Mineralia Slovaca, 42 (2010), 393 – 406
ISSN 0369-2086

Registration and evaluation of newly evolved slope failures in Prešov and Košice regions in 2010

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Abstract

Slope deformations represent the most dangerous exogenous geodynamic phenomenon in the Slovak Western Carpathians, posing a threat for humans and their property as well as for the natural environment. In 2010 we have evidenced numerous landslides throughout Slovakia; the majority of them evolved in the Eastern Slovakia, generated by the excessive precipitation in the late spring. This situation lead to a number of emergency situations in the municipalities of the region and the Ministry of Agriculture, Environment and Regional Development of the Slovak Republic put in charge the geologists from the State Geological Institute of Dionýz Štúr (ŠGÚDŠ) to register and assess the extent and magnitude of evolved slope deformations. For the first time in the history of systematic inventory of the geological phenomena in Slovakia we made use of a very precise, "scaleless" levelling of the slope deformations in the territory morphology, based on GPS technology. This paper presents the application of this quite new method from the in situ measurements to the final output in the form of GIS database along with the classification of the slope deformations registered according to their socio-economic relevance.

Key words: slope deformation inventory, precipitation, socio-economic relevance, GPS – Global Positioning System, GIS – Geographic Information System

Introduction

Slope deformations represent one of the most important manifestations of exogenous geodynamic processes not only in Slovakia, but in the whole Central Europe. Every year they cause a damage to roads, property, agricultural and forest land as well as environmental degradation. These phenomena are usually found in a relatively small number; generally due to a contribution by the inappropriate activity of man. In 2010, however, we have experienced an unprecedented evolution of slope failures, which has been undoubtedly caused by the extremely high rainfall in the month of May, in many places exceeding long term means 4 to 5 times. Particularly affected are mainly the territories of the Eastern Slovakia (Košice and Prešov regions), especially the territories of the Central Carpathian Paleogene Basin, the Flysch Belt, and also a narrow zone of the Klippen Belt.

In dozens of villages in the Eastern Slovakia the situation called for a declaration of emergency. The communication between the Section of Crisis Management and Civil Protection (CO) of the Ministry of Interior, with the Division of Geology and Natural Resources of the Ministry of Agriculture, Environment and Regional Development (hereinafter MPŽPRR SR) has created a list of 73 sites, in which an emergency situation was identified. Highly publicized were the cases of the municipalities Nižná Myšľa and Kapušany; the evacuation of some houses was necessary in a number of other villages in the Eastern Slovakia, due to a scale of damage to buildings. Similarly, the road infrastructure was not only affected by floods, but also landslides, which made some villages virtually cut off from the outer world (Sulín, Medzibrodie, Kače).

The objectives of the project were as follows:

– Registration of new slope deformations in the period after the floods of 2010 in the Prešov and Košice regions except the city of Košice and community Nižná Myšľa.

– Assessment of current situation in the localities where the engineering geological survey has already started.

– Distribution of registered slope deformations in the categories of their socio-economic significance (threat to life and property).

– Implementation of emergency measures.

– Proposal slope deformations for engineering geological exploration.

– Proposal for a method for remediation of selected sites or carried out remediation.

A specific requirement was that the landslides in the city of Košice and Nižná Myšľa were excluded from the exploration area; since at that time the local slope deformations were addressed by other organizations, thus avoid duplication of work.

Overview of up to now slope deformation investigation

First registration of slope movements on the territory of Slovakia was made between 1962 – 1964 by the Geological Institute of Dionýz Štúr in Bratislava (ŠGÚDŠ), Department of Geotechnics of Technical University in Bratislava, Department of Engineering Geology of the Faculty of Natural Sciences, Comenius University (CU), Bratislava and the Central Geological Institute in Prague. Slope movements were registered mainly in the investment--relevant areas, especially around roads, rivers, towns and villages. The records on the occurrence were mostly done on punch cards and drawn into the maps of 1 : 25 000 scale. The results of this first phase of registration are archived in Geofond.

The second stage of inventory of slope deformation was conducted in 1974 – 1978 by the Department of Geotechnics of the Technical University in Bratislava. On the basis of new knowledge about conditions for the occurrence of landslides in the mountain areas the new slope failures were registered in the areas of the Nízke Tatry, Liptovské Tatry, Vysoké Tatry, Malá and Veľká Fatra Mts., etc., as well as in some lower mountain ranges and basins. Their findings were very valuable for understanding the patterns and conditions of the emergence and development of mountain slope deformations in Slovakia. This effort has contributed to a development of a prominent school of Czechoslovak engineering geologists, dealing with landslides, around Nemčok and co-workers (for instance, Nemčok, 1982).

In 1981, the workers of ŠGÚDŠ, Department of Engineering Geology, began the third stage of registration of slope deformations in Slovakia. The aim was to create a new register of slope deformations in accordance with the national Guidelines for the registration of landslides and other dangerous slope deformations. They registered slope deformations of the Flysch Region (Jánová, 2000), mainly, covering also the flysch territories of the Eastern Slovakia (along with Eastern Slovakia neovolcanites and neotectonic depressions).

The output maps were of the scale of 1 : 10 000 containing slope deformations and their documentation in the form of the record sheets for computer processing.

In the scope of the geological projects supervised by the Ministry of Environment various geological organizations carried out extensive research of the slope deformations in particular areas of the Eastern Slovakia (Jánoš et al., 1994; Masný et al., 1997a, b and 1998a, b; Grenčíková et al., 2002; Grenčíková and Žabková, 2002; Demian et al., 2003).

A synthesis summarizing the nearly 50-year regional research in the field of slope deformations was the Atlas

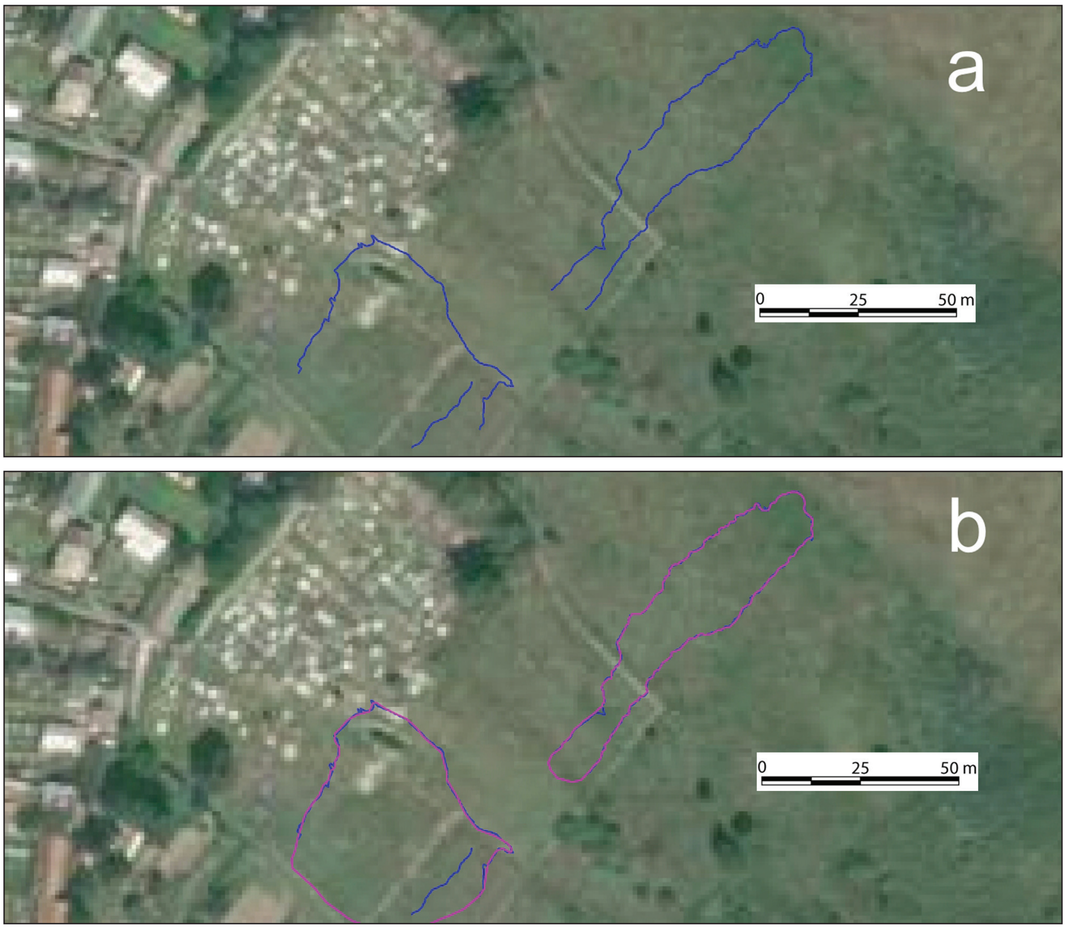

Fig. 1. Accuracy of GPS measurements – class 1. a – rough line of GPS measurement; b – the same line smoothed.

of slope stability maps in SR at scale 1 : 50 000 (Martinčeková and Šimeková et al., 2007). Within this project there have been reviewed results of registration of slope deformations, the final reports of landslide site surveys and scientific and professional publications. The geological project also conducted field work (Kopecký et al., 2008), which consisted of:

– Harmonization of the evaluation of damaged areas;

– Verification of unsatisfactory, or contradictory data on slope movements, retrieved from archival materials;

– Reconnaissance in uncharted territory to detect dangerous slope deformations, especially those that already threaten the civil engineering works.

A total of 21 190 slope deformations were registered, which cover 5.25 % of the area of Slovakia.

Methodology

In principle, the methodology consisted of the following successive steps in the field survey followed by the analysis of the results:

Field works:

a) Identification of slope deformations in the field;

b) The levelling of slope deformations using a GPS device;

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

d) Completion of the special-purpose data sheet.

a) *Identification of slope deformations in the field*

In the course of mapping work and the evaluation results, we followed the methodology approved in the project of geological problems. Given the urgency of the situation, we first registered the landslide sites, in which through the communication between the Section of Crisis Management and Civil Protection of the Ministry of Interior with the Division of Geology and Natural Resources of the Ministry of Agriculture, Environment and Regional Development an emergency situation was identified. In addition, we have co-registered other slope failures, because we assumed that not in all locations such emergencies have been reported, which has been also confirmed in several locations, for example in Ďačov. Thus we have to 11. 7. 2010 registered about 250 slope deformations. We prepared the first set of primary information for the Division of Geology and Natural Resources with the identification of critical landslides:

1. with immediate damage/threat to the lives and property of citizens;

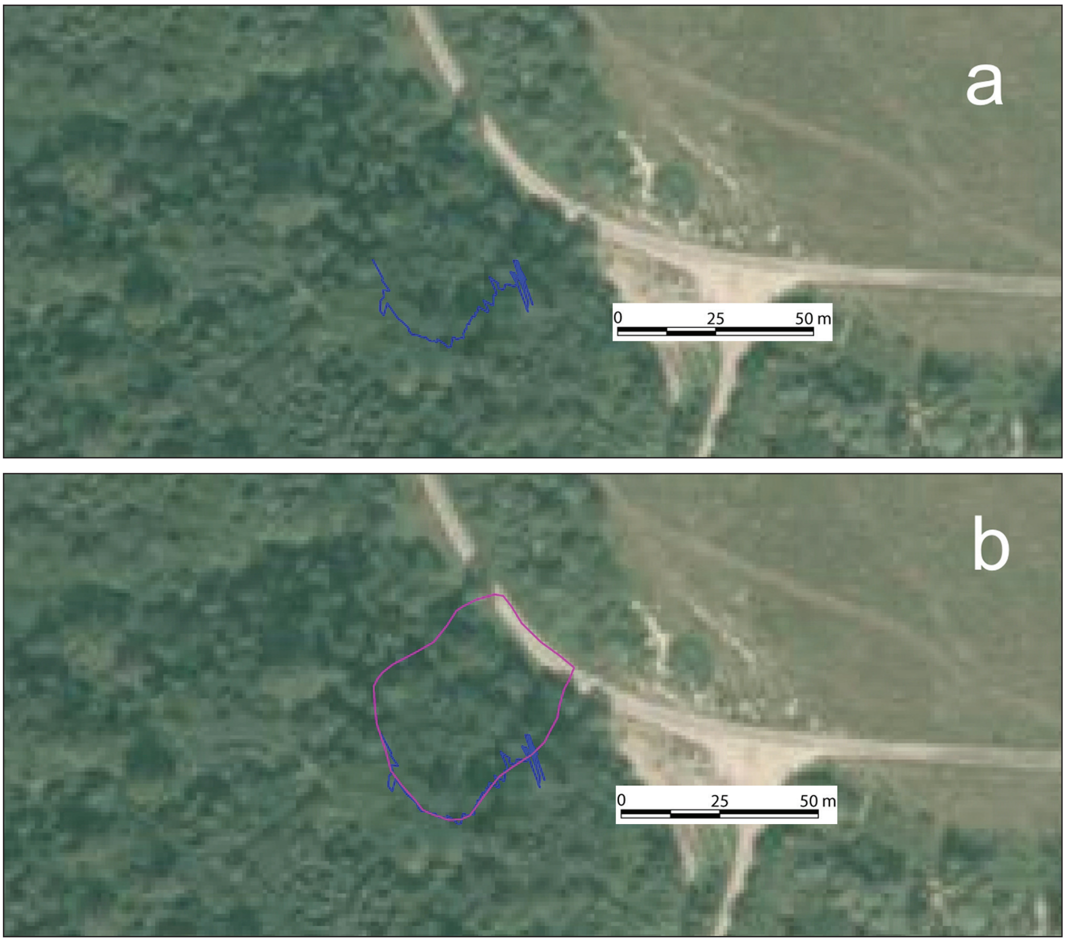

Fig. 2. Accuracy of GPS measurements – class 2. a – rough line of GPS measurement; b – the same line smoothed.

2. with immediate damage/threat to infrastructures;

3. with immediate damage/threat to overhead and underground pipelines (transmission lines, pipelines, water pipelines, telecommunication cables, etc.).

After providing the initial information for MPŽPRR SR we continued in registration of the landslides in parts of areas which have not been mapped yet. In many cases, we communicated with the local administration, or directly with affected citizens. By 29. 10. 2010, we registered 551 slope deformations, the vast majority of landslides which have arisen in the period May – July 2010.

b) *Levelling of slope deformations, using a GPS device*

In the course of field mapping, provided the conditions were acceptable, we used a Trimble GPS unit GeoXT/GeoXH 2005, GIS category with sub-meter accuracy of recording. This device made records of linear trajectories of all major elements of landslide morphology – main scarps, transverse and longitudinal cracks and edges of the accumulation zones. In the case of unavailability of these elements we have recorded with the highest possible precision a pinpoint within an apparent geometric centre, or on conspicuous element of landslide (usually in the centre of head scarp or accumulation zone).

Since the accuracy of recorded data depends on the quality and intensity of the satellite signal, which varies depending both on the terrain conditions (relief topography, vegetation density, etc.), as well as on the fluctuating availability and configuration of the satellites during the day, we divided the data into the following 6 grades (GIS database field „kvalita“):

Class 1: Data recorded with the highest possible precision of the instrument, with an average error of up to 1.5 m, assuming the availability of signals from more than 5 GPS satellites and additional signals from the European Geostationary Navigation Overlay Service (EGNOS). The accuracy of orientation was close to 0.5 m level. Thus, the recorded data are virtually “scaleless” and can be used in accordance with arbitrarily precise map data, including cadastral maps of the largest scales, for example in quantification of damage on individual lots, without the need for additional geodetic survey. With such accuracy **173 slope deformations** were recorded. An example of a contour line retrieved from a GPS measurement is in Fig.1a, the same object with a smoothed line is in Fig. 1b.

Class 2: Data with relatively high accuracy with an error ranging from 1.5 to 7 m. The error was caused in most cases due to unavailability of sufficient number of satellites due to improper daytime (usually around noon), due to dense vegetation or improper configuration of terrain (steep slopes with a strong signal shielding effect). The leap in accuracy compared to the class 1 was mainly due to the unavailability of the signal from the EGNOS satellites. The data are compatible with the map at scales smaller than 1 : 2 000. All in all we have recorded **227 slope deformations** of this quality. An example of a contour line retrieved from a GPS measurement is in Fig. 2a, the same object with a smoothed line is in Fig. 2b.

Class 3: Linear elements with the lowest precision recorded, yet acceptable with an adequate “safe” device sensitivity reducing. This way recorded data were collected in the areas with very unfavourable terrain configuration (usually in a forest on steep slopes), where it was necessary to record at least any indication. Deviations within acceptability limits ranged from 7 to 20 m. Data can be considered spatially compatible with maps at scales 1 : 5 000 – 1 : 10 000. With such low accuracy **12 objects** were recorded.

Class 4: Slope deformations recorded as a single point or more points on significant landslide morphology elements, for example, one point on the head scarp (highest point), one in an accumulation zone and two points on side edges, etc. The reasons for the single point measurements could be various: the unavailability of sufficient number of satellites, even during prolonged observations (more than 5 minutes – in this case point entry was the only one that could be obtained), or unavailability of all elements of the slide – dense stand of bush, shrubs, fenced private property, interference with the watercourse, etc. The body of the slope deformation was plotted on the basis of these point measurements within the orthophoto at scale 1 : 5 000, or within digital matrix ZM10 maps at scale 1 : 10 000. In this class of accuracy **31 slope deformations** were recorded.

Class 5: Slope deformations recorded as a single point using less accurate GPS devices (tourist navigation devices, PDA devices, car navigation, etc.). Despite the fact that for these data we do not have available information on the mean error, their accuracy can be assessed still compatible with the maps in scale 1 : 10 000, like in class 4. Number of objects thus recorded is **18**.

Class 6: Within this category we include slope deformations, which were plotted in a map without GPS levelling, either on the ground or in the office. They were usually drew into basic map 1 : 10 000 (ZM10), or in orthophotos (1 : 5 000) and subsequently digitized into a vector format required. By this way altogether **90 slope deformations** were plotted, particularly in the Košice Region.

Beside the division into classes the database contains the exact figure of the average positional accuracy (median difference in m) as well as the maximum error observed during the observations for the device Trimble Geo (fields “horz_avg” and “horz_worst”).

Fig. 3. Landslide Lužany pri Topli.

c) *A detailed photo documentation of the landslide body and the damaged or threatened infrastructure*

Photographic documentation was performed by digital cameras of different brands; minimum requirement for quality resolution was 3.2 Mpi. After a refinement of a "raw" Photo-catalogue we have got the set of 2 380 photos of 544 sites (Fig. 3).

d) *Completion of special-purpose data sheet*

For the purposes of field research, we developed special-purpose data sheet, in which we usually inserted required data directly in the field. The inventory sheets became the basis for creating special-purpose database.

Office processing

Completion of GIS database

GPS data measured in the field were converted into GIS format using the utilities supplied to the GPS device Trimble GeoXT. Since this device is capable of ground-based recording in the form of vector lines, conversion into GIS represented a relatively trivial operation.

However, the original lines measured in the field were retrieved in the "raw" form, it means they contained errors and various variations due to sudden changes in the quality of the record ("jagged" lines during the loss of satellites under the trees, etc.); thus they were not appropriate for the final drawings into the GIS database. Therefore it was necessary to make additional corrections, particularly those in classes 2 and 3 of the recording quality. Thus additionally smoothed lines were converted into closed polygons representing the final shape of the landslide. For each polygon there were assigned the tabular data.

Data on the area and perimeter of individual landslides have been derived from the classical features of GIS programmes (MapInfo Professional and ESRI ArcGIS). Similarly, other data resulting from the geographical location of landslides (cadastral territory, district, map sheet ZM10, etc.) were automatically derived from the GIS documents (SVM 50 database).

Information on the geological setting of the slope deformation environ was derived through a combination of field records and the digital geological map at scale 1 : 50 000 (Káčer et al., 2005). As a relatively positional accuracy of this map does not correspond to the accuracy of our data retrieved from GPS contouring, we could not proceed in this case automatically using the GIS spatial functions. The geological map was compared with each mapped slope deformation separately and corresponding geological map unit was assigned to relevant slope deformation based on our expertise.

For each polygon there were also assigned the values of the average slope gradient and average slope aspect (fields "slope_avg" and "aspect_avg"). These values were derived from a raster Digital Elevation Model at a scale of 1 : 10 000 (drawn from the documents of ZM10, Esprit, Ltd., B. Štiavnica), elaborated in the scope of the project Integrated Landscape Management (Malík, 2007), with positional resolution of the corresponding grid cell size of 20 x 20 m.

The mean values of the slope gradient and exposure were assigned to each slope deformation on the basis of the average values in all grid cells located inside the slope deformation body. For this purpose, there were standard statistical programmes implemented in GRASS GIS, version 6.2.

The final GIS database consists of 66 data fields; 36 of them contain data of technical character (accuracy of GPS record, date and time of observation, author of the record, etc.) and the rest of the fields store information on the slope deformation from the geological point of view (engineering geological, hydrogeological, geomorphological, etc.). The complete structure of the GIS database is presented in Tab. 1.

Geological-tectonic setting

Evaluated slope deformation are linked to the geological units in which they were evolved; the geological data are retrieved from the digital regional geological maps at scale 1 : 50 000 and lithostratigraphic codification legend used in them.

From the North the geological setting of the area of interest includes the Outer Carpathians (Flysch Externides), Klippen Belt, the Central and more internal units.

The sequence of geological units, registered as a risk in the region, is the following: Quaternary sediments (q), Flysch Zone units (f), Klippen Belt (mk), Neogene of the East Slovakian Neogene Basin (ng), Neogene volcanics (n), units of the Central Carpathian Paleogene Basin (pg), Central Carpathian Core mountains units crystalline of the Čierna hora Mts. (kr), Hronicum of the North Gemericum (mt) and Paleozoic sediments of Gemericum (pm).

The main geological units, affected by the slope deformations are complexes of Quaternary and Flysch Zone dominated by argillaceous rocks with slaty cleavage. The most abundant were the slope deformations in the Zuberec and Huty Formations, Strihov Formation, Bystrica Formation and variegated talus deposits. **q8, q9, q16, q18, q19, q20, q21, q24, q43, q61 Combined talus deposits (85 registered landslides).** This is a mixture of deluvial-solifluction colluvial and talus debris of block, stony-stony, sandy-stony and sandy loams and loamy sandy to loamy polygenetic slope loams in only an estimated thickness from 1 to 5 meters.

f56 Strihov Fm. (54 registered landslides) was distinguished in the Krynica Unit of the Magura nappe in the Eastern Slovakia. It is a thick-bedded flysch complex with a predominance of greywacke sandstone. The sandstone layers are from 0.25 to 3 meters thick. There occur also bodies of turbidite sandstones and disintegrating conglomerates up to 10 m thick, with pebbles to blocks of exotics and Mesozoic carbonates. The ratio of sandstone to claystone is 1 : 10. The total thickness of the formation is about 900 m.

f62 Bystrica Fm. (42 landslides registered) represents a huge flysch complex, which is dominated

Tab. 1
GIS database structure

Field Name	Type	Explanations
ID	int	Identifier
ID_TEREN	char(10)	Interim field identifier
NAZOV_MZP	char(150)	Designation of slope deformation
MZP_LABEL	char(150)	Designation of the slope deformation with diacritics
NAZOV_SSF	char(150)	File label in the GPS Trimble device
INE_NAZVY	char(150)	Equivalent labels in the course of the project solution
KU	char(75)	Cadastre name
OKRES	char(75)	District
ML_ZM10		Map sheet 1 : 10 000
ML_SM5_OFM	char(25)	Map sheet 1 : 5 000, at the same time valid for ortophoto maps layout
MAPOVALI	char(150)	Mapping geologists names
KEDY_DATUM	date	Date of mapping
KEDY_CAS	char(75)	Time of mapping
MIN	float	Time of GPS observation in minutes
KVALITA	float	Quality class
HORZ_AVG	float	Mean horizontal error
HORZ_WORST	float	Largest horizontal error
RCVR_TYPE	char(50)	Type of GPS device
KATALOG	char(75)	File label with representative photo
SPRAC	date	Date of data processing
KATEGORIA	char(5)	Category of socio-economic significance
PRIESKUM	logical	Landslide designed for engineering geological survey
AREA	float	Slope deformation area (ha)
PERIMETER	float	Slope deformation perimeter (m)
AVG_SLOPE	float	Mean slope angle
AVG_ASPECT	float	Mean slope aspect
SIDE	char(5)	Slope aspect calculated in quadrants
GEOL_IDSRF	char(75)	Symbol retrieved from the legend of Digital Geological map SR 1 : 50 000
TYP_SD	char(5)	Slope deformation type
CLENIT	char(1)	Slope deformation complexity
AKTIVITA	char(3)	Activity level
PODLOZI	char(6)	Symbol of basement in terms of engineering geological zoning
HG_STAV	char(1)	Hydrogeological conditions
HL_VZT	char(1)	Relation to streams and reservoirs
SVAH_STV	char(2)	Lithology of the slope
S_MORFO	char(1)	Slope deformation morphology
S_INTPOR	char(1)	Slope damage intensity
TVARY_SD	char(1)	Slope deformation dissection
TRHL_SD	char(1)	Slope deformation cracks
SD_ODLST	char(1)	Head scarp
SD_ODLTV	char(1)	Head scarp shape
SD_OKRAJ	char(1)	Slope deformation edge
SD_CELO	char(1)	Slope deformation front
VYS_ODL_HR	float	Head scarp height
VYS_CELA	float	Slope deformation front height
HAZ_DIAL_P	int	Damaged sections of highway or roads of Ist class (m)
HAZ_DIAL_O	int	Threatened sections of highway or roads of Ist class (m)
CESTA_P	int	Damaged sections of roads of IInd and IIIrd class and local communications (m)
CESTA_O	int	Threatened sections of IInd and IIIrd class and local communications (m)
HAZ_ZEL_P	int	Damaged sections of railway (m)
HAZ_ZEL_O	int	Threatened sections of railway (m)
HAZ_POZ_P	int	Number of damaged buildings
HAZ_POZ_O	int	Number of threatened buildings
HAZ_OST_P	char(75)	Number of other damaged constructions (water management, etc.)
HAZ_OST_O	char(25)	Number of other threatened constructions (water management, etc.)
HAZ_NAD_P	char(25)	Sections of damaged above-ground networks
HAZ_NAD_O	char(25)	Sections of threatened above-ground networks
HAZ_POD_P	char(25)	Sections of damaged underground networks (m)
HAZ_POD_O	char(25)	Sections of threatened underground networks (m)
PR_PRIR	char(5)	Slope deformation generated by natural factors
PR_ANTRO	char(5)	Slope deformation generated by anthropogenic factors
SANACIA	char(5)	Remedial measures realized
DAT_VZNIKU	char(25)	Date of slope deformation activation
POZNAMKA	char(175)	Note

by brown-green and grey calcareous silty claystone with an admixture of plant debris and muscovite in layers up to 12 m. Locally thin-bedded intervals up to 8 m thick are also present. The total thickness of the formation is 900 to 1 200 m.

pg18 Zuberec Fm. (91 slope deformations registered) is a typical, thin to medium thick rhythmical flysch, consisting of alternating pelitic, and aleuritic--psammitic sediments with psephites horizons. The sandstones are typically very thin to thick bedded (0.02 to 1.2 m), of different shades of grey and brown, fine to medium--grained (rarely coarse-grained) with the occurrence of bio- and mechanoglyphs. Locally they contain small pebbles and nodules of pelocarbonates. Generally they show graded or symmetric bedding, less frequent is ripple and asymmetrical bedding. The most common petrographic types are wackes, lithic and sublithic arenites.

The claystones are typical shales, 0.01 to 1.0 m thick, green-grey, brown-grey, variably calcareous and sandy with silt admixture, often arranged in laminae. Quite common are coatings of Mn and Fe oxides. This are typical polymineral rocks (quartz, calcite, dolomite, illite, albite > chlorite, siderite, microcline, rare montmorillonite and gypsum, a frequent pyrite is autigeneous in origin). The thickness of the complex varies from a few tens of meters to max. 1 450 m.

pg12 Huty Fm. (88 registered landslides). This lithotype creates hundreds of meters thick sequence of variably calcareous claystone, claystone with siltstone lamination, or claystone/siltstones that are sometimes interrupted by benches of predominantly fine-grained sandstone, pelocarbonate layers, up to 50 cm thick, fine to medium-grained conglomerates, or sections of flysch character.

Tab. 2
Slope deformations count and area – lithological types

Symbol*	Formation	Freq.	Area	Symbol	Formation	Freq.	Area
f123	Súľov conglomerate	1	0.022	ng99	Kladzany Fm.	2	25.97
f125	Ráztoka Member	1	0.214	pg12	Huty Fm.	80	75.87
f132	Variegated Member	2	0.022	pg12/q24	Combination	4	3.484
f17	Podsmilnianske Member	2	0.380	pg12/q90	Huty Fm./q90	1	0.024
f20	Soláň Fm.	1	0.060	pg13a	Šambron Member	6	1.593
f23	Beloveža Fm., Lower pt.	14	2.951	pg18	Zuberec Fm.	87	42.06
f25	Beloveža Fm., Upper pt.	9	5.876	pg18/pg12	Combination	1	0.019
f27/f56	Lower Beloveža Fm./Strihovce Fm.	1	1.301	pg19	Kežmarok Fm.	13	0.763
f27/f62	Combination	1	0.116	pg19/q24	Combination	1	0.004
f34	Globigerina Marl	1	0.057	pg20a	Claystone Flysch	2	0.224
f34/f56	Combination	1	0.021	pg23	Biely Potok Fm.	23	15.23
f43	Racibor Fm.	5	0.202	pg23/pg12	Combination	1	0.150
f49	Menilite Fm.	1	0.043	pg23/q8	Combination	1	0.212
f5	Strihov conglomerate	4	1.530	pg25	Conglomerate and Microconglom. Flysch	7	1.470
f53	Malcov Fm.	28	11.41	pg7	Tomášovce Member	2	0.580
f53/q24	Combination	1	0.147	pm15	Arkose-Greywacke	1	0.233
f56	Strihovce Fm.	49	3.384	pm15/mt22	Combination	1	0.189
f56/f53	Combination	1	0.024	pm47	Basalts of 2nd er. phase	1	0.032
f58	Zlín Fm.	22	11.30	pm54	Malužiná Fm.	1	0.215
f62	Bystrica Fm.	41	8.089	pm89	Metarhyolite-dacite	3	0.369
f62/f25	Combination	1	0.043	pm91	Petrova Hora Fm.	2	0.056
f65	Makovica Fm.	6	0.439	ps18	Sykava Fm., Lower pt.	1	0.000
f84	Proč-Jarmuta Fm.	1	0.123	ps19	Sykava Fm., Upper pt.	1	0.006
f85	Variegated Fm.	1	0.004	ps82	Drnava Fm.	1	0.222
f94	Allgäu Member	1	0.068	q16	Deluvial-fluvial sediments	1	0.045
kr113	Diaphtorized quartz-mica Čierna hora gneiss	3	0.492	q19	Slope debris	11	3.971
kr48	Biotitic Čierna hora granodiorite	2	0.495	q19/f56/f62	Combination	1	0.841
mk16	Jarmuta Fm.	2	0.047	q19/pg18	Slope debris/deluvial--solifluction sediments	2	0.478
mk29	Púchov Fm.	9	0.570	q19/q43	Slope debris/fluvial sediments of Upper Middle Terraces	1	0.060
mt22	Ramsau dolomite	2	0.235	q20	Erosion-gravitational debris	16	2.741
mt22/mt4	Combination	1	0.020	q21	Redeposited older psephites	1	0.034
mt3	Lúžna Fm.	1	0.063	q24	Combined debris	38	21.18
mt77	Hauptdolomites Fm.	1	0.241	q24/pg12	Combination	1	0.035
n13n23	Extrusions of Slanské vrchy pyroxenic andesite	1	0.110	q43/pg18	Combination	1	0.165
n63f223/q18	Redeposited Slanské vrchy pyroclastic rocks	1	0.528	q61	Aeolian-deluvial proluvial cover	1	3.684
ng84	Stretava Fm.	10	24.54	q8	Proluvial sediments	3	0.132
ng95	Čelovce Fm.	1	10.75	q9	Holocene freshwater sediments	1	0.006

*Symbol corresponds to Digital Geological Map of Slovakia 1 : 50 000 (Káčer et al., 2005)

Results

In the scope of the project ***Registration, evaluation and emergency measures to newly evolved slope failures in 2010 in Prešov and Košice regions*** the ŠGÚDŠ workers registered in the summer 2010 a total of 551 active slope deformations, the vast majority of them were the landslides that hit 2,88277 km^2 area of the Eastern Slovakia. Many of these landslides endangered local municipalities and posed static damages for constructions, other affected road infrastructure and pipelines.

Slope deformations

When assessing the slope deformations occurrence, in terms of their number the most hit was the Prešov Region, namely the districts of Stará Ľubovňa and Bardejov.

Tab. 3
Slope deformations count and area – regions and districts

	District	Count	Area (ha)	Area (%)
801	Gelnica	3	0.2772	0.93
806	Košice – surrounding	21	26.3844	88.57
802	Košice I	2	0.4947	1.66
808	Rožňava	1	0.0063	0.02
810	Spišská Nová Ves	17	2.6256	8.81
Region	**Košice in total**	**44**	**29.7883**	100.00
	District	Count	Area (ha)	Area (%)
701	Bardejov	101	16.7928	6.50
702	Humenné	6	1.0840	0.42
703	Kežmarok	74	14.0977	5.45
704	Levoča	23	2.1019	0.81
705	Medzilaborce	3	0.4188	0.16
706	Poprad	10	0.6411	0.25
707	Prešov	37	92.4652	35.77
708	Sabinov	51	85.0547	32.90
709	Snina	1	0.0236	0.01
710	Stará Ľubovňa	154	16.6825	6.45
711	Stropkov	21	11.2711	4.36
712	Svidník	17	12.3515	4.78
713	Vranov nad Topľou	9	5.5039	2.13
Region	**Prešov in total**	**507**	**258.4888**	100.00

Tab. 4
Slope deformations count and area – type

Type of slope deformation	Symbol	Count	Area (ha)	Area (%)
Massif disintegration	R	4	2.5228	0.88
Block ridges	B	1	0.0063	0.00
Block fields	L	2	0.0203	0.01
Landslides	Z	457	235.7451	81.78
Earthflows	P	70	14.6644	5.09
Rockfalls	S	6	0.5482	0.19
Landslides due undermining	pZ	1	1.4597	0.51
Combination	LZ	3	31.6552	10.98
Combination	ZP	4	1.5321	0.531459
Combination	ZS	3	0.1230	0.042661
Total		551	288.2770721	100

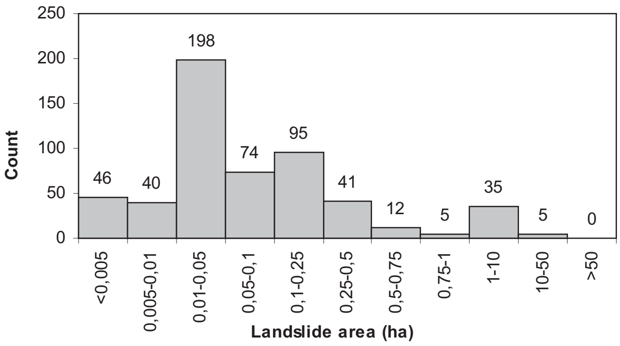

Fig. 4. Distribution of slope deformations according to their area.

The largest landslide was identified in Ďačov, followed by Močarmany, Prešov 2 (Pod Wilec Hôrkou), Kamenica 2, Varhaňovce 1 and Varhaňovce 2, Vyšný Čaj 3, Kapušany, Nižná Hutka 2 and Prešov 1 (Horárska). Tab. 3 shows the count of slope deformations in the affected regions and districts and their total area, Fig. 4 shows the distribution of slope deformations according to their area.

Slope deformation type

The most frequent slope deformations in terms of the type were landslides – **457**, the earth flows are represented by **70** occurrences (Tab. 4).

Tab. 5
Slope deformations count and area – complexity

Complexity	Symbol	Count	Area (ha)	Area (%)
Simple	J	458	135.9419	47.16
Complex	S	93	152.3351	52.84
Total		551	288.2771	100.00

Tab. 6
Slope deformations count and area – geological basement

Geological basement	Symbol	Count	Area (ha)	Area (%)
Solid rocks	S	5	0.6119	0.21
Semisolid rocks	B	6	0.0895	0.03
Alternating solid/ semisolid rocks	F	190	38.6704	13.41
Gravelly/sandy soils	G	19	0.9231	0.32
Fine-grained soils	I	18	57.6299	19.99
Alternating gravelly/ sandy/fine-grained soils	K	6	4.2725	1.48
Anthropogeneous soils	A	7	0.7623	0.26
Mixed talus soils and debris over eluvium	Z	252	158.6209	55.02
Combination	FZ	38	5.0148	1.74
Combination	ZF	3	0.3723	0.13
Combination	BZ	2	0.0963	0.03
Combination	IG	2	20.3758	7.07
Combination	GF	2	0.7583	0.26
Combination	BI	1	0.0791	0.03
Total		551	288.2771	100.00

Slope deformation complexity

The dominant category are simple landslides (Tab. 5), mostly evolved due to one-shot movement. As a rule their area was mostly small.

Geological basement

The dominant category were mixed talus soils and debris over eluvium (**252 occurrences and large surface extension**, Tab. 6) together with alternating of solid and semisolid rocks (**190 occurrences**, a rhythmic flysch).

Hydrogeological conditions of the slope

This item is quite subjective, especially for smaller landslides. In late June and early July, the slopes were still heavy saturated with water, later as a result of increased evaporation and longer droughts, near-surface soil layer dried up. The landslides with springs and wetlands occurred mainly in large bodies, as confirmed by their largest expansion in the relatively lower count (Tab. 7).

Relation to water streams and reservoirs

Dominating were the slope deformations without any apparent relation to the streams or water reservoirs **(391 cases)**. The second most common case, the slope deformations with front extended into the watercourse (**132 cases**, Tab. 8), are apparently conjoined with the lateral erosion interaction. However, these are the largest ones.

Tab. 7
Slope deformations count and area – hydrogeological conditions

Hydrogeological conditions of the slope	Symbol	Count	Area (ha)	Area (%)
Occurrence of springs and waterlogged areas	P	127	144.2055	50.02
With waterlogged areas	Z	170	107.3415	37.24
Dry slope	S	208	32.0361	11.11
No data on hydrogeological conditions	N	46	4.6939	1.63
Total		551	288.2771	100.00

Tab. 8
Slope deformations count and area – relation to water streams and reservoirs

Relation to water streams and reservoirs	Symbol	Count	Area (ha)	Area (%)
Deformation frontal part reaches a stream	C	132	155.5585	53.96
Lake due damming of a stream	H	1	0.0696	0.02
Slumping of a stream bank	B	24	1.3768	0.48
Sliding of a reservoir bank	N	3	2.1475	0.74
No relation to streams and reservoirs	X	391	129.1246	44.79
Total		551	288.2771	100.00

Slope gradient

The most widespread is the category of 7 – 12° – the slope deformations on such slopes occupy almost half the total area affected by sliding (Tab. 9). The second most common gradient class is 12 – 17°; classes 3 – 7° and 17 – 25° have about equal representation.

Slope aspect

From Tab. 10 it is evident that the distribution of slope deformations is not uniform, but the eastern and south-western aspects strongly dominate, followed by the southern and western aspects. We assume that this is caused by the geological-tectonic setting of the areas affected by slope deformations, in which in many cases, we observed planar separation planes in the head scarp areas of the landslides, following the slope of the bedding. This fact deserves further study by the microtectonics.

The main factors which contributed to the emergence, or reactivation of slope deformations

Based on current registration status of slope deformations, among the major factors that contributed to an unprecedented activation of slope failures, we consider the following:

a) extreme rainfall;
b) lateral erosion;
c) lithological-tectonic conditions;
d) anthropogenic impacts.

Precipitation (rainfall)

The analysis of the precipitation totals, which in May and June of 2010 caused widespread flooding and created

Tab. 9
Slope deformations count and area – slope gradient

Gradient	Count	Area (ha)	Area (%)
< 1°	1	0.00691007	0.002
1 – 3°	11	0.657706	0.228
3 – 7°	66	21.5819	7.487
7 – 12°	180	140.519	48.744
12 – 17°	176	96.7891	33.575
17 – 25°	106	27.3402	9.484
25 – 35°	11	1.38198	0.479

Tab. 10
Slope deformations count and area – slope aspect

Aspect	Count	Area (ha)	Area (%)
N	30	1.57284	0.546
NE	57	19.5638	6.786
E	95	55.5856	19.282
SE	80	78.4088	27.199
S	61	32.8561	11.397
SW	95	36.2555	12.577
W	93	47.6225	16.520
NW	40	16.412	5.693

conditions for the creation and mobilization of a large number of slope movements, is based on information from the precipitation stations of the Slovak Hydrometeorological Institute (Dargov – 50 040, Herľany – 60 060, Kapušany – 59 220, Krásnohorské Podhradie – 52 180, Prešov – Planetárium – 59 160, Slanská Huta – 51 160, Spišské Podhradie – 56 180, Starina – 43 320, Široké – 58 080, Terňa – 59 200). To assess precipitation totals recorded in 2010 for each station a set of mean monthly precipitation was derived. To determine the mean values there were used series of records from the period 2001 to 2009.

When compared the mean precipitation totals with those measured during this year it is obvious that in the period from January to April 2010 in most of the precipitation stations the derived mean values were exceeded (Fig. 5). The most conspicuously the mean values were exceeded at the station Krásnohorské Podhradie (154.16 % of the long-term average, representing a 207.1 mm of rainfall). However, the largest rainfall total during these months was recorded at the station Slanská Huta (240.70 mm, which is 138.86 % against the long-term average). The mean rainfall total recorded at assessed precipitation stations during the first four months is 119 % of the long-term average. This indicates that during this period it could happen an oversaturation of the rock environ. In the following month of May all SHI stations experienced exceeded mean values of precipitation on more than 100 %. The most significant long-term mean value was exceeded at the site Slanská Huta. The recorded value of precipitation compared with the monthly normal is 448.0 %, 314.9 mm per month (Fig. 5). The lowest percentage among the current and long-term precipitation totals were recorded in the Spišské Podhradie (211.9 %). The precipitation ratios of previous months in combination with the large amounts of rainfall recorded in the month of May deteriorated rock slopes stability conditions and created favourable conditions for the emergence and development of slope movements.

A similar trend in rainfall continued in the next month of June, when the high precipitation exceeded the long--term means. As a consequence, there has been exceeded the limit equilibrium for several slopes, which is reflected in the occurrence of numerous landslides. This transition was observable earlier this month (04/06/2010), when the greatest incidence of landslide events was recorded in the area of interest. Although the activation of landslides was undoubtedly associated with the development of longer term climatic factors, probably a significant role played intense rainfall events that directly preceded this activation. During 6 days prior to activating the largest number of landslides (30. 05. 2010 – 04. 06. 2010) at the majority of SHI precipitation stations higher rainfall volumes were recorded (e.g. Spišská Nová Ves 142.8 mm, Kapušany – 120.5 mm, Prešov – Planetárium – 102.7 mm and Starina – 100.5 mm).

Negative developments in the rainfall in the Eastern Slovakia persisted during the month of July. Again at all SHI stations there have been considerably exceeded long--term means, leading to further activation of landslides.

Overall, during the first half of 2010 there was recorded in the region of the Eastern Slovakia on 15.0 (Starina) to 105.6 % (Slanská Huta) rainfall total greater than the mean of the years 2001 – 2009. Those conditions can be considered as highly negative in terms of the impact on the stability of slopes.

In the scope of the inventory **539** slope deformations were recorded, for which as the dominant sliding factor the extreme rainfall has been identified.

Lateral erosion

Lateral erosion of watercourses is reflected in the shores scouring, especially at higher water levels. Crucial role plays an increasing flow velocity, associated with the increasing erosive potential. This way the banks are washed away, accompanied by recurrent sliding since the masses are constantly (in the case of smaller landslides) carried away, thus reactivating the landslide.

In the scope of the landslides inventory there were recorded 100 cases where lateral erosion was significant, if not the dominant factor in sliding.

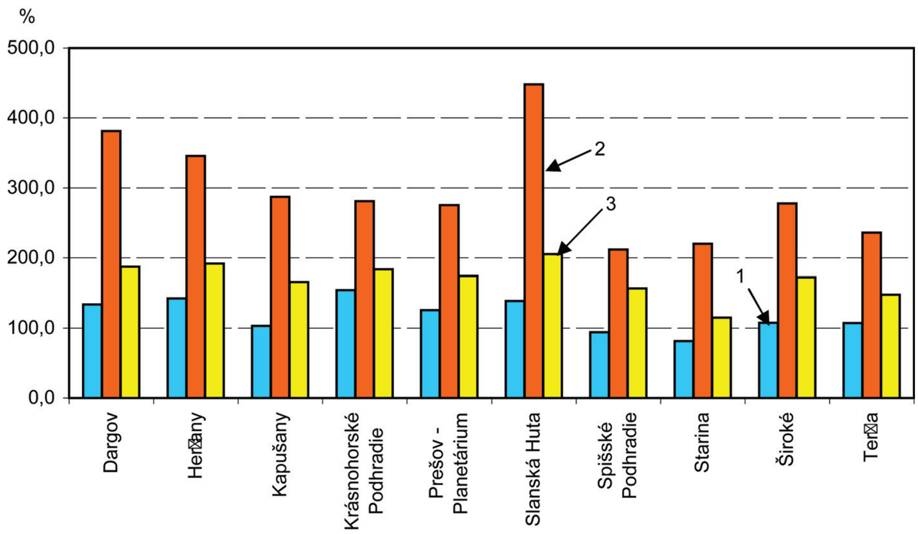

Fig. 5. Ratio between rainfall totals of the first half of 2010 and long--term mean in selected time intervals. 1 – months January to April; 2 – month of May; 3 – months January to June.

Lithological-tectonic conditions

In relation to other lithological complexes there dominates in the slope deformations basement the Zuberec Formation – a complex of typical, thin to medium-rhythmic flysch – 91 slope deformations and the Huty Formation – 88 slope deformations. Both complexes belong to the Central Carpathian Paleogene. Noteworthy is the occurrence of 54 slope deformations upon the Strihov Member, dominated by the thick-bedded greywacke sandstones. The Bystrica Member with a count of 44 slope deformations is the next most abundant basement, which consists of silt, brown--green and grey calcareous claystone.

We consider it important to point out that in many cases we observed planar head scarp areas in the initial parts of the landslide, following the angle of the bedding. This phenomenon was frequently observed in the subregion of the Central Carpathian Paleogene, where the bedding tends usually toward depressions or valleys. We anticipate that this phenomenon was reflected in an uneven distribution of landslides in terms of the slope aspect.

Anthropogeneous effects

The most common causes of anthropogenic impacts tend to be inadequate earth works, reducing its stability – undercutting of the slope in the accumulation, or additional surcharge of the head scarp area, fluctuations in the water reservoir, further deforestation, extensive grazing of cattle, vibration (right). The inventory identified as a contributing factor to sliding has encompassed in 30 cases **vibration** (shock), usually associated with transport, in 19 cases there were registered inappropriate **undercutting** of a slope and also in 19 cases additional **surcharge** of a slope.

Assessing the impact of landslides on the 2010 population and infrastructure in the Eastern Slovakia

This section is devoted to the assessment of our inventory, either from the viewpoint of damage or threat to objects due to slope deformations, which **evolved or reactivated in the first half of 2010**. We point out that in fact a threat to the population and infrastructure is substantially greater because of the fact that not all potential landslides, mapped in the previous period, have been reactivated to-date. We present just a brief statistical recap, the details of individual slope failures are presented in the inventory sheets and database.

Buildings

Perhaps the most serious impacts of slope deformations, sensitively perceived by the public, is considered a direct threat to dwellings and hence life of the inhabitants. Highly publicized are the cases of the municipalities of Nižná Myšľa and Kapušany; evacuation of some houses has been necessary to implement in a number of other villages in the Eastern Slovakia, given the scale of buildings damage.

In the scope of our inventory we have identified **22 buildings** damaged in the Košice Region **(excluding the city of Košice and Nižná Myšľa)** and **80** in the Prešov Region, thus all-in-all **102 buildings**. The most affected have been family houses, many of which were built on landslide sites which had been registered in the past.

As for the threat for buildings, in the Košice Region, we identified **52** such objects and in the Prešov Region **252** buildings, totalling **304** objects. The count of damaged and threatened buildings in different districts is presented in Tab. 11.

Roads and railways

Overall, in the Prešov and Košice regions 4 232 m damaged road sections, 27 m from the road 1st class, and 4 205 m of 2nd, 3rd classes and local roads were found. As endangered, we identified a total of 17 846 m of road sections, 296 m of the road of 1st class and 17 550 m of 2nd, 3rd classes and local roads. Railways were not violated, however, identified were vulnerable sections of total length of 364 m. In terms of damage or threats the most affected are districts of Prešov, Stropkov, Košice – surroundings and Stará Ľubovňa (Tab. 12). In many cases there was a sliding of the masses directly on the road or rail communications; provided there was no breach of such sections and the slipped masses were removed, we included such sections within the category of threatened. In most such cases, however, traffic was stopped or severely limited (one lane and traffic-light) until the sections were open again.

The count of damaged and vulnerable sections of roads in various districts and regions are shown in Tab. 12.

Tab. 11
Damaged and threatened buildings in the districts of Košice and Prešov regions

	District	Damaged	Threatened
801	Gelnica	0	0
806	Košice – surrounding	18	51
802	Košice I	0	0
808	Rožňava	1	1
810	Spišská Nová Ves	3	0
Region	**Košice in total**	**22**	**52**
	District	Damaged	Threatened
701	Bardejov	8	44
702	Humenné	0	0
703	Kežmarok	1	24
704	Levoča	0	6
705	Medzilaborce	0	2
706	Poprad	0	0
707	Prešov	47	22
708	Sabinov	6	72
709	Snina	0	0
710	Stará Lubovňa	9	61
711	Stropkov	3	7
712	Svidník	4	0
713	Vranov nad Topľou	2	14
Region	**Prešov in total**	**80**	**252**

Tab. 12
Damaged and threatened communications of Košice and Prešov regions

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

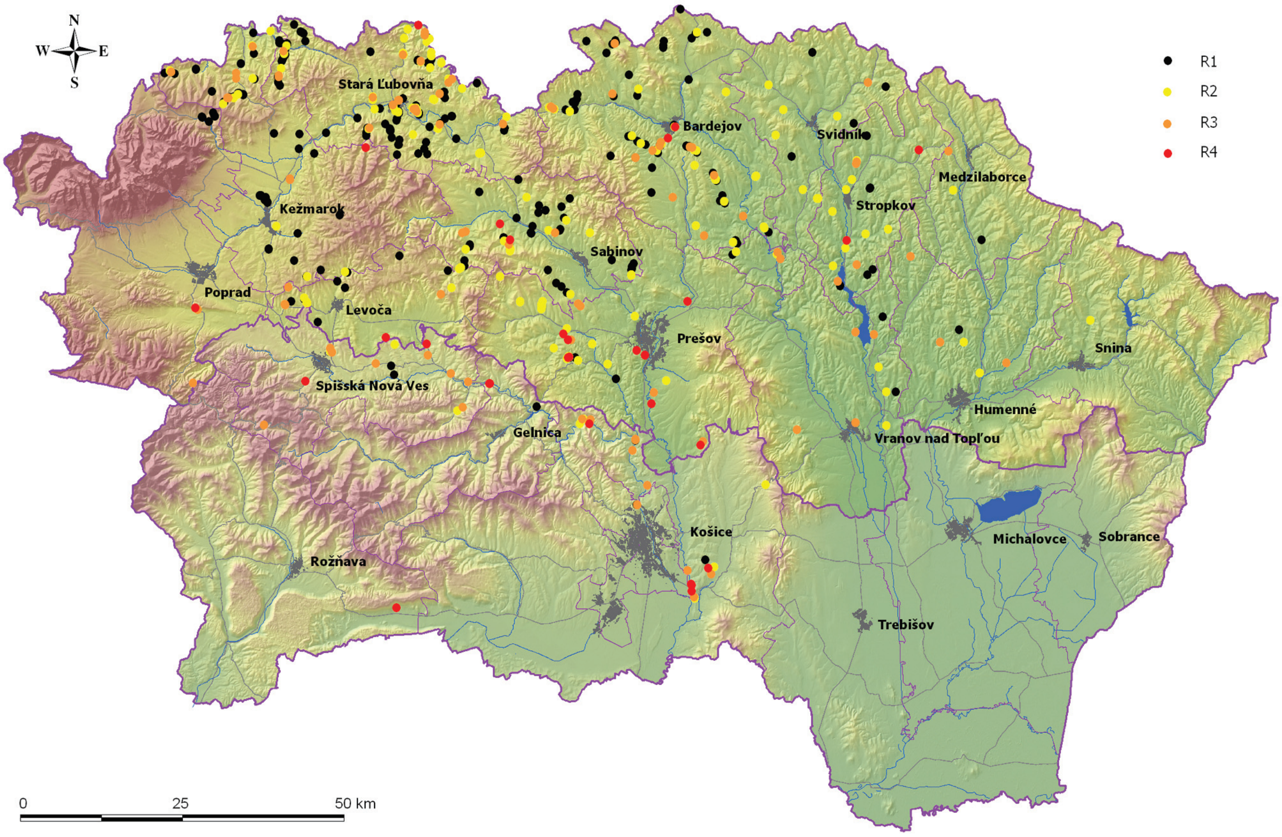

Fig. 6. Landslides activated in May/June 2010 in the Košice and Prešov regions. R1, R2, R3 and R4 are categories of socio-economic relevance.

Purpose-made categorization

The whole set of registered slope deformations was divided in accordance with the ***purpose-made categorization*** of socio-economic significance (threat to life and property) and consequent risk of landslide on the scale recommended by the European Commission for multirisk evaluation (Marzocchi et al., 2009) as follows:

– **moderate (R1):** social, economic and environmental damages are marginal – **273 slope deformations**;

– **medium (R2):** minor damages to buildings, infrastructures and environment are possible. No significant effect on people, functionality of buildings and economic activities – **151 slope deformations**;

– **high (R3):** concern exists on peoples´ safety. Functional damages to buildings and infrastructures are possible as well as interruption of the economic activities and relevant damages to the environment – **98 slope deformations**;

– **very high (R4):** expected damages include casualties and injuries, serious damages to buildings and infrastructures, destruction of the environment and of the socio-economic activities – **29 slope deformations**.

Tab. 13
Abundance of slope deformation categories of Košice and Prešov regions

	District	Count	R1	R2	R3	R4
801	Gelnica	3	1	0	0	2
806	Košice – surrounding	21	2	5	9	5
802	Košice I	2	1	0	1	0
808	Rožňava	1	0	0	0	1
810	Spišská Nová Ves	17	2	3	10	2
Region	**Košice in total**	**44**	**6**	**8**	**20**	**10**
	District	Count	R1	R2	R3	R4
701	Bardejov	101	58	26	15	2
702	Humenné	6	1	2	3	0
703	Kežmarok	74	51	11	11	1
704	Levoča	23	11	7	4	1
705	Medzilaborce	3	1	1	1	0
706	Poprad	10	7	0	2	1
707	Prešov	37	3	20	5	9
708	Sabinov	51	31	14	4	2
709	Snina	1	0	1	0	0
710	Stará Ľubovňa	154	90	41	22	1
711	Stropkov	21	7	8	4	2
712	Svidník	17	5	9	3	0
713	Vranov nad Topľou	9	2	3	4	0
Region	**Prešov in total**	**507**	**267**	**143**	**78**	**19**

Tab. 14
Slope deformation category area

	Count	Area (ha)
R1	273	35.8282
R2	151	45.3940
R3	98	47.9245
R4	29	159.1304
Total	551	288.2771

Overview of single categories within regions and districts is in Tabs. 13 and 14, the arrangement of individual socio-economic categories is illustrated in Fig. 6.

Conclusions

The most important benefit of the inventory is the "instant" information on the status and impact of slope deformations, incurred, or reactivated in May and June 2010 due to climate extremes. The inventory, categorization and update of the current status of landslide sites enable the government and local authorities to lead effectively the necessary funds for exploration and remediation of such territories. The way of data collecting and processing, "scalelessness" of topographic information, registration of damaged or endangered buildings allow to incorporate this accurate documentation into the land use planning documents, regardless of the detail of the processing and geodetic survey (cadastral maps of lots C and E categories, geometric plans, detailed maps of engineering networks utilities, different land maps, documents of Territorial System of Ecological Stability and General Principles of Functional Arrangement, forestry maps, etc.). Thus, based on a compliance with the cadastral map it is possible to quantify precisely the size of a damage to a lot with a possibility of identifying the owner etc., what is such an important input for the documentation for insurance claims, identification of the extent of damage to gas pipelines, water pipes and so on. An example of slope deformations presentation on cadastre groundwork is shown in Fig. 7.

At the same time there has been created an extensive GIS database containing the information about the date of slope failures generation, the first of its kind in Slovakia, which becomes a foundation for future research on the recovery of such phenomena and their more reliable forecasting.

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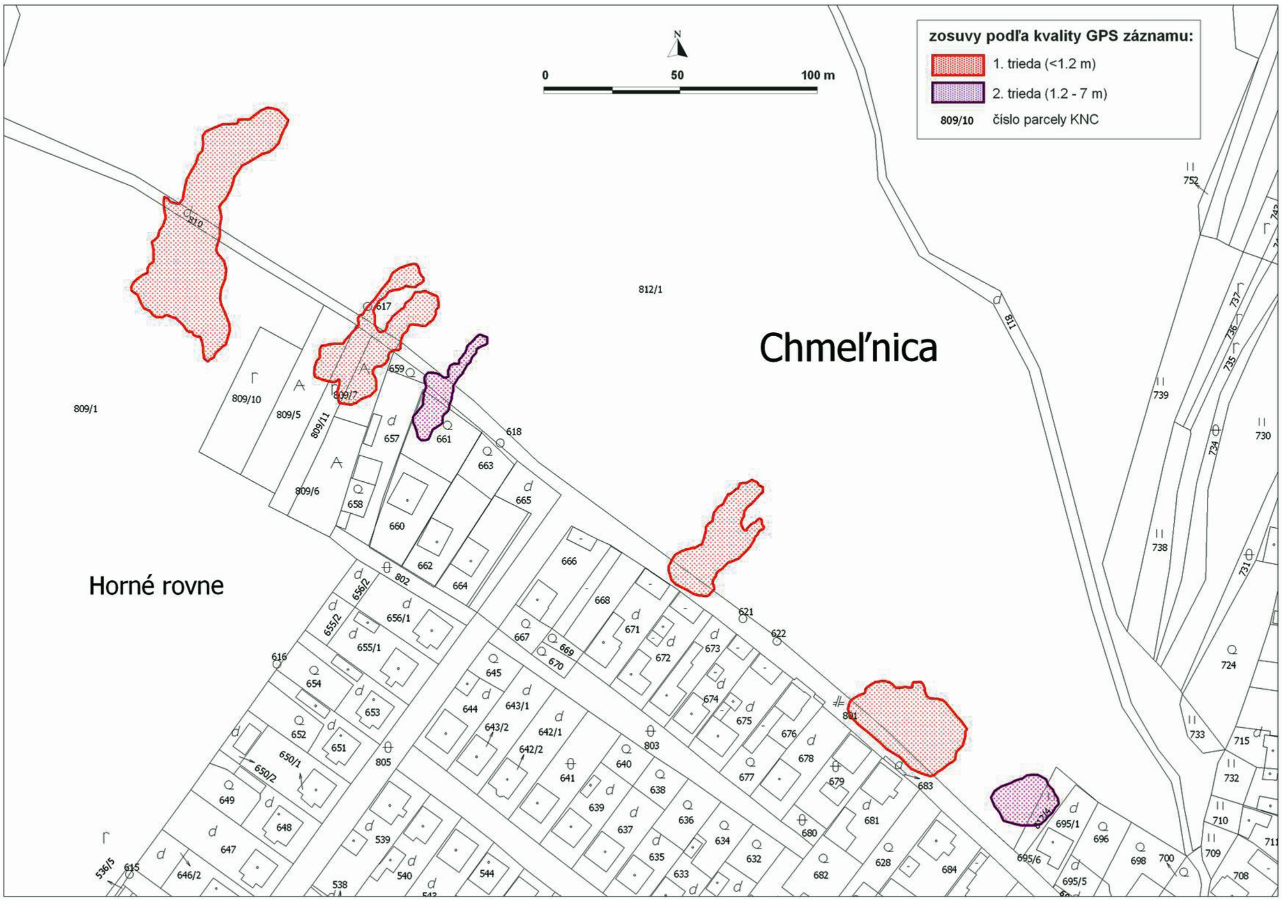

Fig. 7. Presentation of "scaleless" records of slope deformations on cadastre map of Chmeľnica Municipality.

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Digital Elevation Model (DMR 20 – SK) – Esprit Ltd.

Manuscript received 7. 12. 2010
Manuscript accepted by Editorial Board 7. 12. 2010
Revised form received 21. 12. 2010