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Use of GNSS Technology in Engineering Geology in Slovakia

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Abstract

Global Navigation Satellite System (GNSS) receivers are used in many applications, including geological mapping and surveying. Recently, the staff of the Department of Engineering Geology at the State Geological Institute of Dionýz Štúr has adopted this technology and applied it in the solutions of various tasks of civil engineering practice: such as inventory and monitoring of landslides, construction of geological cross-sections, and contouring of specific geological features. This paper presents various case studies, in which the application of this kind of devices is being compared with classical methods of engineering geological practice.

Key words: corrections of code measurings, differential measurements, EGNOS, GNSS, landslides, monitoring, SKPOS

Introduction

Engineering geologists have always wanted to study the evolution of the particular geological phenomena in real time: What is the rate of the slope movement? Which parts of landslide are more active, which are stabilized? How to link direct measurements of various geometric features with the GIS database? Of course, a number of additional questions could be asked about different geological processes or objects.

Today, we can sample in real time the surface effects of on-going geological processes via space-based geodesy. This ability, seemingly, should bring the ability to make prognoses of geological processes. In the Slovak condition the focus is on landslides, but, of course other processes could be studied as well – subsidence, neotectonic movements, erosion propagation, etc. However, despite two decades of the widespread availability of the Global Positioning System (GPS) such information is still relatively little used in the engineering geological community.

In this paper, we review what has been learned to date about the relationship between geodetic and engineering geology observations.

We examine the most common inventory, mapping and monitoring and methods currently used and the issues and artifacts surrounding those methods. For all of these methods, questions about spatial scaling and continuous (or discontinuous) nature of surface deformation are the key. Current advances in constructing geological cross-sections for the purposes of slope stability calculations, or in updating digital elevation model, underscore the utility of working with geodetic data from a geological viewpoint. Finally, we examine how new technology will further enhance our ability to use these data.

Position definition in the field and general mapping

For the purpose of mapping at scales smaller than 1 : 10 000 the use of conventional GPS-based navigation and hiking equipment is sufficient. The accuracy of this device category is of the order of meters: from 4 m in open spaces, to 20–25 m in forests with a dense canopy. Modern instruments are capable of receiving signals continuously, even in a dense forest.

The GPS navigation devices allow recording location data in various forms. Naturally, they enable to save the current position and altitude in a numerical form (waypoints) with metadata: the accuracy of recording, number of satellites, the date and time of recording etc. as well as user's comments. The expensive devices also provide the option of taking photos along with saving their coordinates in EXIF header digital photography (e.g. Garmin Oregon 550 t) and to open a photo directly in the map programme, which is capable to read automatically the position from the header (e.g. Google Earth^{TM}). Another commonly offered function of the navigation devices is the ability to record tracks (movement trajectories). Given the low accuracy and inability to carry out additional corrections, the trajectory records are only approximate and they cannot be used for detailed mapping – e.g. contours of landslides etc..

A standard coordinate system default in the navigation devices is WGS84 with a record in ellipsoidal coordinates (λ, ϕ). Of course, the devices offer the opportunity to change this setting; however, this is quite limited. In Slovakia, the option to record in the coordinate system S-JTSK is lacking, however, the coordinates transformation is possible through the additional processing of data (post-processing) using GIS programmes. It should be preferred to replace a record of position in spherical coordinates by the record in the UTM projection in meters. In our geographical area it is appropriate to use the UTM WGS84 Zone34/Northern hemisphere (UTM-34N).

Prior to leaving for the field work, it is appropriate to prepare the maps in electronic or paper form showing a square grid (map grid) with 50–100 m interval (Fig. 1). The navigation devices allow to load into their database of topographic maps the user-defined maps in the required format (raster or vector). Along with displaying the coordinates on the display a map showing the grid provides very suitable basis for orientation and geological mapping with sufficient accuracy for the map documents in scale up to 1 : 10 000. However, it is not appropriate for a "scaleless" mapping (e.g., the cadastral maps).

The format in the navigation devices is standard and mutually convertible in many freely available programmes. For example records from the devices Garmin in GPX format can be displayed in the current mapping programmes (Google Earth, Google Maps and others). However, for further processing it is necessary to convert the GPX record (point, line) into GIS format. The conversion into GIS (ESRI shape, MapInfo and others), as well as cartographic transformation to coordinate system S-JTSK provides freeware (GPL) programme Quantum GIS (http://www.qgis.org/). It performs the cartographic transformations using libraries PROJ.4 (http://trac.osgeo.org/proj/), which allow for the conversion WGS84/S-JTSK (KrovakG) the accuracy of 7-element transformation with global transformation key with a precision of 30–60 cm for any recording format. Accounting for the accuracy of GPS navigation devices such an error is negligible. However, correct settings of transformation parameters are inevitable (not yet implemented in the programme's current version). For the territory of the Slovak Republic they are the following: (http://wiki.freemap.sk/SJTSK, http://grass.fsv.cvut.cz/gwiki/S-JTSK):
+proj=krovak +ellps=bessel +towgs84=485·021,169·465,483·839,7·786342,4·397554,4·102655,0+lat_0=49.5 +lon_0=24.83333333333333+alpha=30.28813975277778 +k= 0.9999 +x_0=0 +y_0=0 no_defs <>

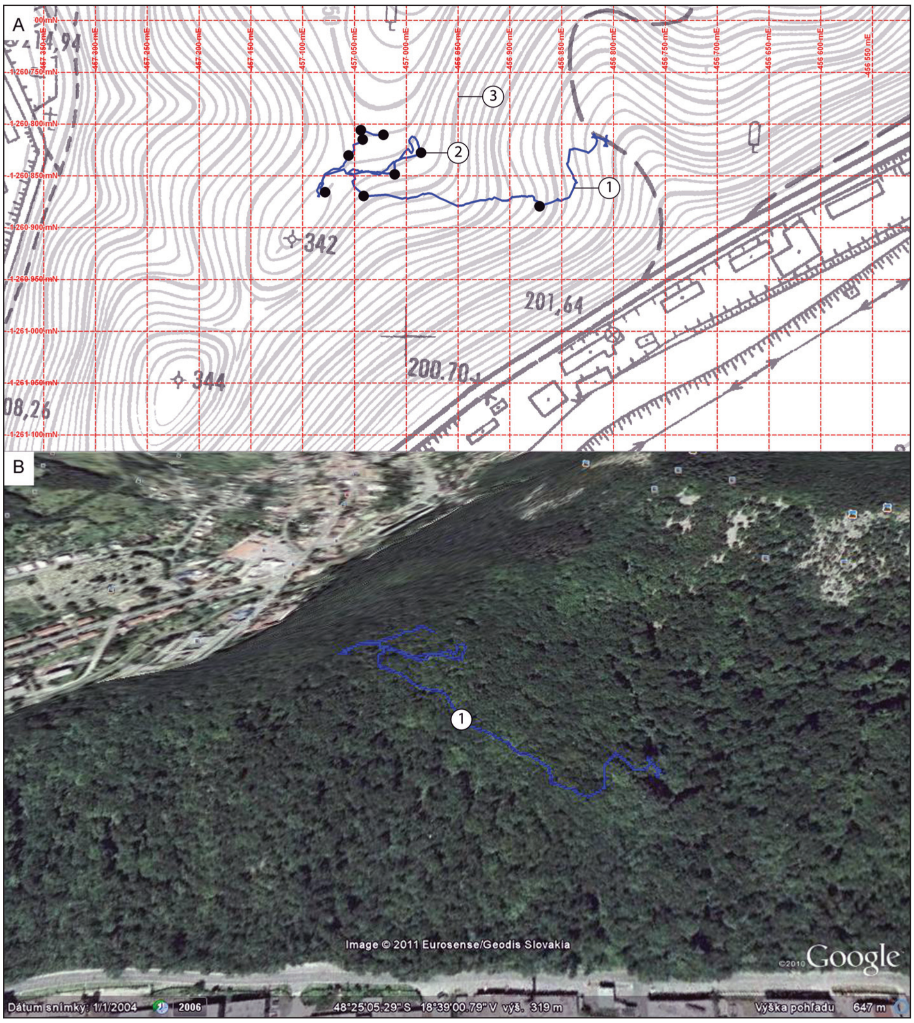

Fig. 1. An example of a record of GPS device. **A** – depiction in the topographic map of ZM10; **B** – depiction on the Google Earth^{TM} image; 1 – route track (blue); 2 – sampling points (black); 3 – regular coordinates (red) in S-JTSK 50 x 50 m.

Detailed mapping and data recording

In the scope of engineering geological mapping higher accuracy of GPS record is required – often below 1 m (sub-meter accuracy), particularly in cases where data must be depicted in maps of larger scales (>1 : 5 000, cadastral maps – KNC, CS, etc.). Such a record we can term as "scaleless" although it does not reach the geodetic accuracy (<12 cm), however, to produce maps at any scale such accuracy is sufficient.

The above accuracy can be achieved with GPS/GNSS devices of GIS category that allow the use of so-called D-GPS corrections, either in real time (during field mapping) or using the so-called RTK equipment, or in the scope of post-processing. In the post-processing of measured data using a special software supplied with the GPS devices. For D-GPS corrections (RTK and post-processing) correction data from stationary GPS receivers (reference station) are needed with high accuracy and frequency of record. In Slovakia, for this purpose a paid service of reference stations SKPOS network can be used (http://skpos.gku.sk/), operated by the state organization Geodetic and Cartographic Institute (GCI). Data from reference stations are available either through the GSM operator (real time), or after requesting additional data for certain period through the web-service organization.

Besides high positional precision the devices of GIS category and their utilities allow much wider possibilities to record attribute data and metadata (in comparison with the navigation device). They offer an option of recording attributes of sensing element in accordance with standard spatial GIS database (point, line, polygon) with pre-defined database structure and selected cartographic representation. The devices of this category offer also commercially available coordinate system setting S-JTSK, or highly accurate cartographic transformation can be carried out with D-GPS correction directly in the utility programme.

The Trimble^{TM} devices enable to record in addition to the data needed for post-processing (the exact date and time of recording, record duration, number and distribution of satellites, signal strength) also basic metadata about scanned elements: 2D/3D line length, perimeter and area of polygon, horizontal and vertical accuracy and user-defined table attributes. All these data can be exported into the GIS attribute table using the GPS utility functions.

In the past, the GPS technology with GIS accuracy was successfully used in the scope of the project of landslides mapping which evolved during extreme rainfall and subsequent floods in the Košice and Prešov regions in the summer of 2010 (Liščák et al., 2010). During the field mapping there were surveyed linear elements of landslides, mostly (peripheral line, head scarps, cracks, etc.). Based on the recorded metadata the mapped elements were divided into 6 categories of precision: the quality of records with submeter accuracy attained mostly on meadows and open spaces as well as less accurate records in the dense forests and steep slopes with shielding effect to the satellites.

While the lines recorded with the highest accuracy achieved did not need any correction and their course could be downloaded to the resulting maps with almost no editing, the lines' course with an accuracy of less than 5 m had to be slightly edited and smoothed prior to displaying in the topographic map.

The accuracy categories were strictly distinguished in the attribute table of GIS databases. Based on this database landslides contours depiction maps and registers have been enhanced from the current precision at scales 1 : 50 000 to 1 : 10 000 to "scaleless accuracy", applicable to cadastral maps, for example to create maps of hazard/risk and quantify the specific damage to each affected lot.

Terrain elevation and planimetric measurements

When assessing of landslide areas in the engineering geological practice we often have to face a challenge of an urgent slope stability evaluation. This is due to a need of a proposal for immediate remedial measures that should prevent further development of slope movement. However, when acquiring the input data, we encounter some difficulties that are related to changes in the slope geometry. Information on the elevation retrieved from map does not reflect a change that has been generated by a new landslide and hence in a very short time it is necessary to define new slope configuration.

The same challenges we faced in the scope of the practical solutions related to engineering geological surveys on the newly formed landslides of 2010 in the villages of Bzenica-Bukovina and Krupina. Thanks to their socio-economic significance, these slides necessitated immediate action. Therefore, in both cases, prompt remedy measures were taken. The key issues were related to the provision of input documents, which would account for landslide-re-built relief and to a proposal of effective remedial measures. Map documents (various scales up to 1 : 2 000), which were available, due to their outdated relief did not enable to define the actual profile of a representative line. Therefore, in order to obtain relevant information about the current morphology configuration, surveying works were carried out using GNSS equipment.

Methodology

The aim was to find a solution which would make possible to provide relevant spatial data with high precision in a very short time, which would serve for preparing of an engineering geological profile. We adopted the measuring technique Trimble (GeoExplorer and Rover R8 GNSS). The above devices differ significantly in their scope, which has been reflected in the differences in the accuracy of the results obtained.

GeoExplorer 2005 XT, similarly to the software TerraSync, has support for GIS spatial data processing, hence the accuracy of this device is adapted for this purpose. In autonomous measurements, without any correction signal (and 6 to 9 satellites availably) a standard accuracy in spatial position ranges from 5 to 15 m. In the case that the number of the satellites falls below 6 as a result of shading, e.g. by vegetation, there is a reduction in accuracy. It is logical that the accuracies are not acceptable for the purposes of compiling engineering geological model, enabling analysis of the stability conditions. To achieve the required accuracy at the submeter level, it was necessary to amend an autonomous measurement on of at least one more receiver. This type of measurement is referred to as differential measurement. This means that the measurement was carried out at least by a pair of receivers, provided the position of one of them has been accurately defined.

The most available alternative to eliminate the uncertainty caused by systematic influences (atmospheric refraction, ephemerides and errors of satellites clocks) were corrections of code measurings, which provides EGNOS (European Geostationary Navigation Overlay Service). Another option represented corrections provided by the Slovak Spatial Observation Service (SKPOS).

The EGNOS satellites cluster is the European satellite correction system that is currently in full operational service and users are provided free of charge. The correction signal is transmitted from three geostationary satellites in real time based on continuous measurements of ground network stations that are located throughout Europe (http://www.egnos-pro.esa.int/index.html).

In the scope of practical solutions the accuracy signals from these satellites can achieve from 0.5 up to 2.0 m. The resulting accuracy depends largely on the number of satellites and their configuration. Certain deficiencies of the correction system are frequent signal failures. Availability problems are caused by the fact that the satellites are located above the equator so that the satellites are very low over horizon at our territory.

Another approach to obtain the desired accuracy offers a SKPOS service. This activity ensures the GCI; this was defined by the Act on Geodesy and Cartography of 2003 (Ferianc et al., 2007). This concerns the processing of measured data in real time or post-processing system based on differential corrections. These correction data can be generated for the selected spatial location from the network solution with different frequencies in the desired time interval. The data are generated in the real time and the user can download them after a few minutes. These data were used for correction of measurement retrieved by receivers GeoExplorer 2005 XT and Rover R8.

The receiver R8 GNSS produced by Trimble can receive signals from all operated and planned satellite systems (GPS-Navstar, Glonass, Galileo). For measurements carried out by R8 GNSS receiver it was possible to work in the RTK regime (real-time kinematic), which means that differential corrections are provided in real time through the VRS network solution that is designed for geodetic work. In order to guarantee homogeneous precision determination of spatial position across the Slovak Republic these corrections are provided in the coordinate system ETRS89 (Ferianc et al., 2007).

Sites description (Study areas)

Landslide territory Bzenica-Bukovina is located in the Žiarska kotlina Basin at the right side slope of the Hron River at an altitude of 245–265 meters a.s.l. The landslide evolved in NE section of the village and caused a severe damage to the cemetery, access roads and several graves.

From the geological and tectonic points of view the territory is built by Tertiary rocks of Neogene age, consisting of varied sedimentary material (clay, gravel, sand), deposited within graben. Peripheral parts of the wider area are made of volcanic rocks. The Quaternary cover formations have varied lithology and genesis. At the site of activated landslide the deluvial deposits overlay high-plastic clays (Otepka, 1991). The territory of the slope deformation is drained by the Hron River.

The initial activation of fossil landslide occurred due to abnormal rainfall totals of the second decade of April and May 2010. In the rain gauges in Hliník nad Hronom and Žarnovica long-term monthly normals during the first six months of 2010 (determined from measurements in the period of 1901 to 1980) were exceeded on 113 to 286 % (excluding the month of March – N = 51 %; Ondrejka et al., 2010).

The second model area is located within the residential area of the village Krupina on the left bank of the Krupinica River with an altitude of 258.74 (erosion base of the

Tab. 1
Evaluation of measurements by devices GPS and GNNS

Receiver	Correction	Direction	Number of meas.	Mean error [cm]	Max. error [cm]	Min. error [cm]
GPS/GIS	Without correction (GPS)	xy	38	570.53	580.00	570.00
		z	38	756.84	810.00	750.00
	EGNOS	xy	453	72.49	120.00	50.00
		z	453	108.81	170.00	70.00
	Postprocessing (SKPOS)	xy	491	36.54	90.00	30.00
		z	491	48.25	90.00	40.00
R8	RTK	xy	48	4.64	46.70	0.90
		z	48	6.06	53.20	1.30

Krupinica River) to 309.19 meters a.s.l.. The landslide originated at the turn of the months of May and June in 2010 (excessive rainfall) and posed a threat for several houses. Its reactivation which occurred at the turn of 2010 and 2011, called for declaration of "emergency situation" (Liščák et al., 2011).

From the geological point of view within the territory studied a varied range of Middle Badenian volcanosedimentary rocks (Miocene, Neogene) of Sebechleby Formation (Konečný et al., 1998) has been identified. The active landslide area is made of epiclastic volcanic sandstones and conglomerates.

GNSS-GIS Measurements Assessment

The positional accuracy of the measured element was verified by the GPS apparatus of GIS category at the Bzenica landslide. In order to compare two different methods of data correction the field measurements were carried out with available signal from the satellite system EGNOS. Further-on, these data were post-processed using differential corrections obtained from SKPOS. The accuracy analysis of the recorded line 1 can be summarized as follows:

– The availability of correction data from the satellite system EGNOS showed lower values of error in both horizontal and vertical directions (measurement errors up to 2 m; Tab. 1). In the case of loss of signal from the correction system EGNOS the accuracy deteriorated significantly and fluctuated in the range of 5.7 to 8.1 m (Tab. 1). The signal losses related primarily to dense vegetation masking of the receiver. All-in-all, the accuracy in the vertical direction is on about 40 % lower than in the horizontal one;

– Through the processing of measured data in the post-processing system using the differential corrections it was possible to achieve average accuracy of 0.5 m in both evaluated directions (Tab. 1). In the case of vegetation shading the post-procedural measurement error increased up to a magnitude of 1 m;

– An interesting conclusion can be reached when comparing the position and also the altitude coordinates of the same measurement (point) using a different way of correction acquisition (EGNOS/GPS/SKPOS). Between the coordinates of identical point with different types of corrections a difference arises which is presented by lines in Fig. 2. These differences may in extreme cases reach a value up to 7.3 meters, but in most cases, the difference magnitude does not exceed 1.5 m. The average value of all differences equals to 0.84 m;

– In the case of an autonomous measurement, surprising finding is that during the period of correction signal loss from EGNOS (the expected measurement error

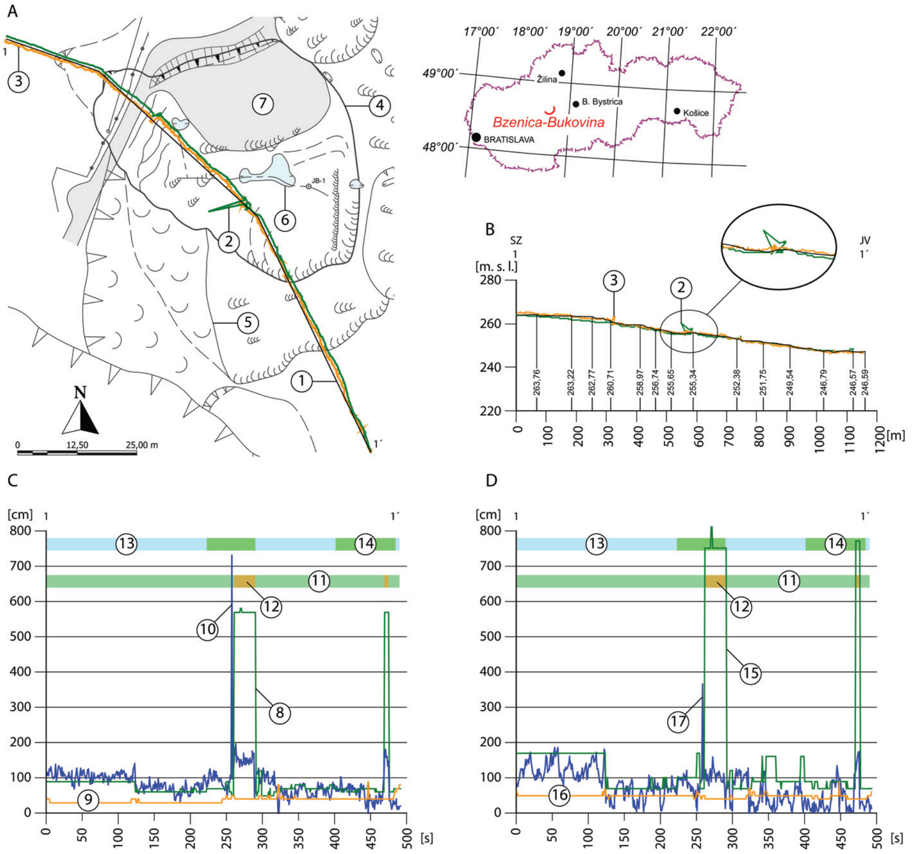

Fig. 2. Analysis of spatial accuracy of GPS device. **A** – schematic map of the landslide area Bzenica; **B** – profile 1 – 1´; **C** – analysis of positional accuracy; **D** – analysis of vertical accuracy; 1 – route of cross-section line 1 – 1´; 2 – trajectory of a record with corrections of code measurings (EGNOS); 3 – trajectory of a record at differential measuring (SKPOS); 4 – active landslide; 5 – various generations of older landslides; 6 – drainless depression; 7 – anthropogeneous sediments of road fill and wild landfill; 8 – expected positional error of measuring at corrections of the satellite system EGNOS; 9 – positional error of measurements at differential measuring (SKPOS); 10 – horizontal difference between trajectory defined from the corrections of the satellite system EGNOS and trajectory defined based on corrections of differential measuring – SKPOS; 11 – time interval with reception of the signal from the satellite system EGNOS; 12 – time interval with lacking signal from the satellite system EGNOS; 13 – time interval without vegetation; 14 – time interval with vegetation; 15 – expected vertical error of measuring at corrections from EGNOS; 16 – vertical error of measurements at differential measuring; 17 – vertical difference between trajectory defined based on corrections of the satellite system EGNOS and trajectory defined based on corrections of differential measuring – SKPOS.

of more than 5.5 m) the difference between measurements of EGNOS and SKPOS does not exceed 2.0 m (in both directions; Fig. 2C, D);

– A significant deviation from the path traversed (Fig. 2A) occurred in the time of the correction signal reception from the EGNOS satellites, possibly associated with the system measurement errors.

Completely different opportunities are offered by an experience with GNSS receivers of Trimble, which was used in the landslide area Nad Kotlom in the city of Krupina. During the surveying, differential corrections were provided in real time, which enabled the measurement with high accuracy in the field. The profile line is led across the landslide area from the foothill (Krupinica River), passes westwards through the territory of fossil landslide to altitudinal point 309 m a.s.l. (Fig. 3). Since the landslide slope remodeled constitutes only a tiny part set of the profile line, its construction is feasible on the current topography map data (1 : 10 000).

Due to the required high precision geometry of a slope in the active landslide the precise measurements were inevitable (using the receiver R8). Thanks to two different procedures of the profile line drawing through the locality Nad Kotlom a verification of information from elevation maps was possible.

From the results depicted in Fig. 4 it is clear that the profile line drawn on the basis of maps neglects many important morphological features. This is valid in particular within the active landslide area. Based on the field surveying the average slope is about 23°. Based on the reshaped line it was possible to carry out a reliable slope stability analysis and propose appropriate remedial measures. When using profile stemming from the topographic documents, the average slope of about 15° would not give proper values for the degree of stability and this could result in inappropriate remedial measures.

Based on the above the following conclusions can be drawn:

– For the purposes of compiling engineering geological profiles with enhanced vertical accuracy with lacking relevant data on the slope geometry it is advisable to use differential measurements either in post-processing or in RTK mode;

– The definition of the location based on the corrections of the code measurements (EGNOS) largely contributes to enhanced accuracy and is suitable for precise ("scaleless") mapping. However it is not suitable for the purpose of precise spatial positioning of points.

Monitoring of landslides

General concepts

A separate group of issues, which usually comes after mastery of remediation measures, represents the acquisition of information about movement activity of landslide masses. These monitoring measurements relate primarily to the effectiveness of the remediation. Given the financial costs, which require remedial works, this problem is biased exclusively to areas of an utmost socio-economic importance. In many cases a monitored slope failure poses a direct threat to human activity and in extreme cases,

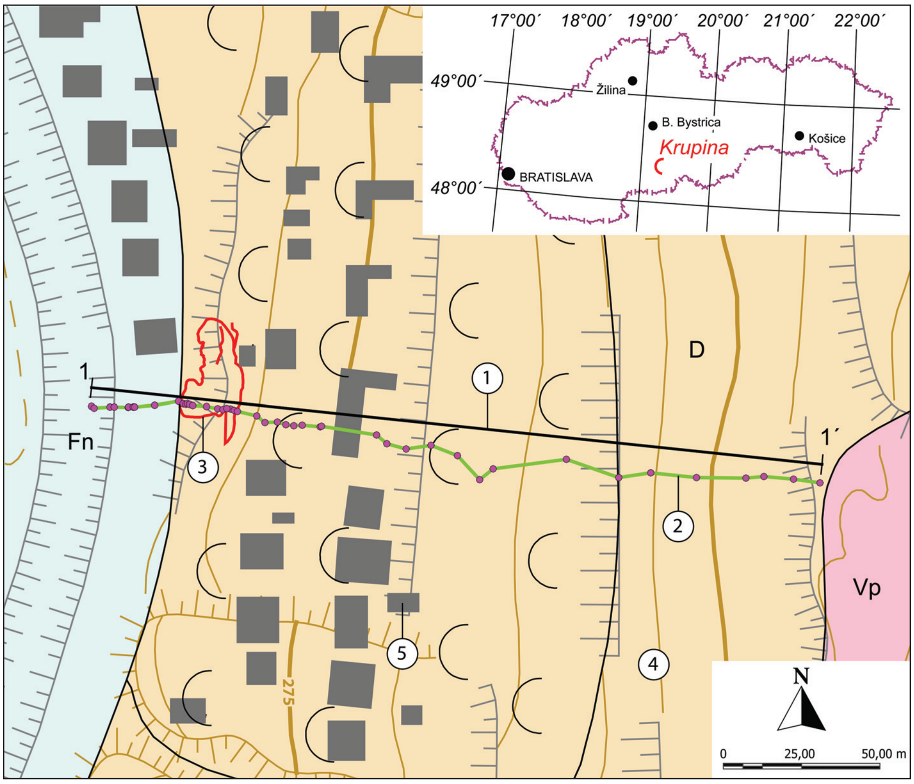

Fig. 3. Thematic engineering geological map of the landslide area in Krupina. 1 – profile line 1 – 1´; 2 – trajectory of landslide area surveying; 3 – active landslide; 4 – potential landslide; 5 – buildings; D – zone of deluvial sediments; Fn – zone of alluvial plain sediments; Vp – zone of pyroclastic rocks.

endanger the health or lives. For this reason, a network of observation points is implemented that allow control of physical activity of the landslide body.

To ensure the monitoring of movement activity we are at hand a whole range of procedures from the geodetic (terrestrial and GNSS measurements, laser scanning – LiDAR) through the remote sensing (SAR/InSAR) to the subsurface measurements of the deformation by accurate inclinometry (in two or three-dimensional system – TRIVEC) or the others. Given the ease of use and high accuracy achieved, we draw our attention to the emerging GNSS measurements.

In order to monitor slope movement activity of the territory, given the required accuracy ranging from mm to cm of the point positioning, only relative measurements of phase carrier waves are used. In this type of measurement a spatial vector is determined (consisting of reference and monitoring point), whereas the surveying is based on simultaneous measurements at both its ends (Hefty and Husár, 2003). The basic method, which enables us to achieve the desired mm accuracy, is a static method in which the receivers on both ends of the baselines do not move. The only condition is clear, preferably continuous receiving of signals from at least 4 satellites at the measured points. Accuracy of baselines depends on several factors, e.g. length of the baseline, the duration of observation, the number of simultaneously measured satellites, their configuration, or quality of signal reception. For documentation and monitoring of rapidly changing sites (moving a few dm/year) there is also possible to use real time measurements, which according to their precision (a few cm) are sufficient for this type of work.

For measurements only the receivers are used which allow reception of carrier waves phases (L1 and L2). The measurements at both frequencies are necessary for enhanced elimination of the impact of the ionosphere and for deciphering of ambiguities. Currently, in addition to the U.S. NAVSTAR GPS navigation system, the measurements of the Russian navigation system GLONASS can be used, which this year will reach full operational status. Their combination will increase the number of available satellites and will also be more efficient to eliminate systematic effects affecting the measurement. An important component of measuring equipment is the antenna allowing receiving of signals. Due to the required high accuracy it is very desirable that the antenna should have high stability of the phase centre and should allow effective elimination of multipath effects. For accurate monitoring work is also necessary to know the phase centre position in relation to the geometric centre of the antenna (antenna phase centre variations). Such criteria meet for instance geodetic receivers Trimble 5700, 5800, R8 GNSS combined with Zephyr antennae, or Zephyr Geodetic (www.trimble.com).

When measuring a key issue is a reference point selection, which should fulfill several criteria. It should be located outside the territory of interest in a stable basement, with no objects that interfere with or restrict an intake of satellite signals (trees, shrubs, buildings, busy traffic road, etc.). The point's stabilization should be reliable, allowing accurate apparatus re-adjusting to the measuring point. The choice of benchmarks depends mainly on the required accuracy, the area of the territory and the nature of movement tendencies.

The measurement at the monitored points is carried out simultaneously with the measurement of the reference point. Duration of observation (min. 20 minutes) at the observed points depends mainly on their mutual distance and the required accuracy. The most appropriate configuration is a scheme with simultaneously observed all points of the network (the reference and the observed ones). This assumption is not always feasible. In such a case the reference points are measured continuously throughout the campaign and the observed points are gradually determined separated in individual groups, depending on the number of available GNSS receivers. Several analyses have indicated that it is very important to use repeated measurements at a given point with the same receivers and antennas.

Processing of GNSS measurements consists of three essential steps: preparation and control of measured data, processing of defined baselines, the resulting estimate of the coordinates and their accuracy characteristics. The whole processing can be performed using either scientific (e.g. Bernese GPS Software) or commercial processing programme (e.g., Trimble Business Centre). In preparing and monitoring an important part is an adjusting of the correct type of antenna used, its absolute height above the point monitored and the method of determining a difference

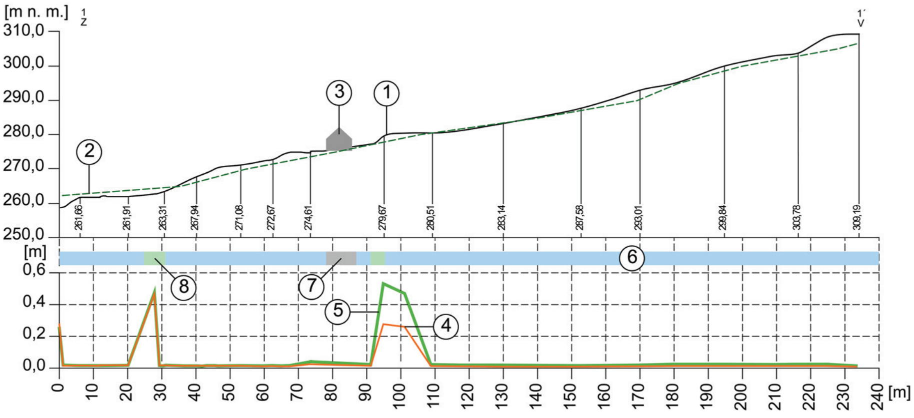

Fig. 4. Profile 1 – 1´ in the landslide area Krupina. 1 – profile constructed based on GNSS measurements in the RTK regime; 2 – profile constructed based on topographic map 1 : 10 000; 3 – building; 4 – magnitude of positional measuring error; 5 – magnitude of vertical measuring error; 6 – reception of unrestrained GNSS signal without restriction; 7 – reception of GNSS signal restrained due to constructions; 8 – reception of GNSS signal restrained due to vegetation.

(oblique, vertical). Processing of individual baselines consists of a combination of simultaneously performed code and phase measurements, whereas various methods of identifying and eliminating systematic ambiguities of the measurement are used (troposphere, ionosphere, satellites ephemerides). This results in definition of baselines parameters in the form of spatial components of the vector and the accuracy of their characteristics. The final estimate of the resulting coordinates and their accuracy characteristics consists of the final combination of all processed baselines. In this step very important is to make a correct connection of the whole network to the reference coordinate system. Commonly, dealing with such networks either global International Terrestrial Reference System ITRS (International Terrestrial Reference System) or its European equivalent ETRS89 (European Terrestrial Reference System 1989) are used.

This connection is done by incorporating of the closest reliable GNSS permanent stations in the processing. In Slovakia, the most common selected are those either from the network EPN (EUREF Permanent Network, http://www.epncb.oma.be/) or from the network SKPOS (http://www.skpos.gku.sk/), which represents a densification of the EPN network in Slovakia. Both networks guarantee high quality and consistency of the measured data provided or coordinates of points and their evolution over time together with the characteristics of accuracy. Final result of such combination are orthogonal spatial coordinates of the network points in the reference coordinate system (e.g. ETRS89), which can be further transformed into a local coordinate system (e.g. S-JTSK).

Model site

The GNSS measurements started in 2008 at the landslide, which has threaten the southern part of the village Veľká Čausa. This sliding area, due to the socio-economic significance, has been included in the geological project of “Partial Monitoring System – Geological Factors” subsystem 01 “Landslides and Other Slope Deformations”. Thanks to several phases of exploration and rehabilitation work in the landslide area a relatively dense network of observation sites has been preserved (Fig. 5; Wagner et al., 2002). The measurements of the movement activity of landslide masses at the site have been implemented at a network of surface geodetic points and the exact inclinometry in boreholes at different depth levels.

In terms of geological and tectonic conditions the territory of interest and its wider surroundings may be designated as favourable for the formation and development of slope failures. Rigid volcanite complexes atop the slope are sinking and generate pressure acting

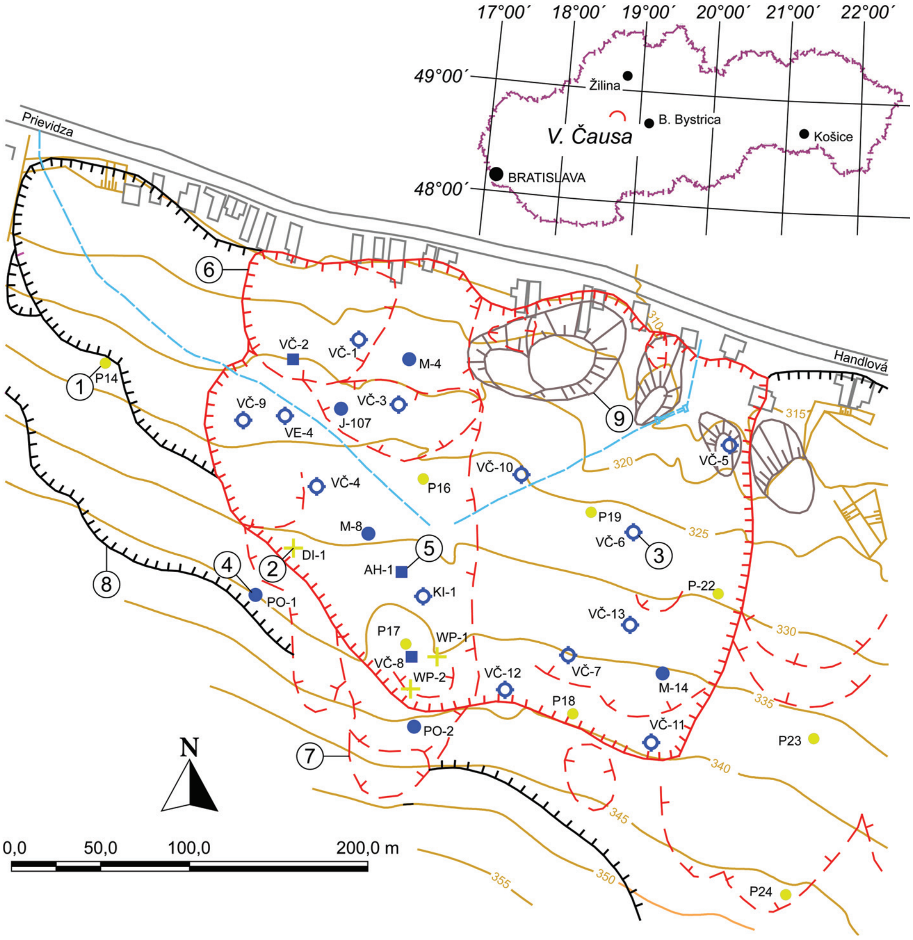

Fig. 5. Landslide above Veľká Čausa Village (according to Jadroň et al., 2000). 1 – geodetic monitoring point; 2 – stabilized monitoring point; 3 – inclinometric borehole; 4 – hydrogeological borehole; 5 – hydrogeological borehole with continuous record of groundwater table level; 6 – active landslide; 7 – transverse ridges and scarps/cracks; 8 – older landslides; 9 – shifted blocks of volcanites.

on the clay subsoil. In addition, upper slopes function as catchments enabling good infiltration of surface water into the environment; the waters accumulate in the contact of tuffs with impermeable bedrock. The accumulated water penetrates into the landslide material in the transitional and accumulation zones at the slope, concentrates in irregular porous, predominantly sandy horizons and acts as confined groundwater against the caprock, less stable sliding materials. The landslide slope re-adjusts the continuous re-saturation by water from the head scarp (Fussgänger et al., 1996).

Monitoring results

GNSS measurements are linked to the long time series of terrestrial geodetic surveying performed there since 1975. Based on the analysis of terrestrial surveying it can be stated that during the monitoring period (1975 to 1995) the biggest shift occurred in the geodetic points P-16 and P-17. In these years, associated with periods of activation of slope movements, the measured azimuth vectors are closely related to slope movement, therefore they are consistent with the slope fall line. In the period of 1995 to 2010 the monitoring of movement activity was focused on the remedial actions undertaken, confirming a general decrease in movement activity of the geodetic points observed, as well as in significant deviations from the fall line of the slope.

Since 2008, the terrestrial measurements have been carried out parallel to GNSS measurements. However, due to unsuitable conditions, mostly associated with vegetation shadowing of the receiver, it is not possible to perform measurements on all GNSS geodetic points.

During the two-year monitoring period there were performed five measurements (one zero and four staged) at 10 observation points. The results of GNSS measurements show that the western part of the landslide area (P-14) has been stabilized (the measured position vector does not exceed 10 mm; Tab. 2).

In the central area the movement activity is monitored at three stable points (DI-1, WP-1 and WP-2) and one geodetic observation point (pillar). During the monitoring period 2008–2010 there was observed a moderately increased movement activity, especially at the edge of the drainless depression (WP-1 point; Fig. 5). The west azimuth of the shift was identified in this area (Fig. 6A). Vertical change indicated a subsidence trend of the territory, but the last measurement in 2010 recorded a significant heave.

Tab. 2
Evaluation of monitoring measurements of the period 2008–2010

Point	Number of meas. stages	Positional displacement [mm]			Vertical displacement [mm]		
		max.	min.	mean	max.	min.	mean
P-14	5	9.43	3.78	6.08	44.83	3.13	22.99
P-17	4	8.52	2.00	5.99	51.87	0.00	24.72
P-18	5	12.81	1.86	6.56	46.00	0.00	21.35
P-19	5	29.53	2.30	14.42	49.00	36.18	40.63
P-22	5	10.44	2.63	6.32	53.58	2.00	23.55
P-23	4	13.60	2.38	7.13	54.40	12.60	30.00
P-24	4	11.63	1.00	6.38	61.08	0.00	27.02
DI-2	4	12.03	7.63	9.83	23.42	3.00	16.85
WP-1	5	27.78	5.39	15.61	83.79	3.00	30.57
WP-2	4	19.73	5.00	13.23	75.00	7.00	32.25

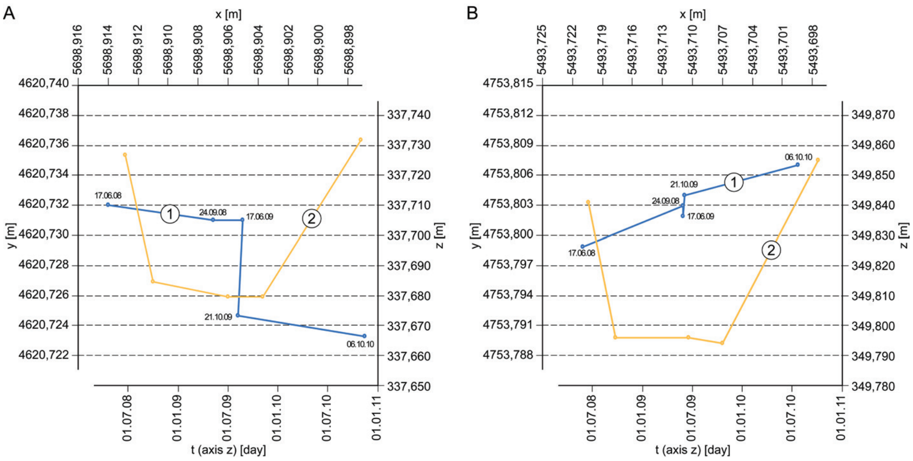

Fig. 6. Positional and vertical change of monitored points. **A** – displacement of the point P-17 within the central part of the landslide; **B** – displacement of the point P-24 within the eastern part of the landslide; 1 – displacement of the geodetic point; 2 – vertical fluctuations of the geodetic point.

The vertical turn of the year 2010 may be related to soil volume changes due to extreme rainfall totals at the turn of spring and summer.

In the eastern part of the landslide area the measured vectors typically do not exceed the value of 15 mm; shifts exceeding 20 mm are rare (P-19, Tab. 2). The vectors measured have the northeast azimuth (Fig. 6B). Vertical changes are of the analogous nature to the measurements on the points in the central part of the landslide area.

Conclusions

Space-based geodetic data have considerable potential to enhance the accuracy and cost-effectiveness of wide spectrum of issues solved by engineering geologists. This paper deals with the application of GNSS (Global Navigation Satellite System) in the practical solutions for several purposes. The method was effectively used in the inventory of landslides evolved in May/June 2010 in the Eastern Slovakia. The mapping of more than 500 landslide resulted in a GIS database of landslides registered which enables the government and local authorities to lead effectively the necessary funds for remediation of the most severe slope failures. A “scaleless” topographic information can be used, for instance, for landuse planning documents, for identifying and assessing the geological hazard/risk; this is important, for instance, for insurance claim.

It has been proven that this technology is very effective in upgrading the topographic information of existing map documents, which naturally cannot display altered morphology due to sliding, both in constructing geological cross-sections or Digital Elevation Model of the landslide area. This is vital for the calculation of the degree of slope stability and finally for the appropriate proposal of remedy measures.

The GNSS methodology is used also in the scope of the project Partial Monitoring of Geological Factors of Environment – subsystem Landslides and Other Slope Deformations. The authors managed to incorporate the network of geodetic points from several landslides across Slovakia which have been surveyed for several decades by classical geodetic surveying methods and to link these older observations with the new ones gained by GNSS measurements.

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