Comparison of results achieved by various methods of landslide monitoring

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Abstract: Landslides are one of the most wide-spread geological factors, which negatively influence the quality of the environment of Slovakia. With respect to this fact, the Geological Survey of the Slovak Republic is carrying out a project of monitoring the most hazardous landslides, which are located in various geological environments.

The monitoring includes surface measurements of the landslide activity (geodetic measurements and measuring of surface residual stresses), subsurface measurements at various depth of the landslide body (inclinometric drill logging, geophysical methods) and regime measurements and observations (measurements of groundwater levels and the yield of water flowing from the horizontal drainage drillholes). Since hydrogeological conditions are usually the main cause of landslide reactivation, observation of the water regime was the most common method used for a slope stability evaluation.

The paper deals with the various methods of derivation of the critical groundwater level, as based on the results of long-term monitoring and stability computing. Results obtained by the methods used are compared and the final critical groundwater level for each borehole in representative profiles is defined. A comparitive analysis is carried out on several landslides situated in various geological conditions.

A great attention is concentrated to these periods of time when the critical groundwater level was exceeded or occurred near to the critical value. The results of the other monitoring measurements (geodetic, inclinometric and precipitation totals) in these, or contiguous periods are analyzed in detail. As a result, the state of landslides in the most unstable conditions is assessed, and the measurable parameters of the landslide reactivation, based on the results of monitoring, are defined.

Résumé: Les glissements appartiennent aux agents géologiques les plus rencontrés, lesquels agissent négativements sur la qualité de l´environnement en Slovaquie. En vue de cette circonstance, le Service géologique de la république slovaque effectue le projet de surveillance des glissements les plus dangéreux, qui sont situés dans l´environnement géologique varié.

La surveillance compris des mesures des activitées des glissements superficielles (mesures géodetiques et mesures des contraintes résiduelles superficielles), des mesures de sous-surface à profondeur differénte du corps de glissement (la méthode d´inclinométrie précis, méthodes géophysiques) et des mesures et observations p iodiques repérées (mesures de niveau d´eau souterraine et des débits des forages/puits horizontaux de décharge). Lorsque des conditons hydrogéologiques à l´ordinaire preséntes la cause principale de reactivation des glissements, l´observation du régime d´eau souterraine reste une méthode la plus universelle pour une évaluation de stabilité de versants.

L´article s´occupe des méthodes de derivation du niveau d´eau souterraine critique varieés, basées sur les résultats de surveillance de long durée et sur les calculs de stabilité. Les résultats gagnés par des méthodes appliqueés on a comparés et on a definit le niveau d´eau souterraine critique pour chaque forage dans les coupes répresentatives.On a effectué une analyse comparative sur quelques glissements situés dans les conditions géologiques variées.

L´attention cardinale on a prêté aux espaces de temps, dans quels le niveau d´eau souterraine critique été dépassé ou quand on l´a trouvé près de valeur critique. Les résultats des autres mesures de surveillance (géodetiques, inclinométriques et des précipitations totales) à cette période ou à période contigue on a analysé en détail. En conséquence, on a évalué l´état de glissement dans conditions les moins stables et on a définit des paramètres mesurés de réactivisation de glissement obtenus sur la base des résultats de surveillance.

Keywords: landslides, monitoring, stability, water table, piezometers, inclinometer

INTRODUCTION

Slope deformations negatively influence the quality of the environment in Slovakia. According to recent data they cover nearly 3,7 % of the entire area of Slovakia, but in some geological structures (Carpathian Flysch and Neogene Volcanics) their occurrence is much greater.

The impact of landslides can be partially mitigated by identifying the landslide prone areas, and by the regular monitoring of potentially unstable slopes. In 1993 the Geological Survey of Slovak Republic initiated a project titled „Partial monitoring system of geological factors of Slovak Republic“, funded by the Ministry of the Environment of Slovak Republic. The principal aim of the project was the monitoring of various types of slope movements, located in various geological environments (Klukanova & Liscak 1998). Recently a primary importance has been the economic necessities of representative landslides.

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Based on mentioned criteria, more than 20 localities of slope movements have been selected. According to their type, landslides, creep movements and unstable road rock cuts are selected (Figure 1). However, the selection of representative localities is dynamic and can be updated. New slope movements, which have become important are continuously added, while for the other ones, such as already stabilized monitoring has been finished.

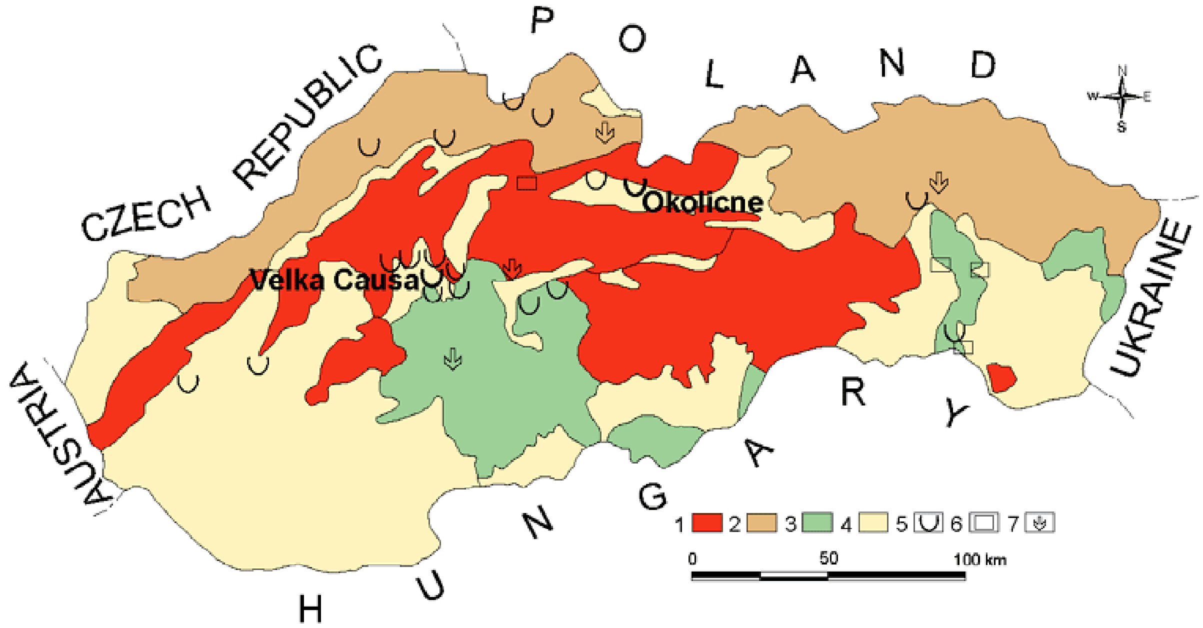

Figure 1. Situation of monitored localities. 1 – region of core mountains, 2 – region of Carpathian Flysch, 3 – region of Neogene volcanics, 4 – region of Neogene tectonic depressions, 5 – landslides, 6 – creep, 7 – road rock cuts

The methods of monitoring and the frequency of data collection depend on economic importance and activity of slope failure. For monitoring of rock cuts the methods of photogrammetry are used, while slope creep movements are investigated by crack gauges. Still, most types of our measurements are connected with landslides.

MONITORING OF LANDSLIDES

Methods and frequency of monitoring

Methods of landslide monitoring can be subdivided according to various criteria. Based on subsistence of monitored changes, the following three groups can be divided:

- Methods recording changes of hydrogeological conditions of the area as a main factor of landslide occurrence and activation (regime observations of groundwater level, yield, temperature or chemistry of water flowing from the dewatering objects etc.). The part of regime observations is an evaluation of precipitation from the nearest ombrometric stations;
- Methods measuring movement of landslide mass (geodetic measurements and inclinometric drill logging);
- Methods measuring actual stress state of landslide body (measurements of surface residual stresses or geophysical methods).

While the methods of stress state measuring give very variable information about immediate state of stresses in the soil mass (or about trends of their changes in the case of high frequently measurements), regime observations and measurements of movement's velocity enable a set of factual data to be obtained which may be analysed and used for slope stability modelling. Therefore, the main attention is directed to this set of data.

For active and economically important landslides the whole collection of monitoring methods is used while for the monitoring of less important localities only regime observation of hydrogeological conditions of landslide area is applied.

Frequency of measurements generally depends on the individual monitoring method applied. Expensive methods, such as geodetic and inclinometric measurements are usually carried out only yearly (in the case of active landslide movements using of these measurements is usually more frequent). We have achieved significant progress in regime observations. Interval of two weeks measurements have been replaced by the automatic water stage indicators measuring the oscillation of groundwater level continually.

As a result, each monitored locality was characterized by a set of measured values of different character and density. In the process of their complex evaluation the results obtained by various measurements are often controversial. Therefore it is a very important task to find some connections among the results of various monitoring measurements and try to define the critical values of measured parameters for which overload may indicate unstable state of landslide.

Because sudden rise of groundwater level is often trigger factor of the landslide and largest collection of data represents just the results of regime observations, it is suitable to use them for primary analyse. The results of this analysis led to the derivation of critical groundwater levels in observed objects and enable to define periods when the critical groundwater level was exceeded or occurred near to the critical value. In these periods the results of the other monitoring measurements may be evaluated. Finally, the questions about connection among the results of various monitoring measurements and about their critical values may be answered. Based on the achieved facts an idea about optimal ways of monitoring observations in future may be formulated.

Derivation of critical groundwater level

Critical groundwater level may be derived by various ways. Most frequently used is a stability analysis. Various empirical methods may be applied in the localities with long-term regime observations.

Stability analyses

These methods go out from the definition of critical groundwater level as such state of groundwater, which indicates limit stability of slope (degree of stability equals 1). The stability of the basic engineering geological slope model is computed in conditions of various levels of groundwater. The groundwater level that responds to limit degree of stability (FS = 1) is defined as critical groundwater level. There is a high probability that overloading of this level originate an activation of landslide movement. All calculations are realized on basic engineering geological slope model characterized by constant values of physical and mechanical properties of soils, using standard software of slope stability computation.

Empirical methods

These methods are based on the results of long-term monitoring of groundwater level changes. Seven states of groundwater level for each observed borehole are defined according to the method, proposed by Scherer (1999). Basic input data for the method are: average groundwater level and maximal oscillation of groundwater level within the whole period of observation. Practical derivation of various limit states of groundwater level is explained in Figure 2. The greatest attention is concentrated to extremely high state (EHS) of groundwater level, which corresponds to critical groundwater level defined according to this method. Exactness of the derived limits depends on duration of the period of observations, and subsequently on possibility to record the maximal values of groundwater level oscillation.

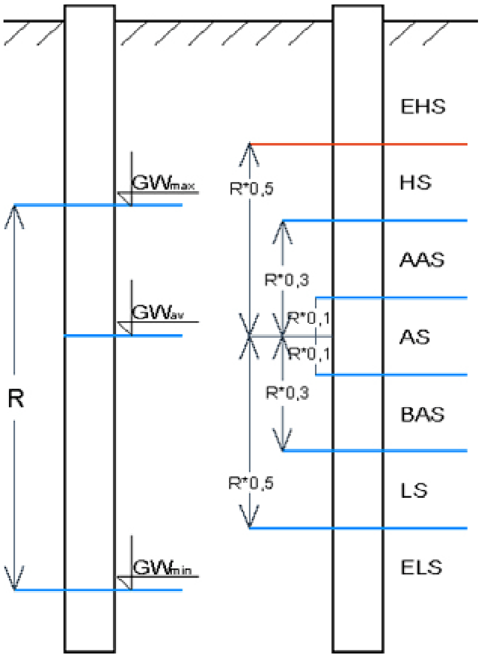

Figure 2. A method of various states of groundwater level derivation. R – maximal oscillation of groundwater level within the whole period of observation, ELS – extremely low state, LS – low state, BAS – state below average level, AS – average level, AAS – state above average level, HS – high state, EHS – extremely high state, GWav – average groundwater level within the whole period of observation, GWmax – maximal groundwater level, GWmin – minimal groundwater level

By comparing the methods above, an advantage of empirical method is a possibility to define critical groundwater level for each borehole with long – term observations (not only for boreholes situated on stability computing profile). Moreover, empirical method enables to define basic values of extremely high state of groundwater level, which may be specified by stability analysis.

ANALYSE OF MONITORING RESULTS

Practical analyse of the results of monitoring measurements were realized on the sets of data from the landslide localities Velka Causa and Okolicne (Figure 1). For both localities the whole scale of monitoring methods has been applied on a relatively dense net of objects with a relatively high frequency of measurements. Moreover, selected landslides jeopardize important technical objects (a part of Velka Causa village and main railway line near Okolicne village in the vicinity of the Liptovsky Mikulas town).

Landslide area near the village Velka Causa

The slope in the vicinity of the village Velka Causa (near the town Prievidza) belongs to well-known landslide territories, where the landslide movements activated several times in the last decades (in 1969, 1975, 1985). The landslide activated during the spring of 1995 (with approximate area of 550 x 300 m – Figure 3 and depth of active slide surface of 5 to 8 m) damaged and endangered several residential houses and local road on the southern margin of the village (Jadron, Mokra & Wagner 2000).

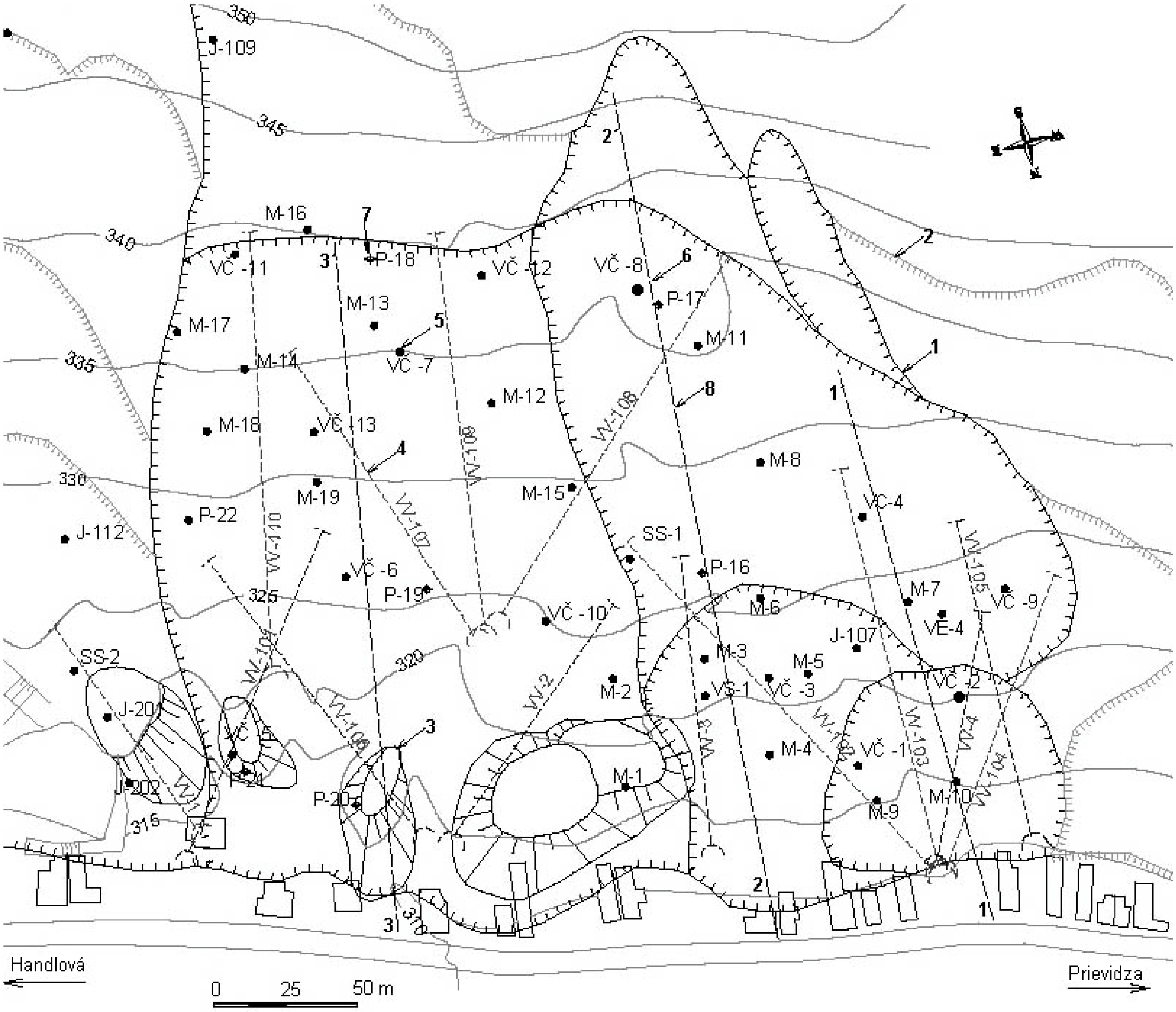

Figure 3. Landslide area near the Velka Causa village (according to Jadron *et al.* 2000). 1 – active forms of landslides, 2 – older potential landslides, 3 – removed blocks of volcanic rocks, 4 – horizontal drainage borings, 5 – exploratory boreholes (symbols VC and VE indicate inclinometric boreholes), 6 – boreholes with the automatic water stage indicators, 7 – geodetic points, 8 – lines of the computing profiles

Geological setting, mitigation measurements and monitoring

From the point of view of landslide development, the landslide area has a very favourable structure. Volcanic rocks (andesites and pyroclastic agglomerate tuffs) are situated in the upper part of the slope. They lie on a weakly consolidated series of clays, claystones and tuffaceous sandstones of Neogene age. This series of strata is subhorizontally deposited on Paleogene flysch rocks. Such a geological structure resulted in a complicated hydrogeological situation. Precipitated water in the infiltration area leaks through the relatively permeable jointed rocks, concentrates in the upper part of the slope in contact with less permeable sedimentary rocks of Neogene age, and creates several pressure horizons in the landslide deluvium. As a result, repeated activation of the landslide movements was noted (Wagner *et al.* 2002). A very important feature of the geological and hydrogeological structure of lower part of the landslide slope is an accumulation of old terrace permeable gravels, covered by landslide deposits (Figure 3). These deposits make today a natural drainage and contribute to the landslide stabilization.

The last activation of landslide in 1995 was caused by the anomalously high infiltration event in the spring of 1995 caused by precipitation and rapid snowmelt. The engineering geological investigation consisted of drilling 14 vertical inclinometric boreholes with depth of about 25 m and 5 horizontal subdrainage borings with length of 110 to 150 m.

The extensive corrective measures consisted of surface and subsurface drainage of the landslide slope (by the rubble ribs, open ditches and drainage trenches). These works continued by boring of new subdrainage boreholes (VV-107, 108, 109 and 110 in 1997 and 1998) of length from 100 to 150 m (Jadron *et al.* 2000).

Simultaneously with the investigation and realization of the corrective measures, observations of the landslide activity began by a complex of monitoring methods. Movements of surface parts of the landslide body were registered by geodetic measurements (on the net of geodetic points, built on 1975) and subsurface deformations were recorded by the method of inclinometric drill logging. Besides, regular regime monitoring of groundwater depth level and discharge from drainage boreholes were realized. The frequency of regime observations was once a week (except boreholes VC-2 and VC-8, where automatic water stage indicators record groundwater level each hour). According to the results of monitoring, eastern part of the landslide area is stabilized due to successful dewatering of the area by the horizontal boreholes. In the western part of the area appearances of activity are occasionally manifested.

Derivation of the critical groundwater level

Both methods (stability analyse and empirical method) were used in process of critical groundwater level derivation. In the first step, the values of extremely high state of groundwater (EHS) for each observed borehole were determined. Then the stability analyse in three selected profiles were realized. According to the results, depth of groundwater responds to limit degree of stability (FS = 1) was defined. This value in boreholes, situated in profiles was compared with the EHS value. As results from Table 1 (which summarize values of groundwater level from boreholes situated in representative profile 2 – 2' in sensitive western part of landslide area), the values determined by both methods are consistent. Based on these verified facts the EHS values are regarded as a representative values of critical groundwater level for each borehole. The periods of time when the critical groundwater level was exceeded or occurred near to this critical values were considered as critical in term of slope stability.

Table 1. Input data and the results of the critical groundwater level derivation

Borehole	**Depth of the groundwater level below surface (m)**				
	Maximal	**Minimal**	**Average**	**EHS**	**FS=1**
VC-8	4,58	1,51	2,60	1,06	1,11
M-3	4,45	2,77	3,34	2,50	3,06
M-4	5,92	5,01	5,54	5,08	5,26
M-5	5,11	0,67	3,61		
M-6	2,65	0,29	1,42	0,24	0,82
M-8	1,54	0,07	0,68	-0,06	0,42
M-11	4,96	0,46	3,21	0,96	1,44

Comparison of the results of various monitoring methods

In the first step of analyse the critical groundwater level (EHS) was computed for each borehole. Then time of duration of such a state was defined. The results of the other monitoring measurements realized in selected periods were analyzed in details. Regime observations and inclinometric measurements were realized in the same boreholes and their results were compared with the movements of the nearest geodetic points.

Preliminary results of the analysis showed that overloading of the EHS level was observed at each borehole in different time periods. Videlicet there was not found a time period, when the critical EHS of groundwater was achieved in all (or in majority) of the observed boreholes. This confirmed a high level of geological and hydrogeological heterogeneity of the landslide area.

Due to the different frequency of the measurements, the comparison among the obtained results is very difficult. It usually consists of qualitative evaluation of character of landslide activity (whether the movements, recorded by geodetic and inclinometric measurements increase during the EHS period or not). Quantitative values of movements can be analyzed only after indicating of the conformity.

Relatively good conformity was found in eastern part of the landslide area, particularly in the borehole VC-7 and geodetic point P-18 (Figure 4). The state of groundwater level, exceeding the EHS was recorded in the borehole VC-7 in the spring 1997 (from 18th January to 14th May 1997). At the same time, the deformations recorded by the inclinometric measurements in the borehole VC-7 showed increasing of movements in the depth of 2 and 9 m. The deformations since the last measurement were 11,85 mm (what represents the average velocity of movement 15,28 mm/year) and 1,29 mm (1,67 mm/year) for the depth of 2 and 9 m, respectively. In this critical period the displacement of the nearest geodetic point P-18 was 31,0 mm since the last measurement (what represents the average velocity of movement up to 85,72 mm/year). After a successful dewatering of the area by the horizontal borehole VV-110 in October 1998 the deformation recorded by the inclinometric and geodetic measurements were essentially smaller.

Unfortunately, relationships among various monitoring measurements were not so clear in other parts of the area. In several cases the differences are unclear due to retardation of the influence of extreme increasing of ground water level to development of deformations, but in other cases the regime of deformations is too individual.

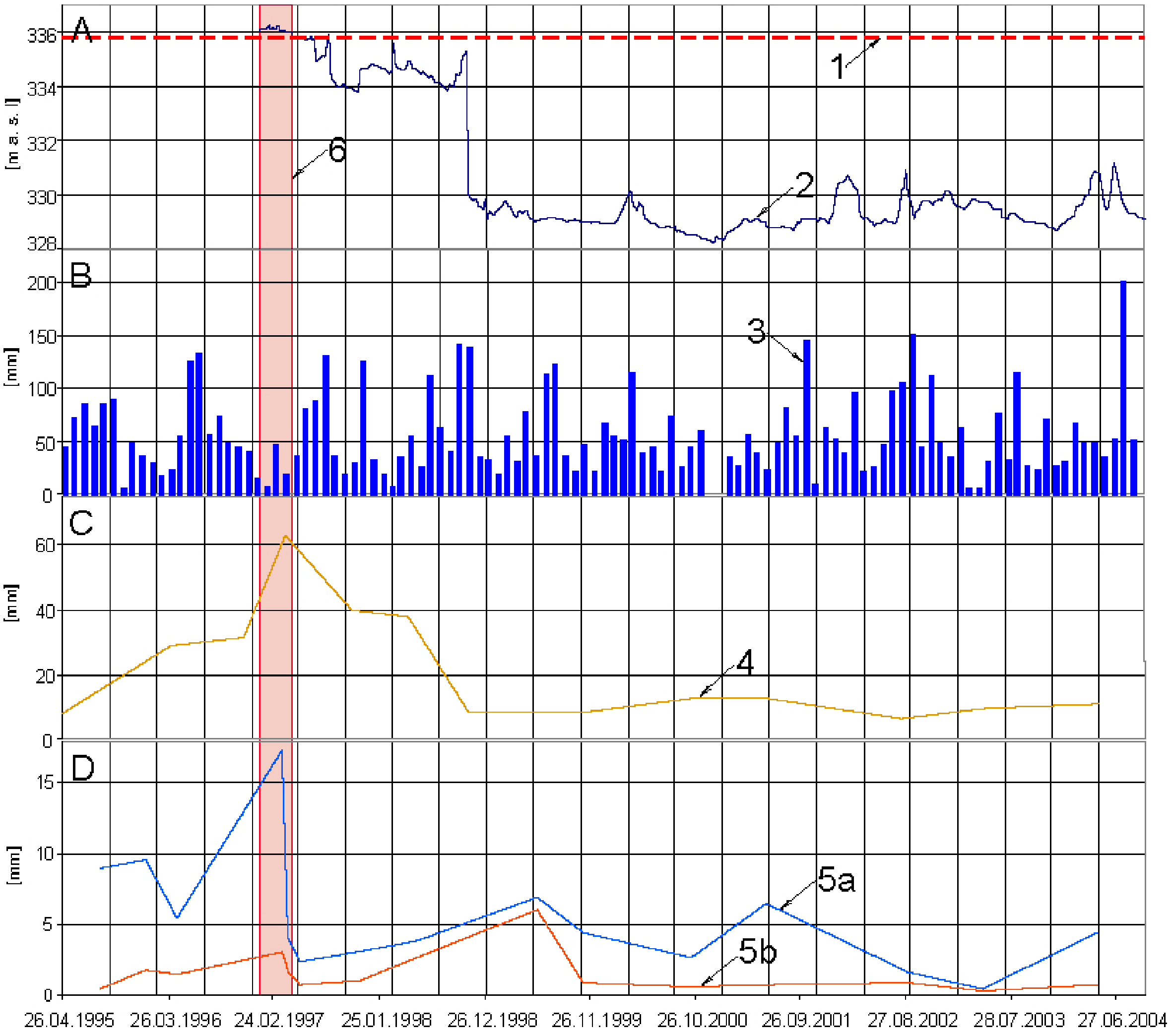

Figure 4. Comparison of the results of monitoring measurements (landslide Velka Causa). A – groundwater level, B – precipitation total, C – geodetic measurements, D – inclinometric measurements, 1 – extreme high state of groundwater level (EHS), 2 – time course of groundwater level changes in borehole VC-7, 3 – monthly precipitation totals from the ombrometric station Prievidza, 4 – displacements of the geodetic point P-18, 5 – deformations in the inclinometric borehole VC-7 (5a – in the depth 2 m, 5b – in the depth 9 m), 6 – critical period of exceeding of the EHS of groundwater level

Based on the monitoring results the following conclusions can be stated:

- Geological structure and hydrogeological conditions of the landslide area are very complicated and heterogeneous. The monitoring measurements are able to record only a part of the results of complicated events and processes. Therefore, connections among the results of various measurements are not clear;
- Nevertheless, there exists some connection among the results of various measurements, especially in the time periods of extreme state of some measured factor (usually groundwater level). These connections enables informative identification of critical values of the results of other measurements;
- The most precise analyses are possible in conditions of approximately similar frequency of the measurements. Existing state with relatively dense regime observations and yearly measurements of deformations is very uneven and unsuitable for detailed analysis;
- Because the most amount of information come from regime observation and influence of groundwater is the most important factor of landslide activation, the actual state of groundwater level may be evaluated as a leading attribute of the actual stability of slope. The proposed methods of critical groundwater level derivation may be practically used as available information.

Landslide Okolicne near the town Liptovsky Mikulas

The landslide Okolicne is the part of the old landslide area where the slope deformations activated through the geological history as a result of undercutting of slope by lateral erosion of the Vah River. Recent activation of the landslide (with the approximate area of 0,16 km^2 and length about 750 m – Figure 5) was caused by a railway cut made at frontal part of the old landslide in 1949. Since that time the slope is potentially unstable and permanently threatens the important railway line (Fussganger & Jadron 1977).

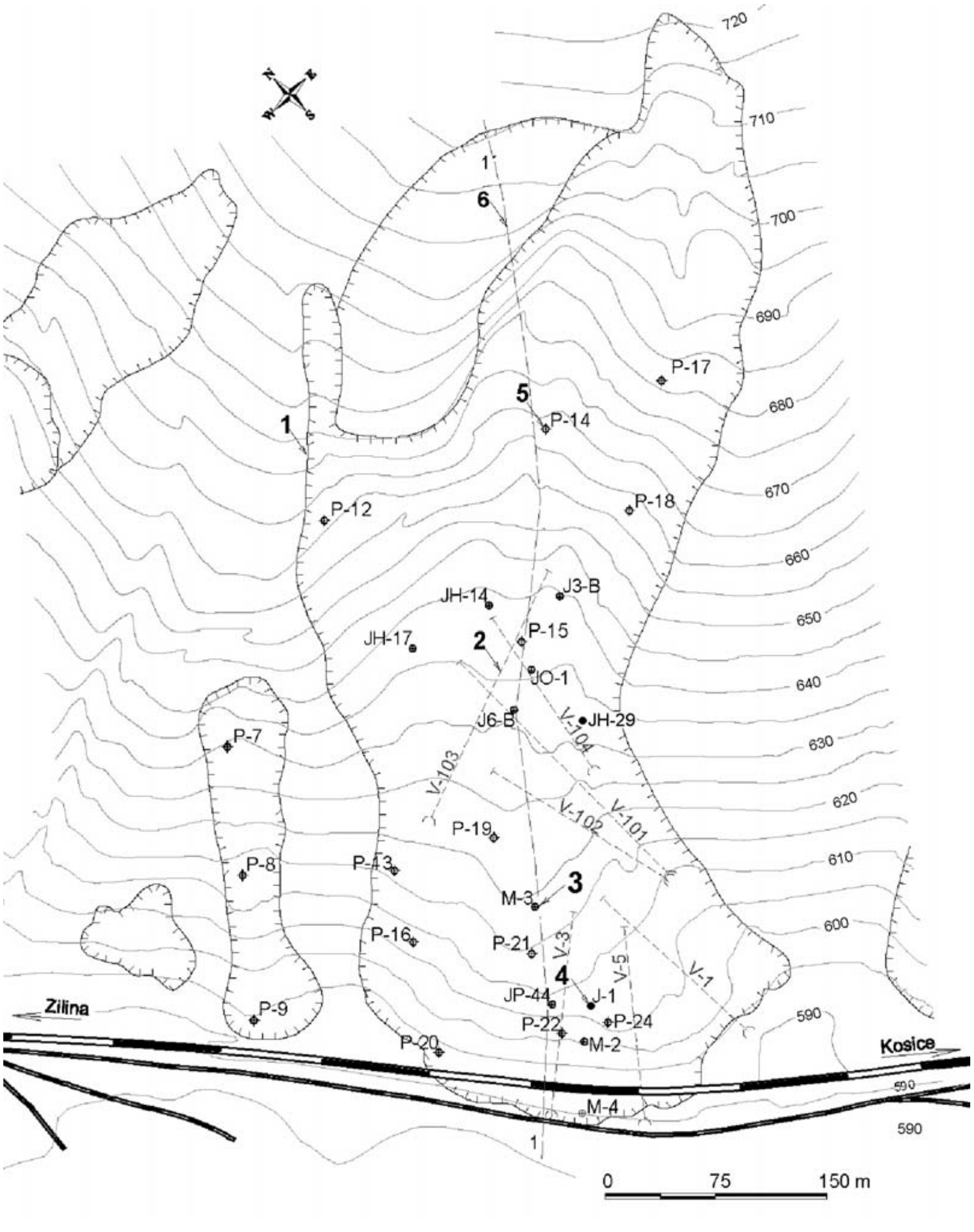

Figure 5. Landslide Okolicne near the town Liptovsky Mikulas. 1 – active forms of landslides, 2 – horizontal drainage borings, 3 – exploratory boreholes (symbol M indicate inclinometric boreholes), 4 – boreholes with the automatic water stage indicators, 5 – geodetic points, 6 – line of the computing profile

Geological setting, mitigation measurements and monitoring

The affected area consists of flyschoid Paleogene strata, in which claystones prevail over sandstones. Quaternary deposits overlaying Paleogene sediments. In the upper part of the landslide, block fields can be finding. They are represented by sandstone blocks, “floating” in the plastic claystones and clays. An accumulation part of the landslide is on contact with the alluvial fan of the Vah River. The flooding plain of the river is covered by the landslide body up to the maximum width of 60 m. Highly permeable gravels of the alluvial deposits then act as a real drain (Scherer & Malik 2002). Hydrogeological conditions of slope are very suitable for the landslide development. Paleogene sandstone intercalations act as aquifers facilitating deep water circulation in the slope. The aquifers are confined and their groundwater level is locally markedly positive.

Since 1952 several stages of the engineering geological investigations and consequential corrective measures (interceptory drainage and a circumjacent open ditch in 1952 – 1954, 5 subdrainage borings with drainage trenches and rubble rib in the frontal part of landslide in 1967) were carried out. The most important were the complex engineering geological investigations and remediation works done from 1971 to 1975. More than 30 exploratory boreholes subsidiary drainage with interceptory shafts and 4 new subdrainage borings (each of the length about 150 m) were realized.

An activity of the landslide was observed by the monitoring measurements during each phase of the investigations and remediation of slope. Systematic long-term monitoring of the locality is carried out since 1993. The net of monitoring objects consists of geodetic points (realized in 1971), 4 inclinometric boreholes (realized in 1991) and selected 10 vertical and 7 horizontal boreholes used for regime observations (Figure 5). The frequency of regime observations is once a week. Automatic water stage indicators have been built in two boreholes (J-1 and JH-29).

Derivation of the critical groundwater level

Similarly as in the Velka Causa locality both methods of critical groundwater level derivation were used. Futhermore the stability analysis in representative profile was realized. Comparison of critical depth of groundwater level is summarized in Table 2. Based on the presented results it may be stated, that differences between the values of critical groundwater level, determined by both methods are small. Therefore the values of the EHS were considered as sufficiently representative for the critical groundwater level.

Table 2. Input data and the results of the critical groundwater level derivation

Borehole	**Depth of the groundwater level below surface (m)**				
	Maximal	**Minimal**	**Average**	**EHS**	**FS=1**
M-4	14,70	12,05	12,98	11,65	11,65
M-2	18,95	1,52	9,98	1,27	1,27
JP-44	20,43	6,44	15,67	8,68	8,68
J-1	7,58	3,58	5,93	3,93	3,93
M-3	12,90	9,37	11,45	9,68	9,68
JH-29	2,85	0,10	1,59	0,21	0,21
JO-1	7,43	3,13	5,22	3,07	3,74
J3-B	6,74	2,58	4,44	2,36	2,78

Comparison of the results of various monitoring methods

The system of monitoring (methods applied, the frequency of measurements) is very similar to those used in the landslide locality Velka Causa. Therefore the methodology for comparison of the results of various monitoring methods is the same.

Similarly as in case of the Velka Causa, overloading of the EHS level, as well as duration of the critical state was observed at each borehole in different time periods. Thanks to this fact the slope is still stable though its parts (especially the frontal part occurred near the railway line) are in limiting state of stability. If the exceeding of the EHS values appears in several boreholes at the same time, probability of the landslide movement is very high (first place in the sensitive frontal part of the landslide).

Comparison among the results of various monitoring measurements during the EHS periods is not clear, as well. After analysing all of the observed boreholes relatively good conformity was found in the transport (central) part of the landslide body, particularly in the piezometric borehole JH-29 with automatic water stage indicator, inclinometric borehole JO-1 and geodetic points P-14 and P-15 (Figure 6).

In consequence of dense frequency of automatic water stage indicator measurements and specific hydrogeological features of locality, the changes of groundwater level are more expressive and critical periods of the EHS exceeding are shorter. Two critical periods of time were defined – in 21st April 1998 and from 1st to 19th April 2000. In the first case sudden increasing of the groundwater level rebound on increasing of geodetic points displacement (Figure 6). Displacements of the geodetic points P-14 and P-15 and deformations of the inclinometric borehole JO-1 in the second critical period are summarized in Table 3.

Table 3. Results of monitoring measurements in the period of critical groundwater level

Type of measurement	**Locality**	**Monitored point**	**Depth below surface (m)**	**Displacement/defor-mation since the last measurement (mm)**	**Average velocity of movement (mm/year)**
Inclinometric	Velka Causa	VC-7	2,0	11,85	15,28
			9,0	1,29	1,67
	Okolicne	JO-1	2,5	8,45	8,88
			13,0	5,33	5,51
Geodetic	Velka Causa	P-18	Surface	31,0	85,72
	Okolicne	P-14		60,87	59,57
		P-15		11,78	11,53

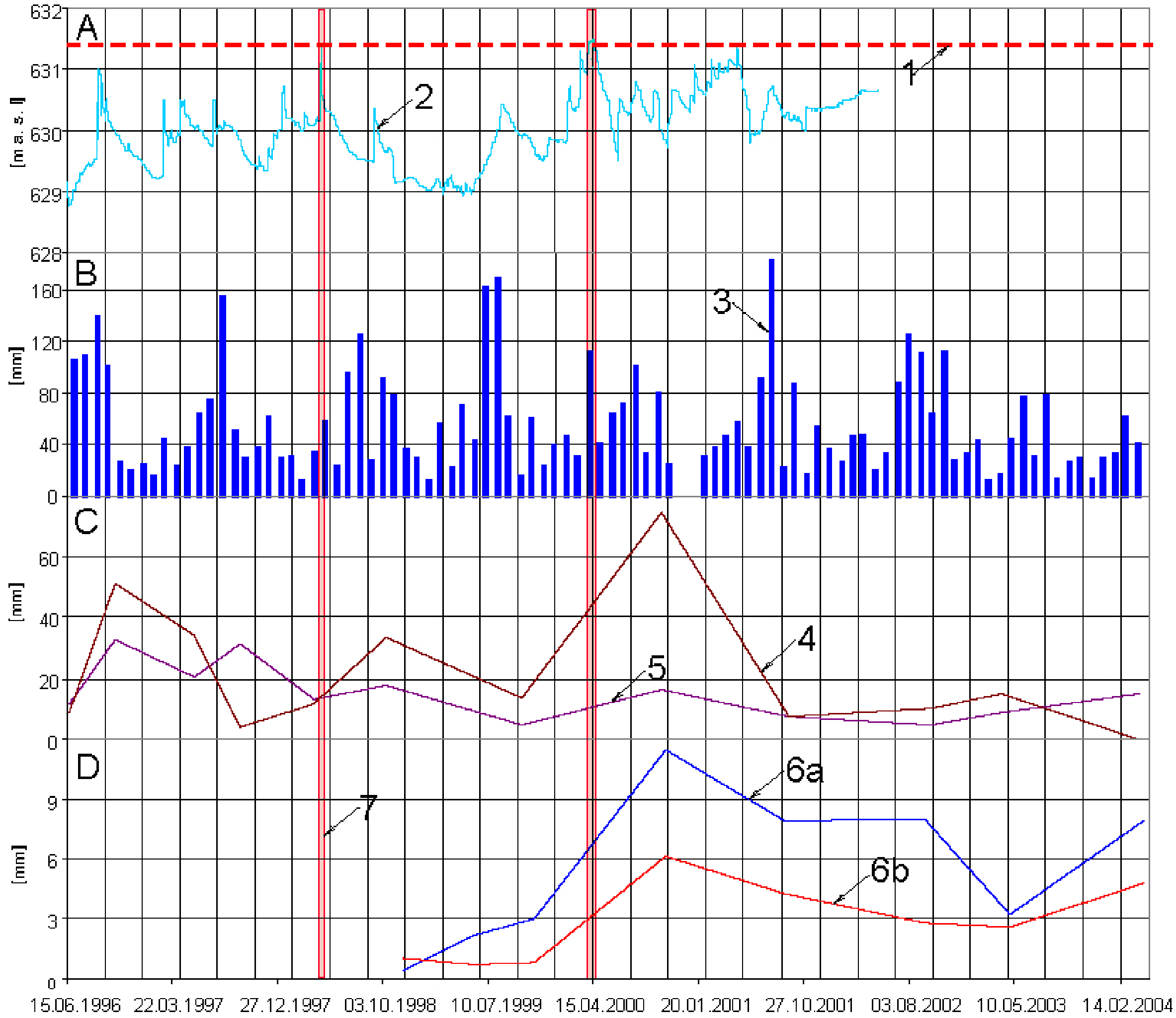

Figure 6. Comparison of the results of monitoring measurements (locality Okolicne). A – groundwater level, B – precipitation total, C – geodetic measurements, D – inclinometric measurements, 1 – extreme high state of groundwater level (EHS), 2 – time course of groundwater level changes in borehole JH-29 (water stage indicator is non-functional since May 2002), 3 – monthly precipitation totals from the ombrometric station Liptovsky Mikulas, 4 – displacements of the geodetic point P-14, 5 – displacements of the geodetic point P-15, 6 – deformations in the inclinometric borehole JO-1 (6a – in the depth 2,5 m, 6b – in the depth 13 m), 7 – critical period of the EHS exceeding

Analyses of the monitoring results in the Okolicne landslide confirmed conclusions, summarized for the Velka Causa. Moreover, dynamics of the groundwater level changes seems to be more expressive in flyschoid environment.

Prime importance of the groundwater state on the stability of slope was confirmed on both localities. Therefore the idea to use existing information from regime observations in wider extent is reasonable. As mentioned above, due to high degree of geological and hydrogeological heterogeneity of the landslide area, critical groundwater levels appear in individual piezometers in different periods of time. In case of synchronous increasing of water in several observed boreholes, the stability of slope is markedly endangered. Comparison of time courses of groundwater level changes in selected boreholes situated in the Okolicne landslide is illustrated in Figure 7. Unfavourable state of the groundwater (exceeding the EHS or near to it) results from course of each curve and time periods, when this state occurred in several boreholes, is marked. The stability of slope for this critical moment of unfavourable groundwater level was computed. The results showed the critical stability state of the slope in selected intervals.

CONCLUSION

Based on the results of long-term monitoring of selected landslides the following principal problems were carried out:

- An evaluation of influence of groundwater to activation of the landslide and deriving of methods for critical groundwater level determination;
- An evaluation of the results of various monitoring measurements with aim to find some relations among them.

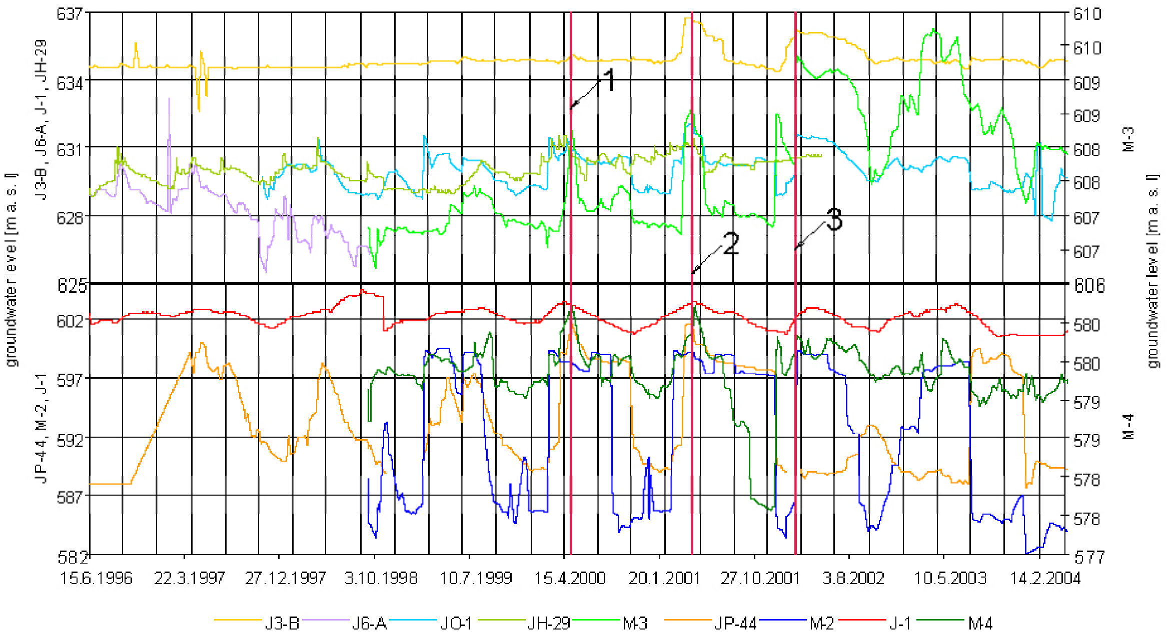

Figure 7. Comparison of time courses of groundwater level changes in selected boreholes (Okolicne landslide). 1 – unfavourable state of the groundwater in several boreholes in 10th May 2000 (computed degree of stability corresponding to these conditions is FS = 1,10), 2 – conditions in 30th April 2001 (FS = 1,41), 3 – conditions in 22nd March 2002 (FS = 1,03). The boreholes are grouped according to their altitudes

As for the first group of problems the results of the critical groundwater level determination by stability analysis and by empirical method indicated their sufficient coincidence. Moreover, empirical method enables to define critical groundwater level for each borehole (not only for boreholes situated on stability computing profile) and after comparing with stability methods may be considered as sufficient.

Because of high degree of heterogeneity of the geological and hydrogeological environment as well as different frequency of monitoring measurements, the comparison among the results of various monitoring measurements is not clear. Some results of detailed analyses of displacements and deformations during the periods of critical groundwater levels exceeding are summarized in Table 3. In spite of the great dispersion of values and their selective character, the presented values makes it possible to consider the average velocity of displacements of geodetic points of more than 50 mm/year and average velocity of inclinometric boreholes deformation more than 5 mm/year as critical from the point of view of the slope stability.

A quantum of various information, results of analyses and evaluations enable to define the most important principles for methodology of present and future monitoring of landslides.

Actual monitoring based on the existing monitoring nets, methods applied and frequency of measurements has to be concentrated to the following questions:

- The most important factor of landslide activation is the state of groundwater. Therefore the quality of regime observations is the first condition for the successful and efficient monitoring.
- Empirical method of the extremely high states (EHS) of groundwater derivation is simple and sufficiently responsible. In practice, a value of the EHS may be computed for each observed borehole and passed to observers. From the stability point of view the most unfavorable state of slope is in such time period, when groundwater level is near, or exceed the EHS in several observed piezometers. This must be transmitted to the center of monitoring as serious warning signal;
- Quality of monitoring will rise with amount of classical or on-line automatic water stage indicators;
- Geodetic and inclinometric measurements, realized in long time intervals (for example per year) have only complementary and verifying position.

In the future, the monitoring of landslides should be oriented to the following methods:

- Automatic water stage indicators, which are on-line connected with the centre of monitoring and equipped by warning systems will record the groundwater changes. Because of high degree of heterogeneity of landslide environment, usually several indicators, which record different levels of groundwater have to be situated in selected points within a landslide area;
- Advanced methods, based on the GPS of high accuracy will be used for the surface changes measurements;
- Likewise, advanced methods of continual measuring of deformations in various depths will be used in selected boreholes.

Continual information concentrated in the centre of monitoring enables to know all important facts about the actual state of landslide and predict its nearest development.

Acknowledgements: The authors are thankful to The Ministry of the Environment of Slovak Republic for its support and kind permission to publish this paper.

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