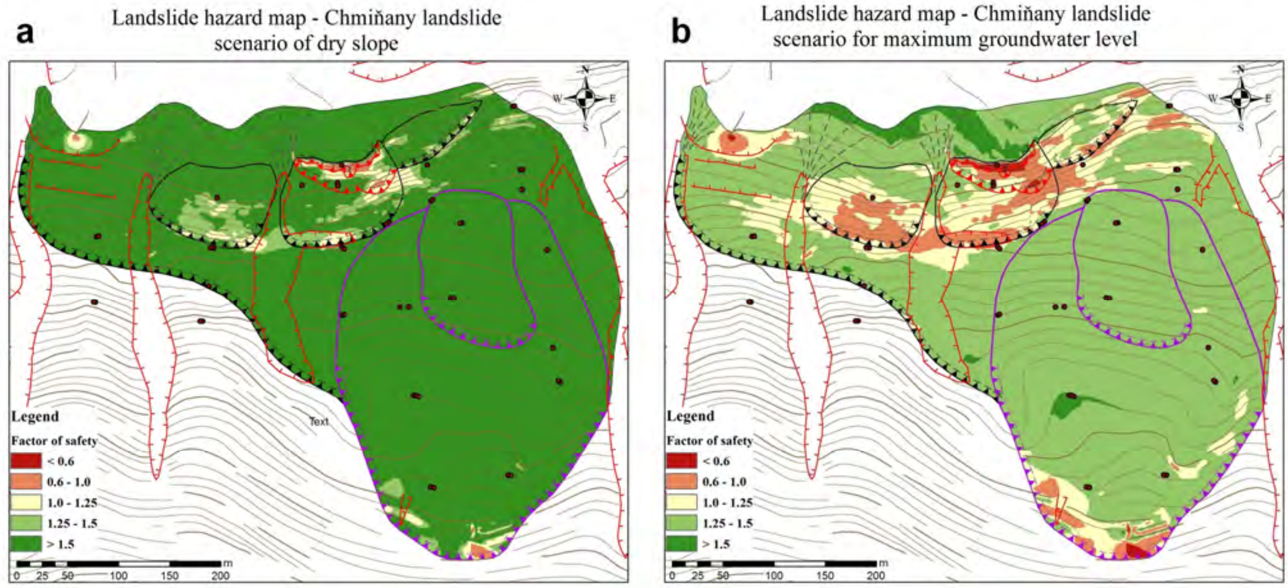

Fig. 6.4 Final stability maps: a, scenario of dry slope; b, scenario for maximum groundwater table level

Tab. 6.3 Spatial distribution of landslide hazard represented by factor of safety value

Class	FS	Scenario of dry slope		Scenario of maximum groundwater level	
		Area [km^2]	Area [%]	Area [km^2]	Area [%]
1	< 0.6	0.00	0.00	0.02	0.50
2	0.6 - 1.0	0.02	0.50	0.28	7.02
3	1.0 - 1.25	0.08	2.08	0.54	13.79
4	1.25 - 1.5	0.19	4.94	2.99	75.94
5	> 1.5	3.65	92.48	0.11	2.75

parameter of water pressure *u* represented the depth of maximum groundwater table level enters to the analysis, the area of class where the FS was less than 1.0 increased up to 0.3 km^2. The second relatively high change in degree of factor of safety was within the 5th class. In the dry slope scenario, there was a relatively high percentage of stable area - 92.48%.

Fig. 6.5 Active part of landslide - undercutting of landslide toe (photo: Kopecký, 2008, in Trangoš, 2013)

As for the verification, the results of inclinometric measurements from August 2012 to May 2013 were used. Trangoš (2013) interpreted the complex assessment of inclinometric measurements, which are illustrated in Fig. 6.6. The higher activity, which was equal with stability model for the second scenario, was measured just in the boreholes located near to the active part of the slope deformation. These were boreholes INK-7A and INK-14N, where the deformation values reached the size of 10 mm and more. This activity was demonstrated for shallow slip surfaces (to 5 m below the surface), which also enters to stability models. The factor of safety which has been calculated less than 1.0 has not been confirmed by inclinometric measurement in part near the main scarp zone. There was measured the deformation of only 1-5 mm interpreted as low activity.

Summary and discussion

Since, landslide hazard assessment using the deterministic method requires relatively high accuracy and variability of input parameters; it is therefore applied to the smaller areas with homogeneous geomorphological and geological conditions. According to van Westen (1993) this method is not suitable in small and medium scales by reason of absence of detailed input data, mainly data on physical and mechanical properties of soils and groundwater conditions.

GIS is very powerful tool supporting all processes of a map creation including the spatial interpolation of input parameters, data processing and analysing. The most important part of the landslide hazard assessment is the collection of data and preparation of input maps. The selec-

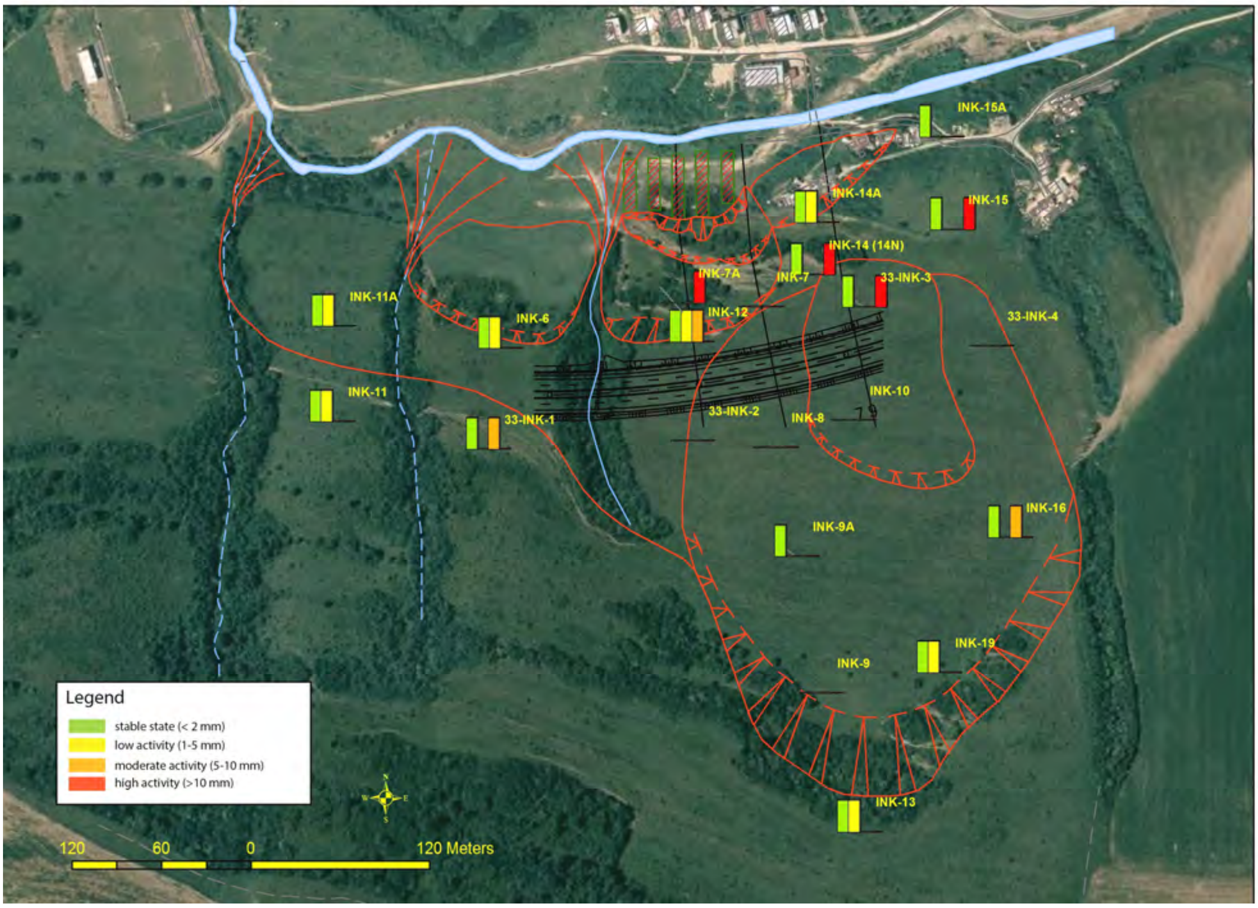

Fig.6.6 The results of inclinometric measurements expressed by point values from measurements realized by FNS CU during the time period August 2012 - May 2013 (Trangoš, 2013)

tion of interpolating method and its correct settings in GIS environment may cause a considerable subjectivity and an error in a preparation of input parametric maps. In this paper, we used the IDW interpolation method which has been considered as the basic interpolation method implemented in GIS environment.

The final degrees of stability calculated for each cell in GIS environment should not be interpreted individually, but globally as a whole unit. The final degree of stability could be used for testing different instability scenarios and their mutual comparison.

Using the deterministic analyses, it was possible to estimate the stability state of the investigated Chmiňany Landslide. This landslide is interesting mainly in relation to the construction of important highway in Slovakia (D1- Fričovce – Svinia section). The highway investigations provided data concerning the engineering properties of the soils, the groundwater conditions and other data necessary for the deterministic assessment. The unstable part (in the area of the undercut landslide toe) was calculated for both stability scenarios and which were verified by inclinometric measurements. Factor of safety higher than 1.3 was required for the highway construction, which represents classes 4 and 5 in the resultant hazard maps. Within these categories fall more than 78% and 97% of the investigated area for the dry scenario and the scenario without groundwater table level, respectively. The area with factor of safety in an interval 1.0-1.3 has been considered as conditionally suitable (class 3). The areas with FS value less than 1.0 are unsuitable for any constructions. This class occupies 0.5% of the total area for the dry slope scenario. This percentage is higher with groundwater influence; it increased up to 7.5% of the study area. At present time the unstable part is stabilized and there is still realized a continuous monitoring (inclinometric measurements, measurements of groundwater table level and yields of drainage elements).

By using the deterministic analysis it is possible to assess stability of a landslide for selected scenarios, as well as to assess different progress of slope deformations in the area.

Acknowledgments:

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7. Main Results of the Slope Deformations Monitoring

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Abstract: The presented contribution gives brief information on the development and status of the slope deformations monitoring in the Slovak Republic under the umbrella of the project Partial Monitoring System - Geological Factors. In addition to basic information the attention is given to study cases of monitoring of various types of slope failures and to the research achievements. At the same time the authors present the current state of knowledge in developing of Early Warning Systems for landslides.

Key words: landslide, creep, monitoring of slope movements, monitoring methods, Early Warning Systems

7.1. Introduction

There is no need at all to stress the importance of slope deformations and their adverse effects on the development of certain parts of our territory. Also recently - since 2010, more than 600 new landslides have been registered (joined with extreme rainfall totals Liščák et al., 2010) – their severity is perceived not only by experts and organizations dealing with the issues of slope stability, but also by media and the lay public. Increasing awareness and interest of the population for information related to slope failures, is confirmed by the number of incentives for registration of activated landslides. These come either directly from the threatened owners of housing estates, or personnel of local authorities or other government organizations. From the relatively large amount of landslides, which are activated through every year in different parts of our country, the attention is given especially to those that directly threaten or harm destructively the roads, housing estates, buildings or other objects important for the whole society. Naturally, these slope failures remain sensitive subjects of interest even after the implementation of emergency or remediation measures. Therefore, in these areas monitoring has been performed, which is adjusted to provide the available information on significant developments of landslide-forming factors and physical activity of the landslide bodies. The basic monitoring observations start from the launch of exploration and restoration works. As a rule, however, they are based on the observation of changes in the groundwater table level depth solely, or they encompass one or two stages of measurements of physical activity of landslide masses. Accounting for relatively short time-limited period of implementation of exploration activities, monitoring results rarely gives a comprehensive picture of the stability conditions of the landslide areas and their evolution. In many cases, after a period of remediation, or exploration activities, the monitoring measurements are completed and usually maintenance of the monitoring objects ends up.

Due to some changes in the overall understanding of the meaning and importance of long-term regular monitoring of slope movements sites, in 1993 the project of "Partial Monitoring System - Geological Factors" (PMSGF) was launched; the Orderer is the Ministry of Environment of the Slovak Republic (MoE) and the Contractor is the State Geological Institute of Dionýz Štúr (SGIDŠ) Bratislava. The component of this project is to ensure regular monitoring at selected locations of slope movements from all over Slovakia.

Currently, after more than 20 years of the project solution the monitoring system has experienced several significant changes. In particular, the principle of flexibility in the selection of monitoring sites is consistently applied, consisting in the fact that the observed sites have been annually complemented on new, socio-economically significant landslides. On the other hand, the monitoring intensity at long-term and stable socio-economically minor sites has decreased, or has been suspended.

Many of the changes relate to monitoring hardware. Development of measuring facilities has allowed to improve technically the indicators of their status and trends in virtually all applied methods. For example, the monitoring of the changes in the groundwater table level depth is gradually moving away from the Rang whistle measurements (which is generally carried out 1 time per week) to continuous recording by automatic level gauges. Similar progress in technical provisions is evident also in some other monitoring methods (Wagner et al., 2010), making possible to accurately determine e.g. magnitude of physical activity of sliding masses.

Relatively rich set of information has also allowed for certain interventions in the methods of project solution. Procedures for evaluating indicators have been gradually developed and later optimized (Wagner et al., 2012, Ondrejka and Wagner, 2012), so as to best describe the state of development of the stability of the slope failures and also to be understood for wide range of end-users of this information.

In the present paper the basic principles of the project PMSGF, subsystem 01 Landslides and Other Slope Deformations are summarized. In the form of case studies, attention is paid to the most important current monitoring sites, representing sliding - Nižná Myšľa, creep - Košický Klečenov, and indications of rock fall - Banská Štiavnica.

7.2. Actual state of the solution of the subsystem 01 - PMSGF

7.2.1. Selection of monitoring sites and the objectives of the project solutions

The objective of the project solution was to allow the application of certain specific monitoring methods in order to obtain a set of necessary data. Their processing should establish the parameters characterizing stability conditions of selected slope deformations. When selecting representative sites, number of factors has been taken into account. The first was the typology of slope failures. The monitoring system encompasses slope deformation of the type of sliding and creep and sites with signs of rock fall. The second selection criterion was based on regional geological division of the territory of Slovakia (in accordance with the engineering geological zoning of Slovakia - Matula and Pašek, 1986). The third, and often the most important criterion was the socio-economic importance of the affected sites.

Initially, the project should have solved spot sites and after securing a certain amount of information about the behaviour of individual slope failures the lessons learned should be extrapolated to a wider area with similar geological, geomorphological and climatic conditions. This intention, however, has been fulfilled only partially. It has been established that each individual slope failure is a very complicated system and approximation results to areas outside the monitored area hinder diversity and different factors weights affecting the stability of surrounding territories, although with similar geological and geomorphological settings.

In the initial phase of sites selection the goal was to keep to certain proportionality between different types of slope movements and their presence in different engineering geological regions. The selection was focused on slope deformations, which constituted a threat to existing objects of technosphere, or to the areas of significant investment plans. Thus, the monitoring system has involved sites such as Morovno settlement in Handlová (the first settlement in Slovakia, which was in the years 1974-1977 consciously built on the territory affected by slope failures - Nemčok, 1982); landslide slope between Hlohovec and Sereď (a section of a projected Waterworks Sereď - Hlohovec; overall width of the slide area is up to 18 km and it is the largest frontal landslide in our territory - Otepka et al., 1983), the slope in the cadastre of Liptovský Mikuláš (landslide, threatening traffic on the main railway line Žilina - Košice - Fussgänger et al., 1976) and many others.

In accordance with the above principles in the course of the project solution a file of monitored sites was created, which has been gradually upgraded and adapted according to socio-economic requirements and monitoring results. Among the monitored sites the number of landslides was growing with implemented engineering geological survey and/or corrective measures. Conversely, suspension, or attenuation of monitoring activities have experienced the sites where the measurement results indicated favourable long-term stability of slope.

In assigning a slope deformation into the monitoring system a significant milestone in the project represents the year 2011, when the number of monitored sites significantly increased. The original 14 sites were amended on 15 new ones which emerged in 2010. This fact has significantly influenced the basic criteria for the selection of representative sites. The socio-economic dimension of threatened areas has got into the forefront. The landslides of 2010 were generated by intense rainfall events (during the months of May and June 2010). The greatest concentration of newly-evolved landslides was recorded in the eastern Slovakia. In several territories roads and railway communications, houses, farm buildings, and many other objects have been damaged or destroyed. The most markedly damaged in terms of a measure of incurred losses was Nižná Myšľa Village. As a result of activation of landslide movement 38 houses had to be demolished. A little less unfavourable situation was reported in other communities (e.g. in Kapušany 11 houses were destroyed).

As a result of the inclusion of new landslides (which were added after 2010), currently in the subsystem Landslides and Other Slope Deformation 49 sites are monitored (Fig. 7.1, Tab. 7.1), of which 35 are landslides, 3 belong to the group referred to as signs of rockfall movements and 4 are slowly creeping slope failures. At 6 localities processes of weathering are monitored and 1 site is of a special character - a stabilizing embankment of the catastrophic landslide of 1960 in Handlová. It is essentially a stabilizing element, which is classified as a water management work.

7.2.2. Review of recently used monitoring methods

After the transition to systematic monitoring, usually after the measurements made in parallel with the implementation of the survey and remediation activities, routine measurements provide basic information on the status and activity of the landslide area. Monitoring activities are conducted to examine the main landslide-forming factor - changes in groundwater table levels and physical activity of the landslide body. At the same time efficiency (yield) of drainage facilities is observed and

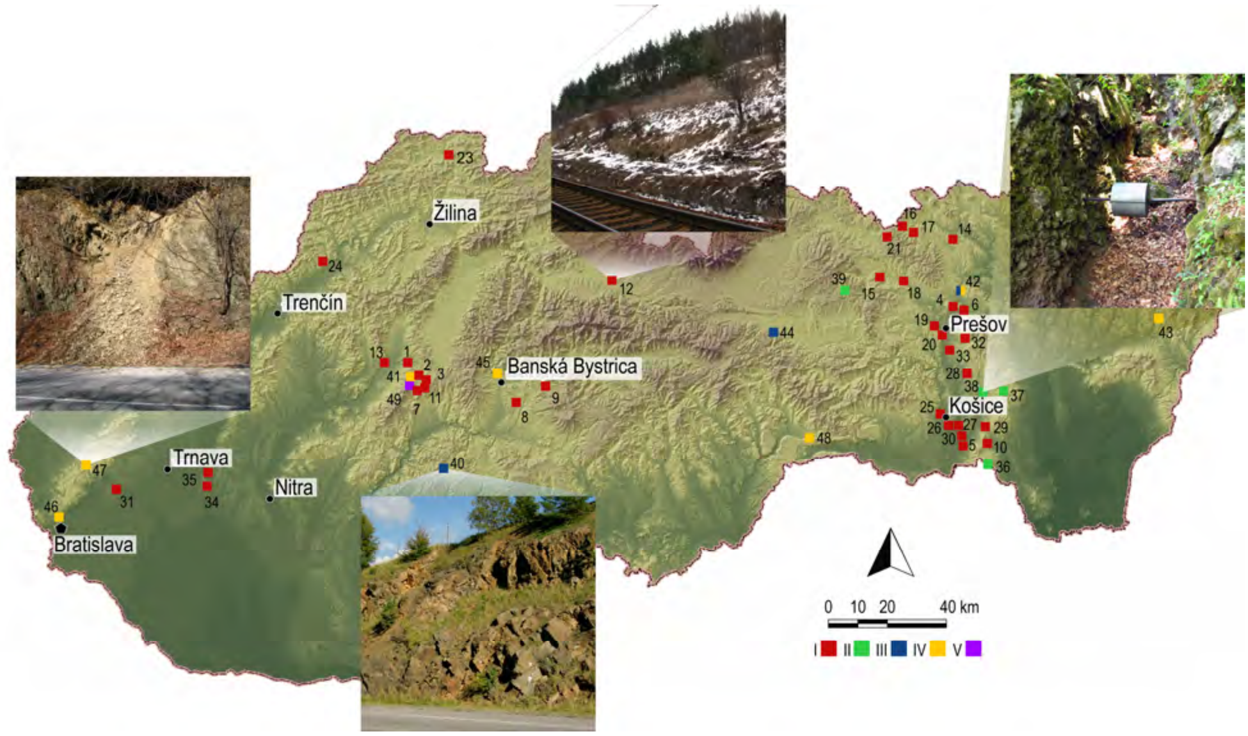


Fig. 7.1 Arrangement of monitored sites of PMSGF, subsystem 01 - Landslides and Other Slope Deformations (state of monitored sites in 2013; according tab. 7.1). Monitored sites of the type: I - sliding, II - creep, III - rock fall, IV - weathering, V - special (stabilising fill).

Tab. 7.1 Overview of the monitoring sites of landslides and other slope deformations

Slope movement type	Geological setting	Sites
Sliding	Neogene volcanites and their contact with Paleogene and Neogene deposits	1. Veľká Čausa 2. Handlová, Morovnianske sídlisko 3. Handlová, Kunešovská cesta Street 4. Fintice 5. Nižná Myšľa 6. Kapušany 7. Handlová, Žiarska ul. Street 8. Dolná Mičiná 9. Ľubietová 10. Slanec - gas pipeline 11. Handlová - landslide of 1960
	Sediments of flysch character	12. Okoličné 13. Bojnice 14. Bardejovská Zábava 15. Ďačov 16. Lenartov 17. Lukov 18. Pečovská Nová Ves 19. Prešov, Horárska ul. Street 20. Prešov, Pod Wilec Hôrkou 21. Čirč 22. Krajná Poľana 23. Čadca 24. Kvašov
	Neogene sediments	25. Košice, sídlisko Dargovských hrdinov 26. Košice, Krásna 27. Nižná Hutka 28. Varhaňovce 29. Vyšný Čaj 30. Vyšná Hutka 31. Šenkvice

Slope movement type	Geological setting	Sites
		32. Ruská Nová Ves 33. Petrovany 34. Vinohrady nad Váhom 35. Hlohovec-Posádka
Creep	Neogene volcanites	36. Veľká Izra 37. Sokoľ 38. Košický Klečenov
	Sediments of flysch character	39. Jaskyňa pod Spišskou
Rockfall	Neogene volcanites	40. Banská Štiavnica 41. Handlová-Baňa
	Sediments of flysch character	42. Demjata 43. Starina
	Rocks of Mesozoic and Pre-Mesozoic	44. Slovenský raj-Pod večným dažďom 45. Jakub 46. Bratislava-Železná studnička 47. Pezinská Baba 48. Lipovník
Stability of water-management work	Anthropogeneous deposits overlying Quaternary and Paleogene rocks	49. Handlová-Stabilizačný násyp (Stabilisation Fill)

regularly information on climate (rainfall) conditions (from stations SHMI) is gathered. In selected areas landslide deformation evolution is observed at different depths of the ground (method of precision inclinometer), as well as the development of a stress state of a landslide body (at depth in boreholes, changes in electromagnetic field emissions activity). The used monitoring methods are based on long traditions and are specifically designed for different types of slope movements. To description and specification of currently used, but also envisaged methods, attention is given in a number of already published papers (Wagner et al., 2000; 2002; 2010; Ondrejka et al., 2011; Ondrejka and Wagner, 2012). Therefore, in this contribution we focus mainly on the summary of the results obtained by applying the technically most advanced monitoring facilities.

Measurement of regime indicators

The advent of advanced modern automatic equipment has offered greater accuracy and in particular higher frequency of measuring of changes in groundwater table levels, and often their continuous recording. For example, changes in the groundwater table level depth, which in our conditions represent decisive factor in the development of slope stability, are monitored thanks to installed automatic level gauges continuously for nearly two decades. Regular observation of changes in the groundwater table level depth is generally provided at 32 locations, of which only 10 are equipped with automatic level gauges. The equipment is thus placed within 20 piezometric wells. In this way the monitoring of landslide areas of the most socio-economic importance is ensured. The longest record of the depth of groundwater table level obtained by automatic measurement comes from the Veľká Čausa and Okoličné landslide sites. At these locations the groundwater table level has been observed by automatic level gauges since 1996. The largest number of sensors on a single location is in turn placed on the landslide Nižná Myšľa (4 level gauges). Sufficiently illustrative is an indication of the total number of records obtained by long-term monitoring (level gauges are set at an hourly rate of recording of the groundwater table level). For the whole period the landslide sites have collected more than a million data (Tab. 7.2)

The series on changes in the groundwater table level depth (Fig. 7.2) allow to create perception of the regime, and thus on their effect on the stability conditions of landslide area. This knowledge is applied to create classification systems of regime indicators assessment, which help simplify the interpretation of the state of the indicator to a wider range of users. At the same time they serve in the derivation of the limit levels of the groundwater table level depth in the development of early warning systems for landslides.

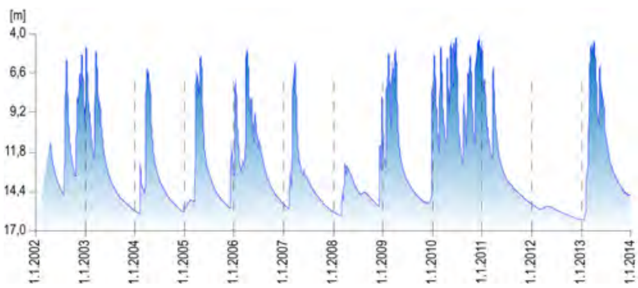


Fig. 7.2 Results of long-term monitoring of groundwater table level depth in borehole JM-6 at the landslide site Dolná Mičiná.

The quality of information obtained from the automatic level gauges is considerably higher than that of the conventional measurements performed at longer intervals. Fig. 7.3 shows a comparison of continuous measure-

Tab. 7.2 Landslide sites with installed automatic piezometric gauges

Site	Well designation	Date of installation	Measurement termination	Note
Okoličné	J-1	14.06.96		On 6.11.07 former piezometer was replaced by MARS 4i type
	JH-29	14.06.96	15.05.2002	
	AH-2	12.10.05		Early Warning System (MARS 5i)
Veľká Čausa	VČ-2	07.11.96		On 23.4.08 former piezometer was replaced by MARS 4i type
	VČ-8	07.11.96		
	AH-1	11.10.05		Early Warning System (MARS 5i)
Dolná Mičiná	JM-19	16.04.02	23.04.2009	
	JM-6	16.04.02		
Handlová-Morov. sídlisko	P-17	21.11.03		
	P-19	21.11.03		
Liptovská Mara	J-10	14.05.03	24.3.2012	Automatic piezometer gauges in 12 wells
	J-19	15.05.03	24.3.2012	
	J-5	18.06.09	24.3.2012	
Fintice	K-1a	27.04.05		
	K-2a	27.04.05		
Nižná Myšľa	JV-17	12.02.13		
	JV-22	12.02.13		
	JV-44	12.02.13		
	JV-54	12.02.13		
Kapušany	V-POZ-3	11.02.13	21.08.13	
	V-POZ-1	30.09.13		
Šenkvice	PVZS-1	19.04.12		
	PVZS-2	03.05.11		
	PVZS-3	03.05.11		
Prešov-Horárska ul.	JH-3	30.09.13		
	JH-4	05.12.12	30.09.13	
Krajná Poľana	KP-1	01.10.13		

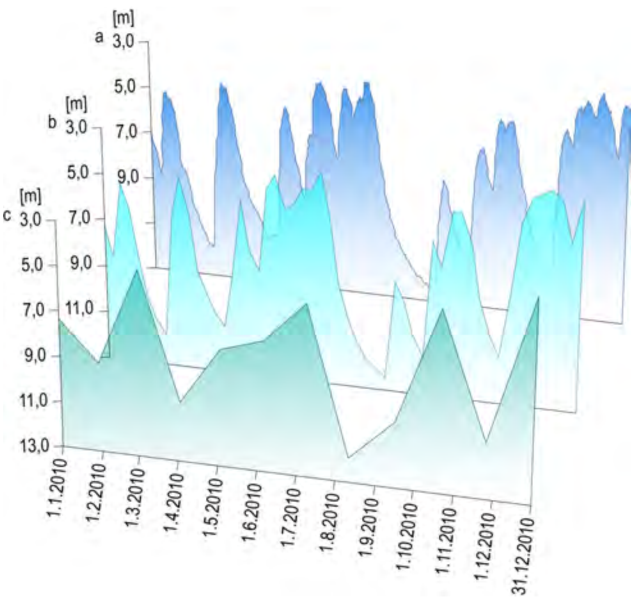


Fig. 7.3 Comparison of results of monitoring of groundwater table level with different frequency in borehole JM-6 at the landslide site Dolná Mičiná. a - continuous measurements using automatic piezometers, b - weekly frequency, c - monthly frequency of measurements

ments with the results obtained during cycles of field measurements carried out by observers (with weekly and monthly frequency). The above example clearly documents the differences between the quality of information obtained. The monthly measurement doesn't reflect the dynamics, or cyclical changes in the groundwater table level.

In order to evaluate the stability of the landslide area a great asset is to obtain information on the levels development in several aquifers (Fig. 7.4). Such solutions, however, allow only the placement of automatic level gauges in a pair of wells, which depict various groundwater horizons.

Although in the process of evaluating the stability conditions we are almost exclusively focused in the changes of the groundwater table level depth, in certain cases it is necessary to analyze the information on the development of groundwater temperature changes and specifically, to determine the origin of groundwater. The example (Fig. 7.5) clearly shows a close relationship between recharge of groundwater and its temperature changes. In the first part of the graph, about the mid of May, increase of the groundwater table level leads to a drop in its tem-perature. On the contrary, over the next five months, the rise of groundwater table level causes an increase in its temperature. The demonstration of this fact was of great importance in the derivation of the relationship between changes in the groundwater table level depth and physical activity of the landslide masses, which we studied using a stationary inclinometer (Ondrejka et al., 2011).

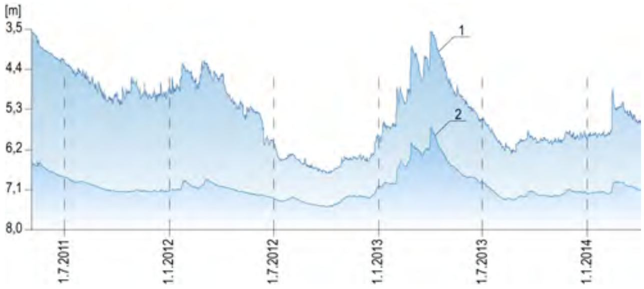


Fig. 7.4 Example of monitoring of two horizons of groundwater in the landslide area of Šenkvice. 1 - borehole PVZS-2, 2 - borehole PVZS-3

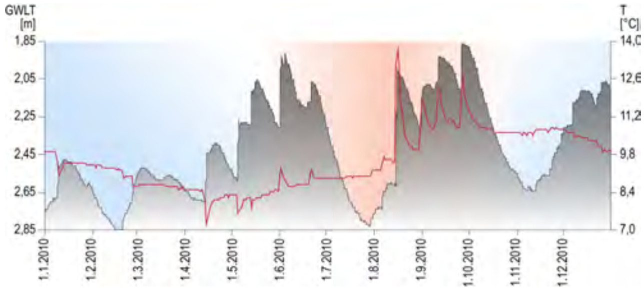


Fig. 7.5 Relation between change in groundwater table level depth and change in its temperature

Recently, among the most progressive equipment that we use in the monitoring of slope deformations, are automatic level gauges working in online mode, which allow adjustment of critical values for several parameters. After reaching, or exceeding a certain defined threshold value, the system automatically generates a SMS message via the GSM network and delivers the warning to predefined phone numbers. The main studied factor, based on which warnings are generated, are the groundwater table level depths. At the same time a gradient in changes of the groundwater table level depth is evaluated. Similarly, with integrated rain gauge, there are considered the intensity and the size of total rainfall. The equipment is currently installed at the landslide location Veľká Čausa and serves as landslide early warning system.

The calculation of the direct benefits of using automatic level gauges would be quite extensive. There can be mentioned, for example, the elimination of subjective effects in the implementation of field measurements by observers or reduction in costs for measurements made. Nevertheless, in addition to all the positives the limitations in the use of these devices should be also noted. These are problems related to the installation of the level gauges and the prevention against damage. Finally, it is necessary to address the question whether this expensive equipment is convenient for a geological setting at a site (as in the case of landslide bodies built predominantly by clayey material). During many years of experience in solving the project of PMSGF there have occurred the cases where relatively expensive automatic level gauges did not yield the expected results. Changes in the groundwater table levels were minimum due to the very low coefficient of filtration of surrounding rocks (e.g., during the years of monitoring at the landslide site Kapušany in borehole V-POZ-3 the amplitude change was only 0.02 meters). For this reason, in the slide areas pore pressure sensors are gradually begin to be used. The most commonly used are piezometers to measure pore water pressure (Thut and Gróf, 2010).

For yet not-fulfilled objective of the project can be regarded ensuring a continuous monitoring of changes in the yield of drainage facilities. This information should clarify ideas about the run-off situation of a slide area and should provide quantitative data on the effectiveness of the established depth drainage.

Measurement of kinematic activity of landslide areas

This issue has recently seen very significant progress. In addition to traditional methods, which are based on direct measurements of displacements and deformations, there have been recently developed a variety of methods based on remote sensing (Wagner et al., 2010). In the PMSGF project solution primarily used are geodetic surveying (terrestrial and GNSS), inclinometer, dilatometer and photogrammetric measurement methods. This fact is mainly conditioned by the need to detect very small changes in magnitude of the order of millimetre, maximum changes at the first centimetres. In the sphere of slope movements monitoring of the sliding type the most commonly applied are methods of surveying and inclinometer. Others mentioned methods are applied to monitor the movements of rock mass (signs of rockfall movements - dilatometric and photogrammetric measurements; slow creeping movement of rock blocks - measurement by optical dilatometer - TM-71). The results of these measurements are summarized in Chapter 7.3.

In the issue of movement monitoring there can be considered a significant advance in trial run stationary inclinometers (provided by Geoexperts, ltd.). For about one-year of operation (March 2009 - July 2010) deformations were documented at the level of the shear surface within the landslide area in the village of Veľká Čausa (Ondrejka et al., 2011). The data obtained illustrate the idea of the evolution of deformation, which had been possible to observe in the past only in stages, about once a year. The stationary inclinometer enables to obtain a perfect picture of the daily values of deformation, which clearly point to the fact that the movement of the landslide mass occurs only under certain conditions. In this case, the movement has been directly related to the changes in the groundwater table levels. When there were no changes in the groundwater table level depth, the land slide slope was in a relatively stable state. The above knowledge has contributed significantly to the creation of an early warning system (this topic more attention is given in Chap. 7.4), but also gave an impetus to fundamental changes in the classification assessment of physical activity (Wagner et al., 2012).

In geodetic methods-based monitoring of physical activities in addition to terrestrial measurements rapidly

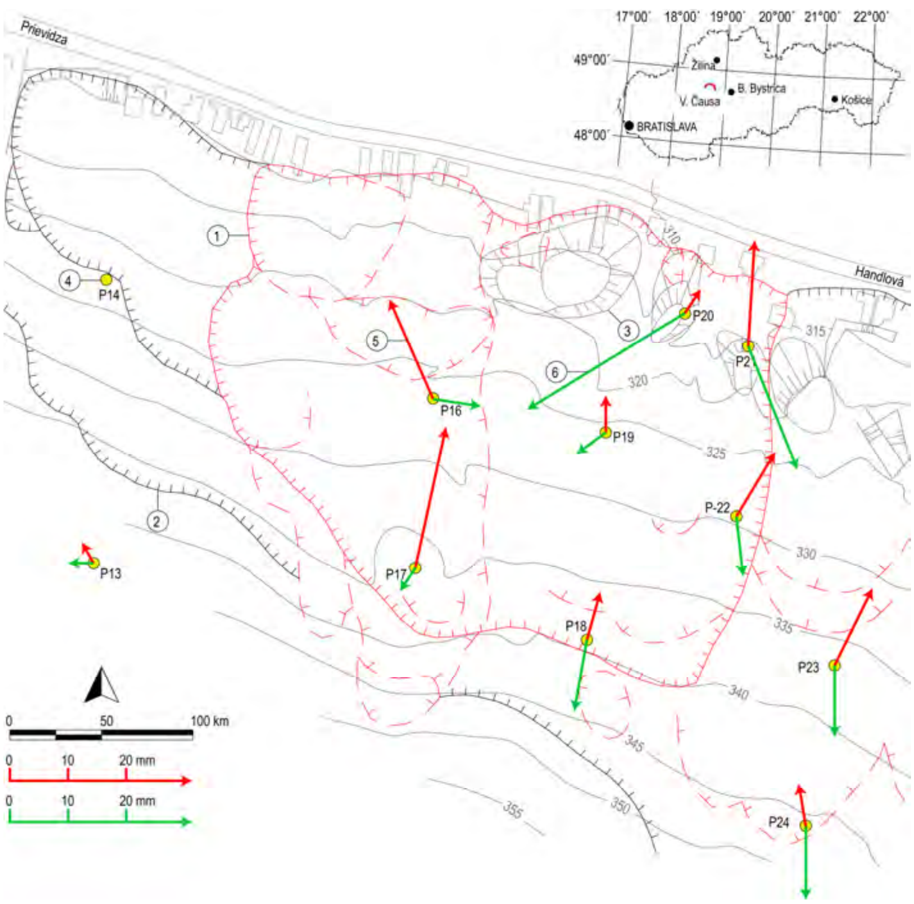


Fig. 7.6 Map of the landslide area in the cadastre of Veľká Čausa with indicated vectors of geodetic points shifts. 1 - active landslide area, 2 - potential landslide area (older landslides), 3 - detached blocks of volcanites, 4 - network of geodetic points, 5 - vectors of horizontal shift of geodetic points measured in May 2011, 6 - vectors of horizontal shift of geodetic points measured in May 2012

developing GNSS technology is increasingly used. To its development contributes an improvement of satellite navigation systems, but also user-friendly operation and high precision, adequate to monitoring needs. The above arguments contributed to the fact that since 2008, the project specialists have been directly involved in the realization of the monitoring measurements of physical activity using GNSS equipment. Similarly to using a stationary inclinometer, even in this case, the increase in the frequency of monitoring has enabled to clarify the idea of physical activity. In localities with high social importance the measurements are performed at least once a year (up to three times a year) and at the localities in which the long-term favourable stability condition was identified, measurements are made every two years.

Like the other measurements, during the PMSGF project solution the GNSS measurements collected a rich data set that provides room for various analyzes. When evaluating the measured vectors the attention is preferentially focused in orientation of azimuths of measured vectors that help shed light on the mechanism of landslide movement. However, the analysis highlighted the problems which caused some uncertainty in interpreting the results, since they have not coincided with the basic knowledge on the functioning of slope movements. In analyzing the results of geodetic measurements it has been shown that the azimuth vectors recorded at different times, in several cases differ significantly. As it is apparent from Fig. 7.6, in some cases the difference is close to 180°. When searching for an explanation of this problem we used the definition of landslides, which states that the landslide movement is a result of gravitational forces. From this it follows that the vectors orientation must always be close to down-slope. Significant differences in the orientation of the recorded vectors thus indicate that the measured shifts are not only directly related to the actual slope movements, but can also be influenced by changes in the inclination of the observation point (geodetic pillar). This theory is generally unknown, even among experts in the field of geodesy, carrying out monitoring measurements of landslides. We therefore assume that the measurement vector is the result of a combination of different movements in terms of Fig. 7.7. In the case of measured vectors the component magnitude is, however, questionable, which is related to the actual manifestations of slope movement. This question can not be answered without direct measurement of changes in the inclination of the monitoring pillar. Therefore, the developed methodology of inclinometric probe (Fig. 7.8) allows us to track down the changes in monitoring pillars inclination with 0,001 sinus angle accuracy. The carried out measurements indicate that the prepared methodology will contribute to bet-

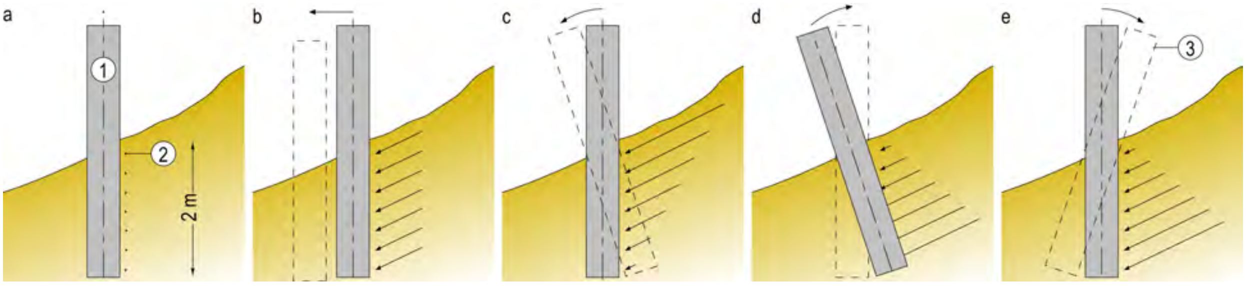


Fig. 7.7 Assumed change in angle of geodetic pillar. a - without change, b - shift in fall-line direction, c - change in angle in fall-line direction, d - change in angle against fall-line direction with ascending vertical change, e - change in angle against fall-line direction with descending vertical change; 1 - geodetic pillar (point), 2 - deformation acting below surface, 3 - observed change in position between measurements periods

ter interpret the results of geodetic measurements, but for the final and comprehensive solution of a proper evaluation of these measurements wide range of issues need to be solved, e.g. the method and depth of stabilization of geodetic points, changes in moisture content of the aeration zone and the impact of these changes on soil consistency changes in the installed survey pillar, etc. Addressing this issue requires a longer period of time, therefore the results will be presented in subsequent stages of the project solution.

Fig. 7.8 Principle of measurements of change in angle of geodetic pillars by inclinometric probe

Ways of results processing and assessment

When processing the results of individual measurements, the focus is on their evaluating over time. This means that for greater transparency and clarity the measured value is primarily expressed through individual steps, which are based on special purpose classifications, thus allowing to assess promptly the significance of the measured variables in terms of the current state of stability in place of the measured object. Basic assessment scales consist of three stages, the first one is characterized by a stable condition, the second one expresses mild to moderate signs of activity, and the third one displays significant activity, leading to slope instability.

The grading scales are set in a way, which enables to assess all the observed parameters. Some of them are based on the results of long-term monitoring of changes in observed indicators. In this way the changes in the groundwater table level depth are evaluated and physical activity measured by precision inclinometer and geodetic survey (these are separate classification systems - Wagner et al., 2012; Ondrejka and Wagner, 2012).

However, there is a group of indicators for which it was necessary to create a purpose-made classification scale, for example, when evaluating the yield of drainage facilities, where the degree of "friendliness" to the stability of the landslide area is not unequivocal. For the evaluation of this parameter there was introduced three-stage classification based on conventionally defined stages of average yield of the observed object during the reporting period. Similarly, even when interpreting the results of activity measurements of the field pulse electromagnetic emissions, a method was examined that accurately reflects the relationship between the measured values and the stability conditions in the facility.

During the solution of PMSGF different ways of assessing indicators have been evolved. This is related to the increasing degree of understanding relationships among the components, affecting the resulting stability of the landslide environment.

7.3. The most significant actual results of the PMSGF solution

During the PMSGF solution every year at all monitoring sites observations of selected factors are evaluated. These results are presented in several ways. They are primarily processed in a report, which is published on the internet http://dionysos.gssr.sk/cmsgf/. In the event of significant facts these are immediately brought to the attention of government authorities and all relevant organizations. With this practice we have managed to provide improved stability condition for several landslide sites (Wagner et al., 2010).

In the following text, the contribution of three separate case studies, which are represented by different types of slope failures, we try to present the complexity and functionality of the monitoring system.

7.3.1. Nižná Myšľa Site

In June 2010, in the Nižná Myšľa Village a landslide has been generated, which is ranked due to the extent of damage among the most devastating slope failures recorded in our area since 1960. Besides extensive material damage equalling to millions €, many families have become homeless. Due to the extremely negative economic-social aspect several stabilization phases have been carried out to ensure the area remediation.

Geomorphological and geological conditions

The landslide area is located in the southern part of the Košice Basin, at the southern tip of Torysa Downs – Varhaňovce Ridge. The Village is situated between two rivers, on the East Olšava and on the West Hornád. The emergency landslide has been activated directly within the cadastre of Nižná Myšľa (Fig. 7.9).

Wider vicinity of the landslide area is formed by Neogene and Quaternary sediments. The Neogene deposits are represented mainly by Stretava Formation, which consists of clays, sands and tuffs (Kaličiak et al., 1996). The Stretava Formation builds up the eastern slopes of the village. The foot of the slope in the southern part of the village is made up of Neogene redeposited tuffs and volcanic epi-

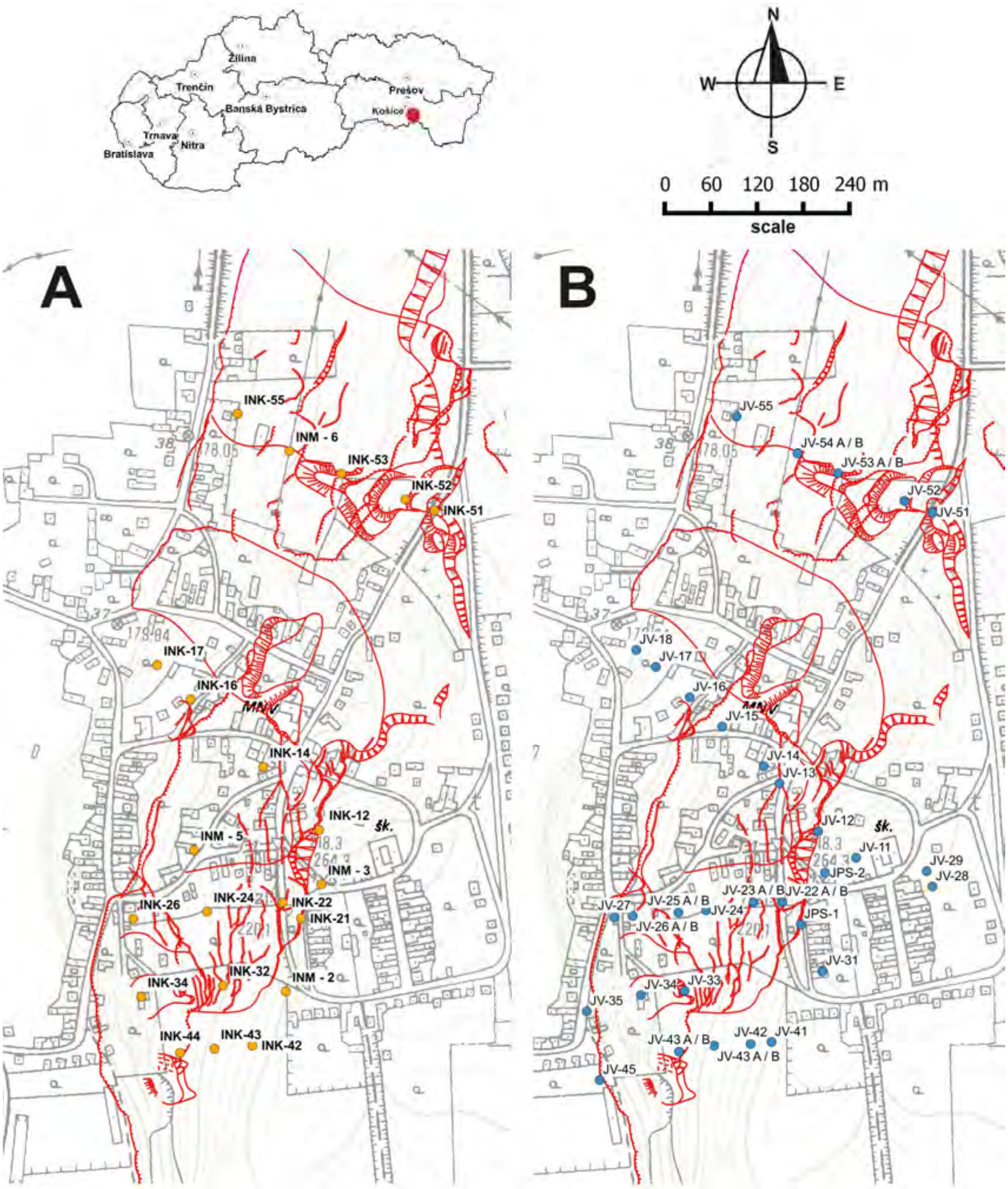


Fig. 7.9 Situation of the landslide area in the Nižná Myšľa Village. A - monitoring network of inclinometric boreholes, B – monitoring network of piezometric boreholes

clastic sandstones. The Quaternary sediments are formed by landslide deluvia, covering the slopes of the Neogene hummock, and fluvial sediments that fill the river valley of Olšava and extensive alluvial floodplain of the Hornád River. From the hydrological point of view the Neogene sediments form a structure in which an alternation of aquifers and aquicludes leads to occurrence of groundwater table level with a confined character. This fact is reflected adversely on the stability conditions of the area.

The potential for slope deformations in the Varhaňovce Ridge is well known to geological public. In the scope of the SGIDŠ research of geological environmental factors, within subproject Engineering Geological Research for Optimal Land Use and Environmental Protection during inventory of slope deformations the landslide in Nižná Myšľa was mapped in 1991 (Fig. 7.10; Modlitba et al., 1991). The author of the map (Spišák in Modlitba et al., 1991) described the site as follows: the area between Varhaňovce, Ortáše and Kecerovské Pekľany is a huge complex made of epiclastic facies of the peripheral zone of the Slanské vrchy Mts. stratovolcano. These solid, rigid rocks overlay soft, plastic clayey sediments of Sarmatian. Gradual depth erosion has exposed a contact between these two different complexes and has created favourable conditions for the subsequent deformation of both epiclastic rocks, as well as the clayey sediments (Modlitba et al., 1988). In 1985 within the landslide area engineering geological exploration of the slope deformation which threatened cemetery in the northern part of the village, was conducted (Ondrejka, 1985).

The above authors identified as an important factor for reactivation of landslide processes the interaction between anomalous precipitations with untreated runoff conditions. By precipitation station of the SHMI Košice - Airport the anomalous atmospheric precipitations on the territory Nižná Myšľa were recurrent. The anomaly of 2010 (200 up to 300% of long-term normal) resulted in reactivation of the largest landslide in Nižná Myšľa so far. Considerable share in the reactivation have had also improper anthropogenic interventions in the form of various construction impacts, and leaky septic tanks and cesspits.

The first signs of reactivation of landslides were reported from 1 to 4 June 2010. Finally, they led to the massive failures in housing, water, gas, power lines, roads and sanitation (29 houses had to be demolished, Fig. 7.11).

Immediately after the landslide generation a Crisis Staff was convened and subsequently indicative engineering geological survey was realized in which they initial immediate remedial actions were made.

Monitoring measurements are focused in observation of movement by method of precision inclinometer and groundwater regime (measurements of the groundwater table level depth and yield of drainage wells). Systematic monitoring of the site started in 2011. Initially, attention was paid to monitoring of kinematic activity (inclinometry) in the most critical parts of the slide area. With enlarged number of monitoring objects, which were built during the remediation of the landslide area (2012), the volume of information on the most significant landslide-forming factor - the depth of the groundwater level - increased. Currently, the site monitoring network consists of 21 inclinometric and 56 piezometric wells.

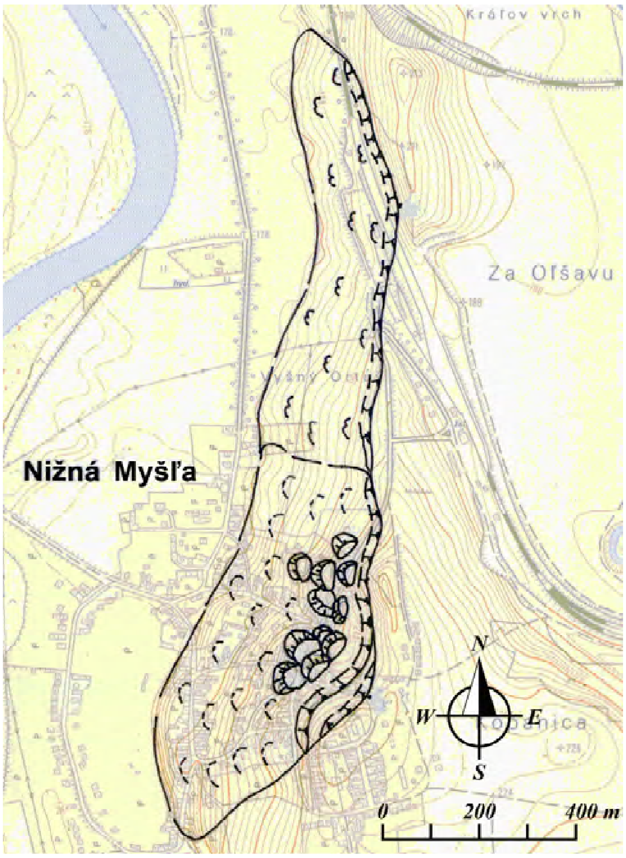


Fig. 7.10 Detail of the map sheet ZM 38-31-06 (Spišák in Modlitba et al., 1991)

Fig. 7.11 Village road destroyed by landslide

The inclinometer measurements are carried out regularly three times a year. The groundwater regime is monitored with a weekly frequency. In addition to regular monitoring activities automatic level gauges are installed in the most vulnerable areas, which provide a continuous record of changes in the groundwater table level depth. At

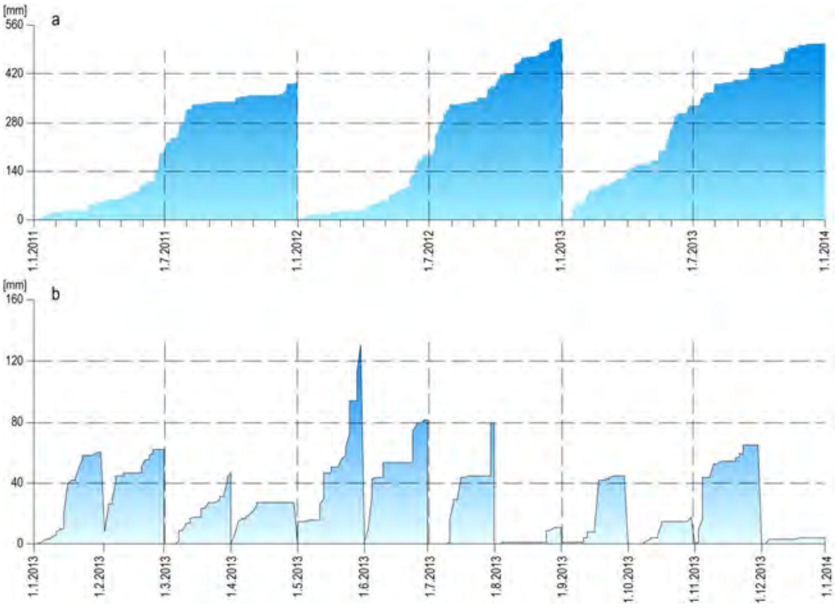


Fig. 7.12 Precipitation totals of the SHMI station Čaňa. a - cumulative yearly precipitation totals in the years 2011 to 2013, b - cumulative monthly precipitation totals in the year 2013

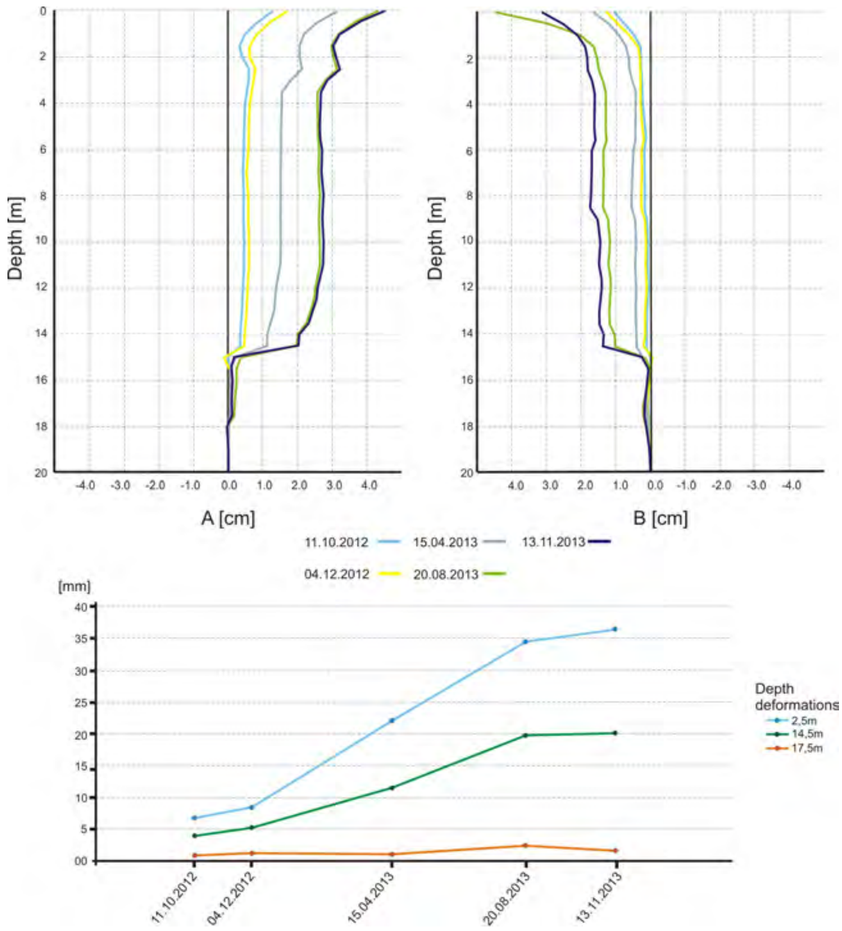


Fig. 7.13 Course of deformation in inclinometric borehole

the same time, the discharge of all constructed drainage wells is monitored.

Climatic and regime factors. Currently, after approximately three-year period of monitoring of landslide-forming factors, it can be stated that the landslide area is extremely sensitive to changes in precipitation totals.

Fig. 7.12a shows cumulative rainfall totals recorded between 2011 and 2013 SHMI station, which is located in the neighbouring Čaňa cadastral territory (southwest of the village Nižná Myšľa). From the comparison of the development of cumulative precipitation during the winter and spring months (for each year) follows, that in 2013 the measured rainfall totals increased (Fig. 7.12b).

In the synergic effect of the melting snow cover significantly increased the groundwater table level. In several parts of the slide area the groundwater level reached the terrain surface.

Inclinometer measurements. Adverse stability conditions in 2013 were also reflected in the results of kinematic activity monitored by precision inclinometer. During the first two stages of measurements (April and August) there were recorded on the shear plane extremely high levels of deformation. For example, in the territory above the Elementary School (well INM-6 - Fig. 7.13), but also in the southern part of the Varhedňá ul. Street (borehole INK-32) there were measured deformations of 10 mm. Both cases represent the areas without implemented remedial measures. In the borehole INM-6 (Fig. 7.13) there can be observed deformation of inclinometer casing in three different depth horizons (slip planes). The most striking of them is located at a depth of 14.5 meters below the surface. In 2012 there were measured on the slip surface deformation vectors in the range of 0.85 to 1.65 mm. These relatively low values are a result of favourable climatic conditions in 2011 and the first half of 2012. In this period similar stability development was observed also in other parts of the slide area; the only exceptions were wells near Obchodná ul. Street (in borehole INM-2), Hlboká ul. Street (INM-5) and virtually the entire southern part of the slide area.

7.3.2. Results of long-term monitoring at the site Banská Štiavnica

Geomorphological and geological conditions

The monitored site is located in the two-sided road cut of the state road No. 524, in a communication bypass of Banská Štiavnica towards Štiavnické Bane. The territory belongs to the Štiavnické vrchy Mts. According to the engineering geological division of the Western Carpathians (Matula, Pašek, 1986) the territory is included in the region of Neovolcanites, the Areas of Volcanic Highlands. The geological setting of the site in the wider area is quite complicated due to contact of more resistant varieties of pyroxenic andesite with less durable hornblende-biotite andesite. The andesites are strongly faulted and in conjunction with the ore mineralization they are affected by various degrees of hydrothermal alteration, which caused significant disruption of the structure of rocks, minerals alterations, distortion of the original bonds in the rock massif. The monitored roadcut of a length of about 80 m and height up to 8 m exposes a typical rockmassif; other cuts are affected by diverse disintegration of rocks from the decomposition and disintegration of structures on the blocks up to crumbling of rock mass into fragments and scree. The most intense manifestations of disintegration are bound to hydrothermal and tectonic weakening of the massif.

The monitoring takes place in the eastern part of the roadcut, consisting of massive clinopyroxene-andesite porphyry. In the western side of the slit, supported by protective wall, hydrothermally and tectonically affected argillitized andesite is exposed. During the construction of the protective wall the rock mass was seemingly solid, after its exposure it began to degrade progressively. Primary loosening of the rock mass is connected with its massive tectonic-erosion restrain during the development of the morphological forms (valleys, etc.). The anthropogenic interference with blast-works caused further cracks opening leading to penetration of exogenous factors and uneven break up of internal bonds in the massif, which was associated with changes in the lithological composition of the rocks and manifested in two ways:

- Loosening of rigid massif and gravitational release of blocks and fragments of different dimensions;
- Complete disintegration of rocks into zones of soil character along the intense tectonic and hydrothermal alteration horizons.
- The massif's stability is reduced by the effect of groundwater:
- Effects of alternating cycles of freezing and melting, thereby increasing the volume of the massif in near-surface zone;
- Leaching of crevasse-fill binder,
- Wedge effect of frozen water saturated surface layer in the forehead of slopes in winter.

The rock mass is highly dissected by irregular network of discontinuities. The collection of structural data enabled to analyze grouping of discontinuities into systems (Fig. 7.14). In the lower part of the massif the orientation of discontinuities was determined by direct field measurements and the inaccessible parts of the massif were scanned by ground photogrammetry.

The primary separation of the massif by fissures are caused by cooling of volcanic bodies which are continuous and their orientation is 20°-40°/30°-50°. They form subhorizontal benches 30 to 80 cm thick.

Regional tectonic disposition copies three tectonic discontinuities systems:

- System of persistent discontinuities with similar orientation as the wall of the roadcut 100°-140°/70°-89° is a manifestation of a regional fault systems NNE-SSW;
- A system of relatively flat persistent discontinuities that are approximately perpendicular to the front cracks and parallel to the wall of the roadcut; the aspect is 170°-220°/35°-60° and represents a regional system WNW-ESE;
- Widely dispersed system oriented 140°-170°/60°-80° and the antislope one 320°-350°/60°- 85° which follows a regional system NE-SW.

The slope of the discontinuities is subvertical, locally the joints of a smaller angle are also present. To these zones of the massif's weakening the processes of erosion and release, blocks and debris are bound.

The next system of discontinuities 240°-300°/30°-50°, which is not affiliated to the regional tectonic systems, is relatively flat, oriented diagonally to the roadcut wall. Within the massif other unsystematically arranged tectonic fissures are frequent, along with weathering and stress-release cracks, typical to volcanic rock.

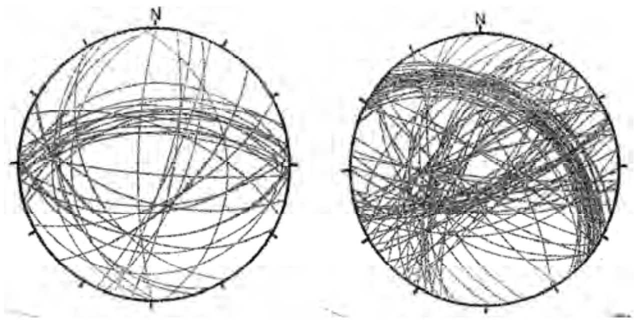


Fig. 7.14 Discontinuity diagram of spatial orientation of discontinuities from field measurements (left) and by ground-based photogrammetry (right)

Methods of monitoring

Since 2004 the monitoring is based on two methods – photogrammetry and dilatometry.

Long-term monitoring by terrestrial photogrammetry methods assumes each epoch measurement in identical coordinate system - a network of control points. The network consists of 5 points stabilized by nails installed in the curb of the road where there is no presumption of horizontal and vertical changes. In every epoch position stability of these points is verified, using conformity transformation. The residues on points after the transformation document eventual change in the position of these points and, on the contrary, their stability. In the long-term the residues are ranging max. up to 2 mm, which corresponds to the accuracy of the measurement and does not show a statistically significant change. Height stability verified by trigonometric measuring does not manifest any significant changes.

Spot measurements (observation of the upper edge of the roadcut). The observed points form a reflective film stabilized on the posts of the fence above the upper edge of the incision. The spatial accuracy of these points is better than 3 mm. All the geodetic measurements are carried out by universal measuring station TS30 with the measurement accuracy of lengths 1 mm + 0.5 ppm and angles 1[cc]. The Tab. 7.3 documents positional (tilt and shift) and the height activity of the fence posts at points 3006, 3007 and 3071 (Fig. 7.15), near vertical profiles No.5 and 6. Other points have not shown statistically significant shifts.

Tab. 7.3 Shifts of control points installed on fence at the upper edge of the roadcut

	Difference March 2011 - September 2011			Difference September 2011 - September 2013		
	dX [mm]	dY [mm]	dZ [mm]	dX [mm]	dY [mm]	dZ [mm]
3031	-1,8	-2,1	-1,1	5,1	0,7	-2,8
3041	-1,4	-1,6	-0,7	-	-	-
3006	**-61,6**	**-11,8**	-2,7	-	-	-
3007	**-11,2**	2,9	0,0	**-5,1**	**19,2**	**-5,3**
3071	**-6,1**	2,1	-0,9	3,1	**10,5**	**-5,2**
3008	-0,4	-0,4	-0,3	2,6	-1,8	-1,5
3081	-1,5	0,2	-0,6	0,9	-0,2	-1,8
3009	-2,8	3,0	-1,4	**-3,7**	1,0	-2,7
3091	-1,5	1,8	-0,2	-1,1	0,6	-0,1

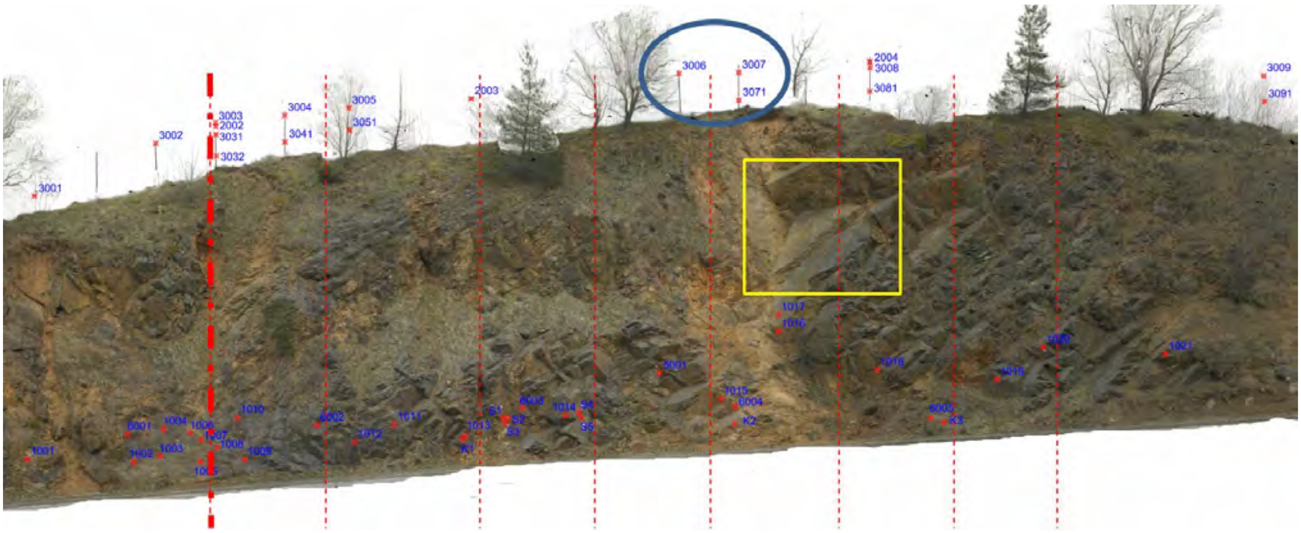


Fig. 7.15 Arrangement of control points and points on fence (atop). Yellow frame indicates the detail on the Fig. 7.16

Area monitoring. In 2011 and 2013 in the roadcut photogrammetric method of image scanning was applied, because previous experiments indicated high spatial accuracy of the rock surface $m_{XYZ} < \pm 5$ mm.

To transformation to a coordinate reference system served control points placed in the roadcut. These were determined by the geodetic survey with space accuracy of 2-3 mm using universal measuring station. The scanning was made from images with a resolution of 1 pixel ~ 3 mm. Like the laser scanning, the image scanning provides a detailed areal recording of a surface with high density and precision. This makes it possible to observe a roadcut throughout all profiles. A problem to tackle is vegetation cover (grass, shrubs, trees). The scanning was carried by mid-format LEAF Aptus Mamyia digital camera with digital back Leaf Aptus II-7 and PhaseOne lens with a focal length of 45 mm. The camera was pre-calibrated at the Testing and calibration polygon of the Department of Geodetic Surveying, FCE STU Bratislava and consequent full calibration was carried out during the image processing.

The result of the scan is a cloud of points or a network of irregular triangles - TIN model (Fig. 7.16).

The areal monitoring enables a comprehensive documentation of the roadcut by comparing (different) epochs of imaging, either in individual axes of the coordinate system, planes or by 3D comparison. The result may be a colour difference model, where the colour gradation reflects the size difference (Fig. 7.17). Such a differential model provides immediate information about the major changes throughout the roadcut. Specific approach is needed in evaluating the locations covered by vegetation, shaded areas and on the edges and any significant chan-

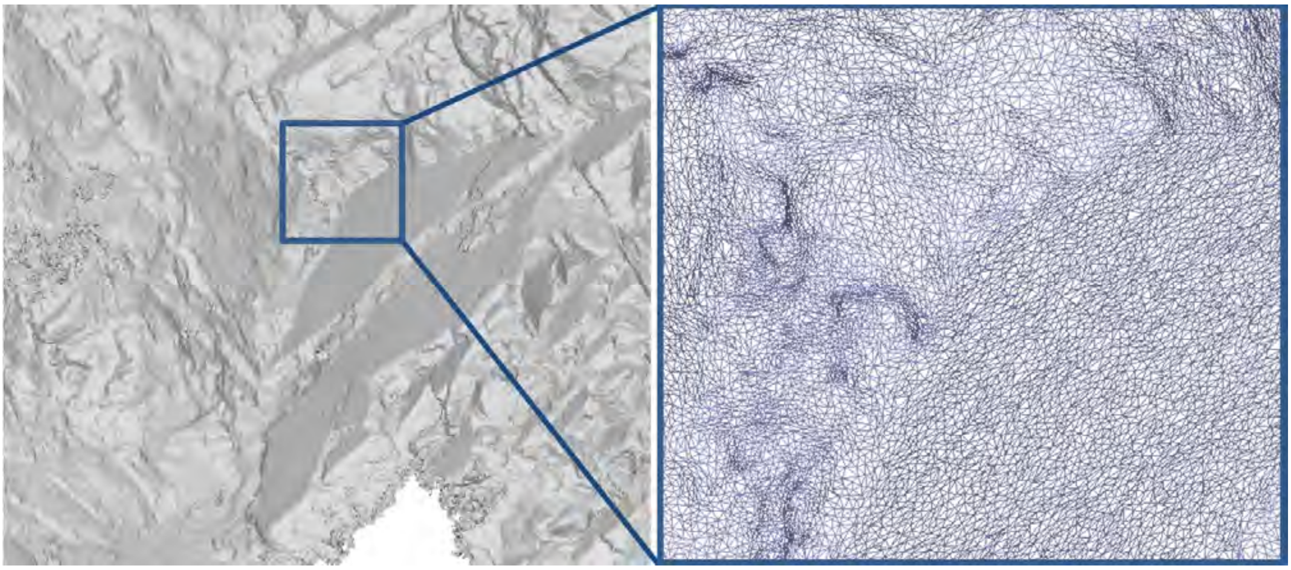


Fig. 7.16 Cloud of points (left) and detail of TIN model (right)

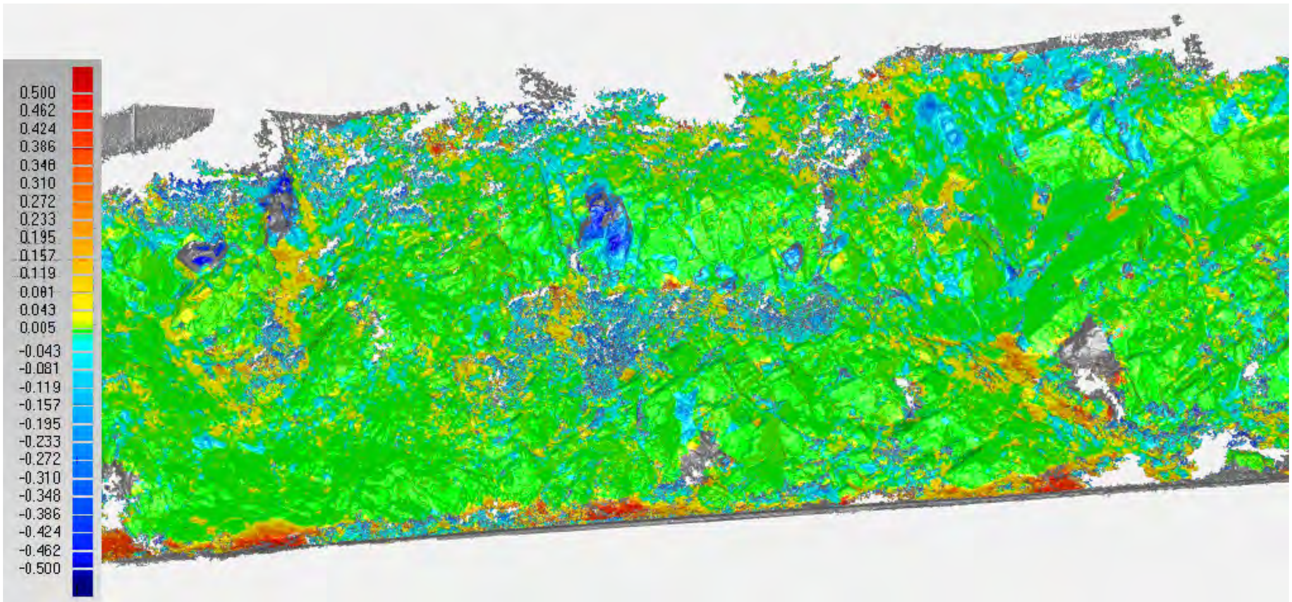


Fig. 7.17. 3D difference model of the period 2011-2013. Green colour highlights the difference of ± 3mm, in blue the loss of material up to –0,40 m, in red increment of material (accumulation of scree, fallen blocks, vegetation), in grey - difference model was not calculated because of missing data

ges have to be visually verified on the original picture or detailed orthophotomosaic.

Profile measurements. Historically oldest method applied was analogue, then digital stereophotogrammetric profiles measurement (Fig. 7.18), which has been applied at the site since 2004. Currently, the profiles are not measured directly, but are extracted from planes cuts of the TIN model (Fig. 7.16) created by image or laser scanning. Within the profile various types of terrain alternate (rock, rubble, loam and grass), whereas these types of roadcut surface affect the quality of the generated sur- faces. The most accurate surface is generated from images of bare rock surface. Another factor that has a significant influence on the final accuracy is the slope of the terrain. In the vertical profile uncertainty grows in the direction of observation (X-axis) on surfaces which diverge horizontally or vertically off the frame plane. Small uncertainty in the profile stationing can cause relatively large uncertainty in the depth (X-axis). This effect can be significantly manifested provided a diversion is greater than 50°. Therefore, it is vital to take into account the slope of the terrain against the time baseline in the process of the stability determining (change vs precision). The accuracy of the profiles in the reference coordinate system X, Y, Z depends on:

- The size of a pixel on the object (GSD - ground sampling distance = 4 mm);
- Baseline ratio (0.2);
- The accuracy of the reference coordinates of control points (1 mm);
- Method of control points definition (perspective transformation);
- Surface texture (satisfactory texture);

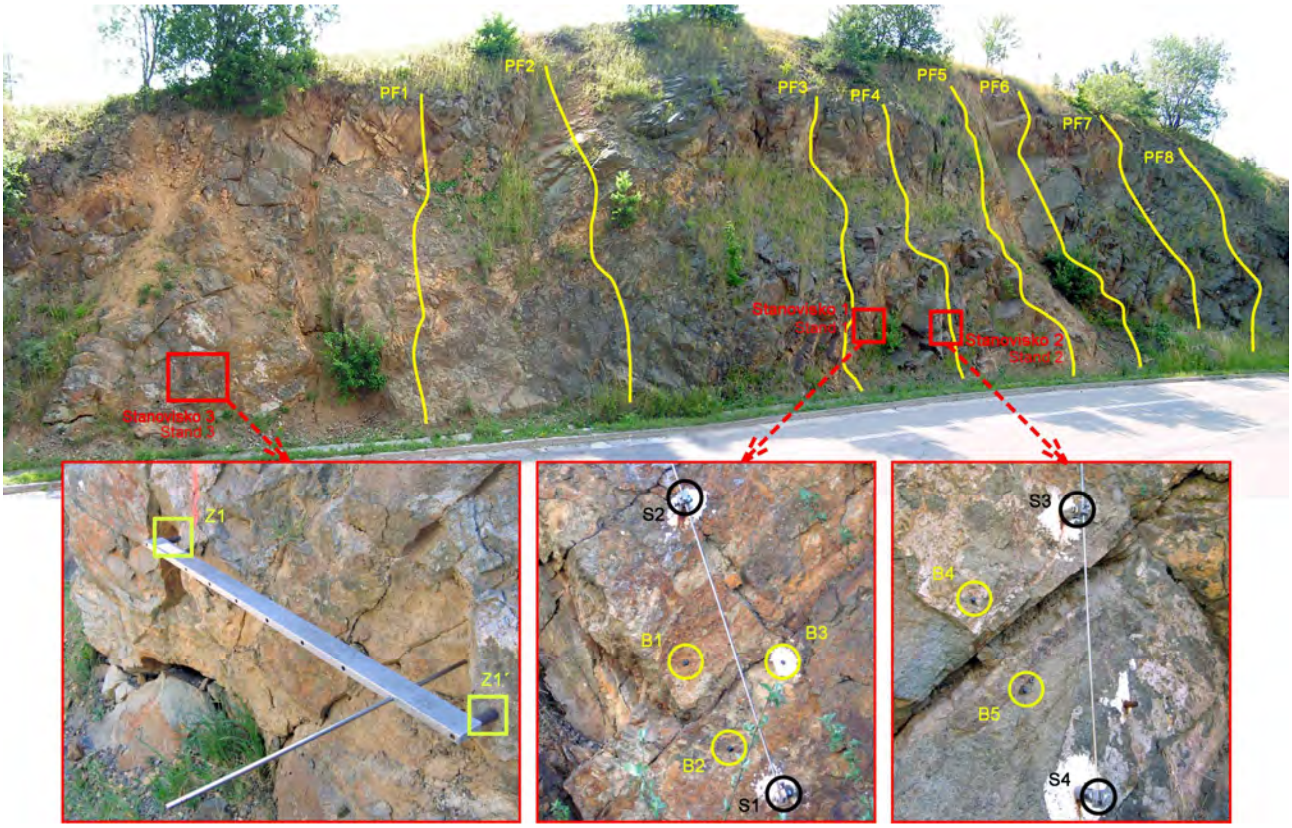


Fig. 7.18 Arrangement of monitored profiles and points in the roadcut near Banská Štiavnica. PF1 to PF8 - profiles of stereophotogrammetric measurements, points B1 to B5 for measurements by dilatometer Somet, S1 to S4 for dilatometric measurements by Vernier gauge, Z1 - Z1´ pins for mounting of gauge for micromorphologic changes measurements.

- The accuracy of the surface reconstruction (step 1 pixel, sub-pixel interpolation);
- Snapshot quality material (using digital wall).

For the above data we obtain the spatial accuracy of the reconstructed m_{XYZ} pure rock surface greater than 5 mm. The disadvantage of the profile measurement is that it does not describe the whole surface of the roadcut and, consequently, the changes outside of these profiles. Comparing the profiles of the different epochs of monitoring minor changes were observed in the bottom of the profiles 3, 4, 7, and 8. The blocks loosening from the top of the slope indicates a change in the profiles No. 6 and 5. The largest overall configuration changes are observed on the slope profile no.1. The instability of the first roadcut of this profile is observed for a long period of time (Figs. 7.18 and 7.19) and also a method of areal monitoring has identified loss of the material in this part of the slope (Fig. 7.17 - blue areas on the left side of the roadcut).

Dilatometric measurements have been carried out on two spots, installed in the southern part of the slope (Fig. 7.18). The blocks, separated by a distinct discontinuity, are equipped with fixed measuring points for dilatometric observations of loosened blocks movement. The observed parameter is the distance between points installed in the massif – the points placed in the stable part of the roadcut and loose rock block separated by persistent discontinuity. At the first stand margins are monitored between the points separated by a discontinuity with the aspect 326°/44° (the point B1 is on the same block and the points B2 and B3 on the second one). On the second stand the distance between the points B4 and B5 is measured, placed on the blocks, separated by a discontinuity with the aspect 350°/50°. The measurements are carried by portable rod-type SOMET device. Despite the quality design of the device made of invar material the measurements are very sensitive to the conditions of data collection. The obtained values of the distance of two points are therefore subsequently corrected at various stages of monitoring by adjustment to the measured distance between two stable points located on a single rock formation with an intact structure, which is regarded as fixed. Since the beginning of monitoring on both stands there has been observed the trend of slow disintegration of rock blocks.

The development of changes in the distance among the points measured by the dilatometer Somet since 2001 is shown in Fig. 7.20. In 2013, the disintegration of the monitored block at the stand 1 has been slightly intensified, with observed shift in the annual cycle of monitoring (since 2012) of 0.23 mm between the points B1-B2. On another block (stand 2, points B4-B5) the displacement of 0.26 mm was observed during the annual cycle of monitoring. The observed increase in loosening blocks B1-B2 is intensifying since 2007 and since 2010 between the points B4-B5. In the period from the beginning of monitoring in 2001 till November 2013 the increase of the relative distances between separate blocks reached 1.505 mm at the stand (points B1-B2) and 1.10 mm at the stand 2 (points B4-B5).

On the same rock blocks as a benchmark points for Somet device measuring points S1 to S4 are installed for measuring shifts between two separate blocks by Vernier depth gauge (the arrangement of the measurement is in Fig. 7.18). Trends in the values measured by the gauge confirm slow loosening of the rock mass.

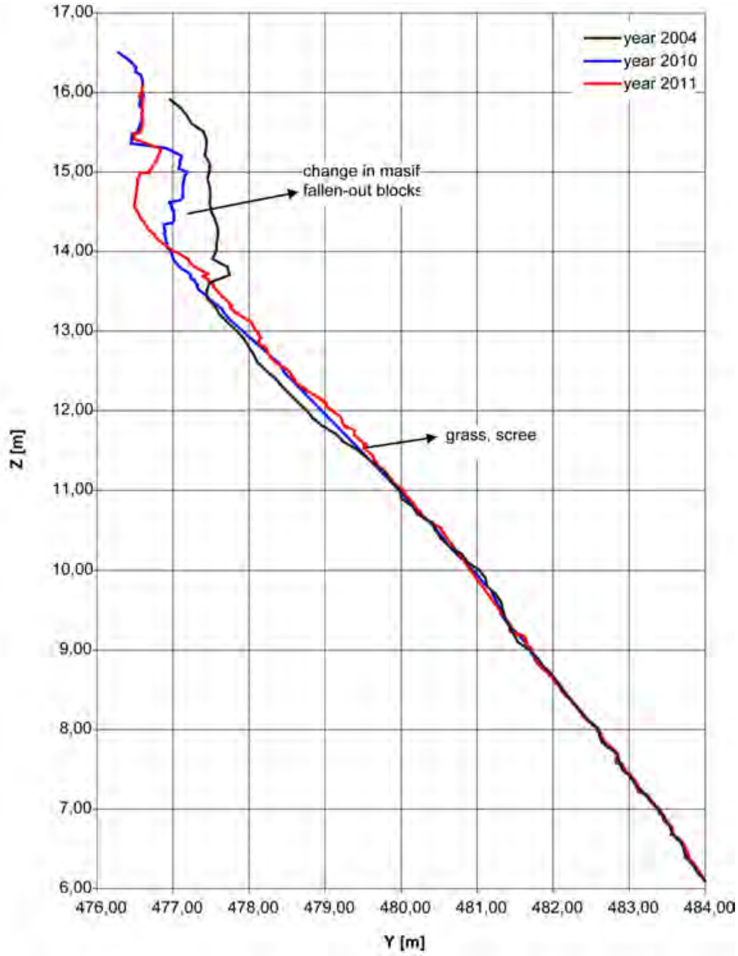


Fig. 7.19 Profile in the stationing –17,5m from the years 2004, 2010 and 2011

Until 2008, the measurements of micromorphological changes in the surface of the rock massif had been carried out, focused in the weathering process in the slope of the roadcut (Fig. 7.18). The profile was abandoned after denudation of the fixed rods.

Long-term monitoring of the rock massif in the roadcut has confirmed the activity especially in the upper part and the top edge, as illustrated by the instability of the fence posts and constant rockfall of smaller blocks from the top. On the contrary, at the slope heel the fallen rock and debris are accumulated.

7.3.3. Results of the long-term monitoring at the site Košický Klečenov

The volcanic mountain ranges belong to the areas with the highest incidence of slope deformations in Slovakia. The most numerous and the most widespread are landslides of various types, less frequent are slope failures of a character of block fields and disintegrating block ridges. In the Slanské vrchy Mts. the block slope failures are concentrated mainly on the edges of the stratovolcanoes, rarely in their central parts (Petro et al., 1993). Due to the action of gravity, weathering, erosion, neotectonic movements and seismic quakes, the solid volcanic rocks overlying plastic (Paleogene and Neogene) sediments, or hydrothermally altered rocks, are disrupted. The site Košický Klečenov was selected to monitor the creep movements within the state research project ZP-547-008-03 Research in Geological Environmental Factors (1990-1992). In late 1990ies a dilatometer of the type TM-71 was installed within a crevasse between two blocks on the western edge of the Strechový vrch andesite stratovolcano (Kaličiak et al., 1991). The second device was installed into the crack at the edge of intact massif within the project PMSGF in 1995.

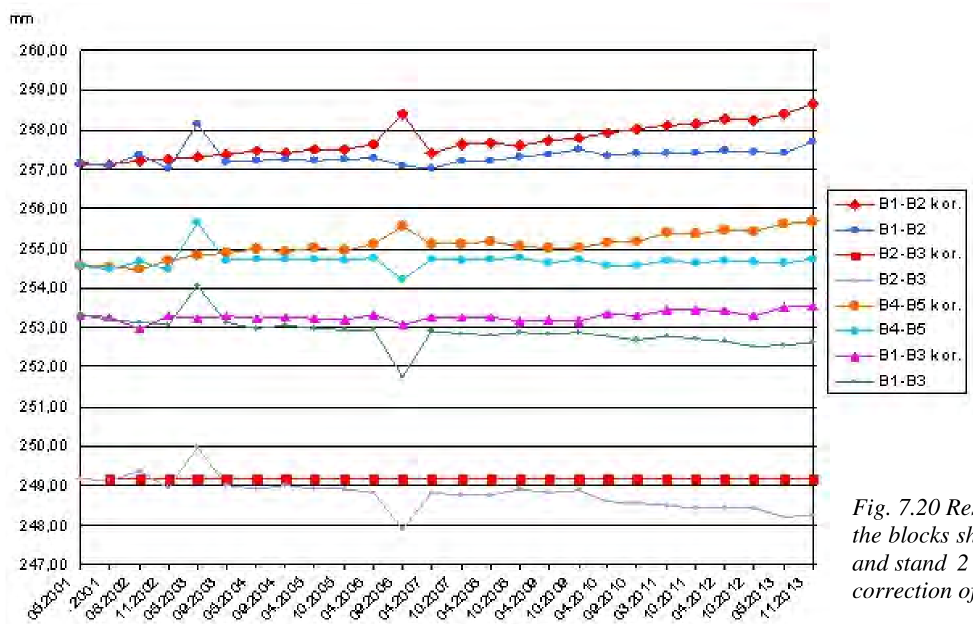


Fig. 7.20 Results of long-term measurements of the blocks shift at the stand 1 (points B1 to B3) and stand 2 (points B4 and B5), graphs with correction of measured values (with affix kor.)

Geomorphological and geological setting

The site is located on the western edge of the Slanské vrchy Mts. (Fig. 7.21), about 2 km north of the former spa Borda. The wider vicinity belongs to mildly modelled Podslanská Upland (part of the Košice Basin), which passes eastward into volcanic massif characterized by high energy relief and steep slopes (up to 24°). The area is drained by smaller streams surging in Slanské vrchy Mts. and mouthing into Svinický potok Brook, the lefttributary of the Olšava River. The volcanic mountains margins are typical of frequent occurrence of slope failures of various types. The block ridges gradually pass into block fields or directly into landslides. Their occurrence was studied in detail by Malgot (1969, 1977). The monitored block failure along with block fields is a component of one of the largest slope deformations (10.19 km^2) not only in the Slanské vrchy Mts. (Fig. 7.22), but also in Slovakia (Petro, in Šimeková et al., 2006).

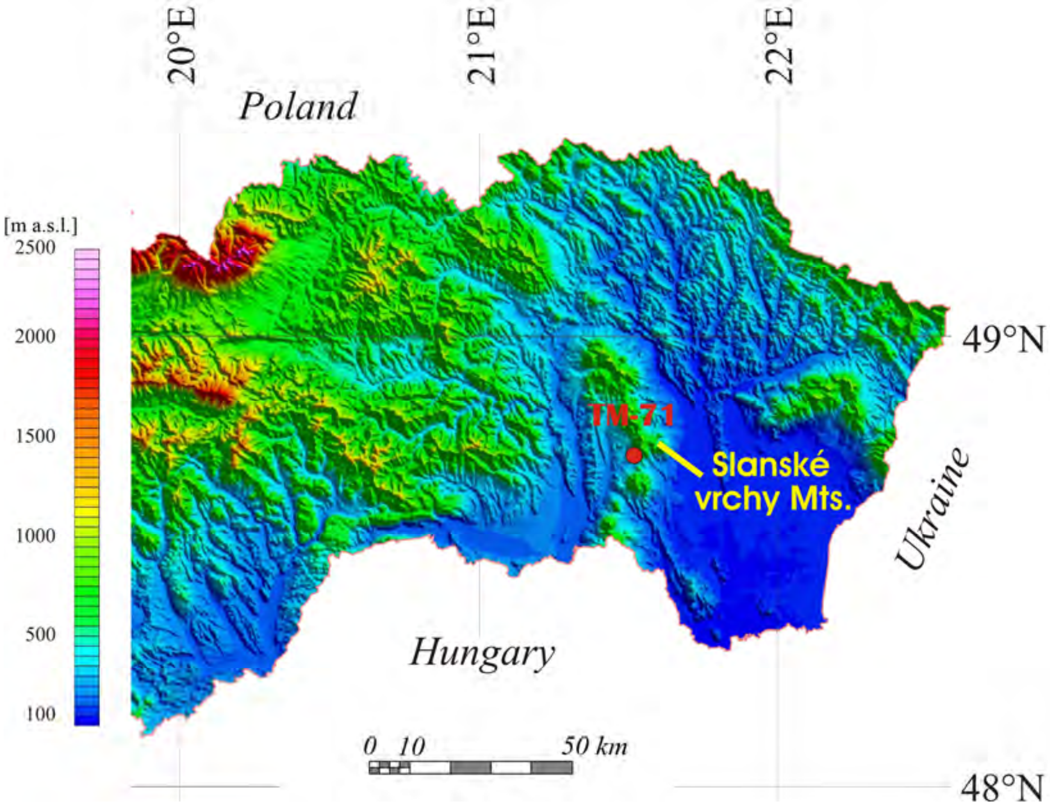
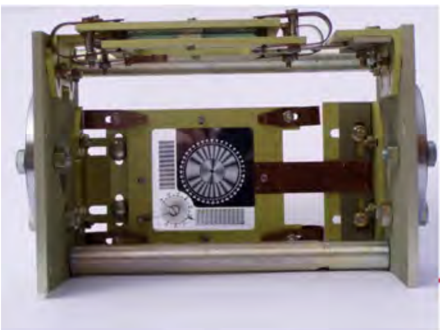


Fig. 7.21 DMR of the Eastern Slovakia with indication of the Slanské vrchy Mts. and Košický Klečenov site



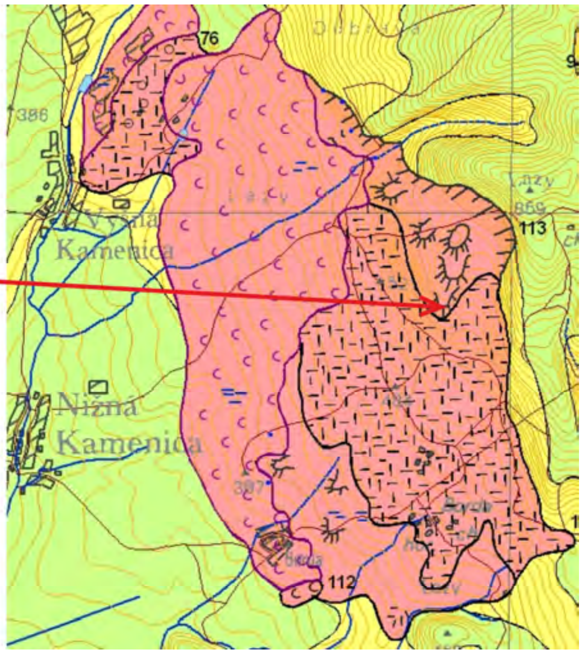


Fig. 7.22 Mechanical-optical dilatometer TM-71 and its installation within a part of extensive slope deformation made of block ridges, block field and potential landslide (Petro in Šimeková et al., 2006)

In the geological setting of the site effusive rocks are involved, represented by lava flows, the thickness of which reaches tens of meters. In terms of their lithology they are andesites and breccias (Kaličiak et al., 1991). These solid rocks overlay the massive complex of more plastic volcaniclastic rocks, among which dominate pyroclastic rocks, or redeposited tuffs and pyroclastics (Fig. 7.23). Under these volcanic rocks, or in their forefront, Neogene calcareous clays with interlayers of volcanic material are present, which are affiliated to the Kochanovce Formation (Karoli in Kaličak et al., 1991). The sliding slopes below the block ridges are built of clastic fragmented-bouldery sediments (debris), with local occurrence of disintegrating and weathered andesite blocks (block field).

The edge of the andesite lava flow is morphologically very conspicuous (height difference of 100 meters) and is the result of tectonic activity. It is crossed by fault of NSdirection at the western margin of the Slanské vrchy Mts. Its recent activity was for the first time reported to by Janočko (1989). Moreover, the main head scarp of the extensive potential landslide is directly linked to the fault (Fig. 7.23).

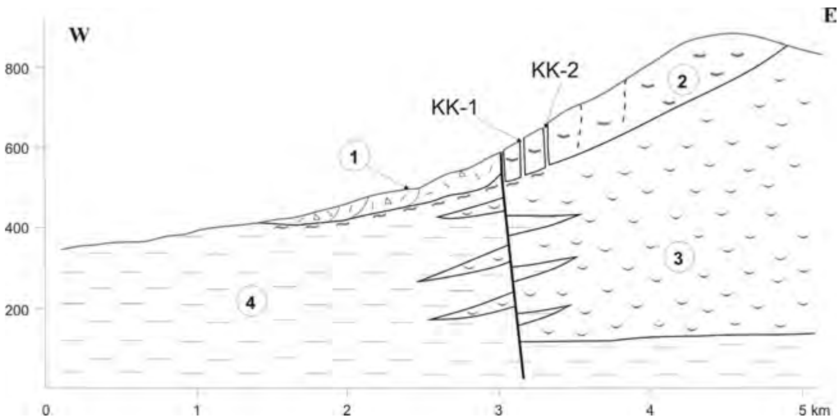


Fig. 7.23 Geological cross-section through the western margin of the stratovolcano Strechový vrch and monitored slope deformation at Košický Klečenov. 1 - potential landslide with block field, in the top part transition into block ridge; 2 - lava flow made of andesites and breccias; 3 – complex of volcaniclastic rocks - pyroclastics and redeposited pyroclastics and tuffs; 4 – Neogene calcareous clays of the Kochanovce Fm.; KK-1 and KK-2 – dilatometers TM-71 installed in the open crevasses in 1990 and 1995

Monitoring

For creep movements measuring, or shifts in the rock environment, there are a number of monitoring devices or techniques. One of the practical devices is the mechanical-optical dilatometer TM-71 (Fig. 7.22) constructed by Košťák B. (1969, 1991), which was granted two Czechoslovak patents (131631, 246454). The device is based on the principle of moiré, i.e. optical interference resulting from the mechanical motion. The interference occurs between two glass plates coated on adjacent sides of a thin chrome layer of circular shape. As a result of the mutual shift of platelets the interference fringes are generated and the displacement of the centres of the plates. From the strips and shape pattern it can be calculated the size and direction of the displacement. The shift recording is continuous. The shifts are expressed in three mutually perpendicular planes - x (crack opening/closing), y (shear movement along cracks) and (sink/heave of one of the blocks). On two adjacent sides of the inner plates are chrome layers of rectangular shape used to record the rotational motion of monitored blocks. The structure of the device is designed in such a way that a pair of plates is arranged in two perpendicular planes, so it is possible to measure relative movements and rotation of blocks, i.e. their spatial movement. The shifts are defined along the axes or as the resulting 3D vectors.

The dilatometer allows measurement of displacements of rock blocks along cracks wide about 0.5 to 2.0 m with an accuracy of 0.01 mm and rotation with an accuracy of 0.01 gr. (π/200). The dilatometer is installed in the cracks between two thick-walled steel brackets clamped to opposite walls. The variant with bent brackets allows measurement in narrow cracks. The dilatometer amenities include its durability (long life), weather resistance (moisture, temperature changes, stray currents, corrosion), easy to maintain and relatively uncomplicated method of evaluation of the measured data and interpretation of results using tailor-made software. The disadvantages include the vulnerability of the device to vandalism and to some extent, its price.

The instrument application began in the late sixties and was aimed at monitoring of slow movements of landslides (Košťák, 1969). In the following years, the landslides measurements was extended to multiple sites in Czechoslovakia (e.g. Košťák, Rybář, 1978; Košťák, 1991), but also across Europe (e.g. Fussgänger, 1985; Petro et al., 1999) and out of Europe (e.g. Košťák, Cruden, 1990). In addition to monitoring of landslide movements the TM-71 dilatometers are used to observe violations of historic buildings and their subsoil (e.g. Fussgänger, 1985; Košťák, Sikora, 2000; Vlčko, Petro, 2002; Vlčko, 2004) and to measure micro-shifts on active tectonic faults (e.g. Avramova-Tacheva, 1988; Košťák, 1998; Petro et al., 2004; Košťák et al., 2007; Stemberk et al., 2010; Košťák et al., 2011).

The site monitoring began on December 4, 1990, when the dilatometer TM-71 was installed within open crack between two large rock blocks (lower and upper) on the edge of the andesite lava flow (Figs. 7.23, 7.24). The device was labelled KK-1. On July 25, 1995 the second dilatometer of the same type (KK-2) was placed in the crevasse between the upper edge of the block and intact lava flow (Figs. 7.23, 7.25). The long-term objective of both devices was to monitor creeping motion of rock blocks atop more plastic basement. The prerequisite for creep was based on the detailed knowledge of geological setting (Kaličiak et al., 1991) and regional engineering geological works (Spišák et al., 1987; Petro et al., 1993).

Monitoring results and their interpretation

The dilatometers' reading is done visually with a frequency of 1-7 times per year. By the end of 2013 the number of readings with KK-1, which measures relative displacement between two blocks (the lower and the upper) on the edge of the lava flow (Figs. 7.23, 7.24), has reached 99. Since 1995 on the dilatometer KK-2 (Figs. 7.23, 7.25) the total number of measurements at the end of 2013 has attained 77. The results of the measurements processing are graphs of displacement and rotation of individual blocks. Spatial displacement was evaluated with respect to relative position of the two dilatometers against monitored cracks. Eight, respectively three-year measurements showed a trend of blocks movement in all three axes (Petro et al., 1998; Figs. 7.26, 7.27). The most significant was the movement in the z direction (downward), which exceeded 3 mm (KK-1), and 1 mm (KK-2). Shear movement along the vertical axis and the opening of the crack (movement along the x axis) reached about 1 mm (KK-1). Measurements of rotations of both blocks did not show significant movements. Interesting is the correlation between bound in the rotation record of the dilatometer KK-1 in the XZ plane in the second half of 1999 (Fig. 7.27b) and strong earthquake in the Turkish city of Izmit (M = 7.8) registered on 17/8/1999 (Košťák et al., 2007). The link between this earthquake and the fluctuations in the records of rotations was found in dilatometer TM-71 in several European locations. In 2000, because of the obvious link between the motions of the monitored blocks with active fault failure at the edge of the Slanské vrchy Mts., the site Košický Klečenov was included among Slovak tectonic sites within the project COST 625 "3D monitoring of active tectonic structures". The measurements in 2005 were evaluated in the final report for the Slovak Republic (Petro et al., 2005). Since that year all the measured data have been processed using new software MSDilat (Stercz, 2004). By the end of 2013 the measurement results showed a long-term trend in both blocks. The most significant movements are of the sink character (movement in the z direction), which for 23 years has reached 10.93 mm (KK-1), and for 18 years 9.28 mm (KK-2). From the average rate of sink of 0.48 mm and 0.52 mm per year it is clear, that the upper block is sinking faster than the bottom one (Figs. 7.26, 7.27). The shearing motion along the cracks (in the y direction) reached a total of 4.07 mm, and 2.99 mm, respectively. Even in this case, the upper block moves faster than the bottom one. Different results have been found in the direction of blocks displacement along the x axis. While the crack opening

Fig. 7.24 Dilatometer TM-71 (KK-1) installed in the open crack between two (bottom and top) blocks at the western margin of the lava flow of the stratovolcano Strechový vrch

Fig. 7.25 Dilatometer TM-71 (KK-2) installed in the open crack between upper block and intact massif of the lava flow at the western margin of the stratovolcano Strechový vrch

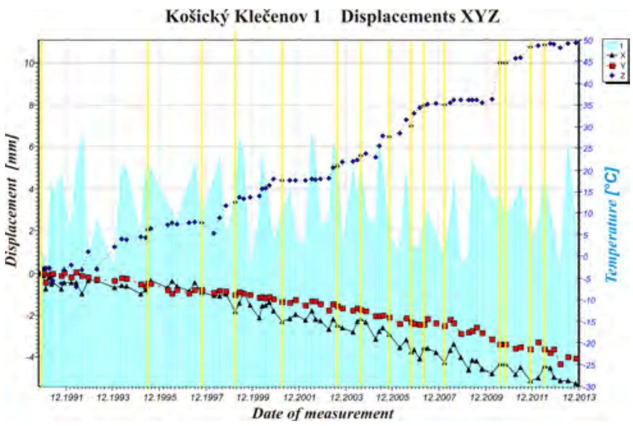


Fig. 7.26a Diagram of shifts along axes x, y, z recorded by dilatometer KK-1 installed in the open crack between bottom and top blocks at the site Košický Klečenov for the period 1990- 2013

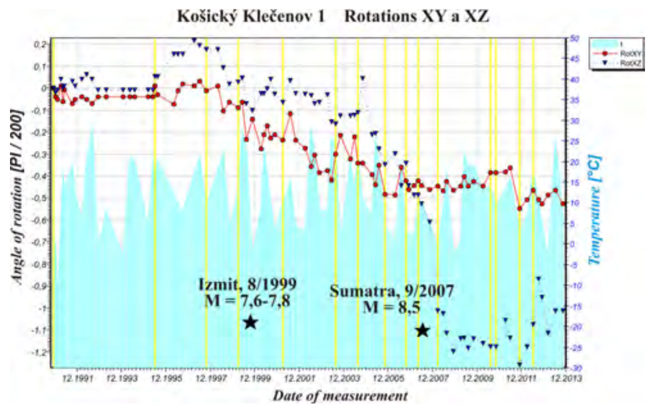


Fig. 7.26b Diagram of rotations in the planes XZ and XY recorded by dilatometer KK-1 installed in the open crack between bottom and top blocks at the site Košický Klečenov for the period 1990-2013

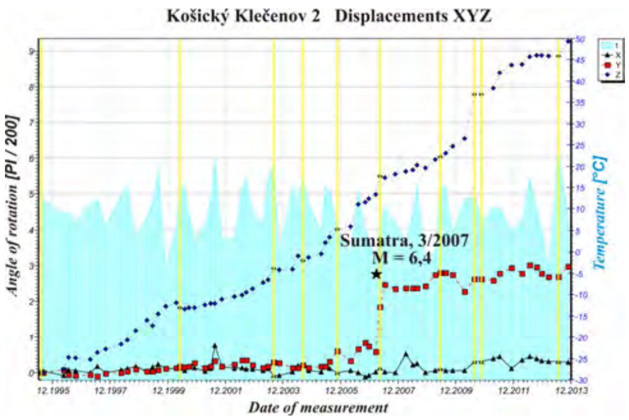


Fig. 7.27a Diagram of shifts along axes x, y, z recorded by dilatometer KK-2 installed in the open crack between upper block and intact massif at the site Košický Klečenov for the period 1995-2013

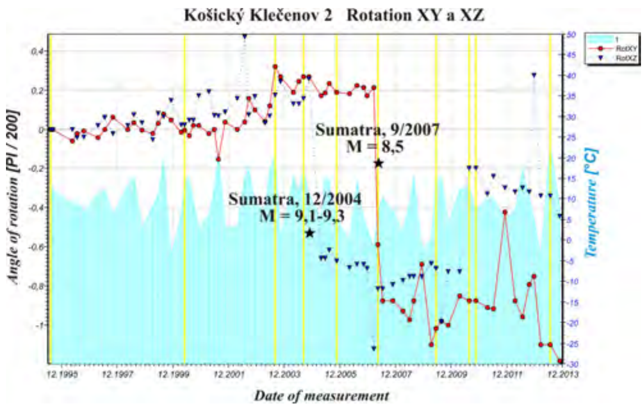


Fig. 7.27b Diagram of rotations in the planes XZ and XY recorded by dilatometer KK-2 installed in the open crack between upper block and intact massif at the site Košický Klečenov for the period 1995-2013

between the two blocs reached 5.25 mm (KK-1), the crack opening between the upper block and the intact massif has reached only 0.29 mm.

The results of the measurements of rotations of both blocks for the entire monitoring period have not shown significant values (Figs. 7.26b, 7.27b). More interesting are some sudden rotations. For dilatometer KK-1 except in August 1999, striking rotation of the lower block was recorded in the fourth quarter of 2007, which corresponded quite well to strong earthquake on Sumatra 09/2007 (M = 8.5). Sudden rotations of the upper block (Fig. 7.27b) in both planes (XZ and XY) in turn correspond very well with two strong earthquakes in Sumatra (12/2004 M = 9.1 to 9.4, 09/2007 M = 8.5). Certain consensus seems to be in increase of shear component of movement of the upper block with the seismic event on Sumatra 03/2007 (Fig. 7.26b). High sensitivity of the dilatometers, more accurate records of rotations of blocks (+/-0.01 gr) in relation to distant earthquakes have been demonstrated many times simultaneously at several locations abroad (Košťák et al., 2007).

Summary of the long-term monitoring results

The results of long-term monitoring of creep motion of rock blocks at the site Košický Klečenov using dilatometers TM-71 can be summarized as follows:

1. The dilatometers have confirmed the long-term trend of uneven sink of the two rock blocks, their movement along the shear cracks and opening of crack between them.

2. Slight (not very significant) uplift of the Slanské vrchy Mountains in terms of Neotectonic map of Slovakia (Maglay et al., 1999) corresponds to the observed vertical movement of blocks.

3. So far detected rotations of rock blocks are not significant in terms of their magnitude.

4. Due to the high sensitivity dilatometers (0.01 gr rotation and shift +/-0.01 mm) the relatively large and rapid rotations (in both planes - XY and XZ) and shifts (along the x and y axes) correlate well even with very strong distant earthquakes in Turkey (Izmit, 8/1999) and Sumatra (2004 and 2007).

5. The resulting motion of the blocks is a result of several natural factors – gravity force, recent tectonic movement along the marginal fault passing through the western edge of the stratovolcano Strechový vrch and seismic effects of very strong and distant earthquakes.

7.4. Early warning systems for landslides

In different parts of the world, depending upon the acting geohazards, the warning systems are implemented. Accounting for the extent of the damage caused by earthquakes, the identification of this phenomenon is the most important. Similarly, a prominent place all over the world have occupied systems developed to forecast the landslide phenomenon.

In general, worldwide the warning systems for landslides prediction can be divided into three different levels (global, regional and local - Fig. 7.28), based on the coverage of an area by prognoses on the state of stability.

Global early warning systems alert us to extensive territories in which activation of slope movements can be expected with high probability, or where their consequences could be the most unfavourable. It should be noted, however, the scale (at the continental level), in which individual phenomena are evaluated. For this reason, finer detailed analysis on the regional and local levels of the warning systems is needed. At the regional level of the early warning for landslides, as illustrated by several examples from different countries (Huggel et al., 2008; Jakob et al., 2006; Chan and Pun, 2004 and many others) it is a basic idea of global early warning development to more detailed levels. Even this level is based on an appreciation of the environment in which the landslides occur frequently and the main landslide-forming factors assessment, to which preferably belong precipitations. While previous levels of warning systems alert us to the possibility of the slope movements activating for larger territorial units in the case of passing through certain thresholds of landslide-forming factors, in local early warning systems for landslides usually emerges a practical problem of protecting a particular object (system of objects) against well-defined slope movement (or slope movements within the wider unstable area). In practice, the solution tackles a very complex and demanding issue. Creation of a local warning system requires a multidisciplinary approach in which the application of the findings of geological sciences plays a key role. In addition to purely geological issues, which clearly include selection of decisive landslide-forming factor and also the derivation of critical levels, there is a need to address the issues related to the selection of technical equipment for the collection and remote data transmission, and substantiated distribution of surveillance equipment within the monitored slide area. Separate issue are the legislative provisions of the early warning system operation, which must include a directory of responsible authorities, the procedure of their activity and level of responsibility upon notice on a criticality of the observed parameter.

Fig. 7.28 Early warning system levels on landslides. a - global level, b - regional level, c - local level

7.4.1. Development of early warning systems at monitoring landslide locations

As already indicated, the geological issues, which are essential in functional warning system implementation, have to handle two crucial tasks. The first one is to set out correct critical levels of observed factors and the other one is connected to verification of initiated warning.

In the scope of the PMSGF there were tested several methodological concepts of warning systems development, depending on the specifics of individual landslide sites, on the basis of the derived diagram (Fig. 7.29), which can be applied to a fairly wide range of monitored landslides. A choice among different modeling processes of an early warning system creation is determined by the quality as well as quantity of time series records of changes in the groundwater table level depth at each site assessed. From the geological point of view, a warning-system is based on two essential platforms. The first one is primarily of prognostic character with a regional impact. It is based on an evaluation of available climate data and hence the output information is related to the potential risks of negative climate indicators. The outputs obtained alert in advance on the possible variants of evolution of kinematic activity that can be applied also to assess the wider area of the evaluated landslide (so-called Model of Climate Parameters). In order to establish a functioning early warning system transition to the next - second level is needed (Fig. 7.29), which assesses and analyzes in detail the elements of the landslide environment. Based on data collected in real environment there have been specifically designed procedures of deriving

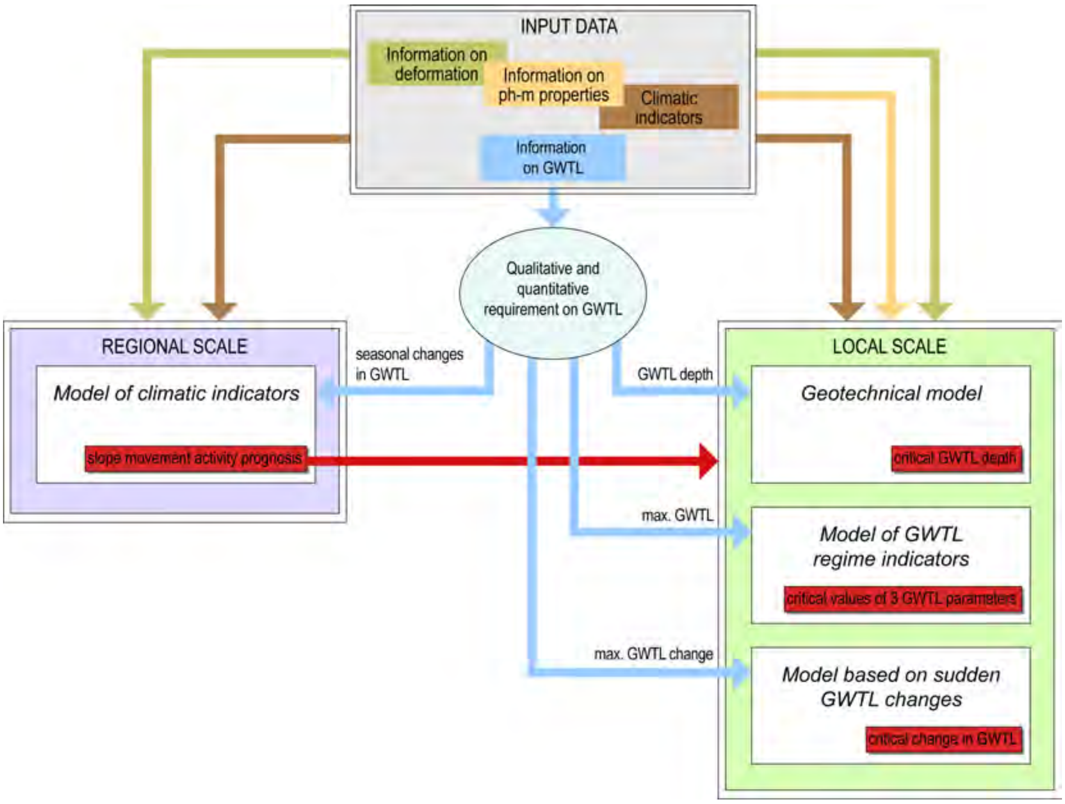


Fig. 7.29 Scheme of early warning system, which was applied at selected monitored sites

certain thresholds of the observed parameters. Several practical solutions have been successively published in the works Ondrejka, 2009 and 2012; Ondrejka et al., 2011; Wagner et al., 2014. Therefore, we focus only on a brief description of the uses of each method.

7.4.1.1. Early warning system based on climate indicators

The model is based on the notion that the emergence of landslide events is linked to a longer period, which precedes the activation of landslides. This was indicated by Záruba and Mencl, 1987; Kopecký, 2007; Novotný, 2002. The proposed method therefore relies on functioning warning systems, which rely on the assessment of climatic factors and are installed in different parts of the world (e.g. Jakob et al. 2006; Restrepo et al., 2009).

The proposed warning system is based on the actual conditions that are characteristic for each monitored landslide site. Due to their large number, the procedure has been applied to the landslide types, in which by the monitoring measurements the most comprehensive time series data have been obtained on all factors affecting stability conditions in the area. The evaluation and forecasting is described in the works by Ondrejka (2010, 2012).

The resulting prognostic model is the result of correlations between the aggregate effective precipitations, changes in groundwater table levels in the study area and the kinematic activity of landslide masses. On the basis of certain generalization of climatic conditions (semi-annual stages, which is a fundamental principle of the model presented) there were defined relationships between climatic factors and kinematic activity of landslide masses. Derived dependencies enable practical solutions to determine, or forecast certain trend of physical activity in the evaluated area. Based on the analyses it has been shown that the cumulative rainfall totals for October to March in many cases had influence on the stability conditions during the rest of the year. Thus, the volume of water that falls during a period of dormancy may affect the stability of landslide area conditions even for the following months (April to September). For the substantiated prognosis of the stability of the landslide area in the coming months there is inevitable to currently review the development of climate variables, and thus to refine prognosis of the stability development. It should be noted, however, that this level of prognostic evaluation gives only approximate results, applicable in regional scale. There have to be completed and refined the procedures aimed at detailed assessment of changes in groundwater table levels at sites under consideration.

7.4.1.2. Geotechnical model

This is the first of the proposed procedures with detailed evaluation of the stability of the landslide area under certain conditions (Fig. 7.30). In practice, the procedure is one of the frequently used methods of defining the critical values of the groundwater table level depth in the slide area. The critical depth level represents the state corresponding to threshold value of slope stability. Although it is quite a simple principle, in order to achieve the most substantiated results the process of deriving critical groundwater table level was adjusted to reflect the specifics of the hydrogeological regime of groundwater in the evaluated area. Firstly, it was extended on empirical approach, derived by Scherer (1999), which on the basis of long-term changes in groundwater table level (in monitoring objects, for a period of about 10 years) enabled to identify critical values which may actually occur in the landslide area.

Consequently, the values that were derived by empirical approach, were further refined in the calculation model. This involved series of procedures in a real environment in which impact of groundwater table level upon kinematic activity of landslide masses is assessed (supported by geodetic and precision inclinometer survey). In the analysis, the attention was focused on the state of the groundwater table level, which can be described as the least favourable, this means, the time of groundwater table levels measurement, during which in all observation wells the groundwater table level is the closest to the ground surface.

Final derivation of critical values for the early warning system rests in the verification of the calculated degree of stability based on the values of physical activity.

The whole process of modeling, as well as the resulting values of the critical groundwater table levels for early warning systems have been published in the works Ondrejka (2009, 2010).

7.4.1.3. Model of groundwater regime indicators

To evaluate the stability condition or to forecast its development the proposed model gives the most comprehensive information that can be directly used for early-warning systems. When compared with the previous methodology, in which the attention is narrowly focused in the determination of the critical value of the groundwater table level depth (Fig. 7.30b) it accounts for the time parameter. This means that in the analysis, in addition to depth of the groundwater table level, a particular attention is paid to the date of occurrence of its high levels and also to the duration of these conditions. The procedure of derivation of critical groundwater table level through the present methodology is described in great detail in the work of authors Wagner et al., 2014. This is a model example in which at the landslide site Okoličné different steps leading to the actual derivation of the warning signal, are presented.

Although the above procedure gives reliable results useful in developing early warning systems, its application is limited by the extent of time series of long-term monitoring of regime indicators and physical activity. Another condition is also sufficient density of such records.

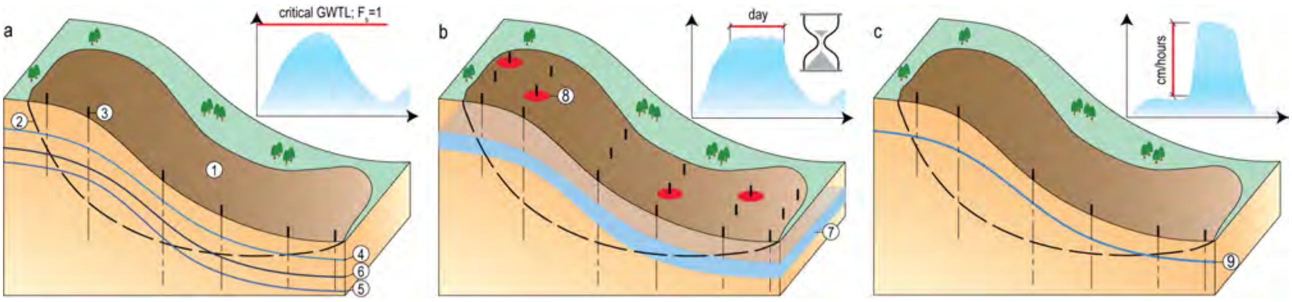


Fig. 7.30 Models of autonomous warning signals based on groundwater table level assessment. a - model based on geotechnical principle, b - model based on results of long-term groundwater table level changes, c - model based on sudden changes in the groundwater table level depth. 1 - landslide body, 2 – shear plane, 3 - piezometric boreholes, 4 - maximum groundwater table level for a long period, 5 - minimum groundwater table level for a long period, 6 - mean groundwater table level for a long period, 7 - range of maximum yearly groundwater table level depths for the monitored period, 8 - the most unfavourable groundwater table level during yearly period, 9 - continuous record of the change in groundwater table level

7.4.1.4. Model based on sudden changes in groundwater table levels

In terms of building an early warning system this is technically the most demanding solution. The principle of operation of such a system has been described in the works Ondrejka, 2010 and Ondrejka et al., 2011. Essence of this system is to analyze the impact of sudden changes in the groundwater table levels upon the formation and development of conditions suitable for the process of sliding (Fig. 7.30c). In addressing this issue it was necessary to dispose of detailed information on changes in the groundwater table level depth and the development of kinematic activity.

Such solutions offered a system that was built on the site of the landslide Veľká Čausa. It allowed to establish correlations between changes in the groundwater table level depth and the magnitude of deformation, measured at the shear plane (method of precision inclinometer) with a one-day frequency. Moreover, it has been shown that the measured deformation is not only the result of a sudden change in the groundwater table level depth, but it is di-rectly related to the initial depth of the groundwater table level. It has been also shown that the greatest effect upon the kinematic activity have had the changes in the groundwater table level depth of 12 hour interval. Based on the results obtained, methodology for forecasting the expected size of deformation has been compiled. The analysis is described in detail in the work by Ondrejka et al. (2011). The results obtained by this analysis were the basis for setting up the early warning system for the landslide site. In the warning system the rate of the groundwater table level rise has been set out, which was defined as the critical one. After reaching or exceeding the defined values, a responsible employee is informed in the form of short text message. Upon receipt of such report usually follows a procedure that is aimed to verify the stability situation in the landslide area. After real assessment of the situation, whether the state really constitutes a risk to the population, their activities or assets, it is possible to refer such report to employees of the municipal administration.

Although individual systems offer positive results in solving the project, the issue of refinement of the knowledge of the relationships among the monitored components remains necessary.

7.5. Conclusions

Monitoring of slope movements has been developed in parallel with the increase of knowledge about this geohazard, the advance in possibilities and methods of remediation, but also with the requirements for forecasting the emergence and development of the phenomenon.

In the early stages of development the monitoring represented a tool for verifying the functionality of the remediation of stabilized emergency landslides. The monitoring was usually focused in measuring changes in the groundwater table level depth and the yield of drainage equipment. Based on the values observed it was considered whether the conducted remediation of slope movement was sufficiently effective. Unfortunately, such a verification monitoring was generally performed only for a relatively short time after corrective measures implementation and beyond there was a gradual deterioration of monitoring objects.

Significantly higher level of the monitoring of slope movements was launched in the scope of the PMSGF project solution, which has been based not only on the verification of monitoring measurements, but it has been understood as a tool to provide data for understanding the patterns of development of slope movements and their forecasting. Thanks to the project solution extensive data sets have been acquired that are saved in purposefully structured databases, allowing to perform various operations to derive patterns between the changes of the observed factors (most often indicators of the groundwater regime) and kinematic activity of the observed landslides. Simultaneously there have been selected and gradually complemented the optimal ways of the monitoring of the slope movements of creep character and indications of rockfall. During more than 20 years of the projects PMSGF solution there have been observed several dozens of different types of slope movements, verified the number of observation methods and evaluation methodologies of measured data. In addition to great benefit in monitoring theory, valuable practical results have been achieved, summarized in alerts, which have allowed the responsible authorities to take actions in a timely manner, prior to activation and development of emergency slope movements (e.g. landslide Bojnice location, locations of rockfall Demjata and Slovak Paradise - Suchá Belá and others).

The extensive database of collected data and a gradual transition to the preferential application of continuous monitoring methods (primarily the installation of automatic level gauges) provide the opportunity to address perhaps the whole society most desired issue – the prognoses of landslide evolution. For this reason, in recent years several models of creation of early warning systems have been under development and some of them were practically verified in selected locations (Veľká Čausa landslide sites and Okoličné).

The investigators have no doubt that the transition to the development of early warning systems is the best and most desirable culmination in terms of long-term monitoring activities. Of course, the transition to the highest stage of monitoring is conditional upon obtaining large sets of data, application equipment for continuous data collection, but also asks for new methods of assessing the state of the rock mass stability (e.g. innovative geophysical measurements). The creation of an early warning system also requires long-term verification process of the correctness of its functionality. Accounting for all the above facts we believe that the early warning systems need to be built in concrete, the most socio-economically important areas where these systems can contribute to the protection of human life and significant material assets. Assessing the threat of larger landslide areas, especially useful in land-use planning and investments, should become the scope of the maps of landslide hazard and risk compiled by increasingly sophisticated methodologies.

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8. Geotechnical Monitoring of Landslides on Slopes of Water Reservoirs

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Abstract: In the design, construction and subsequent operation of water works the stability of slopes is one of the fundamental problems. Slope failures, especially landslides, affect site selection of dam body, threaten reservoir shorelines and also endanger smaller water management constructions. If water works are built up in the environment with landslides, then their monitoring is essential.

The article evaluates stability (monitoring results) of landslides next to two major water reservoirs in Slovakia. The first is a landslide at the water reservoir Liptovská Mara, which with its volume of water 362mil. m^3 is the largest reservoir in Slovakia put into operation in 1975. The purpose of this hydraulic structure is to use the hydro power potential of the Váh, to improve the flow of water under the dam and to protect the area from floods. On the right side of the dam body there is landslide displacing about 5mil. m^3, which strikes the reservoir with its toe. The second landslide is a landslide on the water reservoir Nová Bystrica, located over the reservoir water level, but its possible instability is threatening the water discharge object. Both landslides are located in the geological environment of Carpathian Flysch. The article assesses a current stability of landslides, remediation measures and especially results of a long-term monitoring.

Key words: landslides, geotechnical monitoring, slope stability, water reservoir

8.1. Introduction

In Slovakia, the occurrences of landslides (Liščák & Káčer, 2011) significantly obstruct the construction and operation of water works. Engineering geological investigation in the 50-80's of the 20th century primarily dealt with the preparation of large water works in Slovakia.

Because of massive landslides (thickness from 150 to 200 m) for a dam a morphologically advantageous profile near the village Tichý Potok westward of Prešov on Torysa River in the Inner Paleogene Flysch was abandoned (Malgot & Baliak, 1990). Landslide area near Martin influenced design of water work Krpeľany-Sučany-Lipovec. The derivation canal was moved and divided into two zones (Záruba & Mencl, 1958). On construction of the water work Dobšiná there had occurred rock slide of tectonically damaged block of diorite along the surface of graphite slate with dipping toward the slope (Záruba & Mencl, 1987). An example of a strong abrasion of reservoir shoreline is on the water reservoir (WR) Orava. After the first 15 years of operation of the WR Orava in some sections of shoreline

Fig. 8.1 Localization of the water reservoirs in the map of Slovakia

there were widespread landslides, the destruction of land occurred up to 160 meters from the shoreline in a slope (Horský & Bláha, 2011).

At present, none major hydroelectric project is built, but many of already constructed are threatened by landslides. The article evaluates stability (monitoring results) of landslides next to two major water reservoirs in Slovakia. Water reservoirs Nová Bystrica and Liptovská Mara are located at northern part of Slovakia (Fig. 8.1). Both reservoirs are built in the environment of Carpathian Flysch, whereas the reservoir Liptovská Mara in not folded, and the water reservoir Nová Bystrica in folded flysch environment. On both water works the slopes above the reservoirs are affected by landslides, which are threatening their safety and operating. In the next text we present:

- the nature of the landslides,
- hazard for the dams,
- a way of their remediation,
- a landslide stability assessment based on results of ongoing monitoring and proposal of new system of monitoring.

8.2. Landslides at the dam Liptovská Mara

On the right-side of the dam body of WR Liptovská Mara, which dammed the Váh River, there are located two landslides. On the water-side bank it is Veľkomarský landslide and on the downstream face of the dam it is Malý Vlaštiansky landslide (Fig. 8.2).

Both landslides at the Liptovská Mara dam are developed in the area consisting of unfolded Inner Paleogene flysch strata. The area of Veľkomarský landslide extends with length 900 m and width 550 m. The maximum thickness of the sliding material in the accumulation zone of the landslide exceeds 30 m (Fig. 8.3). The whole landslide is composed of several partial landslides of various ages. The supposed volume of the sliding mass exceeds 5 mil. m³ (Antolová, 2010).

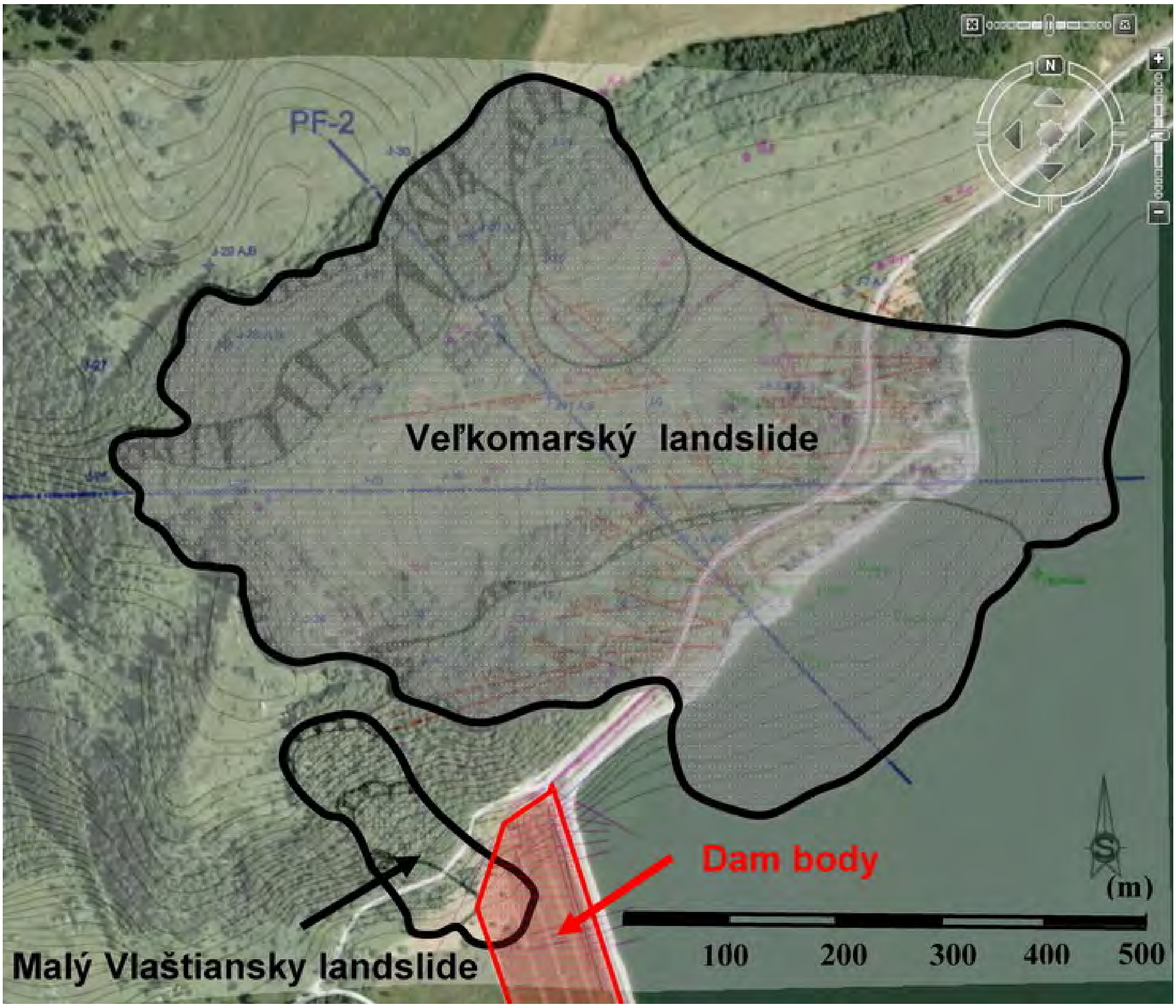

Fig. 8.2 Localization of the dam profile between Veľkomarský and Malý Vlaštiansky landslides (satellite photo by Google Earth)

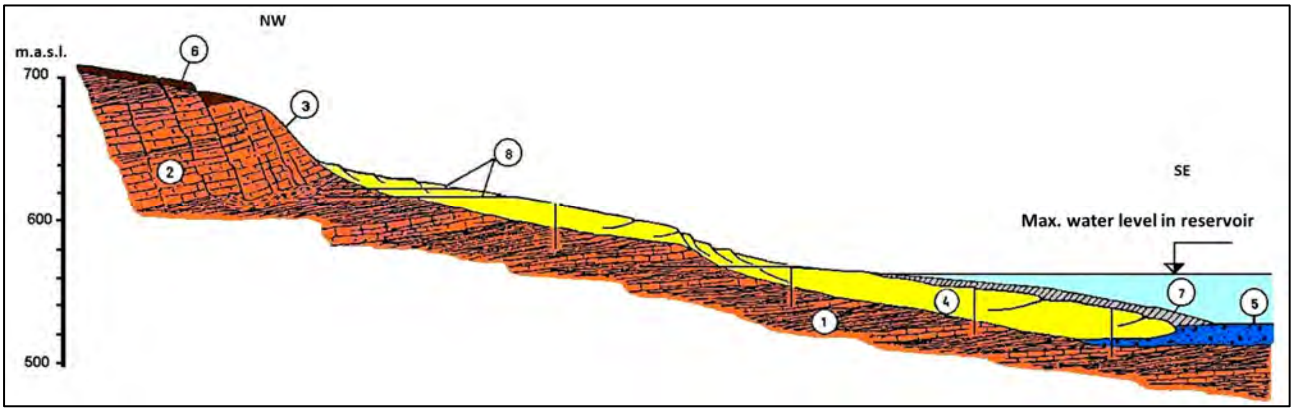

Fig. 8.3 Profile through the landslide Liptovská Mara (modified after Nemčok, 1982)
1- marly shale with intercalations of sandstones, 2 - sandstones with intercalations of shales, 3 - block field, 4 - landslide, 5 - fluvial deposits, 6 - slope loams,7 - gravely-sandy back fill, 8 - horizontal drainage boreholes

8.2.1. Remediation measures at the Veľkomarský landslide

The stability calculation of the Veľkomarský landslide performed prior to the WR construction had appointed to low stability of the slope. The calculation result meant concern about significant instability of the landslide after finishing the dam construction due to water buoyancy acting on the accumulation zone of the landslide.

To improve the Veľkomarský landslide stability condition after finishing the construction of the WR the following remediation measures were taken (Fig. 8.4):

- building of stabilization anti-abrasion embankments consisting of gravel and sand on the landslide toe (in 1974-1975) – the thickness of the embankments is 7 m (volume 700,000 m³),
- realization of horizontal drainage boreholes (HDB) - 4 stages in 1974-1977,
- creating a system of surface drainage gutters (in 1976-1978).

8.2.2. Recent activities on the landslide based on the results of geodetic monitoring

Evaluation of the recent landslide activity is possible only according to analysis of movement of geodetic points located on the landslide surface.

8.2.2.1. Classical geodetic methods

Although the Veľkomarský landslide is equipped with a network of geodetic points (observation and control points), the measurements of position changes of the observation points on the landslide cannot be used for qualified assessment of the activity of the landslide because of movement of the control points. Therefore for overview of activities of the Veľkomarský landslide changes of altitude of observation points are used only.

In late March 2006, a sudden warming and rapid melting of very thick snow cover led to infiltration of water from the melted snow into massif what resulted in increase of groundwater table levels in the sliding slope to the maximum one ever observed during the entire monitoring history. These high groundwater table levels were synchronous with changes of elevations of the observation points. A significant decrease was recorded on points from B-1 to B-6, which are located in the head of the landslide area (from 6.9 to 12.2 mm – 9.8 mm on average!, Fig. 8.5), what indirectly pointed to a partial activation of the landslide area.

8.2.2.2. Global Navigation Satellite System (GNSS)

Since 2007 geodetic measurements of displacement of geodetic points are made by method GNSS (Prvý, 2010), because there is no problem, with influence of the undesirable movement of the control points. The resulting vectors of the displacements of the geodetic points are given in Fig. 8.6. These vectors already could suggest the real trend of movement of the landslide surface. The maximum observed values of movement were 80 mm, this means ca 10 mm per year on average.

The monitoring network (Fig. 8.4) of both landslides was built 40 years ago. On the Veľkomarský landslide in 1974-1975 there were built sites for observation of groundwater table levels (observation wells - 30 pcs). As remedial measures also 28 horizontal drainage boreholes (HDBs) with the total length of 3,800 m were built in 4 stages.

The groundwater table level and discharge rate of HDBs are monitored once per 14 days. In the period 2003-2010 sixteen observation wells were equipped with automatic piezometers. Monitoring is carried out in order to assess the effectiveness of the remediation measures. For tracking the movements of the landslide a network of geodetic control points, consisting of 6 reference points and 17 observation points was built in the landslide area. The geodetic measurements are performed once a year.

8.2.3. Status of the current monitoring network on the landslides

With regard to the long term monitoring of the HDBs discharge, it is possible to observe decrease of the total volume of the water being removed from the landslide (Fig. 8.7).

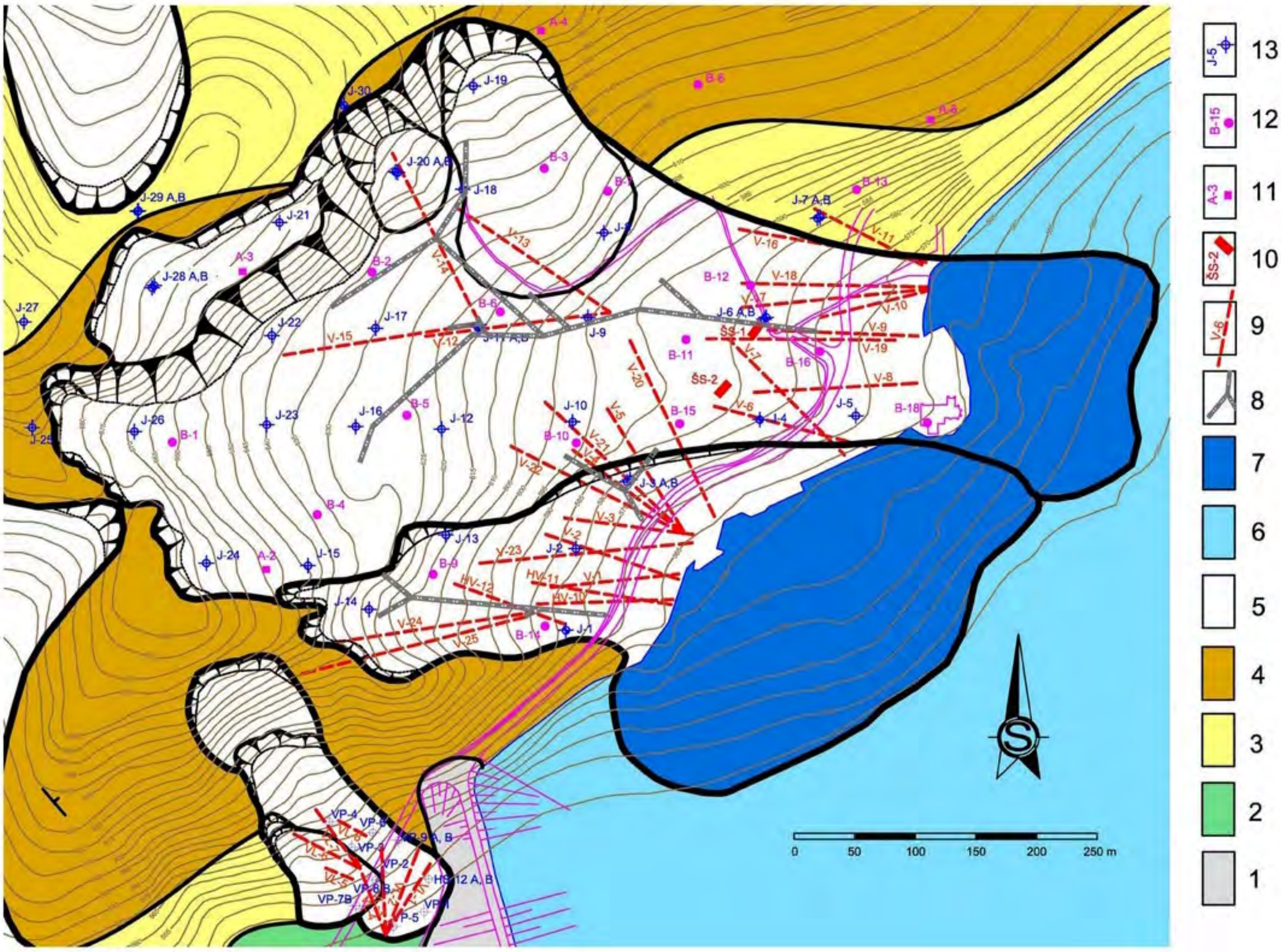

Fig. 8.4 Scheme of existing monitoring points and remediation measures on the Veľkomarský and Malý Vlaštiansky landslides (Kopecký, 2010)

1 - Earth dam, 2 - Váh River fluvial sediments, 3 - deluvial sediments, 4 - Paleogene strata, 5 - landslide bodies, 6 - water surface, 7 - part of the Veľkomarský landslide overflooded by the water of the reservoir, 8 - surface drainage gutters, 9 - horizontal drainage boreholes, 10 - gravel walls, 11 - control geodetic points, 12 - geodetic observation points, 13 - observation wells

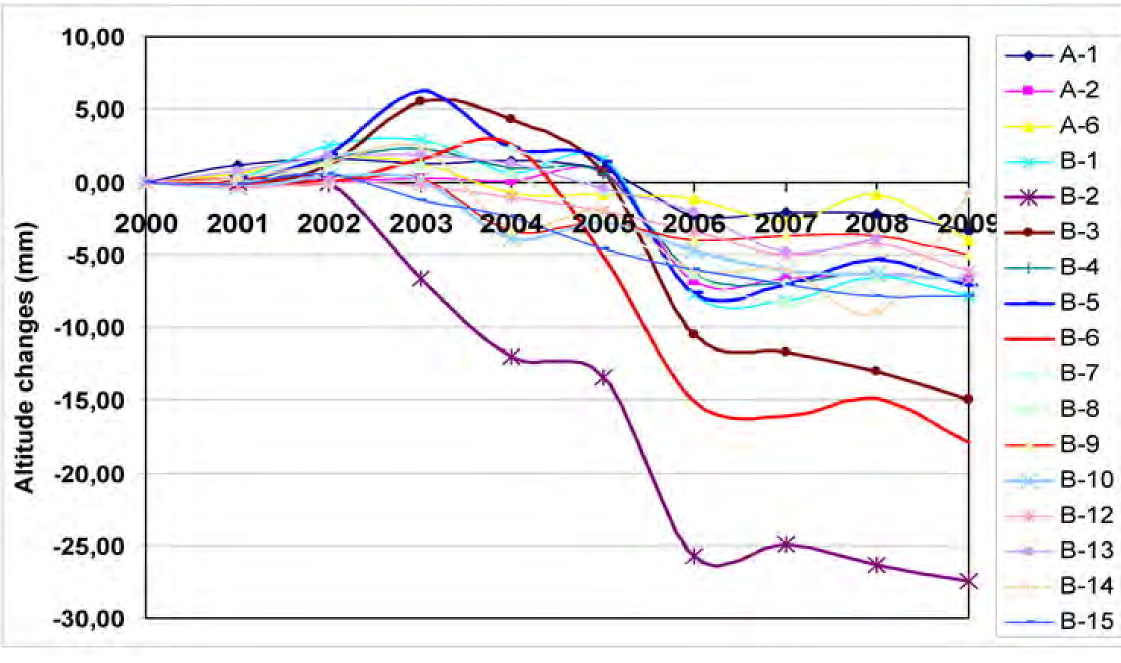

Fig. 8.5 Cumulative curves of altitude changes (mm) of geodetic observation points during years 2000-2009

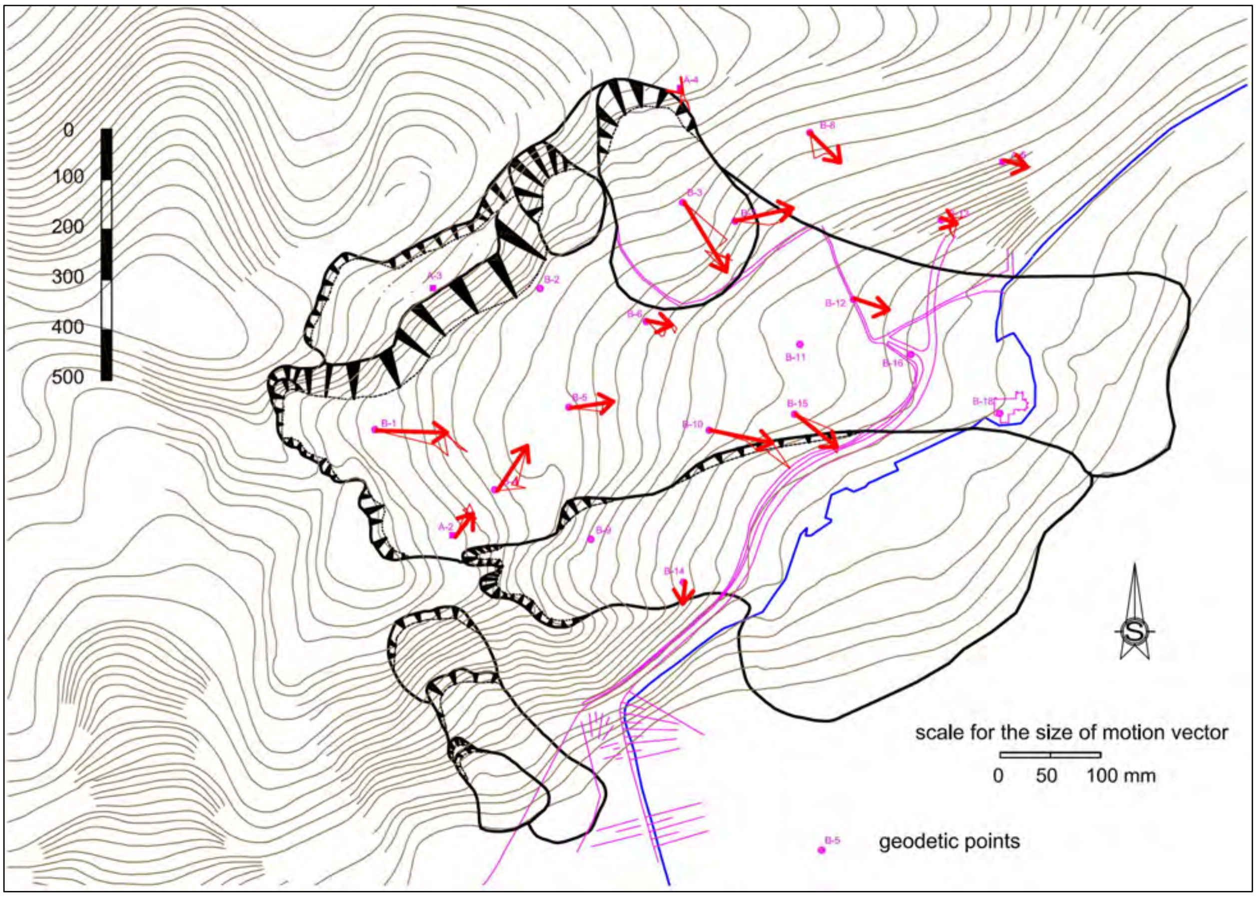

Fig. 8.6 Horizontal displacement of fixed and control points during period 2007-2013 by method GNSS

However, this overall groundwater level (GWL) decline does not have to play a role in reduction of the local slope stability, unless due to decrease of the water discharge from HDBs the groundwater level is not increased in the nearby observation wells. The negative impact of the discharge decline in HDBs from V-12 to V-15 located in the landslide head area is quite obvious. In this area (Fig. 8.4), in observation wells J-16, J-17 (Fig. 8.8), J-18, J-11B, J-11A the groundwater level is increasing for long time period, in the case of J-11A the groundwater freely flows out of the well as from artesian well. Inspection of the horizontal drainage boreholes was made with use of camera (Fig. 8.9). The largest throughput was observed only up to 30 m. In most cases the camera got only a few meters away from the HDBs mouth. The inspection results have pointed out that the broken HDBs should be either cleaned or replaced by new HDBs.

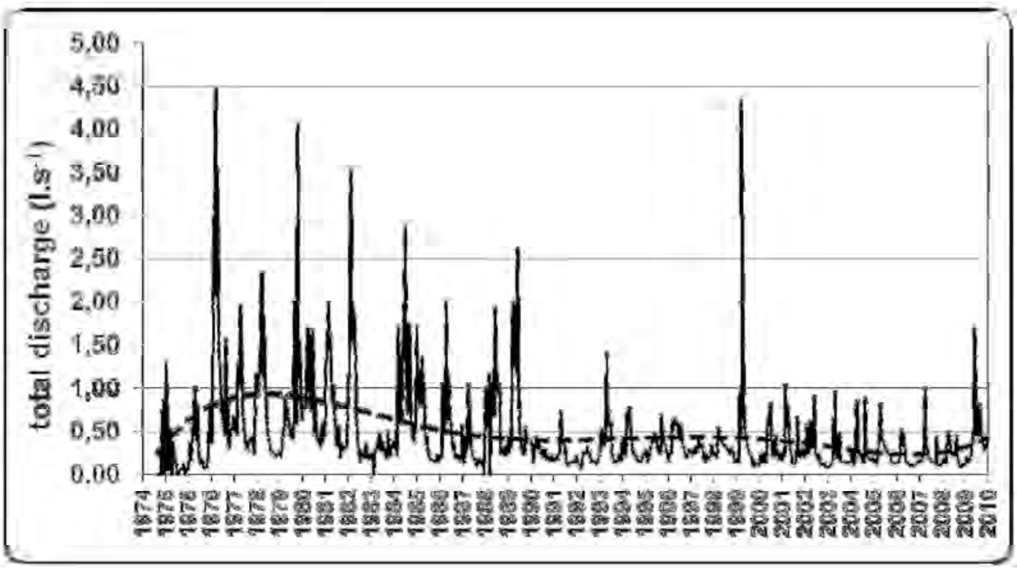

Fig. 8.7 Downward trend of the total discharge from all HDBs on the Veľkomarský landslide

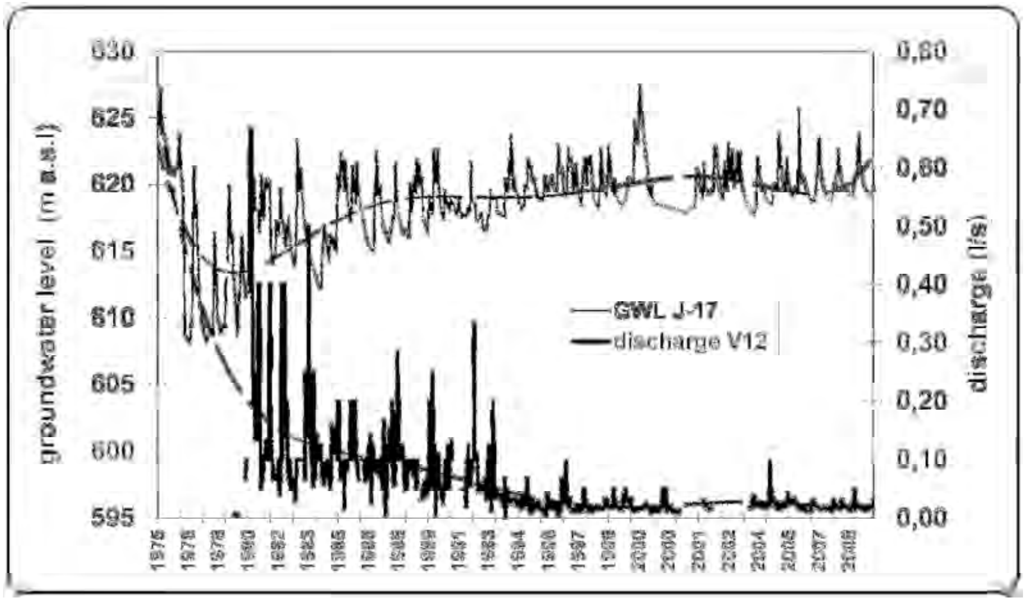

Fig. 8.8 Decrease of functionality of HDB V-12 and GWL rise in observation well J-17

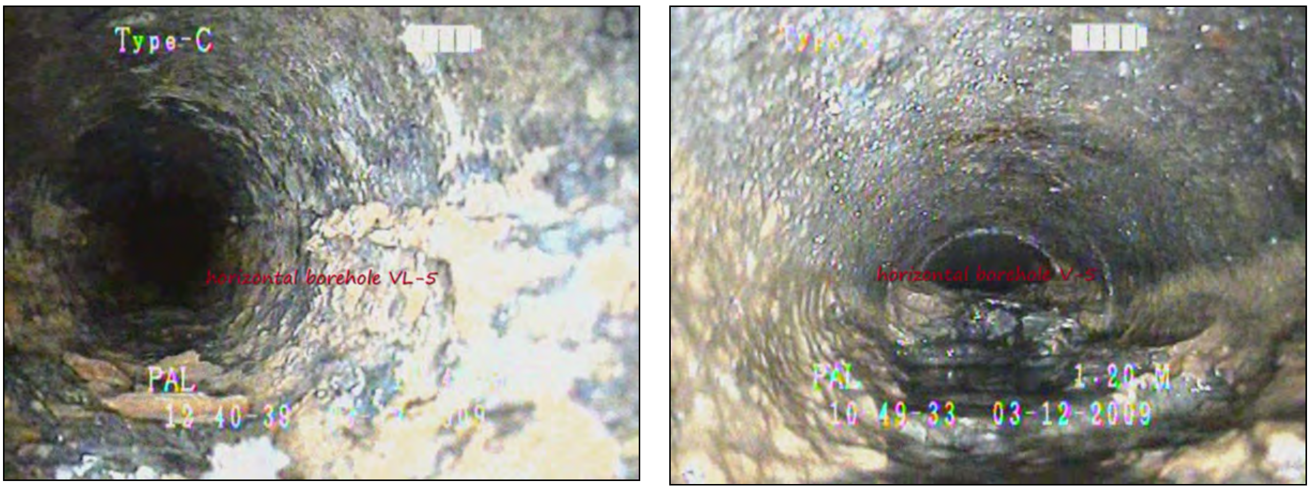

Fig. 8.9 State of the HDB casing after 38 years in operation revealed by the camera inspection

8.2.4. Proposal of design and maintenance of the monitoring network of the Veľkomarský landslide

The proposal of the complex monitoring of the landslides on the right-side of the dam body of the WR Liptovská Mara was designed in such a way that its results were:

- determination of the landslide recent activity,
- forecasting the future development of the stability,
- setting the critical values for need of implementation of additional remediation measures.

The proposed measures were split in to 3 stages – Tab. 8.1. Emphasis is placed especially on the building of inclinometer boreholes and reconstruction of network of geodetic points, because stability (or better dynamics) of any slope can be judged the best way by combination of geodetic measurements of the surface movement with inclinometric measurements of movement below the surface. It will be also necessary to clean the existing HDBs. If such measures prove ineffectiveness, it will be necessary to proceed with a construction of new HDBs.

Even during the renovation and reconstruction of new elements of the monitoring network it is necessary to continue with monitoring measurements on both landslides. However, gradually it is necessary to upgrade the system to automatic data acquisition in order to determine the threshold conditions for a possible activation of the landslides. Only then it will be possible to implement necessary measures in time and to provide a safe operation of the WR Liptovská Mara.

8.3. Landslides at the Dam Nová Bystrica

The reservoir Nová Bystrica is located in the northern Slovakia, about 6 km south of the border with Poland on the river Bystrica (Fig. 8.1). It is used to supply the population with drinking water and was put into operation in 1989 (Bednárová et al., 2010).

Tab. 8.1 Proposed measures on the Veľkomarský landslide in 3 stages

Proposed measures	Purpose and output of the measures
1st stage - specifying and obtaining additional information on landslide area	
a) **Geodetic survey** of existing monitoring elements and important elements of the landslide areas	Creating a representative model of slope deformations + positioning of the network elements
b) **Geophysical measurements** – 4 profiles with total length of 2,380 m	Determination of surface and depth extent of the landslide area + precising the location of new inclinometers
2nd stage - building of new elements of the monitoring network	
a) **Building inclinometer boreholes** – total 7 pcs - 200 m	Observation of movements in depths of the massif. Determination of residual shear strength parameters of soils from samples taken during the drilling
b) **building new piezometers -** total 4 pcs - 100 m	Measurement of GWL in the vicinity of inclinometer boreholes + installation of automatic piezometers
c) **new geodetic points - 5 pcs**	Measurement of surface movements of landslide area – movement of blocks in the upper part of the landslide area.
3rd stage - reconstruction of the current monitoring network elements	
a) **geodetic points** – rebuilding all 22 pcs	Rebuilding of geodetic points in their original places and adjusting their surroundings for measurements by methods of very accurate leveling and GPS
b) **piezometer -** reconstruction of approximately 11 pcs - 265 m	Reconstruction of the broken wells
c) **horizontal drainage boreholes – about 2 000 m**	Cleaning those HDBs which show long-term decline in yield and those in which there is a rise of GWL (Fig. 8.5). In a case of inefficient cleaning new HDBs will be necessary to build

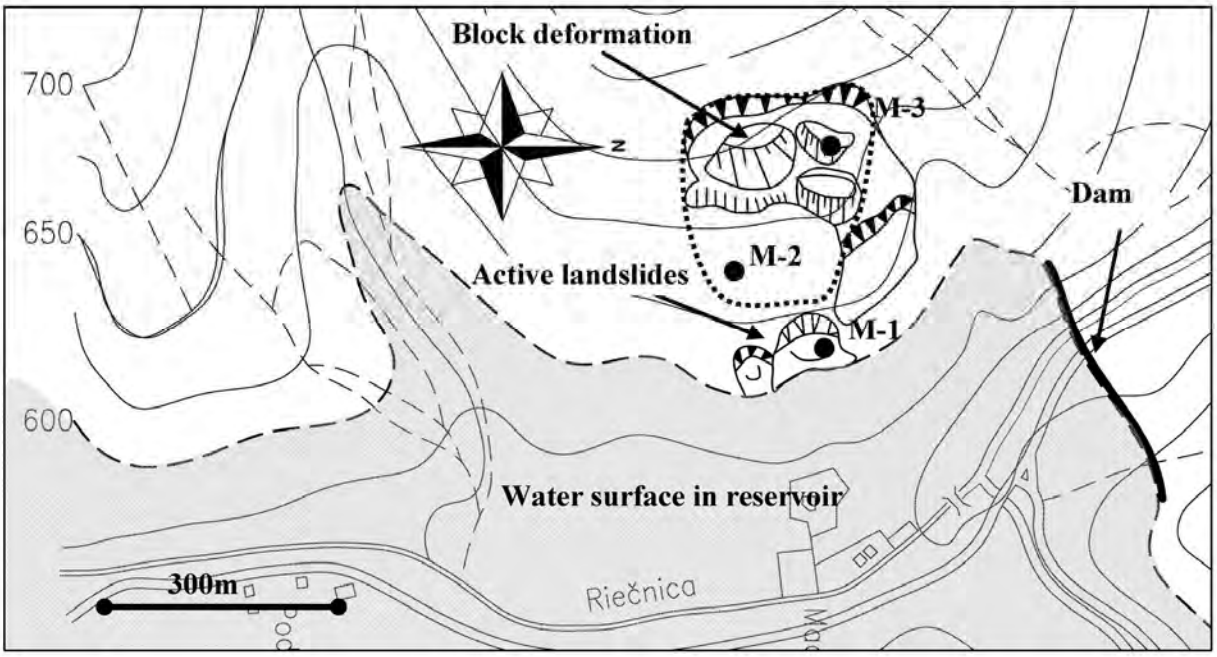

Fig. 8.10 Scheme of the landslides at the slope located on the dam left-hand side

Rock environment of the area consists of rocks belonging to Outer Flysch Zone. The flysch formation is characteristic by the alternation of pelite (claystone, marlite and siltsone) with sandstone. The most dominant strike of the flysch layers is E-W, while their dip is almost vertical (80-90°). The formation has due to multiple folding of the area complex overthrust structure.

Even before the construction of the water reservoir Nová Bystrica, during the implementation of a detailed engineering geological survey (Nevický et al., 1977), the presence of slope deformations was observed at the slopes on the left side of the designed dam (Fig. 8.10), which are located above the maximum shoreline. Two slope deformations of varying activity are located on the slope. In the area between the reservoir shoreline and the forest road there are active landslides with overall area of about 120x60 m. The landslides were probably caused by improper intervention during construction of the forest road. Active landslides are bound only to the slope debris containing coarse fragments from 40 to 80% and the slip surfaces were detected by the inclinometric measurements at depths from 3.5 to 5.0 m. In the higher part of the slope (in the range of about 630-690 m above sea level) there is a block deformation (Fig. 8.10). Based on initial investigation works (Jadroň & Fussgänger, 1993) its dimensions were estimated to approximately 100 x 140 m. According to our latest knowledge, this could be up to 220 x 140 m (dotted line in Fig. 8.10). Block deformation is result of gravitational movement of relatively rigid sandstones over the layer of plastic claystone. During the movement from the main scarp zone the sandstones were disintegrated to individual blocks. The maximum depth of the slip surfaces was detected by inclinometric measurements at a depth of 34.0 m below the surface (Figs. 8.11 and 8.13).

8.3.1. Landslide activity - monitoring and its results

In 1993, investigation boreholes (Jadroň & Fussgänger, 1993) were equipped for the combined observations of groundwater levels (GWL) and movements on the slip surfaces (7 pcs). Four of them, which were placed in the active landslides, become inoperative since 2001. In 2002 there were made 6 new inclinometric boreholes (without possibility of measuring GWL) in the active landslide on the forest road. Furthermore, in 1995 there were built 4 drainage fans (each with 3 horizontal boreholes), and their discharge is monitored. These drainage wells are the only remediation measure performed on the landslide up to now.

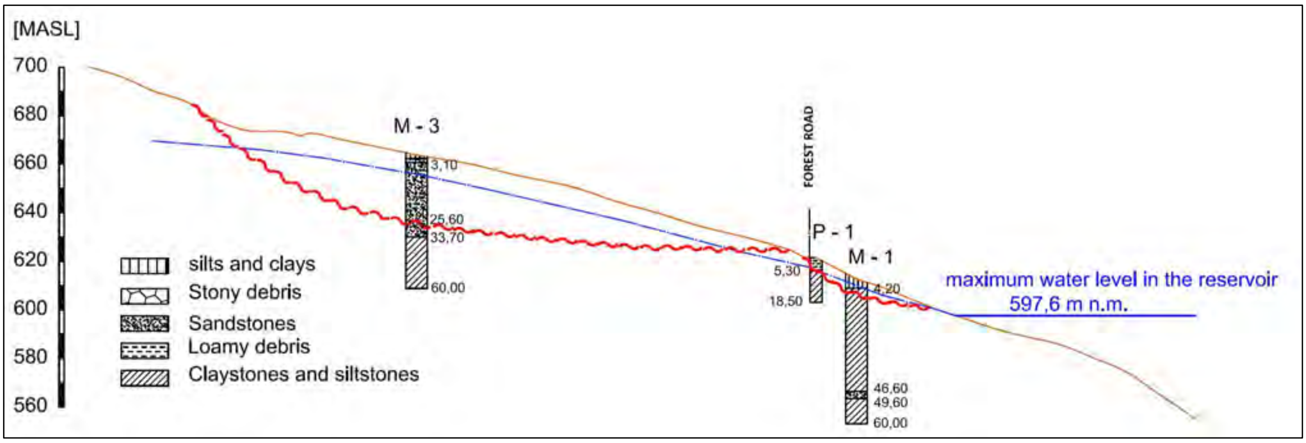

Fig. 8.11 Profile across block deformation and active landslide on the slope above the water table level in the reservoir

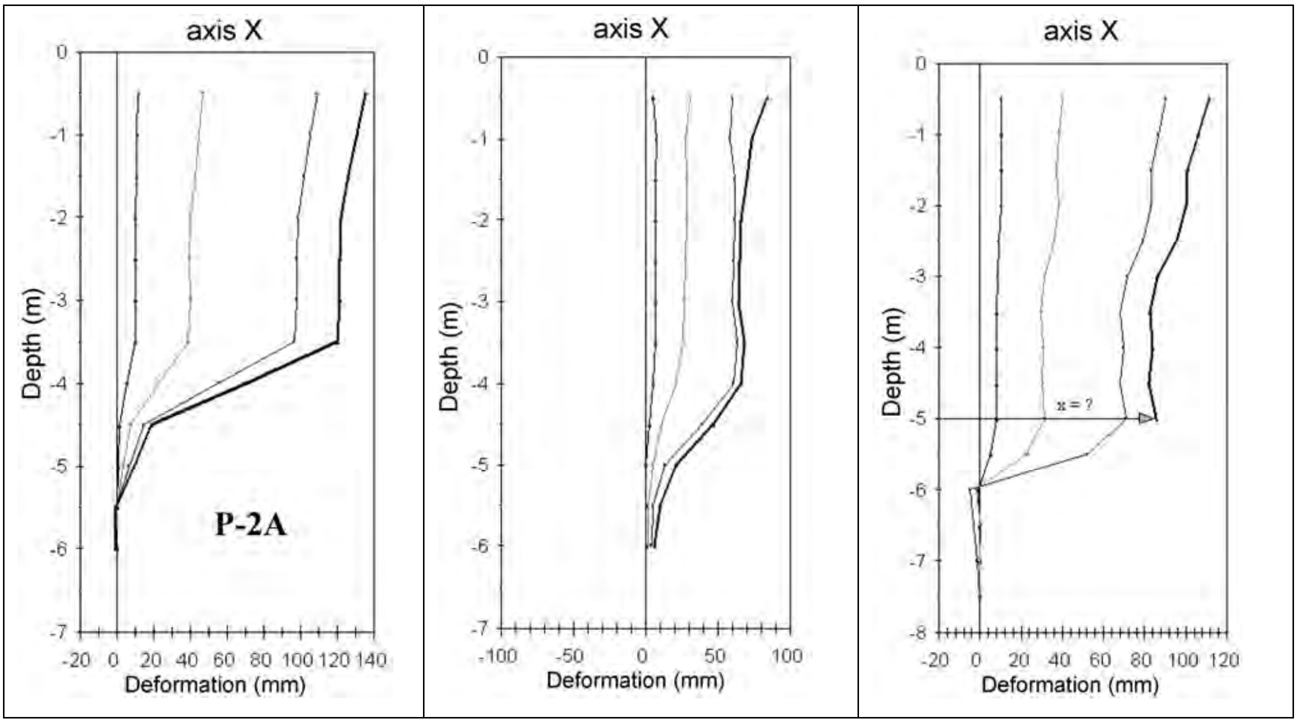

Fig. 8.12 Movements in three inclinometers, including P-2A, located in the active landslide on the forest road

At present, GWL can be measured in 3 wells and movements on the slip surfaces in 5 inclinometric boreholes (of which 3 are in active landslide and 2 in the block deformation).

The analysis of measurements of movements in the inclinometric boreholes is the most important. Due to the nature and depth of the measured movements it was necessary to assessed independently the active landslides at the forest road and the block deformation.

Active (little) landslides

In the landslide area with the forest road it has been confirmed that the activity of the movement still persists. The maximum deformation observed from 1993 to 2006 was 300 mm (sum of deformations from two inclinometers - the second one replacing the first one damaged). The movement is probably not continuous and uniform, it occurs only under extreme climatic conditions (excessive rainfall and snow melting). The depth of the slip surface of the active landslide on the forest road was found 3.0 - 5.5 m below the surface (Fig. 8.12).

Based on the analysis of the inclinometric measurements it was found in 2 inclinometric boreholes located outside the presumed area of the landslide active in 1993 that since 1999 there was gradual expansion of the landslide and significant distortion of the forest road (Fig. 8.13).

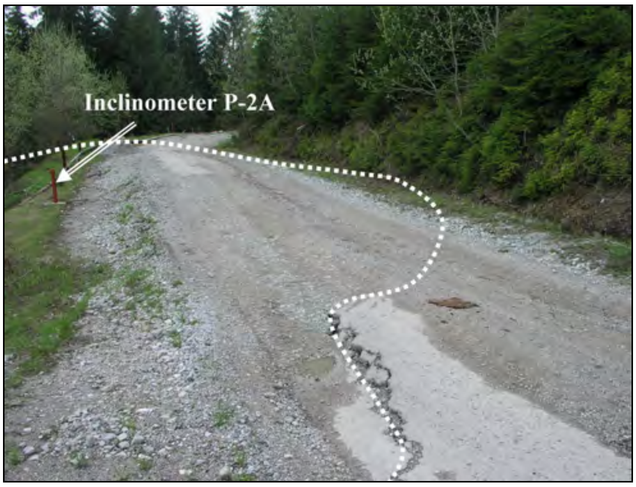

Fig. 8.13 Main scarp area of the active landslide in the body of the forest road with inclinometer P-2A

Block (large) deformation

The block deformation, which is situated in the slope above the forest road, there is a gravitational movement of relatively rigid sandstones over the surface of a plastic claystone. Inclinometric measurements under the main scarp zone of the block deformation (borehole M-3 - Figs. 8.10, 8.11) confirmed the existence of a relatively thick slip zone (about 7 meters), along which there is a movement of the block of sandstone up to 34 meters thick (Fig. 8.14).

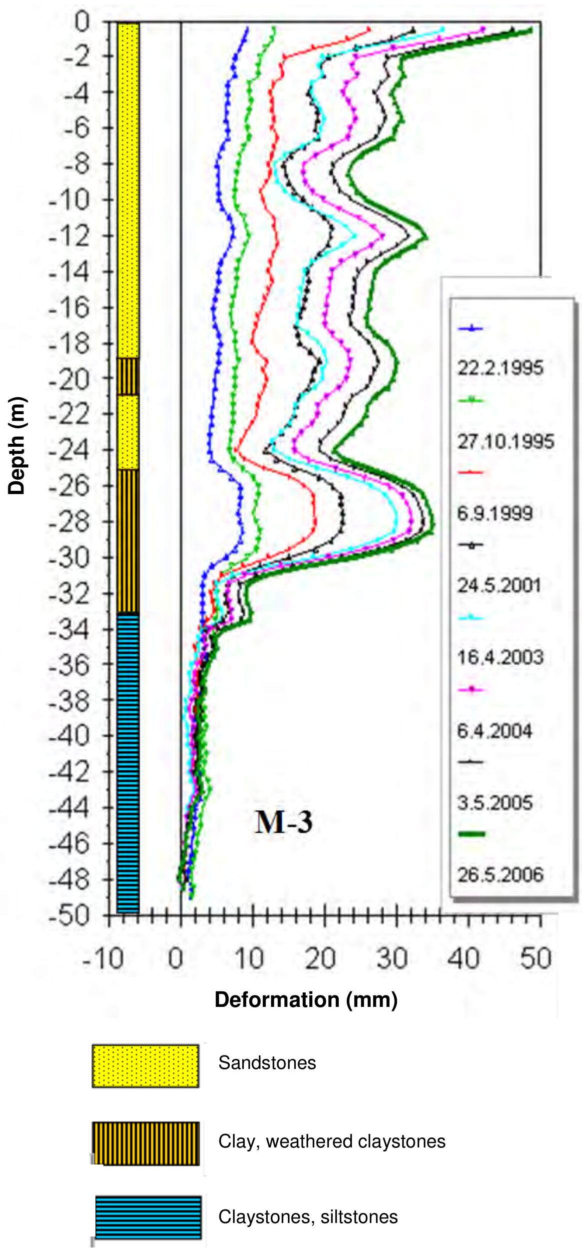

Fig. 8.14 Inclinometric measurements in the borehole M-3 located in the block deformation

Total movement of 47 mm during 15 years was detected. However it is important that the movement at a depth of about 28.0 meters is relatively uniform up to now (Fig. 8.15).

Borehole M-2 (Fig. 8.9) was situated on morphological platform about 60 meters above the forest road, and it was assumed (Jadroň & Fussgänger, 1993), that the platform was not the result of the slope movement. However, subsequently realized inclinometric measurements showed quite a clear movement on the contact between sandstone and claystone (13.0 meters below the surface). The total resultant movement in this depth is almost 98 mm for 15 years. These findings led us to an opinion that the areal and depth extent of the block deformation is greater than it was originally anticipated.

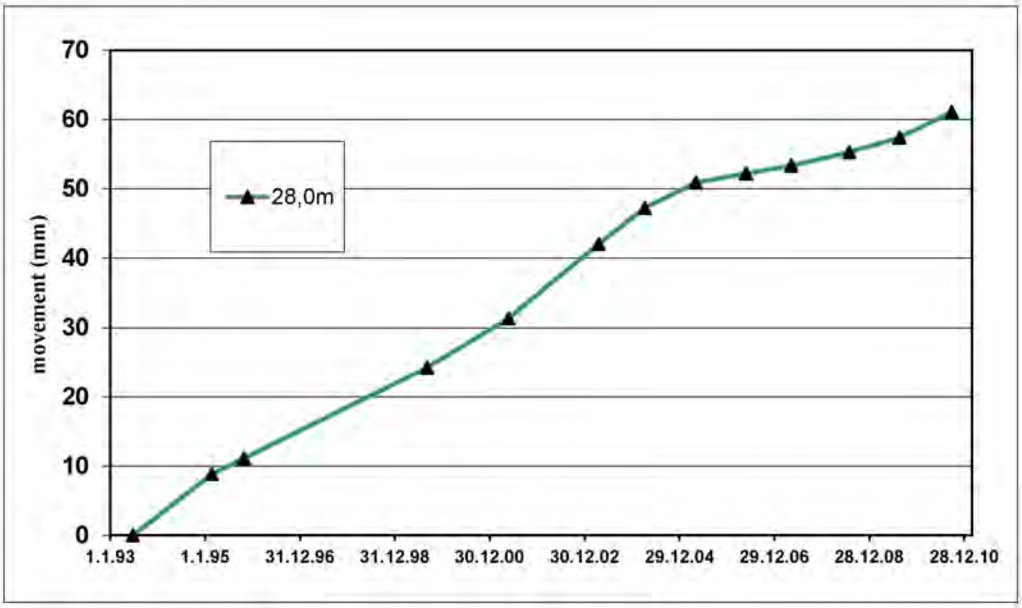

Fig. 8.15 The curve of movements vs time in depth 28.0 m in the borehole M-3

8.3.2. Forecast of development of the slope deformations and their influence on the operation of the water reservoir

Development of the existing slope deformations and their potential impact on the operation of the water reservoir can be forecasted based on the measurements of the monitoring network (especially in inclinometric boreholes), and also calculations of slope stability (Kopecký & Hruštinec, 2006). Results of the calculations of the slope stability showed that the most important factor affecting the stability of the slope deformation is the groundwater level in the slope. This fact will have to be taken into account when designing remediation and stabilization measures.

8.3.2.1. Active (small) landslides

It is obvious that, provided no remediation works will be made on the active landslide area with the forest road (Kopecký & Hruštinec, 2006), than in some time there will be an absolute destruction of the slope and sliding of the deluvial sediments to its lower part and partially into the water reservoir. About 55,000 m^3 of debris can be mobilized. However, we assume that in this process there is no threat to the inflow waterworks facility remote about 150 m from the accumulation of the active landslides. On the other hand, removal of rock masses from this area can cause acceleration of movements of the block deformation situated above the forest road.

8.3.2.2. Block (large) deformation

Based on the inclinometric measurements a link between deformations in an area of borehole M-2 and the deformations around the borehole M-3 cannot be ruled out. The knowledge of the fact whether there is accelerated motion or movement is steady is crucial to the prognosis of further development of the movements (Fig. 8.15). However, as the inclinometric measurements are carried out only once a year, it is not possible to determine the nature of the movement reliably.

If there are demonstrably accelerated movements in the area of the block deformation, it will be necessary to proceed to remedial or other measures, because at certain acceleration it will not be possible to stop the given movement. The subsequent movement of the rocks would likely jeopardize the operation of the water reservoir.

8.3.3. Recommendation for the following monitoring

Assessment of the stability of the slope on left side of the dam Nová Bystrica and forecast of its future development with respect to the operation of the water reservoir were based only on pre-existing knowledge, where the inclinometric measurements play the critical role. Assumptions obtained by calculations and analyses correspond to the accuracy of all existing data.

For clarification of existing knowledge (especially in the area of the block deformation) the further works recommended are summarized in Tab. 2.

8.4. Conclusion

Based on the monitoring we assume that the landslide at the WR Liptovská Mara is temporarily calming; the movement has slow creep character. The only activation was recorded in the spring 2006, when there was a downturn in the crown zone of the landslides. The stability of the landslide slope described in this paper is primarily a function of groundwater levels and water level in the reservoir.

On the WR Nová Bystrica the stability calculations demonstrated instability of the shallower landslides

Tab. 8.2 Recommended remediation works on the Nová Bystrica landslide

Recomended works	Purpose and output of the works
Geodetic survey of the terrain morphology	Creating a representative model of slope deformations (active landslides and block fields)
Installing surface geodetic points and measuring their movement	Understanding the relative speed and direction of the movement of blocks on surface (forecast of their future development)
Inclinometric measurements (twice a year) Construction of 2 pieces of new inclinometer boreholes in the block deformation Restoration of functionality of inclinometers P-5 and M-1	Determination of the depth and size of the deformation in the rock environment – prediction of further development of the movements with identification of critical values of their velocities
Groundwater level (3 new piezometers with continuous measurement of GWL), discharge of horizontal drainage boreholes	Optimization of boundary conditions for stability calculations and determination of the critical levels of GWL
Geophysical measurements	Determination of areal and depth extent of the block deformation + specification of location of new inclinometers

threatening the forest road, what was subsequently proven by measurements of the movements in boreholes equipped with inclinometer. The movement was more than 30 cm in 15 years. More dangerous for the operation of the water reservoir may be activation of the block deformation above the shallow landslides. The movement of the blocks occurs along slip surfaces in greater depth (34 m and 12 m below the surface). The movement is uniform and is about 3-5 mm per year. Acceleration of this movement could have disastrous effects on the safe operation of the water reservoir.

On the WR Liptovská Mara, the only representative measurements proving the actual movement of the landslide are measurements of elevation changes on geodetic points. Positional changes of geodetic points are irrelevant because unstable are even the reference points. It is necessary to rebuild a network of the measured geodetic points. It is also necessary to build several boreholes to monitor movement within the soil mass (inclinometer boreholes). Only then we can determine the critical groundwater levels and predict the actual development of the landslide slope. With respect to poor condition of the monitoring elements after 40 years of their operation it is necessary to build new or refurbished the old monitoring elements.

In turn, on the WR Nová Bystrica there are quite good data on the movement of the landslide slopes, however less satisfactory there are data on groundwater levels and particularly there is a lack of data on the extent (area and depth) of the block deformation.

The output of the article is therefore not only information about the current stability of landslide slopes, but especially the proposal for their continuing monitoring, enabling reliable prediction of their further development and hence it is also the proposal of measures ensuring long-term trouble-free operation of the referred to water reservoirs.

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