Stability assessment as a tool for design of landslide early warning system in Liptovská Štiavnica village

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Abstract: With its complicated geological structure and relief, The Slovak Republic represents a country with high occurrence of different types of slope deformations which appear hazardous from the socio-economic point of view. One of these slope deformations is an active landslide located near the village of Liptovská Štiavnica directly jeopardising workers, livestock, and the property of a local agricultural cooperative Ludrová - Liptovská Štiavnica. Using an engineering geological investigation, an analysis of the amount of precipitation in the wider area, groundwater regime observations and inclinometer measurements, the data were obtained in order to calculate the factor of safety (FS) in geotechnical software GEO 5 and thus assess the stability of the landslide. The analysis of the amount of precipitation showed that the extreme precipitation amounts recorded during the year 2010 preceded the last reactivation of the landslide on March 14th, 2011. The results from groundwater regime observations showed that groundwater level in the landslide rises within the higher precipitation amounts. As stability calculations demonstrate, the stability of the landslide is conditioned by groundwater level in the landslide body. Based on stability calculations, the critical groundwater level at 3 meters below the surface has been established. Although more accurate stability assessment requires long-term monitoring, the results of this study support the inevitability of remediation works which will secure permanent stability of the landslide and provide a useful tool for future early warning system.

Key words: engineering geological investigation, landslide monitoring, stability calculations, factor of safety, early warning system, Liptovská Štiavnica

1. INTRODUCTION

The landslide-prone slopes are affected by a variety of processes which results in a movement of materials including rock, soil, artificial fill, or all of them combined. Landslides represent a frequent natural hazard and a major threat to humans and the environment, both in the world and in the Slovak Republic. According to Atlas of slope stability maps of the Slovak Republic (2006) most of the landslides occur in areas built by Paleogene rocks (Šimeková et al., 2006). Intense erosion and frequent landslides occur mainly in the slope sediments on flysch bedrock where thick clayey-siltstones and clayey sandstones with variable fragment content are accumulated (Tornyai & Dunčko, 2013). Flysch rocks' occurrence is typical mainly in The Outer Western Carpathians however it is possible to find flysch-like bedrock also in the Inner Carpathian Paleogene Basins.

Based on current knowledge, the most important factors reflecting suitable conditions for landslides' origin are geological settings (structure, lithology, tectonics), the geomorphological settings, georelief character, climatic factors, hydrogeological settings as well as actual land-use (Tornyai et al., 2016). The climate change has quite huge impact on an origin of the new landslides or a reactivation of the existing ones, especially the increased and long-lasting precipitation significantly influence circulation and regime of groundwaters (Petrýdesová & Liščák, 2009). During the years 2010 and 2011, the extreme precipitation amounts were recorded what resulted in activation and reactivation of many slope deformations in Slovakia (Buša et al., 2019). The landslide localized nearby village of Liptovská Štiavnica was one of the slope deformations reactivated in 2011. The bedrock of the landslide-affected slope is built by Paleogene rocks of Huty Formation, which is typical with its claystone predominance over sandstone. The landslide body is composed of slope deposits such as silts and clays with the low proportion of sands. The stability of the landslide-prone slope was changed by a cut which was made at the base of the slope during the construction of the agricultural objects in 1979. In March 2011, after heavy rains the lower part of the landslide body was reactivated and the activity of its upper part was triggered.

As a part of the engineering geological investigation (Tupý et al., 2019) the boreholes with inclinometer and piezometric casings were installed into the landslide body for the monitoring purposes. Long-term monitoring of the landslide-affected areas provides the information, which helps to prognose the evolution of further movements and to observe the functionality of remediations works after being realized (Petrýdesová & Liščák, 2009). The understanding and forecasting of landslide movements largely depend upon empirical investigations or tasks combining multidisciplinary achievements such as geology, monitoring, surveying, geomorphology, and hydrogeology as well as numerical modeling (Jiao et al., 2013). Based on the obtained data from the engineering geological investigation and monitoring measurements, the mathematical model of the slope profile was constructed, and stability calculations were performed using geotechnical software GEO 5.

The slope profile included the inputs for stability calculation

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such as relief in chosen coordinate system, lithological boundaries in between different types of rocks and soils, groundwater levels, shear planes, unit weights and shear strength parameters obtained by reverse calculations (Bednarik et al., 2018). Modulus of geotechnical software GEO 5 solve the stability of any slope with a round-shaped or a polygonal-shaped shear plane using two-dimensional model of the slope body. The analyses of two-dimensional slope geometry, in which stripe solutions are used, provide an important knowledge in the initial design and risk assessment of slopes (Abramson et al., 2002).

In stability calculations, it was necessary to consider an influence of groundwater level on the stability of the landslide body. Groundwater level modelling was based on groundwater regime observations from engineering geological investigation. A change in groundwater regime causes a change in tension along the slope as well as the changes in physical properties of the soils and rocks of a landslide body (Petrýdesová & Liščák, 2009). In fact, the groundwater regime observations are inseparable part of the slope deformations' monitoring.

The most common indicator of slope stability is the factor of safety (FS) defined as the value by which the shear strength of the slope material must be reduced in order to bring the slope to the point of failure (Renani & Martin, 2020). The value of factor of safety defined as FS = 1 represents the stability as the equilibrium between active and passive forces/moments present in the slope. However, this value can be replaced by so called required value of factor of safety (FS_{req}) which is usually higher than value FS = 1 and is significantly dependent on the complexity of geological conditions and the difficulty of designed construction. For instance, for the slopes with permanent constructions $FS_{req} \geq 1.5$; for the slopes with temporary constructions $FS_{req} \geq 1.3$; and for the slopes affected by seismic strain $FS_{req} = 1.0 – 1.1$ (Petro et al., 2008). In case of the slope near the village of Liptovská Štiavnica, the required value of factor of safety was chosen as the value $FS_{req} = 1.3$ because the slope is already in the movement and the slope is used as a pasture for livestock.

2. STUDY AREA

The village of Liptovská Štiavnica is situated in the northern part of the Slovak Republic, in the district of city Ružomberok (Fig. 1). The study is located at the boundary of two large geomorphological units: the Liptovská kotlina Basin and Nízke Tatry Mountains.

According to the climatic classification for Slovakia (Landscape Atlas of the Slovak Republic, 2002), the territory under consideration is a moderately cold, very humid region, The average annual air temperature is 3 to 6 °C; total annual precipitation is on average 600 to 800 mm, and the area has on average 100 to 140 days of snow coverage.

The area is drained by two streams, so called Ludrovianka and Štiavničanka (Fig. 2) which mouth to the Váh river flowing through the city of Ružomberok. Both streams have character of mountainous streams with fast current, which slows down at the contact of the slopes of Nízke Tatry Mountains with the Liptovská kotlina Basin, as evidenced by the presence of accumulated fluvial sediments in the northern part of the study area.

In the northern part of the study area, the Paleogene rocks can be found as the formations of Subtatric group. These rocks are represented by limy breccias and conglomerates of Borové Formation and claystones with thin laminas of sandstones of Huty Formation.

Quaternary sediments are mainly of fluvial origin or as the slope deposits. Fluvial sediments are deposited along Ludrovianka and Štiavničanka streams as fluvial silts which change into fluvial gravels within increasing distance from the stream bed (Fig. 2). The slope deposits and landslide deposits are composed of silts and clays resulting from an occurrence of Huty Formation as their bedrock. Occasionally the freshwater limestones – the travertine deposits can be found what is caused by the presence of highly mineralised groundwaters from recent geological eras.

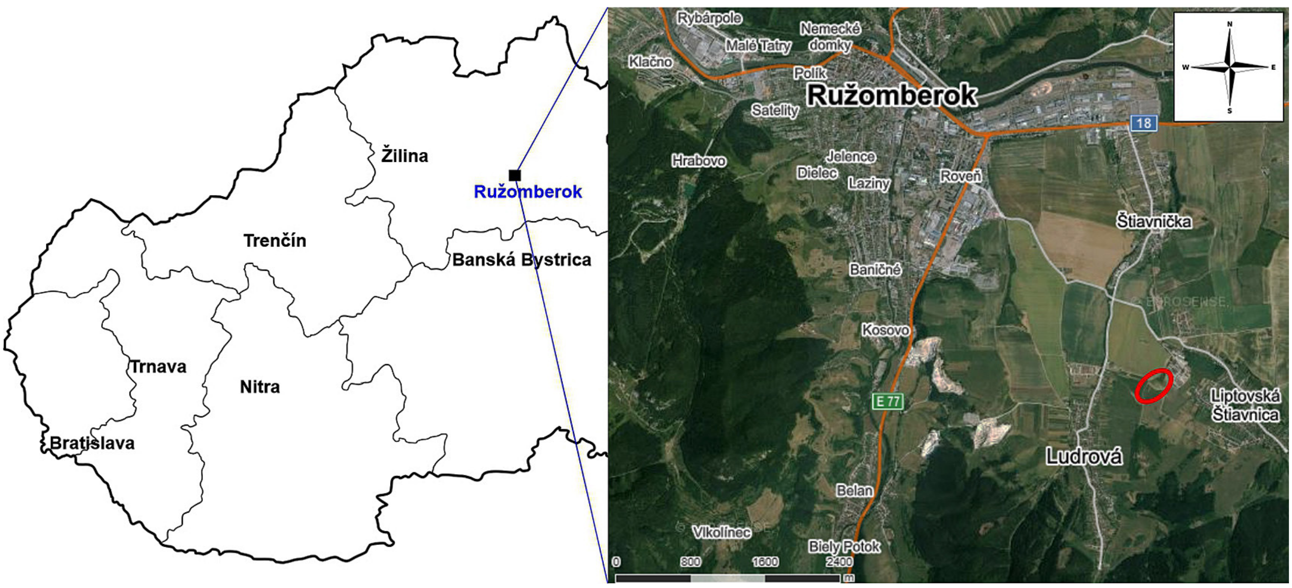


Fig. 1. Geographical location of the study area, active landslide highlighted by a red polygon.

3. LANDSLIDE DESCRIPTION

According to Liščák et al. (2011), the landslide body is 360 meters long, 50 to 80 meters wide, and includes several places with groundwater seepage (Fig. 3a). The slope shows typical geomorphological signs of relief affected by landslide. At its crown, there is a conspicuous main scarp (Fig. 3b, 3c) which is accompanied by presence of several tension cracks. In the zone of depletion of the landslide body, it is possible to see minor cracks, which are becoming deeper and deeper under an effect of ongoing erosion (Fig. 3d).

In 2019, the engineering geological investigation was realized which included construction of 5 inclinometer boreholes named IGI-1, IGI-2, IGI-3, IGI-4, IGI-5 and 4 piezometric boreholes signed as IGP-1, IGP-2, IGP-3, IGP-4 (Fig. 4). The boreholes were drilled using rotary drilling machine without using a fluid medium. After the boreholes had been drilled, the samples of rocks and soils were taken for laboratory determination of basic physical-mechanical properties and classification according to STN 72 1001.

Engineering geological investigation (Tupý et al., 2019) showed that a bedrock of the landslide is built by rocks of Huty formation - calcium rich claystones with thin interlayers of fine-grained sandstones. The claystones are of low to very low strength, occasionally moderate to high strength in case of non-weathered rocks. According to STN 72 1001 these rocks are classified as the rocks of classes R3 to R6 what results in their uneven weathering. Strongly weathered claystones change into the fine soils of stiff to hard consistency belonging to the class F5. The boundary between weathered bedrock and non-weathered bedrock is not very recognizable, rocks show alternated texture. According to boreholes' documentation the zone of weathered bedrock is 1 to 4 m thick. Soil-like weathered bedrock belongs to several classes such as, F4 CS (sandy clay), F6 CI (medium plastic clay), F7 MH (high plastic), F8 CH (high plastic clay). The landslide body is composed of the fine soils such as silts and clays of classes F1 MG, F3 MS, F5 MI (medium plastic), F6 CL (low plastic clay), F6 CI (medium plastic clay), F7 MH (high plastic) a F8 CH (high plastic clay). The thickness of the landslide body's masses reaches from 2.5 to 7 m. At the landslide base, it is possible to find anthropogenic sediments of class G5 GC (clayey gravel) which were used as embankment stabilizing the slope during construction of agricultural buildings (Fig. 3a).

4. RESULTS

4.1. Groundwater regime observations and precipitation amounts analysis

Groundwater regime observations were performed in piezometric boreholes (Fig. 4) with piezometric casings 80 mm in diameter.

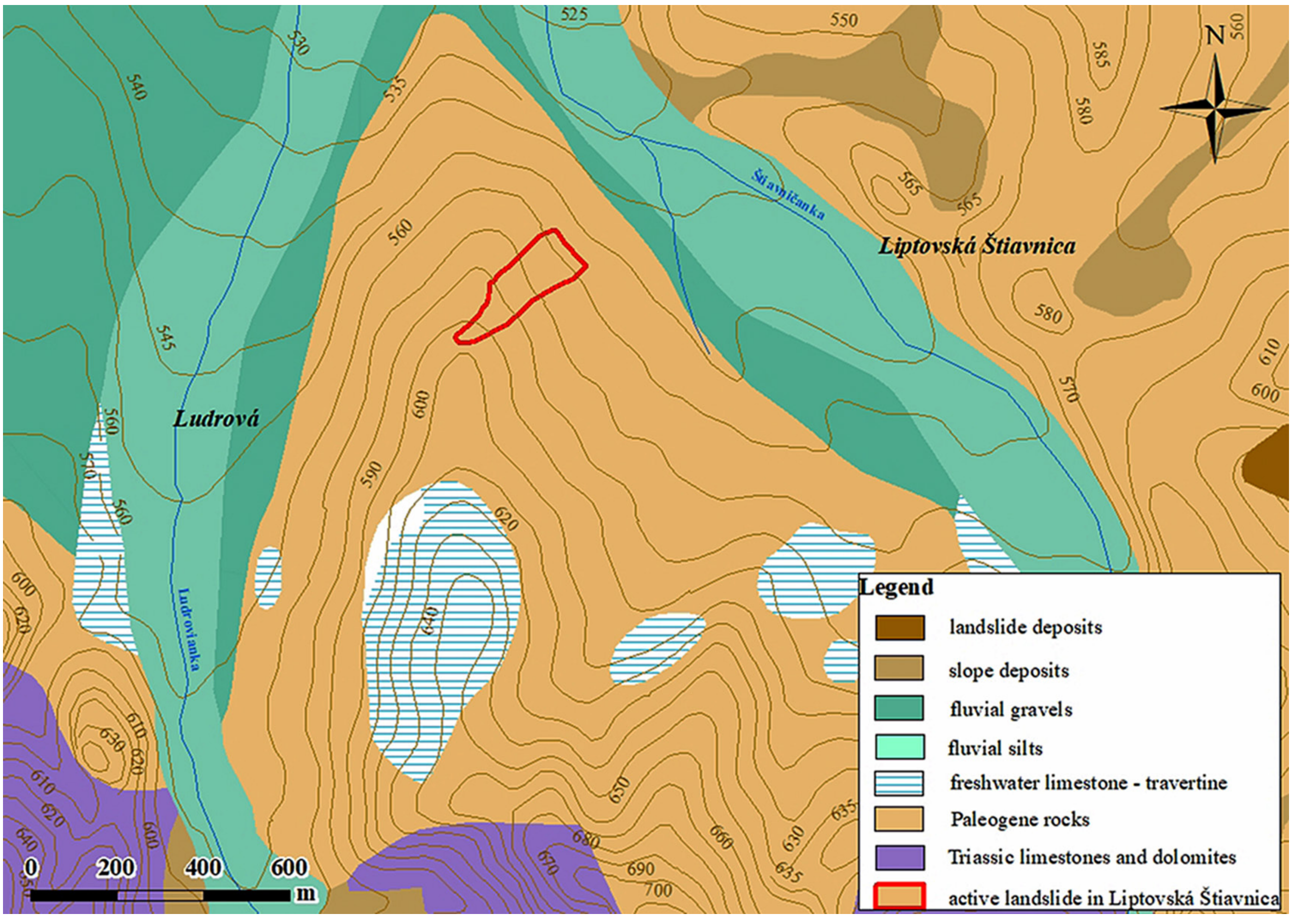


Fig. 2. Simplified geological map of the study area (http://apl.geology.sk/gm50js/).

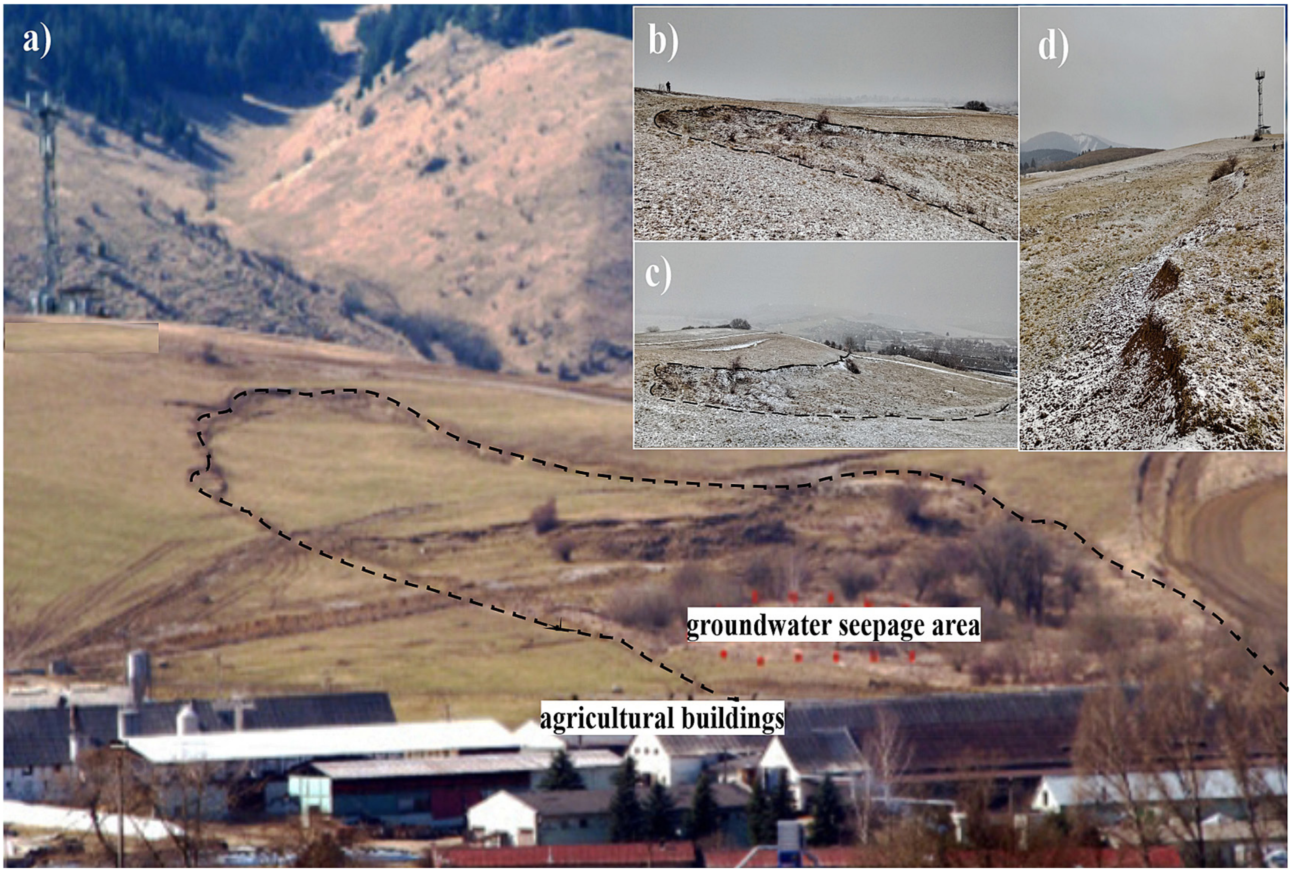


Fig. 3. Active landslide in the village of Liptovská Štiavnica (Liščák et al., 2011); a) a view of the whole landslide body, b) c) main scarp d) crack with ongoing erosion.

The observations lasted from March 2019 to December 2019, in boreholes IGP-1, IGP-3 and IGP-4 two times per week in average. For these boreholes a groundwater level measurement device equipped with a contact probe was used. In the borehole signed as IGP-2 an automatic probe has been installed for continual measuring. Groundwater regime observations identified oscillations of groundwater level which is different in every single borehole (Fig. 5).

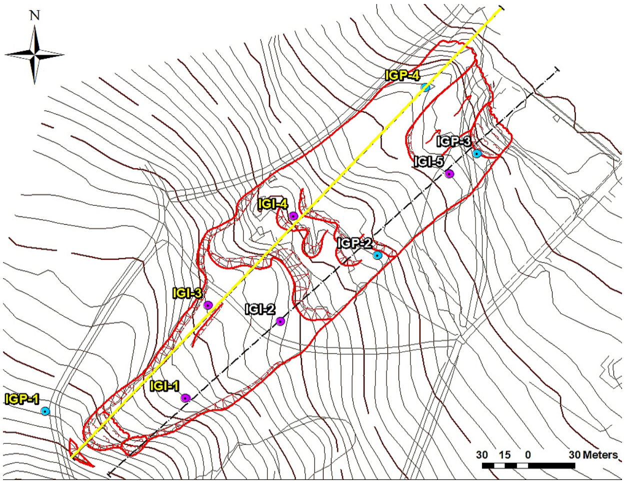


Fig. 4. **Map of landslide with boreholes' location: blue - piezometric boreholes, violet- inclinometer boreholes; a profile chosen for stability calculations – yellow line using boreholes' documentation from yellow signed boreholes (modified according to Tupý et al., 2019).**

During the monitoring period, the groundwater level in borehole IGP-1 reached the values from 9.28 to 1.71 meters below the surface what represents a total amplitude of 7.57 m. After the precipitation amounts analysis had been done it was obvious that groundwater level responses to higher precipitation amounts (≥10 mm/day) in relatively short time compared to data from other boreholes. For example, since November 2nd to November 8th the groundwater level rose from the level at 10.28 meters below the surface to the level at 5.12 meters below the surface. It means, after 5 days of significant precipitation the groundwater level rose by 5.16 meters. The groundwater level not even rises but also drops down quickly what means that in area where IGP-1 is located (above main scarp) the groundwater flows very quickly and inflows rapidly into the landslide body.

The automatic probe was installed in borehole IGP-2 to measure the groundwater level continuously every singly hour at stable temperature 8.9 – 9.1 °C. The measured groundwater level reached from 6.28 to 4.10 meters below surface, what demonstrates an amplitude of 2.18 m. From the end of March to the beginning of April, the groundwater level in this borehole tended to decrease. A small groundwater level rise is recorded in the end of May. The only significant groundwater level rise happened on November 15th when tendency shifted from decrease to increase.

In the borehole IGP-3, the groundwater level seems to be stable with an amplitude of several tens of centimeters. This character of groundwater level can be caused by missing hydraulic interconnection between the boreholes due to mixing of the rock material by sliding.

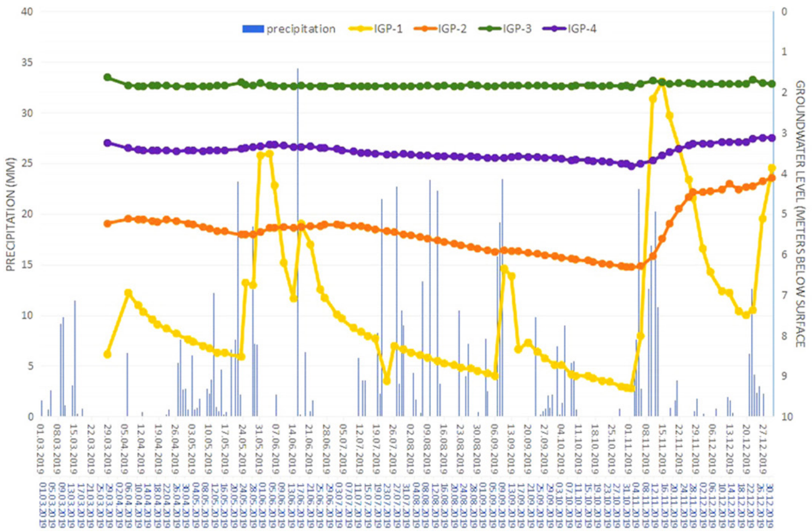


Fig. 5. Graph demonstrating groundwater level oscillations in boreholes and daily precipitation amounts from March to December 2019 (groundwater level observations: author's data; precipitation amounts: SHMÚ (Slovak Hydrometeorological Institute).

The character of groundwater level in borehole IGP-4 is very similar to IGP-2. The groundwater level was generally decreasing from March, the only significant increase was recorded in the beginning of November since when the groundwater level was increasing. The groundwater level with a value range from 3.76 to 3.11 meters below the surface, reaches the total amplitude of only 0.65 m. The amplitudes of values in boreholes IGP-2, IGP-3 and IGP-4 are neglectable compared to IGP-1.

The Slovak Hydrometeorological Institute provided data of precipitation amounts obtained directly on meteorological station in the city of Ružomberok. The data were analyzed and interpreted as graphs and tables shown below (Tab. 1, Tab. 2, Fig. 6). The required databases for precipitation analysis included data of daily and annual precipitation amounts in 2010, 2011, 2019 (March to December). To compare the results, annual normal values, and monthly normal values from 1961–1990 were used. This meteorological station is distanced approximately 2 km from the active landslide.

To demonstrate relations, the data of the groundwater regime observations and daily amounts of precipitation were altogether processed to graphic form (Fig. 5). As Fig. 5 shows, daily precipitation amounts recorded from April 24th to May 5th caused an increase of groundwater level in all boreholes although daily precipitation amount during this time interval was only 4.4 mm on average. The similar situation happened from November 3rd to November 13th when recorded precipitation amounts significantly increased (8.9 mm/day in average). This situation resulted in remarkable groundwater level rise in borehole IGP-1 and less remarkable rise in boreholes IGP-2 and IGP-4. In borehole IGP-3, no groundwater level rise is detected. (Fig. 5).

Daily precipitation amounts recalculated to monthly precipitation amounts, and annual precipitation amounts during years 2010, 2011 and 2019 were compared to normal values statistically processed from period 1961–1990. To find out in which years and in which months the normal values were exceeded, the annual and monthly precipitation amounts were expressed as the percentages of annual and monthly normal values (Tab. 1, Tab. 2).

Fig. 6 demonstrates that in 2010 the normal values was exceeded in 8 months, even 6 months in a row. In some months, the data show the overrun by 200 % (Tab. 1). In 2019, percentage values exceeded monthly normal values in 6 months. Percentage overrun by more than 40 % was recorded in May, September, and November 2019 as a discontinues time period.

Tab. 1. Monthly precipitation amounts as percentages of normal values 1961–1990 (processed on SHMÚ RAW data).

	MONTH	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
2010	Monthly precipitation amounts (mm)	24	27	18	52	235	129	162	166	95	14	89	51
	Monthly precipitation amounts as percentages of normal values (%)	62.4	84.4	52.1	117.1	313.5	141.4	193.3	212.3	161	28.5	164.3	115.9
	Percentages overrun (%)	–37.6	–15.6	–47.9	+17.1	+213.5	+41.4	+93.3	+112.3	+61	–71.5	+64.3	+15.9
2011	Monthly precipitation amounts (mm)	12.1	6.3	12.5	23.6	129	117	116	32	16.4	31.5	0.4	58.6
	Monthly precipitation amounts as percentages of normal values (%)	31.8	19.7	36.8	53.6	171.7	128.7	138.6	41	27.8	65.6	0.7	133.2
	Percentages overrun (%)	–68.2	–80.3	–63.2	–46.4	+71.7	+28.7	+38.6	–59	–72.2	–34.4	–99.3	+33.2
2019 (Mar.–Dec.)	Monthly precipitation amounts (mm)			40.7	26.1	111	45.4	90.6	91	85.3	29.9	106	35.8
	Monthly precipitation amounts as percentages of normal values (%)			119.7	59.3	147.9	49.9	107.9	116.7	144.6	62.3	196.7	81.4
	Percentages overrun (%)			+19.7	–40.7	+47.9	-50.1	+7.9	+16.7	+44.6	-37.7	+96.7	–18.6

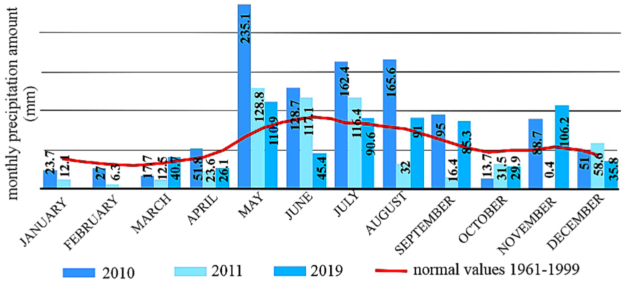


Fig. 6. Graphical demonstration of monthly precipitation amounts exceeding normal values 1961–1990.

Tab. 2. Annual precipitation amounts as percentages of annual normal value 1961–1990 (processed on SHMÚ RAW data).

YEAR	2010	2011	2019 (Mar.–Dec.)
Annual precipitation amounts (mm)	1060.4	555.7	661.9
Annual precipitation amounts as percentages of normal value 1961–1990 (%)	156.4	81.9	97.6
Percentages overrun (%)	+56.4	−18.1	−2.4

According to Tab. 2 the annual precipitation amounts in 2010 exceeded the annual normal value by 56.4 %. This fact indicates that extreme precipitation amounts in 2010 caused saturation of the landslide body what resulted in landslide reactivation in March 2011.

4.2. Inclinometer measurements analysis

The inclinometer measurements were performed in inclinometer boreholes (Fig. 4). The boreholes were equipped by PVC inclinometer casings 80 mm wide in diameter and of total length 17 m. The casings have longitudinal grooves in two perpendicular directions to ensure the probe remains oriented in the predetermined direction. The grooves of the guide casings should preferably be oriented in the expected direction of movement. The data were provided by State Geological Institute of Dionýz Štúr in form of graphically processed measurements (Fig. 7) of all inclinometer boreholes. Using graphically processed data, we could analyse and determine the approximate positions/depths of shear planes/zones in landslide body what was necessary for mathematical model construction of landslide-affected slope.

In 2019, the three inclinometer measurements were performed in total (zero, first and second measurement) from March 29th to November 28th, 2019. The movements detected by first measurement on June 5th, 2019 and the movements detected by second measurement on November 28th, 2019 were compared to zero measurement on March 29th, 2019.

As Tab. 3 shows the movements were detected at different depths below the surface, what indicates presence of several shear zones along the landslide-affected slope. The landslide body probably slides down along a basal shear plane at depth 15 to 16 meters below the surface There are also other shear planes passing throughout landslide body at depths 2 to 8 meter below the surface. The movements are not very significant yet, only several millimeters, what is mainly caused by short monitoring period. Given this circumstance and given that the measured movements are very small, almost negligible, we have decided not to specify the exact azimuth of the recorded movements.

4.3. Stability calculations

The mathematical model construction of chosen profile preceded the stability calculations. The input parameters such as relief in chosen coordinate system, lithological boundaries in between different types of rocks and soils, groundwater levels, shear planes, specific weights and shear strength parameters obtained by reverse calculations were included in mathematical model of the profile (Fig. 8). This mathematical model of the

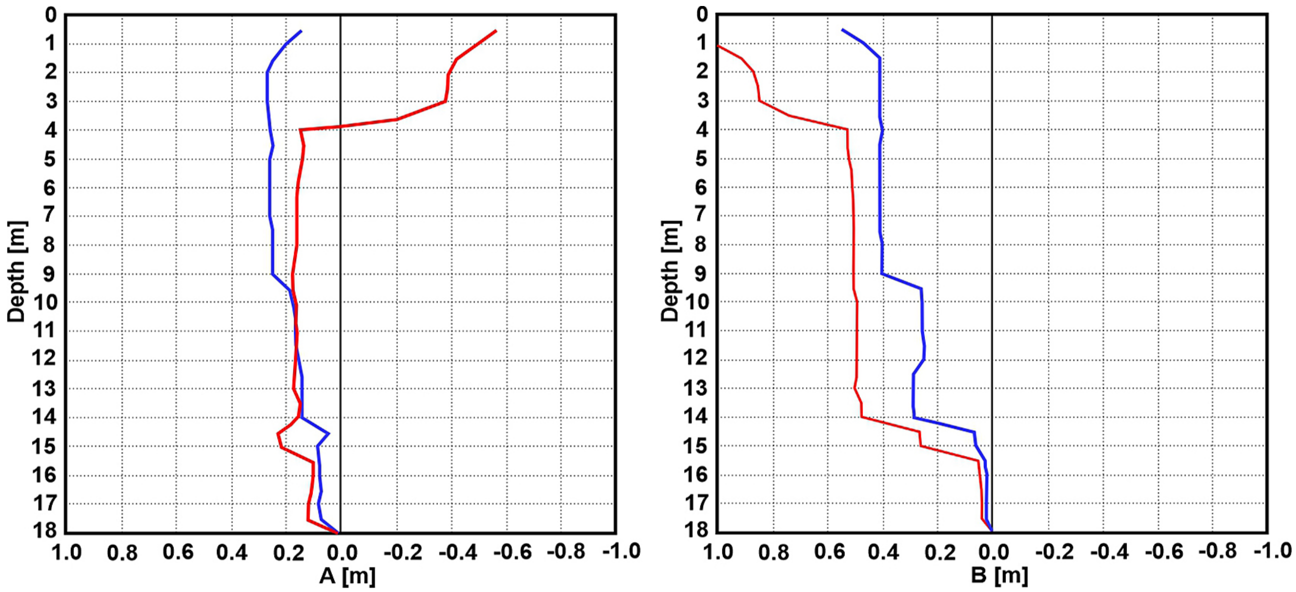


Fig. 7. An example of processed inclinometer measurement; borehole IGI-1, vertical black line- zero measurement, blue curve- first measurement, red curve- second measurement; direction A – left, direction B – right.

Tab. 3. The depths of detected shear zones in meters below the surface and measured movements in mm taken from graphically processed data (2019).

Borehole	IGI-1				IGI-2				IGI-3				IGI-4				IGI-5			
Depths of shear zones (meters below surface)	4		15.5		2		8		11.5		16		7		15				15	
Direction	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Movements (mm)	+4	+5	+2	+3	+1	+2	+3		+3	+1	+1		+4	+1	−1	−1				+1

landslide-affected slope represented by the chosen profile was an objective of stability calculations using geotechnical software GEO 5. For profile construction, the geological documentation (Tupý et al., 2019) of boreholes IGP-1, IGI-1, IGI-3, IGI-4, IGP-4 (Fig. 4) was used to identify boundaries between different types of rocks and soils (Fig. 8, Tab. 4).

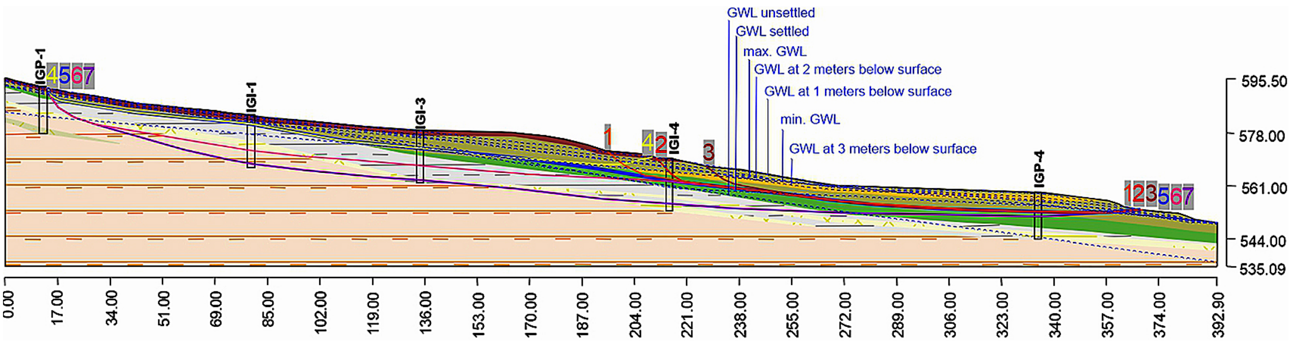
The soils were generalized into four basic layers according to their genesis and physical-mechanical properties. Based on the lithological type and the degree of weathering, the rocks were distinguished as the sandstones – weathered, sandstones – nonweathered, claystones -weathered and claystones – nonweathered. The frequent alteration of sandstones and claystones was defined as one separated layer. This layer was also used as the bedrock below the depth of boreholes (≥17 meter below the surface). Ultimately, all soils and rocks were classified after STN 72 1001 *Classification of soils and rocks.*

To obtain the shear parameters, the reverse calculations were done to achieve the values of factor of safety (FS) equal 1 for all modelled shear planes. Those parameters represent residual values of shear parameters (φ_r, c_r) because of the rocks and soils' depleted shear strength (Tab. 4). Based on comparable knowledge (Tab. 4), the values of specific weights (γ) were used from engineering geological investigations realized in the same geological background (landslide in the village of Lisková, Huty formation) (Bednarik, 2019).

For stability calculations seven groundwater levels were modelled (Fig. 8, 9) – without groundwater, level at 3 meters below surface, level at 2 meters below surface, level at 1 meter below surface, maximum level according to groundwater regime observations (March - December 2019), minimum level according to groundwater regime observations (March - December 2019), unsettled level after drilling boreholes (Tupý et al., 2019) and settled level after drilling boreholes (Tupý et al., 2019).

Stability calculations were performed for 7 different shear planes at 7 different groundwater levels (Fig. 8, 9). The depths of recorded movements from inclinometer measurements were used to construct the seven different shear planes (Tab. 3). They were modelled as combinations of round-shaped and polygonal-shaped shear planes. Stability assessment was made on four identified shear planes (No. 1–4) and three hypothetical shear planes (No. 5–7) (Fig. 8, 9). The shear plane located the deepest below the surface was classified as basal shear zone.

Fig. 8. Mathematical model of engineering geological profile.



Tab. 4. Shear parameters (φ_r, c_r) and specific weights of landslide slope's rocks and soils.

Soils/Rocks	Pattern	φr [°]	cr [kPa]	γ [kN/m³]
Slope sediments F1 MG - F3 MS ***(gravely mud, gravely clay, sandy mud)***		13.00	3.00	18.00
Slope sediments F6 CL. F6 CI. F8 CH ***(clay of low, medium and high plasticity)***		7.00	2.00	19.40
Slope sediments F4 CS ***(sandy clay)***		7.00	2.00	19.30
Weathered bedrock F6 CI. F6 CL. F8 CH. F7 MH ***(clay of low, medium and high plasticity and high plasticity mud)***		7.00	2.00	18.80
Paleogene claystones - weathered		14.00	5.00	20.50
Paleogene sandstones - weathered		14.00	5.00	20.50
Paleogene sandstones - nonweathered		30.00	20.00	25.20
Paleogene claystones- nonweathered		30.00	20.00	25.20
Frequent alternation of sandstones and claystones - weathered		14.00	5.00	20.50

4.4. Stability assessment and design of early warning system

As the stability indicator, the factor of safety was chosen to demonstrate and assess the stability of the landslide-affected slope. Stability calculations were done using geotechnical software GEO 5 (Fine Ltd.), modulus Slope Stability, Sarma's stripe solution. The required value of factor of safety was established as the value FS_{req}= 1.3. The results of stability calculations for all shear planes at all modelled groundwater levels are demonstrated in Fig. 9.

As Fig. 9 shows, the closer the groundwater level to the surface is, the lower values the factor of safety calculated for all shear planes are. Based on these calculations, the early warning system must include the monitoring of groundwater level to detect its critical value. The results also show that the values of factor of safety calculated for shear planes No.1 and No.2 meet the required factor of safety ($FS_{req} \geq 1.3$) only in case of unsettled groundwater level. Regarding stability, those two shear planes pose a problem to the slope to remain stable when the groundwater level gets higher. Compared to others, the shear plane No. 7 (classified as basal shear zone) is the most stable because the calculated values of FS at all modelled groundwater levels exceed FS_{req}. It means that after remediation works the stability of the landslide-affected slope must meet the value of factor of safety $FS_{req} \geq 1.3$. As the slope stability decreases within increasing groundwater level, a goal of remediation works would be to permanently lower the groundwater level (for example by using drainage borings) to secure all shear planes to remain stable. To achieve this situation, further groundwater modelling was necessary to find a suitable groundwater level. After recalculations it was established as the groundwater level at 7.5 meters below the surface (Fig. 9), so called the secure groundwater level for further permanent constructions.

The value of factor of safety defined as FS = 1 represents the equilibrium between active and passive forces/moments present in the slope. The results from stability calculations reveal that calculated FS values for all shear planes reach the equilibrium (FS = 1) when groundwater level is at depth 3 meters below the surface. This groundwater level presents so called critical groundwater level which, when exceeded, would trigger slope's movement. Achieving such a long-term state would pose a risk of landslide reactivation, with a state of emergency declared and immediate action required. The established groundwater levels can also be used to define early warning system:

- critical groundwater level: the level at ≤ 3 meters below the surface, when equilibrium achieved, i.e., FS = 1,
- secure groundwater level for current land-use (pastures) and temporal constructions, i.e., 1 < FS < 1.3
- secure groundwater level for permanent constructions: the level at ≥ 7.5 meters below the surface, when FS ≥ 1.3.

The overall model of the slope profile including shear planes and groundwater levels was constructed based on the data from 2019. However, the monitoring of the landslide in the village of Liptovská Štiavnica is ongoing and provides further information about movements' evolution and groundwater level oscillations. The data achieved in 2020 and 2021 are shown in Tab. 5 and Fig. 10.

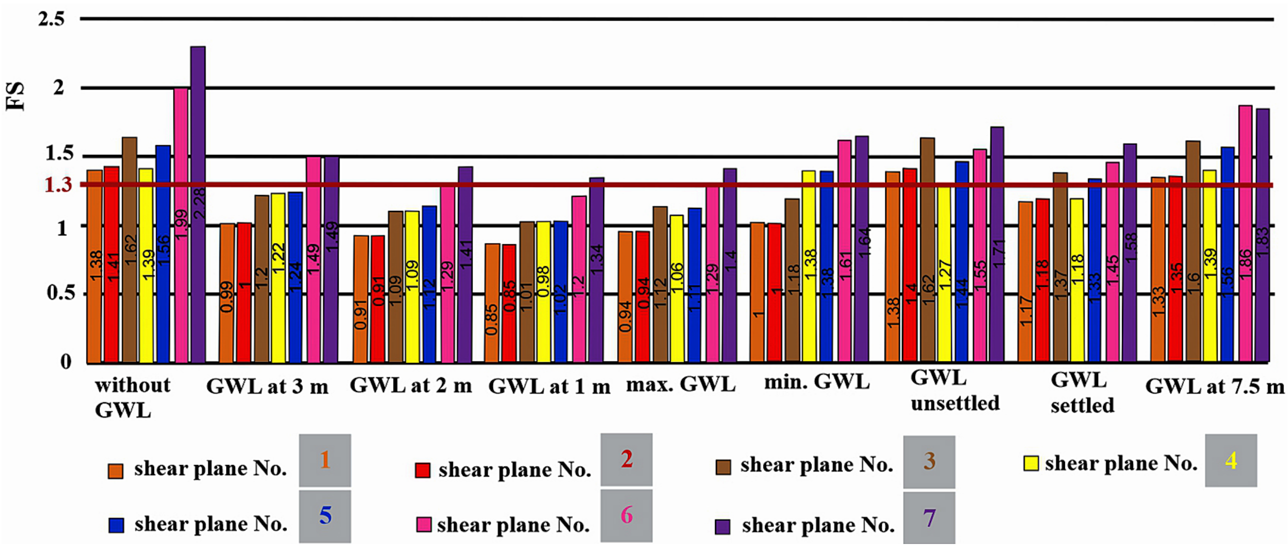


Fig. 9. Graphical expression of FS values calculated for 7 different shear planes at different groundwater levels.

As monitoring of the landslide continues, further data from the inclinometer measurements were obtained and provided by State Geological Institute of Dionýz Štúr. Tab. 5 shows the depths of the partial and total movements in individual boreholes in 2020 and 2021. Compared to data used for shear planes modelling in stability calculations (Tab. 3), the depths of the movements (shear zones) more less correspond to each other. The most obvious movements were detected in 2.5–3.5 m below the surface in IGI-1, in 7–8 m below the surface in IGI-2, in 10–11 m below the surface in IGI-3 and in 5.5–6.5 m below the surface in IGI-4. The differences between the detected shear zones in 2019 and in 2020–2021 might be the result of random errors caused by uneven casing joints.

Fig. 10 demonstrates the groundwater level measurements in boreholes IGP-1, IGP-2, IGP-3 and IGP-4 in 2020 and 2021, established critical groundwater level and secure groundwater

Tab. 5. The depths of detected shear planes in meters below the surface and total movements in mm taken from graphically processed data (2020–2021).

Year	Borehole	Depth of shear zone (meters below surface)	Partial movement in mm (28. 11. 19 – 16. 06. 20)	Total movement in mm (28. 03. 19 – 16. 06. 20)	Year	Partial deformation in mm (28. 11. 19 – 16. 06. 20)	Total movement in mm (28. 03. 19 – 14. 10. 21
2020	IGI-1	2.5 - 3.5	3.24	8.06	2021	12.54	20.59
	IGI-2	7 - 8	4.22	7.09		5.81	12.71
	IGI-3	10 - 11	1.58	4.59		4.98	9.56
	IGI-4	5.5 - 6.5	3.13	7.31		6.15	13.16
	IGI-5	5 - 6	2.14	3.35		1.81	4.97

level for permanent constructions. As shown, the groundwater level in the borehole IGP-3 (located at the accumulation part of the landslide body) permanently exceeds the critical level. From the security point of view, this situation poses a risk of landslide's reactivation especially when the critical level is exceeded in other boreholes, and thus along the whole landslide body.

Landslide-affected slope is currently used as a pasture for livestock of agricultural cooperative Ludrová - Liptovská Štiavnica. The agricultural objects are directly jeopardized by the landslide because they are situated at the base of landslide-affected slope (Fig. 3). Regarding the facts mentioned above, to prevent the socio-economic losses it is inevitable to apply remediation works to drain the landslide-affected slope below the critical groundwater level.

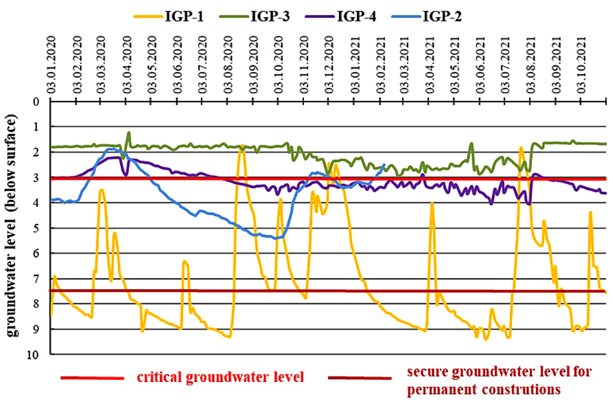


Fig. 10. Groundwater level measurements in boreholes IGP-1, IGP-2, IGP-3, IGP-4 (2020-2021).

5. CONCLUSION

The activity of the landslide in the village of Liptovská Štiavnica, was proven by the inclinometer measurements. The groundwater regime observations showed that groundwater level in the landslide body rises in relation to the higher precipitation amounts. As the analysis of the precipitation amounts demonstrates, the last reactivation of the landslide (March 2011) was caused by the extremely high precipitation amounts recorded during the year 2010. Stability assessment using factor of safety (FS) calculations reveals that the stability of the landslide-affected slope is conditioned by the groundwater level in the landslide body.

To find a critical groundwater level, modelling of several situations was required in favor to combine the most adverse conditions meaning at which groundwater level all the identified and hypothetical shear planes are not stable. Achieving the permanent stability of the landslide means to lower the groundwater level using drainage remediation works. Based on stability calculations and groundwater modelling, three groundwater levels as the warning states have been established. The critical groundwater level at 3 meters below the surface when equilibrium of active and passive forces/moments is achieved, i. e. FS ≤ 1. When long-lasting, this situation can lead to reactivation of the landslide. The second warning state is represented by the secure groundwater level for current land-use (pastures) and temporal constructions established as the groundwater level between 3 and 7.5 meters below the surface when values of FS are higher than 1 and lower than 1.3. The last established is the secure groundwater level for permanent constructions as the level higher or equal to 7.5 meters below the surface when FS is greater or equals to 1.3.

For the future purposes, the established warning states can provide a useful tool to develop early warning system which will monitor the groundwater level. As further groundwater regime observations in 2020 and 2021 show, in the borehole IGP-3 the groundwater level permanently exceeds the critical level. Achieving this situation in all boreholes can be crucial to reactivation of the landslide. As a prevention, the drainage remediation works are necessary to keep the groundwater level at depth greater than 3 meters below the surface.

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