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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).

A.

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;

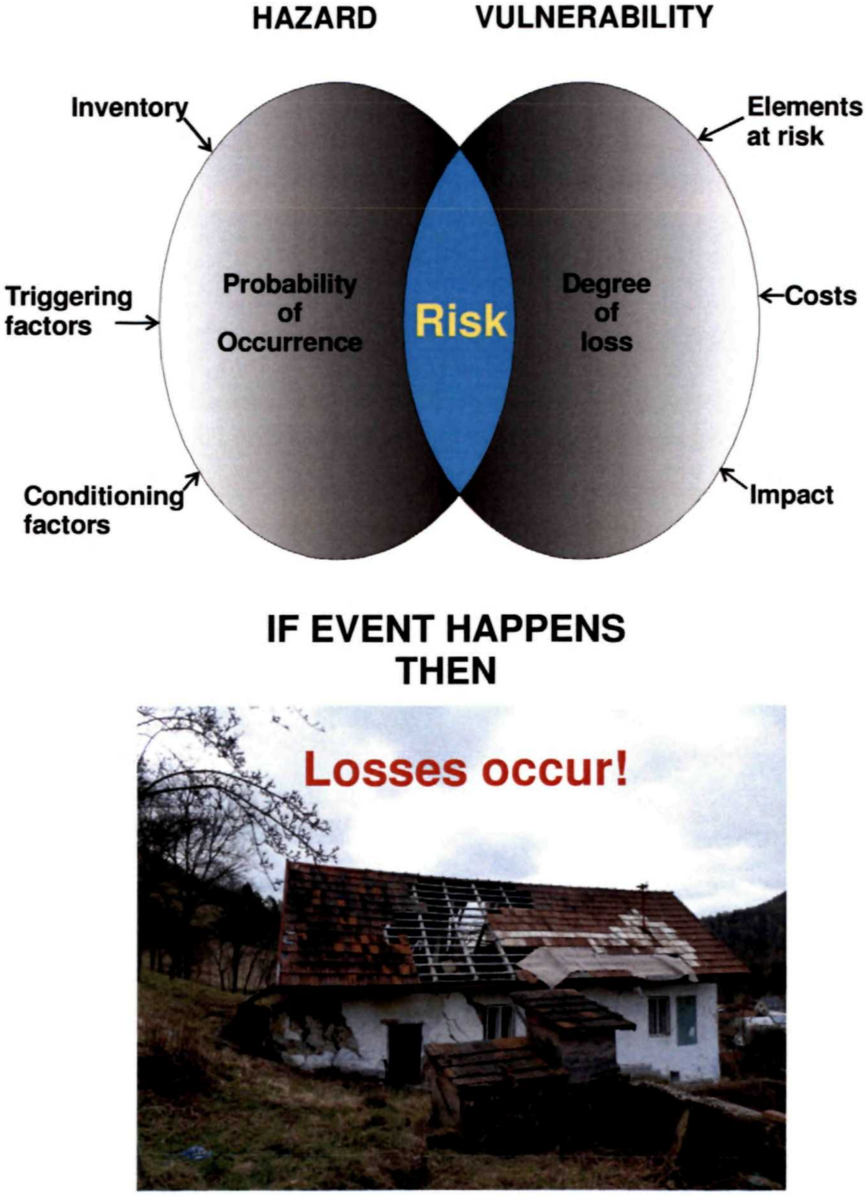

Fig. 1.3 Graphic depiction of the landslide risk assessment methodology (modified according to Alexander, 2002, in Petrýdesová, 2012). Photo of destroyed house in the Červený Kameň village, Liščák, 2013

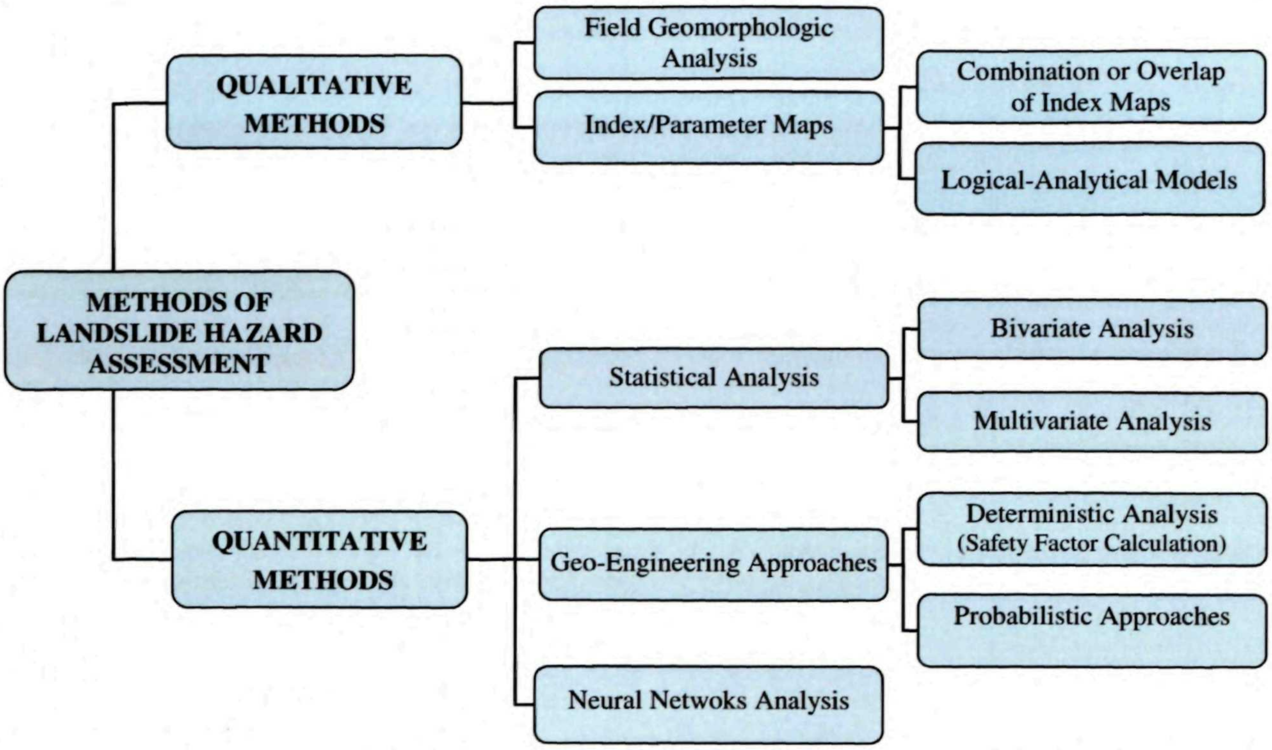

Fig. 1.4 Overview of the methods of landslide hazard assessment (in Petrýdesová, 2012, modified after Aleotti, Chowdhury, 1999)

- 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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