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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

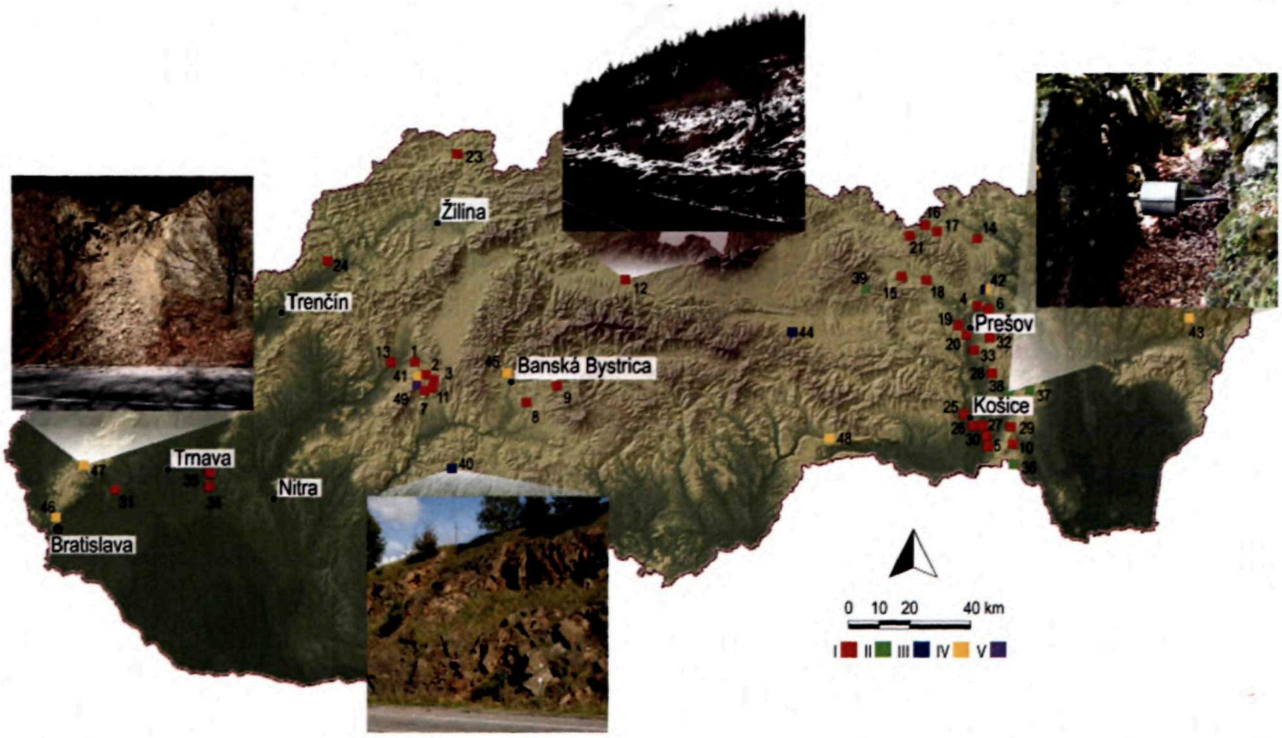

Fig. 7.1 Arrangement of monitored sites of PMSGF, subsystem 01 - Landslides and Other Slope Deformations (state of monitored sites in 2013; according tab. 7.1). Monitored sites of the type: I - sliding, II - creep, III - rock fall, IV - weathering, V - special (stabilising fill).

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

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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.

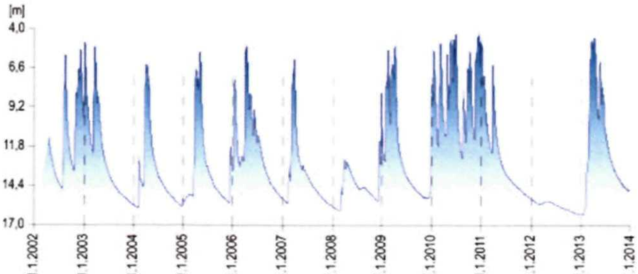

Fig. 7.2 Results of long-term monitoring of groundwater table level depth in borehole JM-6 at the landslide site Dolná Mičiná.

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
	J-1	14.06.96		On 6.11.07 former piezometer was replaced by MARS 4i type
Okoličné	JH-29	14.06.96	15.05.2002	
	AH-2	12.10.05		Early Warning System (MARS 5i)
	VČ-2	07.11.96		On 23.4.08 former piezometer was replaced by MARS 4i type
Veľká Čausa	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		
	J-10	14.05.03	24.3.2012	
Liptovská Mara	J-19	15.05.03	24.3.2012	Automatic piezometer gauges in 12 wells
	J-5	18.06.09	24.3.2012	
Fintice	K-1a	27.04.05		
	K-2a	27.04.05		
	JV-17	12.02.13		
Nižná Myšľa	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		
	PVZS-1	19.04.12		
Šenkvice	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		

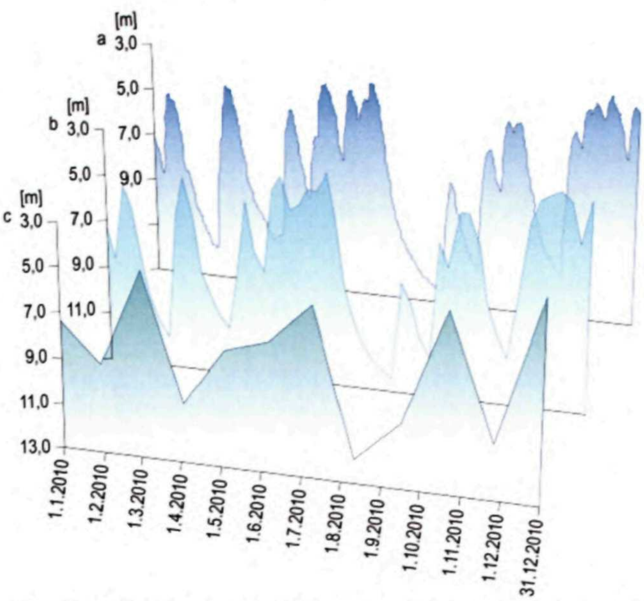

Fig. 7.3 Comparison of results of monitoring of groundwater table level with different frequency in borehole JM-6 at the landslide site Dolná Mičiná. a - continuous measurements using automatic piezometers, b - weekly frequency, c - monthly frequency of measurements

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).

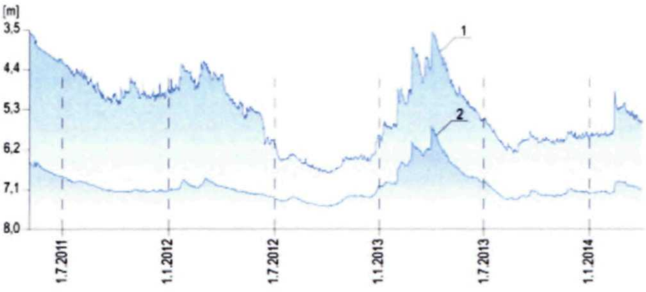

Fig. 7.4 Example of monitoring of two horizons of groundwater in the landslide area of Šenkvice. 1 - borehole PVZS-2, 2 - borehole PVZS-3

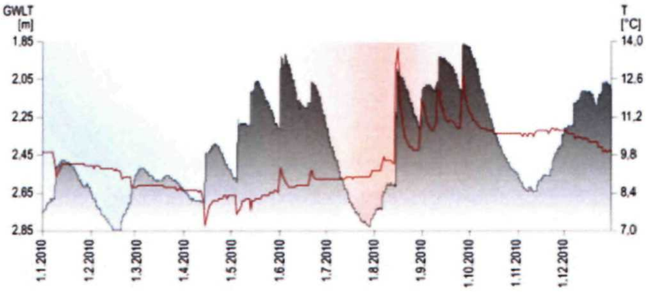

Fig. 7.5 Relation between change in groundwater table level depth and change in its temperature

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

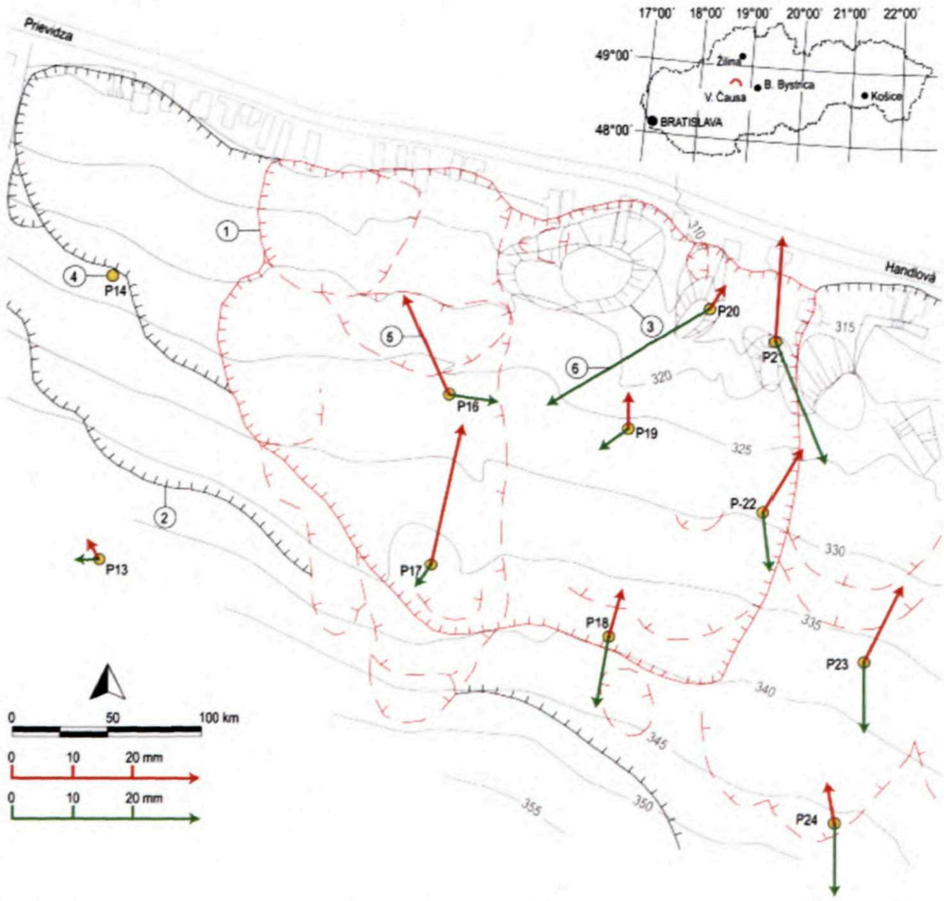

Fig. 7.6 Map of the landslide area in the cadastre of Veľká Čausa with indicated vectors of geodetic points shifts. 1 - active landslide area, 2 - potential landslide area (older landslides), 3 - detached blocks of volcanites, 4 - network of geodetic points, 5 - vectors of horizontal shift of geodetic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

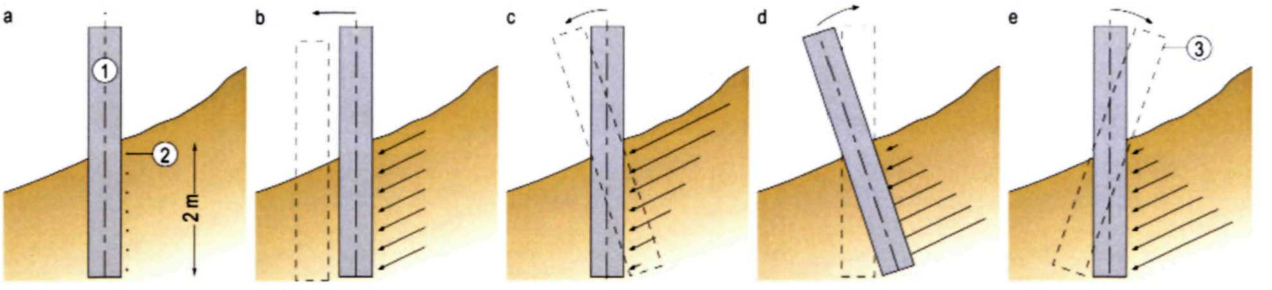

Fig. 7.7 Assumed change in angle of geodetic pillar. a - without change, b - shift in fall-line direction, c - change in angle in fall-line direction, d - change in angle against fall-line direction with ascending vertical change, e - change in angle against fall-line direction with descending vertical 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.

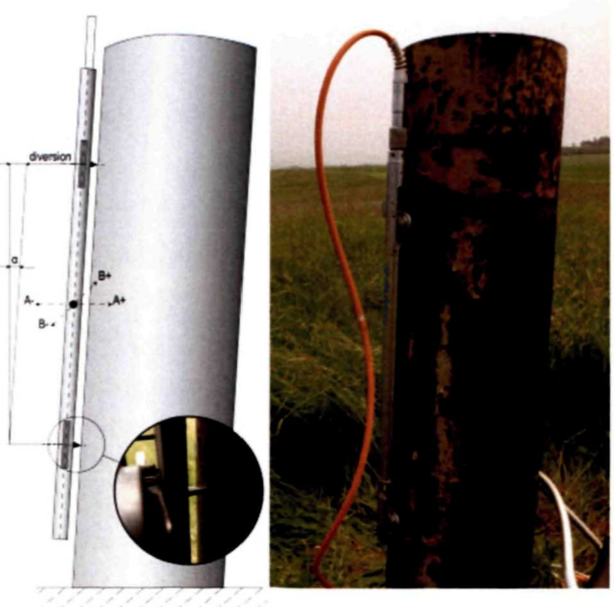

Fig. 7.8 Principle of measurements of change in angle of geodetic pillars by inclinometric probe

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-

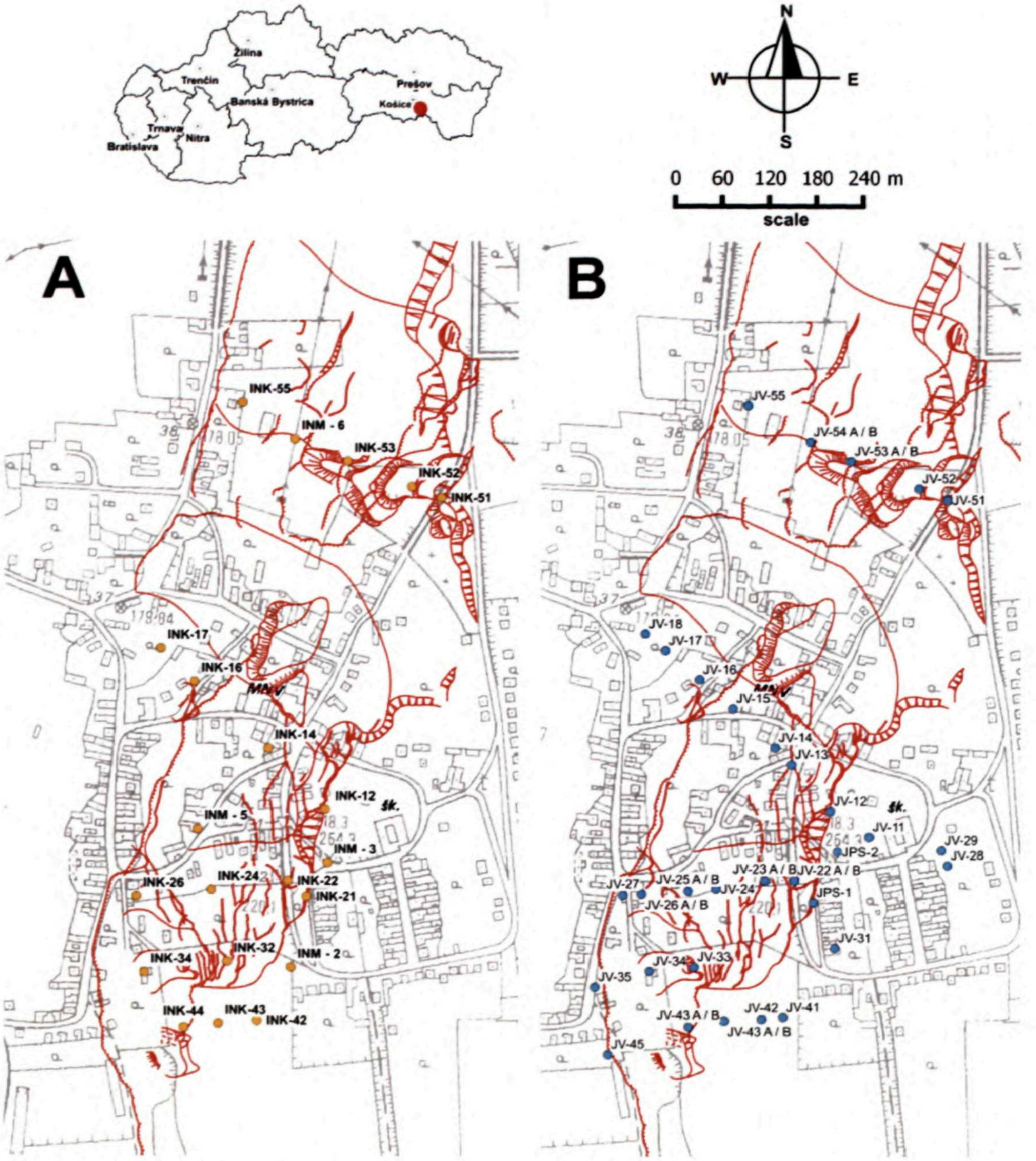

Fig. 7.9 Situation of the landslide area in the Nižná Myšľa Village. A - monitoring network of inclinometric boreholes, B – monitoring network of piezometric boreholes

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.

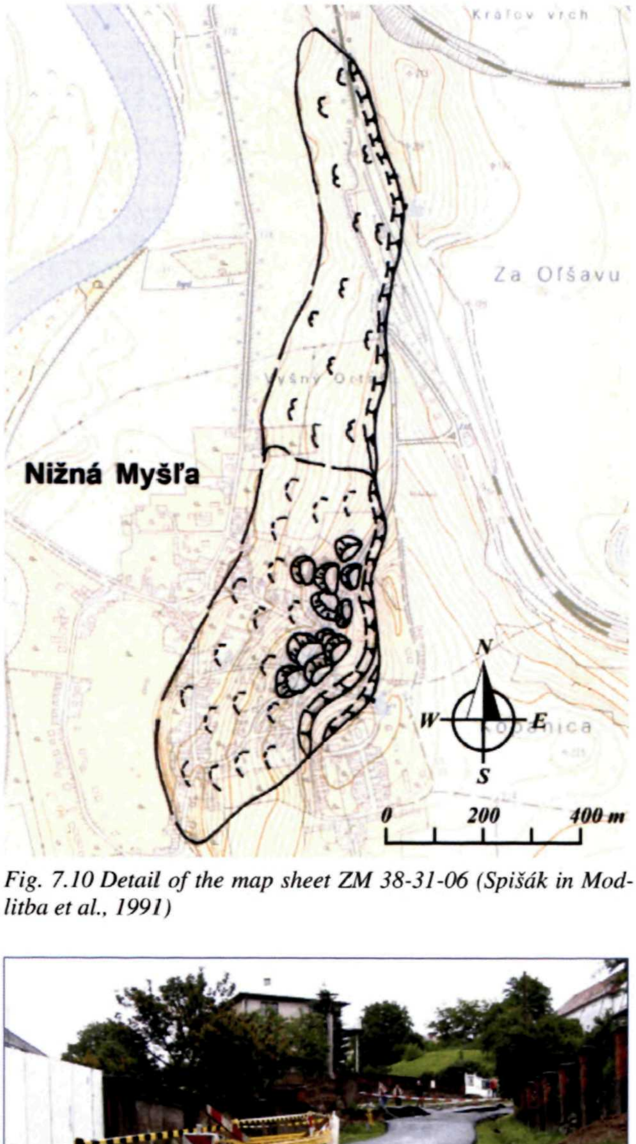

Fig. 7.10 Detail of the map sheet ZM 38-31-06 (Spišák in Modlitba et al., 1991)

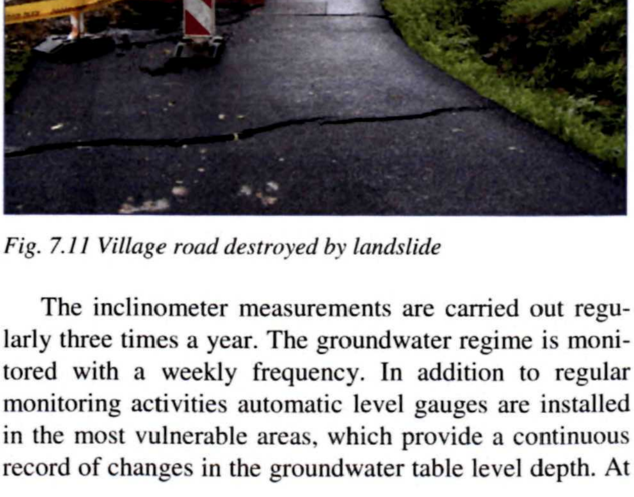
Fig. 7.11 Village road destroyed by landslide

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

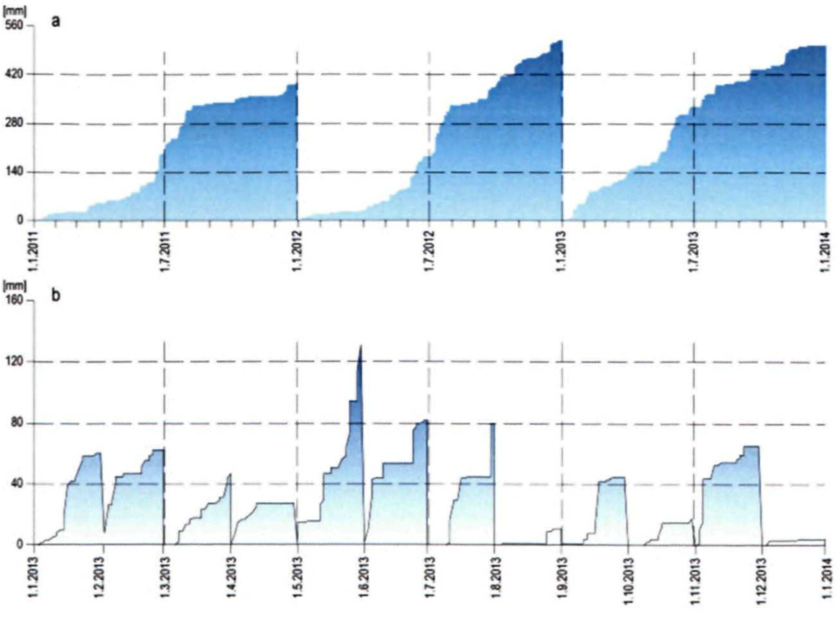

Fig. 7.12 Precipitation totals of the SHMI station Čaňa. a - cumulative yearly precipitation totals in the years 2011 to 2013, b - cumulative monthly precipitation totals in the year 2013

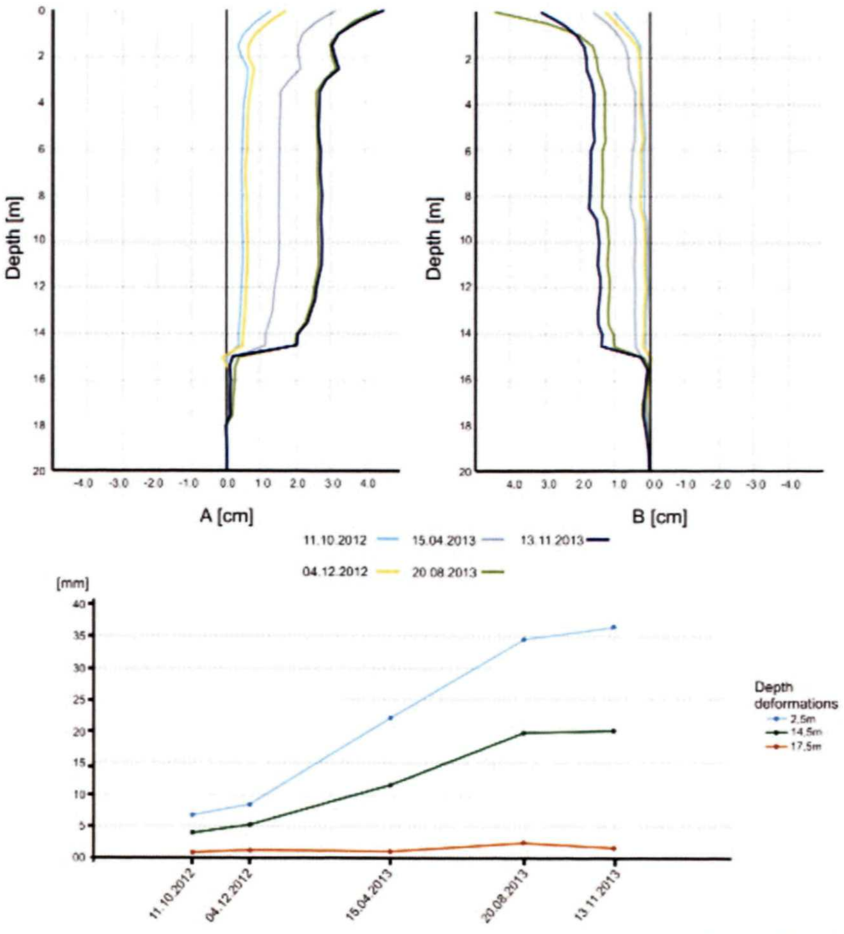

Fig. 7.13 Course of deformation in inclinometric borehole

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 Varhedná 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.

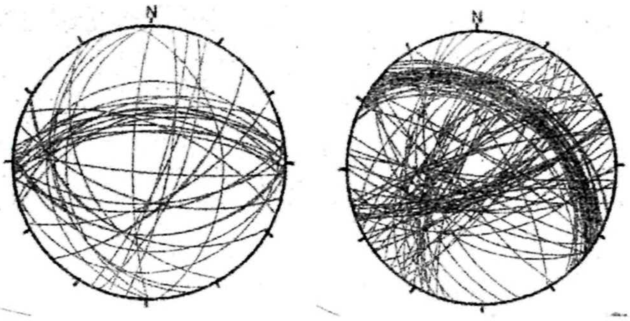

Fig. 7.14 Discontinuity diagram of spatial orientation of discontinuities from field measurements (left) and by ground-based photogrammetry (right)

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

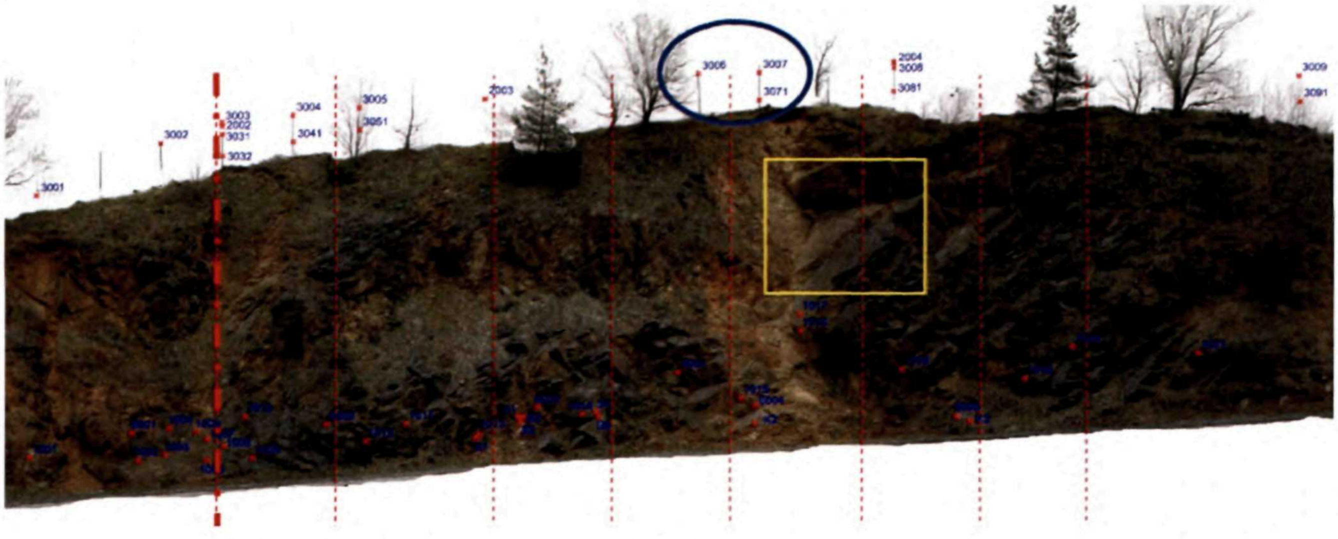

Fig. 7.15 Arrangement of control points and points on fence (atop). Yellow frame indicates the detail on the Fig. 7.16

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-

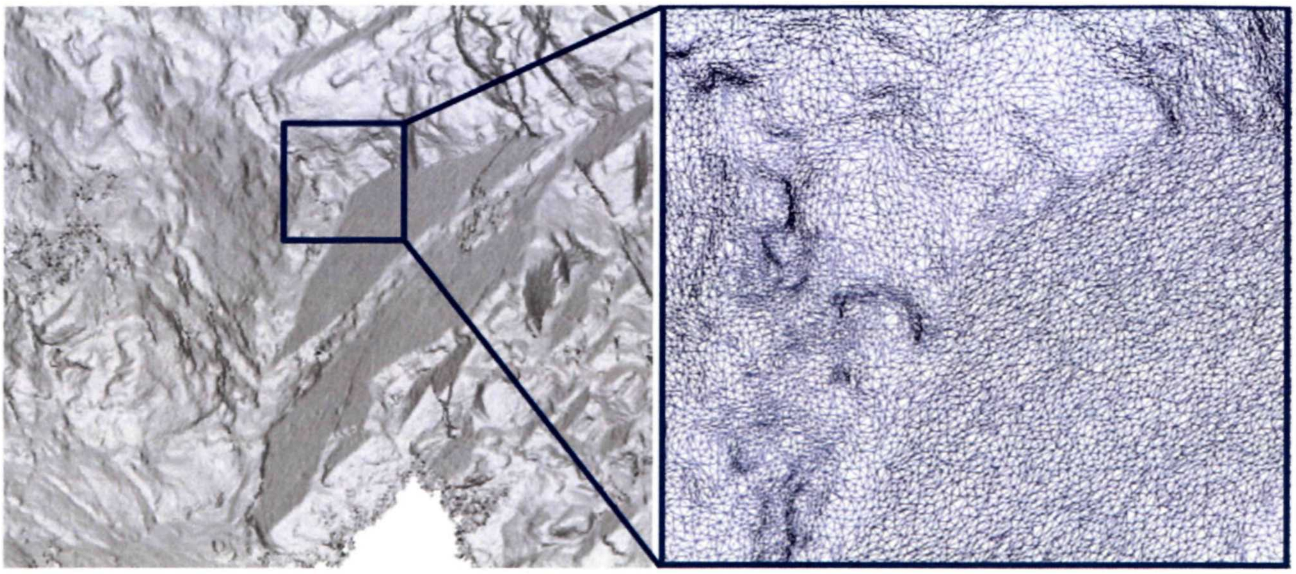

Fig. 7.16 Cloud of points (left) and detail of TIN model (right)

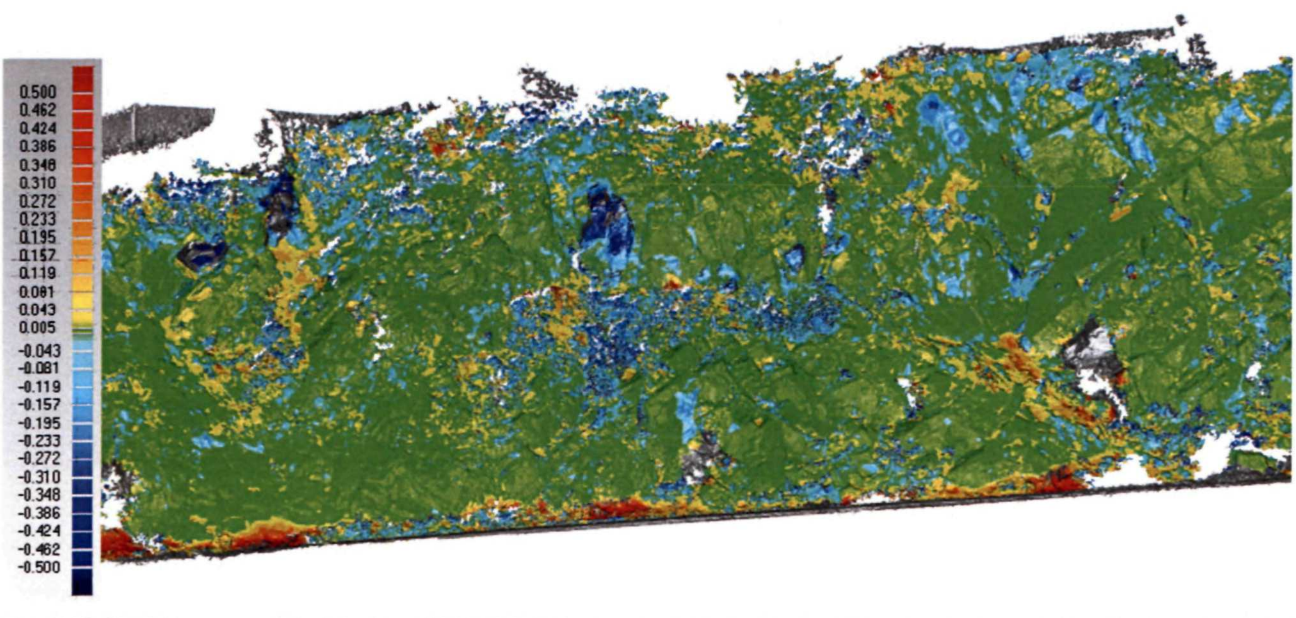

Fig. 7.17. 3D difference model of the period 2011-2013. Green colour highlights the difference of ± 3mm, in blue the loss of material up to –0,40 m, in red increment of material (accumulation of scree, fallen blocks, vegetation), in grey - difference model was not calculated because of missing data

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).

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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.

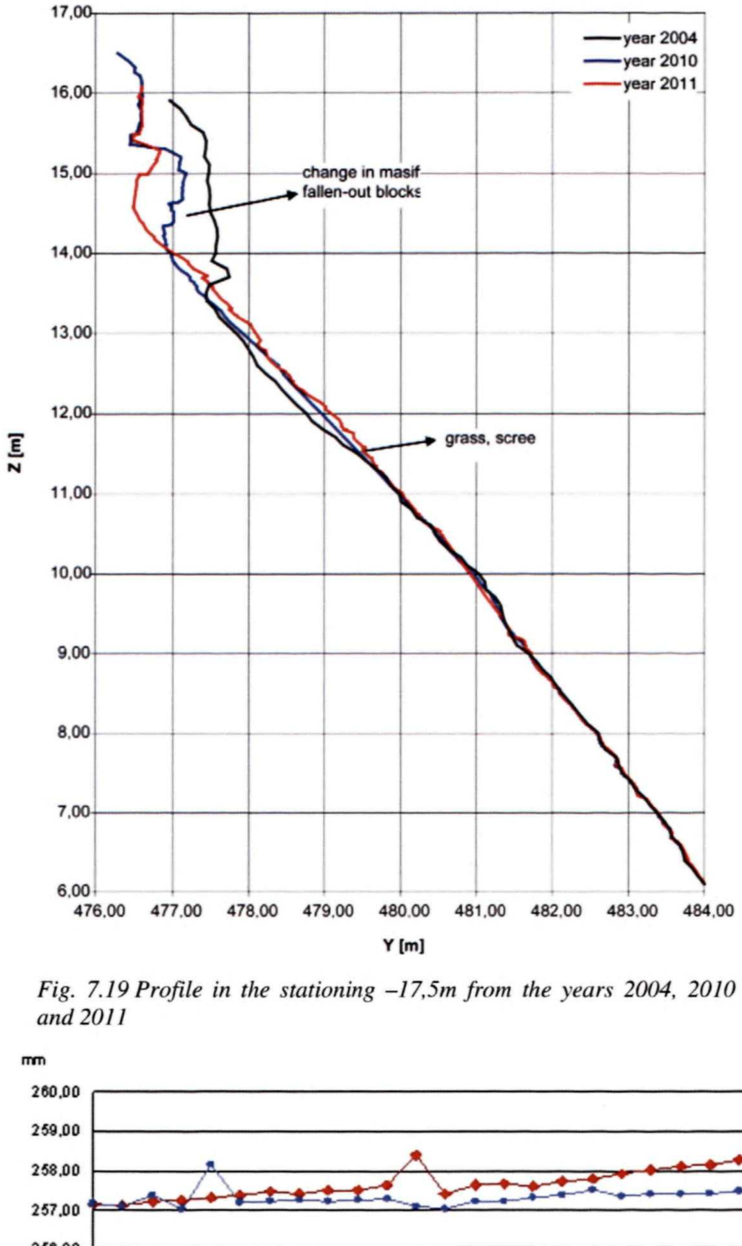


Fig. 7.19 Profile in the stationing –17,5m from the years 2004, 2010 and 2011

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.

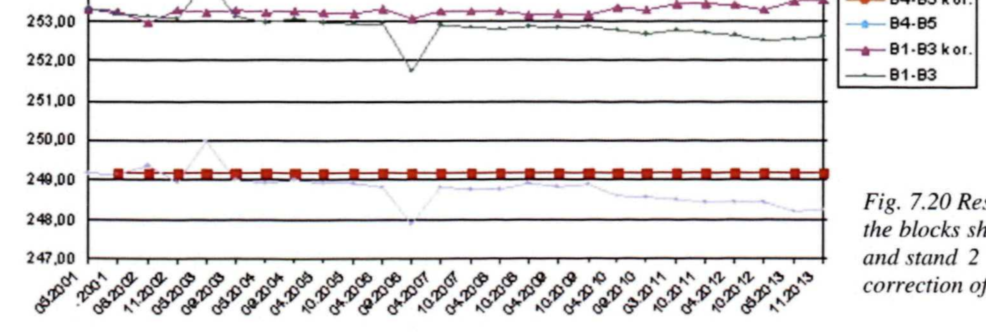


Fig. 7.20 Results of long-term measurements of the blocks shift at the stand 1 (points B1 to B3) and stand 2 (points B4 and B5), graphs with correction of measured values (with affix kor.)

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).

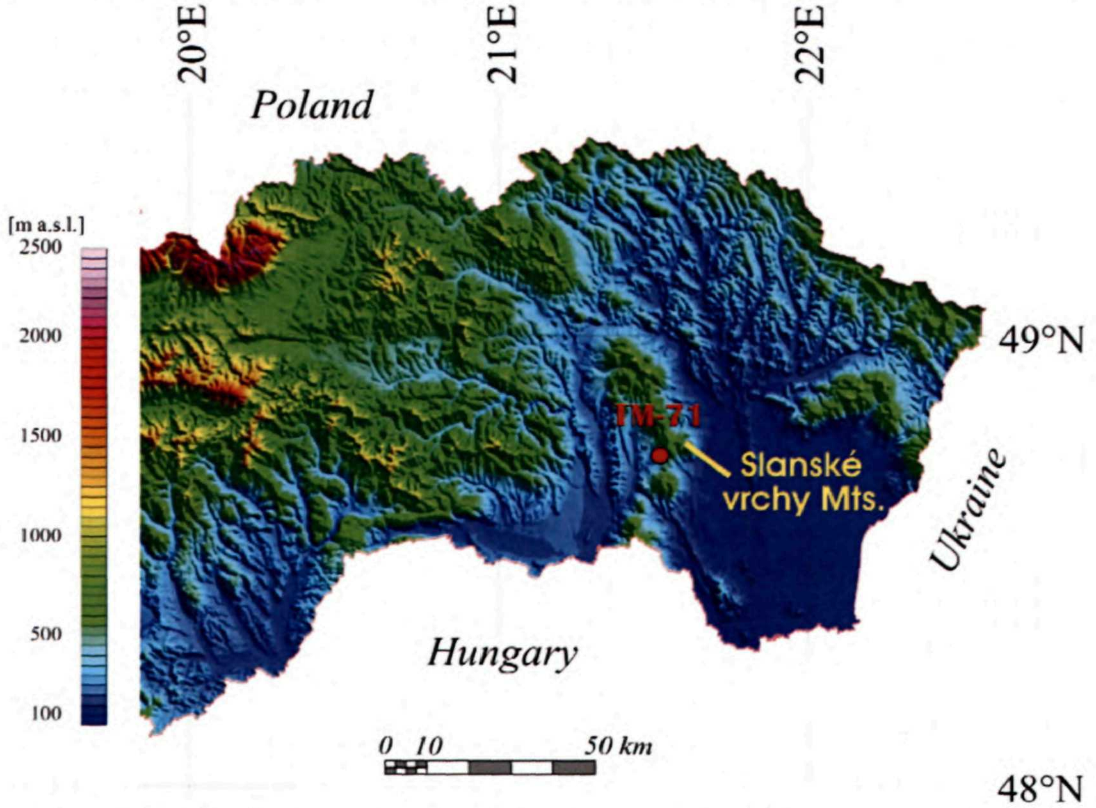
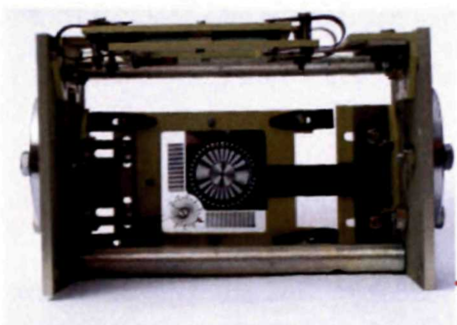


Fig. 7.21 DMR of the Eastern Slovakia with indication of the Slanské vrchy Mts. and Košický Klečenov site



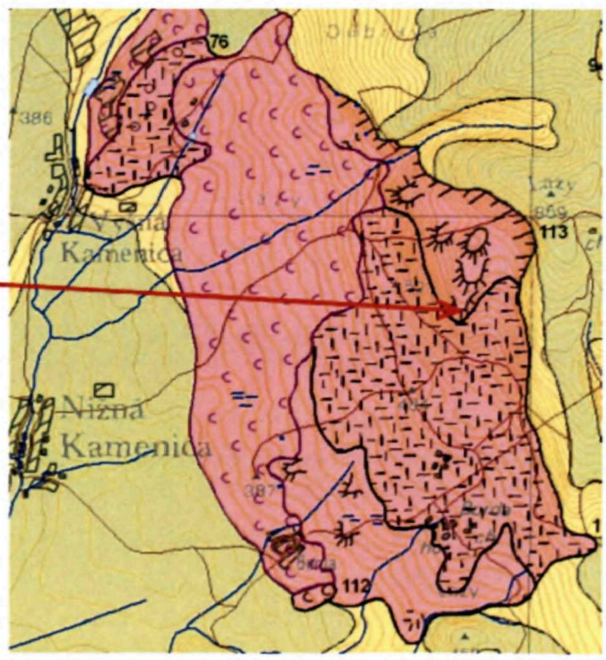


Fig. 7.22 Mechanical-optical dilatometer TM-71 and its installation within a part of extensive slope deformation made of block ridges, block field and potential landslide (Petro in Šimeková et al., 2006)

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).

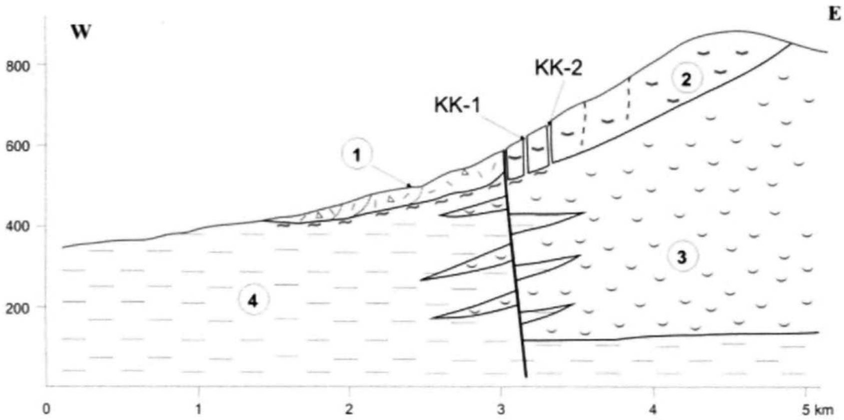


Fig. 7.23 Geological cross-section through the western margin of the stratovolcano Strechový vrch and monitored slope deformation at Košický Klečenov. 1 - potential landslide with block field, in the top part transition into block ridge; 2 - lava flow made of andesites and breccias; 3 – complex of volcaniclastic 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. ($\pi/200$). 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

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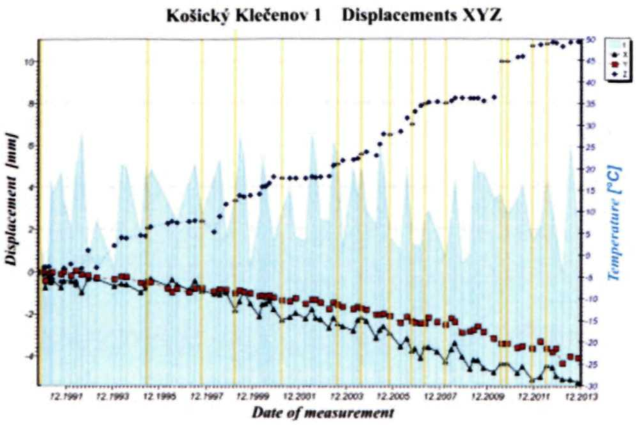

Fig. 7.26a Diagram of shifts along axes x, y, z recorded by dilatometer KK-1 installed in the open crack between bottom and top blocks at the site Košický Klečenov for the period 1990- 2013

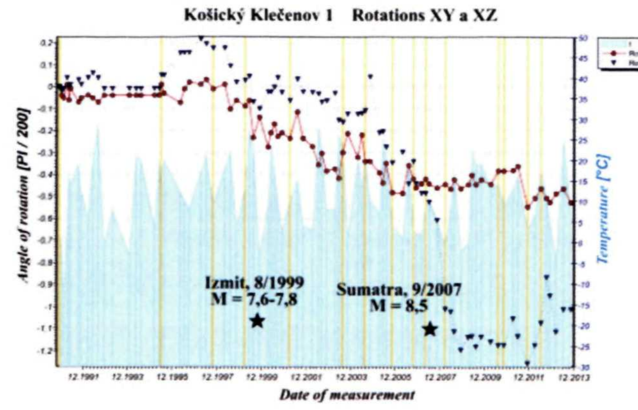

Fig. 7.26b Diagram of rotations in the planes XZ and XY recorded by dilatometer KK-1 installed in the open crack between bottom and top blocks at the site Košický Klečenov for the period 1990-2013

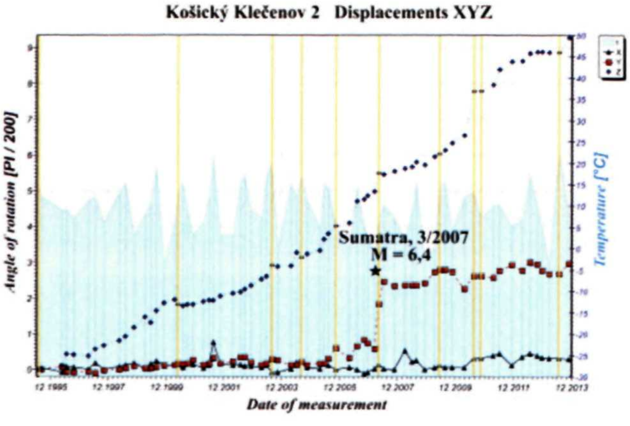

Fig. 7.27a Diagram of shifts along axes x, y, z recorded by dilatometer KK-2 installed in the open crack between upper block and intact massif at the site Košický Klečenov for the period 1995-2013

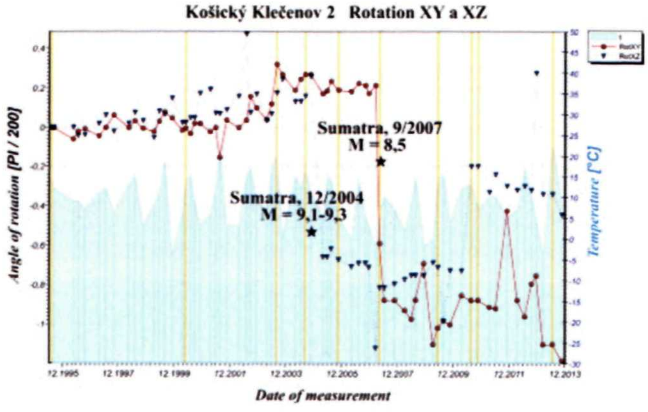

Fig. 7.27b Diagram of rotations in the planes XZ and XY recorded by dilatometer KK-2 installed in the open crack between upper block and intact massif at the site Košický Klečenov for the period 1995-2013

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

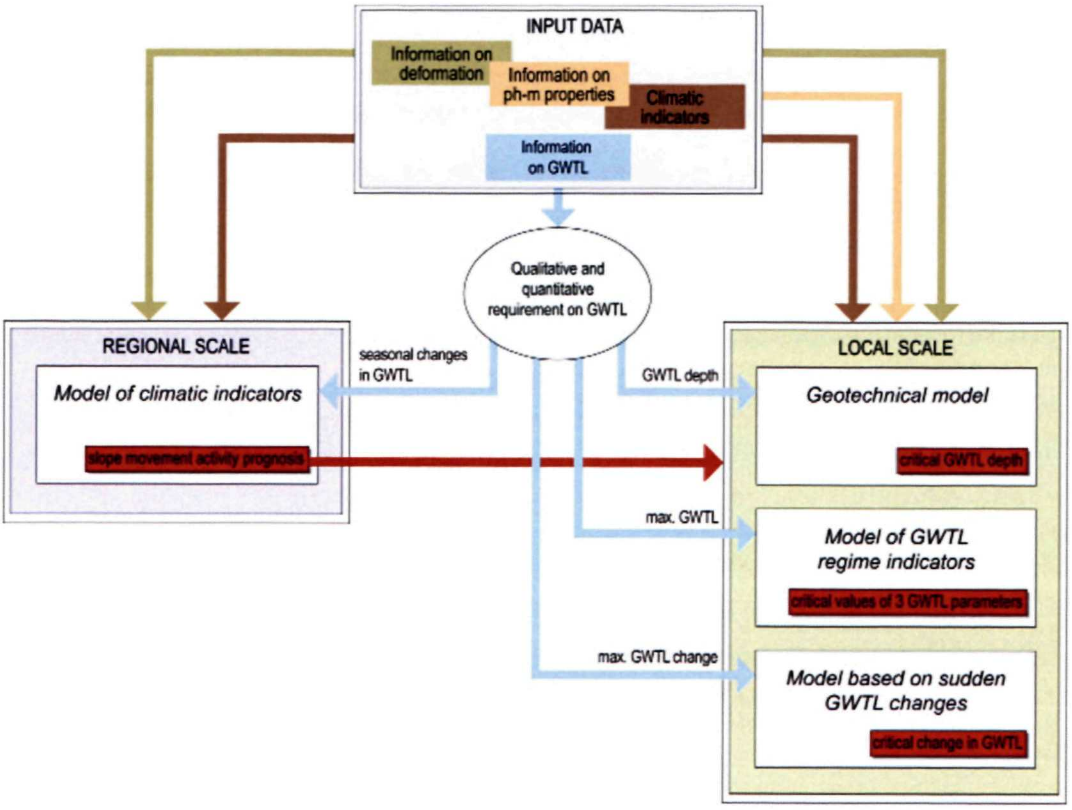

Fig. 7.29 Scheme of early warning system, which was applied at selected monitored sites

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.

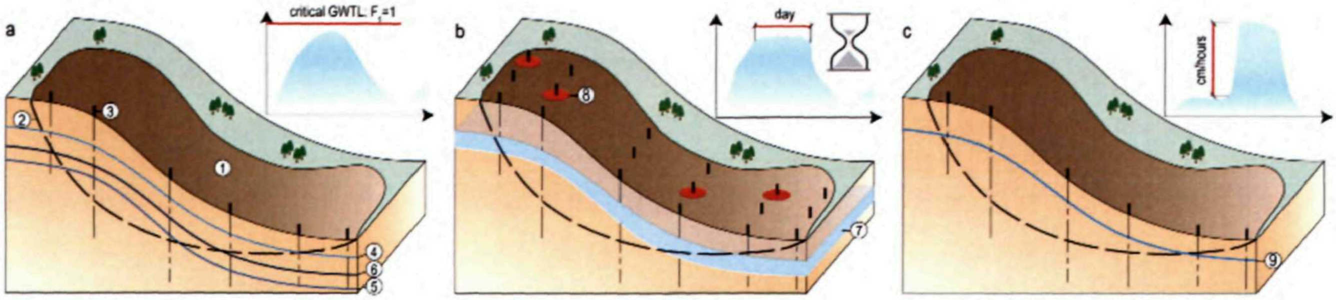

Fig. 7.30 Models of autonomous warning signals based on groundwater table level assessment. a - model based on geotechnical principle, b - model based on results of long-term groundwater table level changes, c - model based on sudden changes in the groundwater table level depth. 1 - landslide body, 2 – 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 analy-

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sis 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.

References

Fussgänger, E., 1985: Poznatky z terénneho výskumu plazivých svahových pohybov travertínových blokov na Spišskom hrade. (*Knowledge from investigation of creep slope movements of travertine blocks on Spišský hrad castle*). Miner. Slov., Vol. 17, No. 1, 15-24. (In Slovak).

Fussgänger, E., Jadroň, D. & Litva, J., 1976: Okoličné – prieskum zosuvu. Záverečná správa z inžinierskogeologického prieskumu. (*Okoličné - landslide investigation. Final report of the engineering geological survey*). IGHP, n. p. Žilina. Manuskript. Archív Št. Geol. Úst. D. Štúra, Bratislava, 163 p. (In Slovak).

Jakob, M., Holm, K., Lange, O. & Schwab, J. W., 2006: Hydrometeorological thresholds for landslide initiation and forest operation shutdowns on the north coast of British Columbia. In: Landslides, N. 3, p. 228-238. http://www.bgcengineering.com/files/publications/KH_Hydro_Meteo_Thresholds_0.pdf (0911-15)

Jančko, J., 1989: Vplyv kvartérnej tektoniky na vývoj územia v severnej časti Košickej kotliny. (*Influence of Quaternary tectonics on the territory development in the northern part of the Košická kotlina Basin, Eastern Slovakia*). Miner. Slov., Vol. 21, No. 5, p. 421-425. (In Slovak).

Huggel, Ch., Khabarov, N., Obersteiner, M. & Ramírez, J. M., 2009: Implementation and integrated numerical modeling of a landslide early warning system: a pilot study in Colombia. In: Natural Hazards, p. 501-518.

http://www.springerlink.com/content/b0t0325571681h02/fulltext.pdf (10-03-11)

Chan, R. K. S. & Pun, W. K., 2004: Landslip Warning System in Hong Kong. In: Geotechnical Instrumentation News - Geotechnical News, s. 33-35. http://www.bitech.ca/pdf/GeoTechNews/2004/GIN_Dec2004.pdf (10-01-20)

Kaličiak, M. (ed.), Baňacký, V., Jacko, S., Janočko, J., Karoli, S., Molnár, J., Petro, Ľ., Priechodská, Z., Syčev, V., Škvarka, L., Vozár, J., Zlínska, A. & Žec, B., 1991: Vysvetlivky ku geologickej mape severnej časti Slanských vrchov a Košickej kotliny v mierke 1 : 50 000. (*Explanations to the geological map of the northern part of the Slanské vrchy Mts. and Košická kotlina Basin at scale 1:50,000*). Bratislava: GÚDŠ, 182-188. (In Slovak).

Kaličiak M. (ed.), Baňacký, V., Janočko, J., Karoli, S., Petro, Ľ., Spišák, Z., Vozár, J., Žec, B., 1996: Slanské vrchy a Košická kotlina, južná časť. (*Slanské vrchy Mts. and Košická kotlina Basin, southern part*). Bratislava: GS SR; http://mapserver.geology.sk/gm50/ mapviewer. jsf?width =699 &height=528

Kopecký, M. 2007: Vplyv klimatických a hydrogeologických pomerov na vznik zosuvov v SR. (*Influence of climatic and hydrogeological conditions on the origin of landslides in Slovakia*). In: Podzemná voda, Vol. 13, No. 2, p. 162-168. (In Slovak).

Košťák, B., 1969: A new device for in-situ movement detection and measurement. Experimental Mechanics 9, 8, Easton, Pa., 374-379.

Košťák, B., 1991: Combined indicator using moiré technique. In: G. Sorum "Field measurements in geomechanics". Proc. 3rd Int. Symp., Oslo, 9-11. Sept. A. A. Balkema, Rotterdam: Brookfield, p. 53-60.

Košťák, B., 1998: Evidence of active tectonic movements in the Krušné Hory Mts. (NW Bohemia). Journal of the Czech Geological Society, 43, p. 287-297.

Košťák, B. & Rybář, J., 1978: Measurements of the activity of very slow slope movements. Grundlagen u. Anwedung d. Felsmechanik. Clausthal: Trans Tech. Publ., p. 191-205

Košťák, B. & Avramova-Tacheva, E., 1988: A method for contemporary displacement measurement on a tectonic fault. Journal of Geodynamics, 10, p. 115-125

Košťák, B. & Cruden, D.M., 1990: The Moire´ crack gauges on the crown of the Frank Slide. Canadian Geotechnical Journal, 27, p. 835-840

Košťák, B. & Sikora, J., 2000: Ověření účinnosti sanačních opatření na Oravském hradě. (*Verifying of the effectiveness of corrective measures at the Orava Castle*). Geotechnika, 3, p. 8-10. (In Czech).

Košťák, B., Cacoń, S., Dobrev, N.D., Avramova-Tačeva, E., Fecker, E., Kopecký, J., Petro, Ľ., Schweitzer, R. & Nikonov, A.A., 2007: Observations of tectonic microdisplacements in Europe in relation to the Iran 1997 and Turkey 1999 earthquakes. Izvestiya, Physics of the Solid Earth, 43, p. 503-516.

Košťák, B., Mrlina, J., Stemberk, J. & Chán, B., 2011: Tectonic movements monitored in the Bohemian Massif. Journal of Geodynamics, 52, p. 34-44.

Liščák, P., Pauditš, P., Petro, Ľ., Iglárová, Ľ., Ondrejka, P., Dananaj, I., Brček, M., Baráth, I., Vlačiky, M., Németh, Z., Záhorová, Ľ., Antalík, M., Repčiak, M. & Drotár, D., 2010: Registration and evaluation of newly evolved slope failures in 2010 in Prešov and Košice regions. In: Miner. Slov., Vol. 42, No. 2, p. 393-406.

Maglay, J. (Ed.), Halouzka, R., Baňacký, V., Pristaš, J. & Janočko, J., 1999: Neotectonic map of Slovakia. Bratislava: Publ. Ministry of the Environment and Geological Survey of the Slovak Republic.

Malgot, J., 1969: Vývoj zosuvných území na okrajoch vulkanických pohorí Slovenska. (*Evolution of landslide territories at the edges of volcanic mountain ranges in Slovakia*). Manuskript. Archív Št. Geol. Úst. D. Štúra, Bratislava, 167 p. (In Slovak).

Malgot, J., 1977: Deep-seated gravitational slope deformations in neovolcanic mountain ranges of Slovakia. Bull. IAEG, Krefeld, 16, 106-108.

Matula, M., Pašek, J., 1986: Regionálna inžinierska geológia ČSSR. (*Regional engineering geology of Czechoslovakia*). Praha: Alfa Bratislava, SNTL. (In Czech and Slovak).

Modlitba, I., Jánová, V., Lobík, M., Vančíková, I., Petro, Ľ., Spišák, Z., 1988: Výsledky registrácie svahových deformácií na území Slovenska v roku 1988 (*The results of inventory of landslide areas in Slovakia in 1988, interim report*). ČZS, názov čiastkovej úlohy IG výskum pre optimálne využitie krajiny a ochranu životného prostredia. Bratislava: GÚDŠ, 1988. (In Slovak).

Modlitba, I., Jánová, V., Kováčik, M., Vančíková, I., Krippel, M., Liščák, P., Petro, Ľ., Spišák, Z., Šarík, M., 1991: Výsledky registrácie svahových deformácií na území Slovenska v roku 1991. (*The results of inventory of landslide areas in Slovakia in 1991, interim report*). ČZS, názov čiastkovej úlohy IG výskum pre optimálne využitie krajiny a ochranu životného prostredia. Bratislava: GÚDŠ, 1991. (In Slovak).

Nemčok, A. 1982: Zosuvy v slovenských Karpatoch. (*Landslides in the Slovak Carpathians*). Bratislava: Veda, 319 p. (In Slovak).

Novotný, J. 2002: Analysis of water effect on slope stability in clayey rocks. In: Acta Montana, 10, p. 51-90.

Ondrejka, J., 1985: Nižná Myšľa – cintorín – zosuv. Záverečná správa z inžinierskogeologického prieskumu. (*Nižná Myšľa - cemetery - landslide. Final report of the engineering geological survey*). Manuskript. Archív Úst. geovied fakulty BERG TU, Košice. (In Slovak).

Ondrejka, P. 2009: Analýza vzťahu medzi vypočítaným stupňom stability a pohybovou aktivitou na príklade zosuvu pri Okoličnom. (*Analysis of the relation between calculated degree of slope stability and kinetic activity of the landslide Okoličné*). In: Miner. Slov., Vol. 41, No. 3, p. 213-224. (In Slovak).

Ondrejka, P., 2010: Systémy včasného varovania na zosuvoch (*Landslide early warning systems*). Dizertačná práca. Katedra inžinierskej geológie. Bratislava: PriF UK, 180 p. (In Slovak).

Ondrejka, P., 2012: Kritické úrovne pri systémoch včasného varovania na zosuvoch. (*Critical levels in early warning systems on landslides*). Geol. Práce, Spr. 119, Bratislava: ŠGÚDŠ, p. 67-78. (In Slovak).

Ondrejka, P. & Wagner, P., 2012: Monitorovanie zosuvov a iných svahových deformácií v období rokov 2002 až 2009. (*Monitoring of landslides and other slope deformations in the period from 2002 to 2009*). Miner. Slov., Vol. 44, No. 4, p. 331-350. (In Slovak).

Ondrejka, P., Wagner, P. & Gróf, V. 2011: Využitie stacionárneho inklinometra na tvorbu systémov včasného varovania na zosuvoch. (*Using of in-place inclinometer for creating early warning systems on landslides*). In: Geotechnika, 1-2, p. 19-23. (In Slovak).

Otepka, J., Menzelová, O., Mesko, M., Čubríková, E., Škripeková, Ľ., Čellár, S., Abelovič, J., Čerňanský, J., Bláha, P., 1983: Hlohovec – Sereď – prieskum a sanácia zosuvov. (*Hlohovec-Sereď - survey and remediation of landslides*). Manuskript. Archív Št. Geol. Úst. D. Štúra, Bratislava, č. 57522, 1983. 120 p. (In Slovak).

Petro, Ľ., Spišák, Z., Polaščinová, E., 1993: Súbor inžinierskogeologických máp 1 : 50 000 - región Košická kotlina a Slanské vrchy. In: Divinec, Ľ. et al., „Súbor regionálnych máp geologických faktorov životného prostredia 1 : 50 000 regiónu Košická kotlina a Slanské vrchy". (*Atlas of maps of environmental geofactors at scale 1:50,000 of the region Košická kotlina Basin and Slanské vrchy mountains*). Manuskript. Archív GS SR Spišská Nová Ves, 103 p. (In Slovak).

Petro, Ľ., Spišák, Z., 1994: Slope deformations in the area of Košická kotlina Basin and Slanské vrchy mountains (Eastern Slovakia). In: R. Oliveira et al. (eds.) "Proc. 7th Int. IAEG Congress". A. A. Balkema, Rotterdam, Brookfield, p. 1585-1590.

Petro, Ľ., Košťák, B., Polaščinová, E., Spišák, Z., 1999: Monitoring blokových pohybov v Slanských vrchoch. (*Block movements monitoring in the Slanské vrchy Mts.*). Miner. Slov., Vol. 31, No. 5-6, p. 549-554. (In Slovak).

Petro, Ľ., Vlčko, J., Ondrášik, R., Polaščinová, E., 2004: Recent tectonics and slope failures in the Western Carpathians. Engineering Geology, 74, 103-112.

Restrepo, P., Cannon, S., Laber, J., Jorgensen, D. & Werner, K. 2009: NOAA/USGS Demonstration Flash-Flood and Debris-Flow Early-Warning System. In: Geophysical Research Abstracts. http://meetingorganizer.copernicus.org/EGU2009/EGU2009-4692.pdf (10-04-03)

Scherer, S., 1999: Metodika hydrogeologického monitoringu na zosuvoch (*Methods of the hydrogeological monitoring on landslides*). In: Podzemná voda, Vol. 5, No. 2, p. 94-104. (In Slovak).

Sláma, M., Gomolčák, M., Komoň, J., Turovský, F., Tunega, O., Mišove, P., Bačo, J., Vrábľová, K. & Pastierik, S., 2012: Nižná Myšľa - sanácia havarijného zosuvu - I. etapa, sanácia geologického prostredia, odborný geologický dohľad. - I. etapa, sanácia geologického prostredia. (*Nižná Myšľa - corrective measures at emergency landslide, first stage*). Geokontakt, s.r.o. Košice. Manuskript. Archív Št. Geol. Úst. D. Štúra, Bratislava, 55 p. (In Slovak).

Spišák, Z., Polaščinová, E., Kaličiak, M., Karoli, S., 1987: Vplyv geologickej stavby územia na vznik a rozvoj svahových deformácií v severnej časti Košickej kotliny a Slanských vrchov. (*Influence of the geological setting upon emergence and development of slope deformations in the Northern part of the Košická kotlina Basin and Slanské vrchy Mts.*). Manuskript. Archív Št. Geol. Úst. D. Štúra, Bratislava, 66 p. (In Slovak).

Stemberk, J., Košťák, B., Cacoń, S., 2010: A tectonic pressure pulse and increase geodynamic activity recorded from the long-term monitoring of faults in Europe. Tectonophysics, 487, p. 1-12.

Stemberk, J., Košťák, B., 2008: Recent tectonic microdisplacement registered in Bedřichov Tunnel "A" in the Jizerské Hory Mts. (N. Bohemia). Acta Geodynamica et Geomaterialia, 5, (152), p. 377-388.

Stercz, M., 2004: SMDilat – aplikácia na vyhodnocovanie meraní dilatometrom TM-71 programovaná v jazyku Delphi pre platformu MS Windows (+ MS Windows XP).

Šimeková, J., Martinčeková, T., Abrahám, P., Gejdoš, T., Grenčíková, A., Grman, D., Hrašna, M., Jadroň, D., Záthurecký, A., Kotrčová, E., Liščák, P., Malgot, J., Masný, M., Mokrá, M., Petro, Ľ., Polaščinová, E., Solčiansky, R., Kopecký, M., Žabková, E., Wanieková, D., Baliak, F., Caudt, Ľ., Rusnák, M., Sluka, V., 2006: Atlas máp stability svahov SR v M 1:50 000, orientačný IGP. (*Atlas of Slope Stability Maps SR at 1:50,000*). Bratislava: MŽP SR, INGEO-ighp, Katedra geotechniky SvF STU, SGIDŠ, GEOKONZULT, PriF UK. (In Slovak).

Thut, A., Gróf, V., 2010: Geotechnical and Hydrogeological Measurements, Safety and Risk in Slovakia and Switzerland. 4. Danube-European Conference on Geotechnical Engineering, Bratislava, Slovak Republic, June 2-4, 2010, p. 242.

Tometz, L. et al., 2010: Nižná Myšla - havarijný zosuv, inžinierskogeologický prieskum (*Nižná Myšľa – emergency landslide, engineering geological investigation. Final report*). Záverečná správa geologickej úlohy. Manuskript. Archív Úst. geovied fakulty BERG TU, Košice. (In Slovak).

Vlčko, J., Petro, Ľ., 2002: Monitoring of subgrade movements beneath historic structures. In: J. L. van Roy & C. A. Jermy (Eds.) „Proc. of 9th Int. Congress IAEG", Durban, South Africa, (CD-ROM), p. 1432-1437.

Vlcko, J., 2004: Extremely slow slope movements influencing the stability of Spis Castle, UNESCO site. Landslides 1-1, p. 67-71.

Wagner, P., Iglárová, Ľ. & Petro, Ľ., 2000: Methodology and some result of slope movements monitoring in Slovakia. In Miner. Slov., Vol. 32, No.4, p. 359-367.

Wagner, P., Ondrejka, P., Balík D. a Žilka, A., 2012: Hodnotenie výsledkov monitorovacích meraní na zosuvoch. (*Evaluation of monitoring measurements results on landslides*). In: Miner. Slov., Vol. 44, No. 2, p. 141-148. (In Slovak).

Wagner, P., Ondrejka, P., Iglárová, Ľ. & Fraštia, M., 2010: Aktuálne trendy v monitorovaní svahových pohybov. (*Current trends in the monitoring of slope movements*). Miner. Slov., Vol. 42, No. 2, p. 229-240. (In Slovak).

Wagner, P., Ondrejka, P., Ondrášiková, B. & Liščák, P., 2014: Niektoré problémy tvorby systémov včasného varovania na zosuvoch. (*Some problems of landslide early warning systems creation*). In: Ageos, Vol. 6, No. 1, p. 71-82. (In Slovak).

Wagner, P., Scherer, S., Jadroň, D., Mokrá, M. & Vybíral, V. 2002: Analysis of landslide monitoring results. In: J. Rybář, J. Stemberk & P. Wagner (red.): „Landslides", Proceed. The first European Conference on Landslides. A.A. Balkema, p. 471- 476, ISBN 90-5809-393 X.

Záruba, Q. & Mencl, V. 1987: Sesuvy a zabezpečovaní svahů. (*Landslides and their control*). Druhé přepracované a doplněné vydání. Praha: Academia, 340 p. (In Czech).