8. Geotechnical Monitoring of Landslides on Slopes of Water Reservoirs

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Abstract: In the design, construction and subsequent operation of water works the stability of slopes is one of the fundamental problems. Slope failures, especially landslides, affect site selection of dam body, threaten reservoir shorelines and also endanger smaller water management constructions. If water works are built up in the environment with landslides, then their monitoring is essential.

The article evaluates stability (monitoring results) of landslides next to two major water reservoirs in Slovakia. The first is a landslide at the water reservoir Liptovská Mara, which with its volume of water 362mil. m^3 is the largest reservoir in Slovakia put into operation in 1975. The purpose of this hydraulic structure is to use the hydro power potential of the Váh, to improve the flow of water under the dam and to protect the area from floods. On the right side of the dam body there is landslide displacing about 5mil. m^3, which strikes the reservoir with its toe. The second landslide is a landslide on the water reservoir Nová Bystrica, located over the reservoir water level, but its possible instability is threatening the water discharge object. Both landslides are located in the geological environment of Carpathian Flysch. The article assesses a current stability of landslides, remediation measures and especially results of a long-term monitoring.

Key words: landslides, geotechnical monitoring, slope stability, water reservoir

8.1. Introduction

In Slovakia, the occurrences of landslides (Liščák & Káčer, 2011) significantly obstruct the construction and operation of water works. Engineering geological investigation in the 50-80's of the 20th century primarily dealt with the preparation of large water works in Slovakia.

Because of massive landslides (thickness from 150 to 200 m) for a dam a morphologically advantageous profile near the village Tichý Potok westward of Prešov on Torysa River in the Inner Paleogene Flysch was abandoned (Malgot & Baliak, 1990). Landslide area near Martin influenced design of water work Krpeľany-Sučany-Lipovec. The derivation canal was moved and divided into two zones (Záruba & Mencl, 1958). On construction of the water work Dobšiná there had occurred rock slide of tectonically damaged block of diorite along the surface of graphite slate with dipping toward the slope (Záruba & Mencl, 1987). An example of a strong abrasion of reservoir shoreline is on the water reservoir (WR) Orava. After the first 15 years of operation of the WR Orava in some sections of shoreline

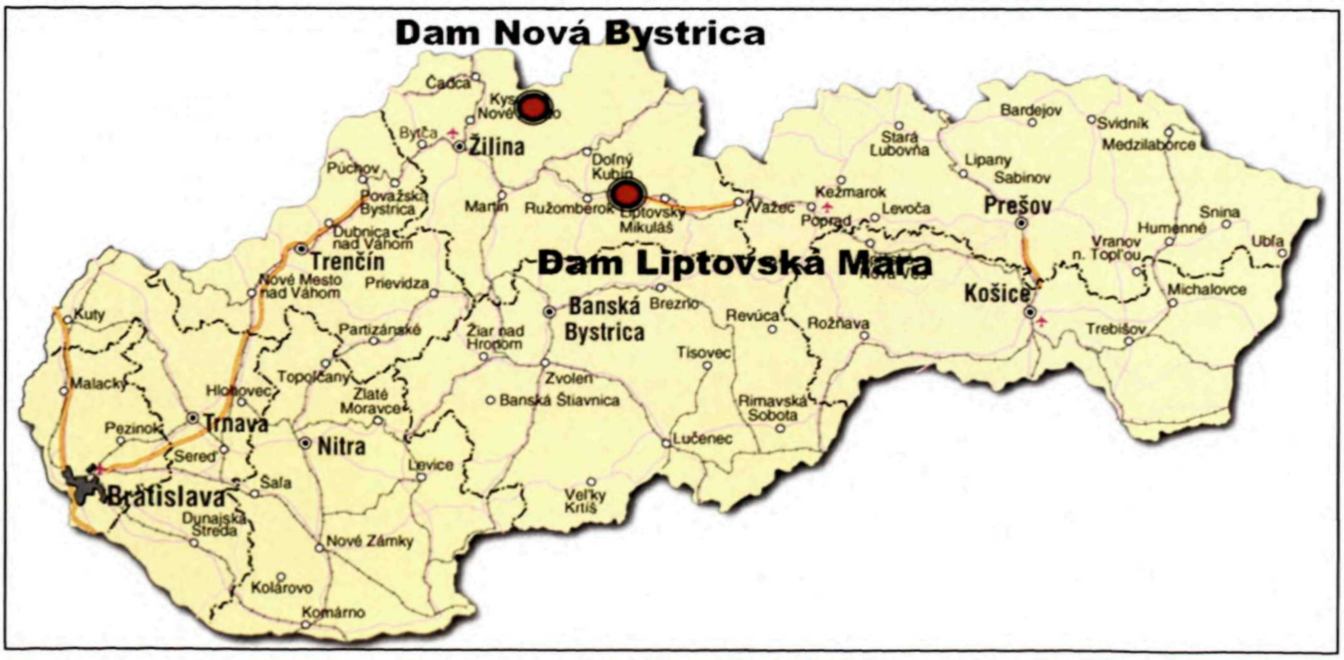

Fig. 8.1 Localization of the water reservoirs in the map of Slovakia

there were widespread landslides, the destruction of land occurred up to 160 meters from the shoreline in a slope (Horský & Bláha, 2011).

At present, none major hydroelectric project is built, but many of already constructed are threatened by landslides. The article evaluates stability (monitoring results) of landslides next to two major water reservoirs in Slovakia. Water reservoirs Nová Bystrica and Liptovská Mara are located at northern part of Slovakia (Fig. 8.1). Both reservoirs are built in the environment of Carpathian Flysch, whereas the reservoir Liptovská Mara in not folded, and the water reservoir Nová Bystrica in folded flysch environment. On both water works the slopes above the reservoirs are affected by landslides, which are threatening their safety and operating. In the next text we present:

- the nature of the landslides,
- hazard for the dams,
- a way of their remediation,
- a landslide stability assessment based on results of ongoing monitoring and proposal of new system of monitoring.

8.2. Landslides at the dam Liptovská Mara

On the right-side of the dam body of WR Liptovská Mara, which dammed the Váh River, there are located two landslides. On the water-side bank it is Veľkomarský landslide and on the downstream face of the dam it is Malý Vlaštiansky landslide (Fig. 8.2).

Both landslides at the Liptovská Mara dam are developed in the area consisting of unfolded Inner Paleogene flysch strata. The area of Veľkomarský landslide extends with length 900 m and width 550 m. The maximum thickness of the sliding material in the accumulation zone of the landslide exceeds 30 m (Fig. 8.3). The whole landslide is composed of several partial landslides of various ages. The supposed volume of the sliding mass exceeds 5 mil. m^3 (Antolová, 2010).

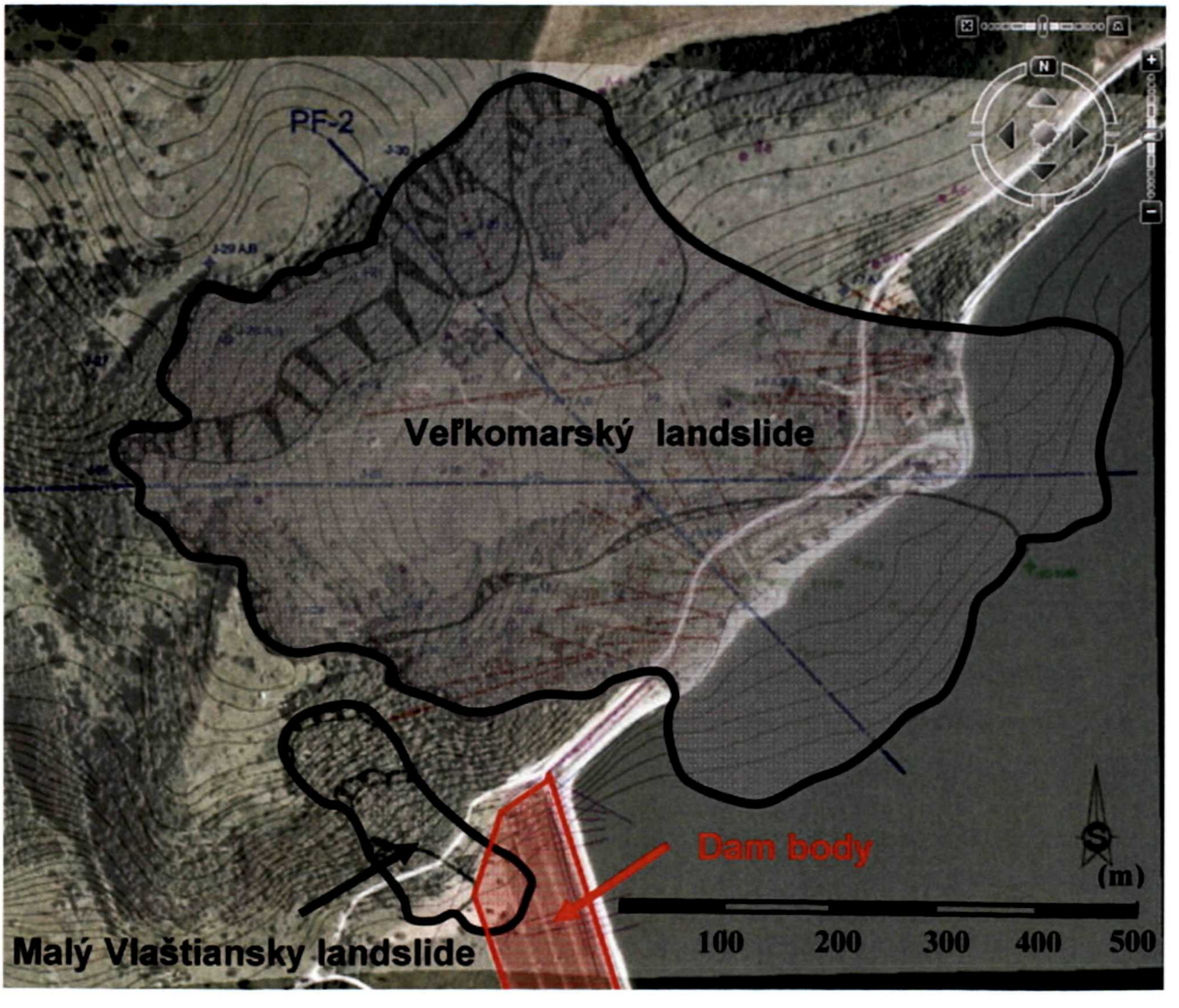

Fig. 8.2 Localization of the dam profile between Veľkomarský and Malý Vlaštiansky landslides (satellite photo by Google Earth)

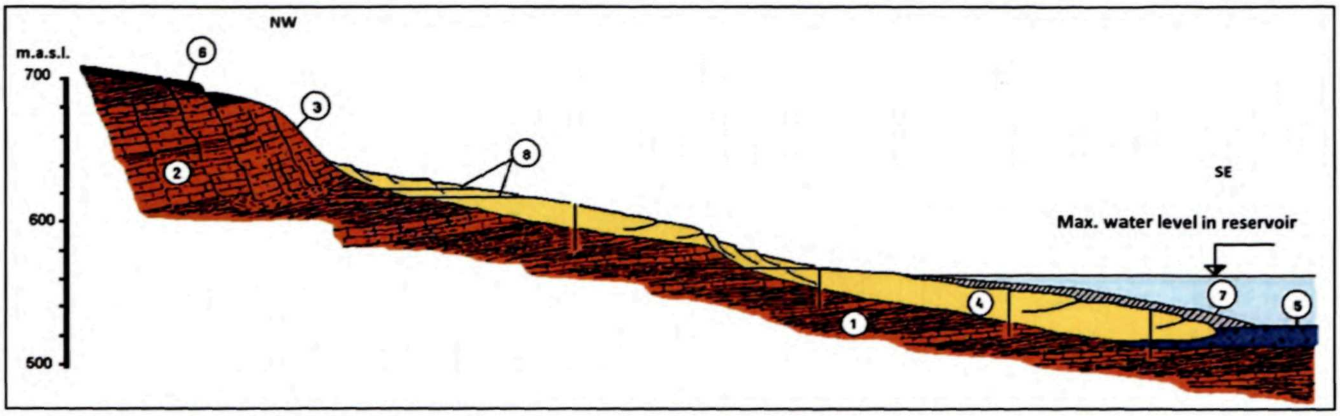

Fig. 8.3 Profile through the landslide Liptovská Mara (modified after Nemčok, 1982)
1- marly shale with intercalations of sandstones, 2 - sandstones with intercalations of shales, 3 - block field, 4 - landslide, 5 - fluvial deposits, 6 - slope loams, 7 - gravely-sandy back fill, 8 - horizontal drainage boreholes

8.2.1. Remediation measures at the Veľkomarský landslide

The stability calculation of the Veľkomarský landslide performed prior to the WR construction had appointed to low stability of the slope. The calculation result meant concern about significant instability of the landslide after finishing the dam construction due to water buoyancy acting on the accumulation zone of the landslide.

To improve the Veľkomarský landslide stability condition after finishing the construction of the WR the following remediation measures were taken (Fig. 8.4):

- building of stabilization anti-abrasion embankments consisting of gravel and sand on the landslide toe (in 1974-1975) – the thickness of the embankments is 7 m (volume 700,000 m³),
- realization of horizontal drainage boreholes (HDB) - 4 stages in 1974-1977,
- creating a system of surface drainage gutters (in 1976-1978).

8.2.2. Recent activities on the landslide based on the results of geodetic monitoring

Evaluation of the recent landslide activity is possible only according to analysis of movement of geodetic points located on the landslide surface.

8.2.2.1. Classical geodetic methods

Although the Veľkomarský landslide is equipped with a network of geodetic points (observation and control points), the measurements of position changes of the observation points on the landslide cannot be used for qualified assessment of the activity of the landslide because of movement of the control points. Therefore for overview of activities of the Veľkomarský landslide changes of altitude of observation points are used only.

In late March 2006, a sudden warming and rapid melting of very thick snow cover led to infiltration of water from the melted snow into massif what resulted in increase of groundwater table levels in the sliding slope to the maximum one ever observed during the entire monitoring history. These high groundwater table levels were synchronous with changes of elevations of the observation points. A significant decrease was recorded on points from B-1 to B-6, which are located in the head of the landslide area (from 6.9 to 12.2 mm – 9.8 mm on average!, Fig. 8.5), what indirectly pointed to a partial activation of the landslide area.

8.2.2.2. Global Navigation Satellite System (GNSS)

Since 2007 geodetic measurements of displacement of geodetic points are made by method GNSS (Prvý, 2010), because there is no problem, with influence of the undesirable movement of the control points. The resulting vectors of the displacements of the geodetic points are given in Fig. 8.6. These vectors already could suggest the real trend of movement of the landslide surface. The maximum observed values of movement were 80 mm, this means ca 10 mm per year on average.

The monitoring network (Fig. 8.4) of both landslides was built 40 years ago. On the Veľkomarský landslide in 1974-1975 there were built sites for observation of groundwater table levels (observation wells - 30 pcs). As remedial measures also 28 horizontal drainage boreholes (HDBs) with the total length of 3,800 m were built in 4 stages.

The groundwater table level and discharge rate of HDBs are monitored once per 14 days. In the period 2003-2010 sixteen observation wells were equipped with automatic piezometers. Monitoring is carried out in order to assess the effectiveness of the remediation measures. For tracking the movements of the landslide a network of geodetic control points, consisting of 6 reference points and 17 observation points was built in the landslide area. The geodetic measurements are performed once a year.

8.2.3. Status of the current monitoring network on the landslides

With regard to the long term monitoring of the HDBs discharge, it is possible to observe decrease of the total volume of the water being removed from the landslide (Fig. 8.7).

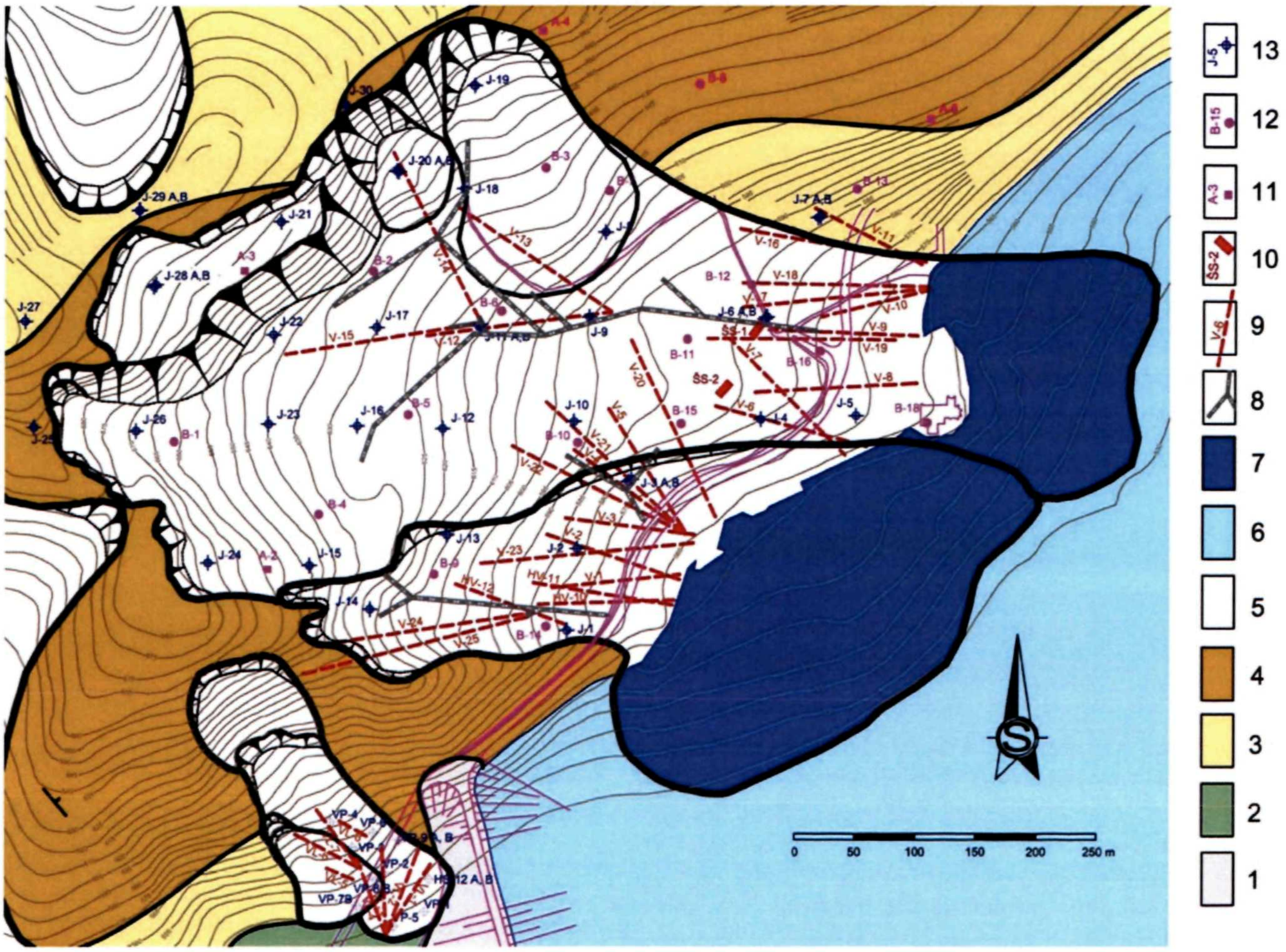

Fig. 8.4 Scheme of existing monitoring points and remediation measures on the Veľkomarský and Malý Vlaštiansky landslides (Kopecký, 2010)

1 - Earth dam, 2 - Váh River fluvial sediments, 3 - deluvial sediments, 4 - Paleogene strata, 5 - landslide bodies, 6 - water surface, 7 - part of the Veľkomarský landslide overflooded by the water of the reservoir, 8 - surface drainage gutters, 9 - horizontal drainage boreholes, 10 - gravel walls, 11 - control geodetic points, 12 - geodetic observation points, 13 - observation wells

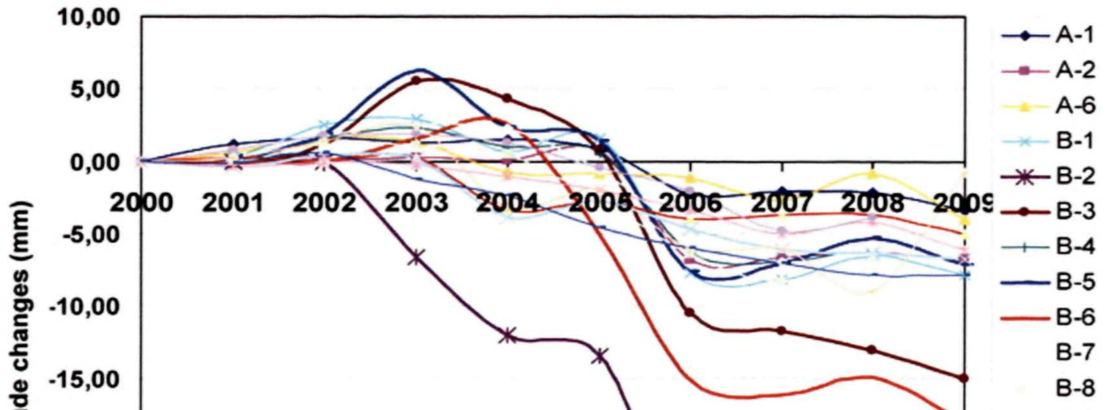

Fig. 8.5 Cumulative curves of altitude changes (mm) of geodetic observation points during years 2000-2009

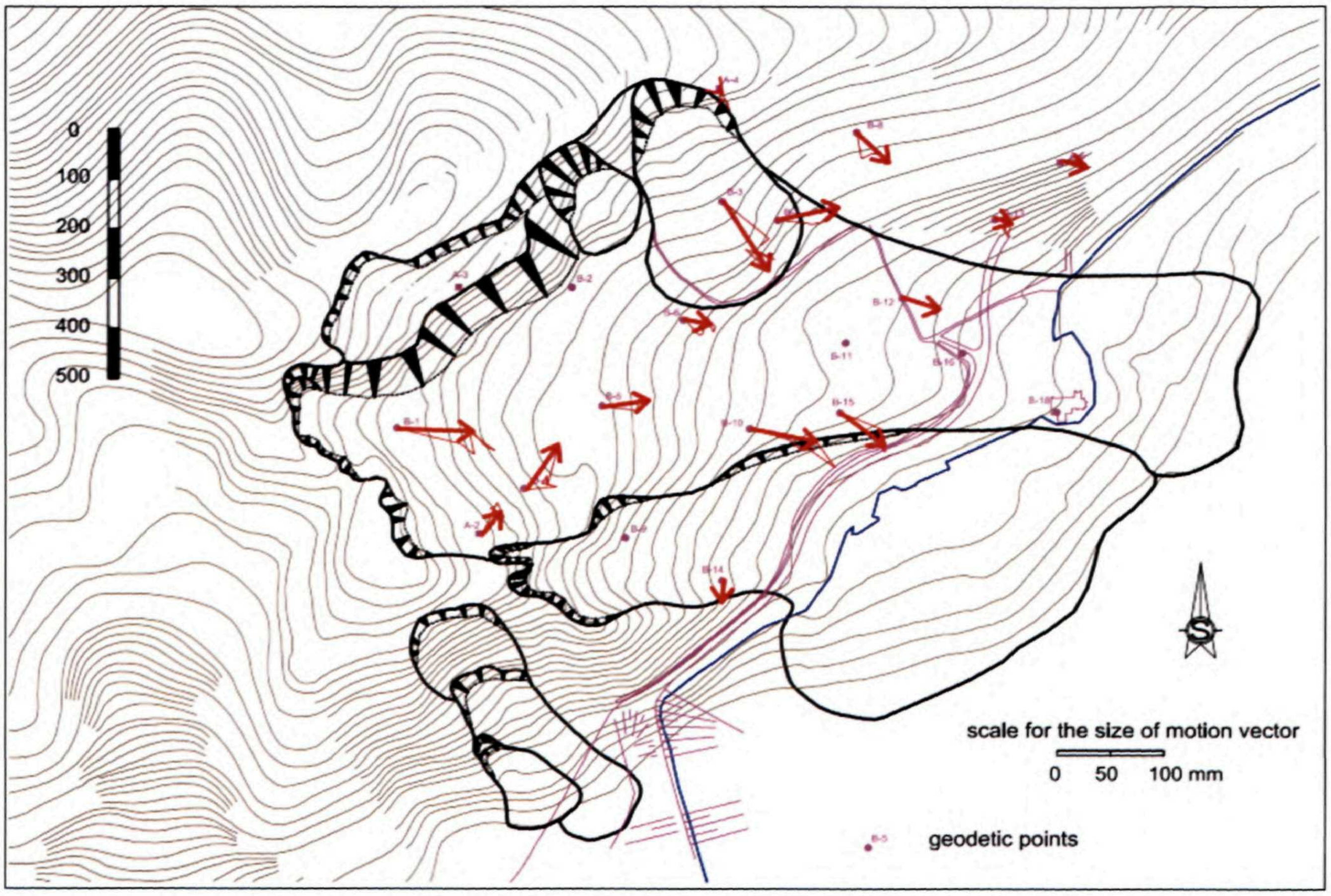

Fig. 8.6 Horizontal displacement of fixed and control points during period 2007-2013 by method GNSS

However, this overall groundwater level (GWL) decline does not have to play a role in reduction of the local slope stability, unless due to decrease of the water discharge from HDBs the groundwater level is not increased in the nearby observation wells. The negative impact of the discharge decline in HDBs from V-12 to V-15 located in the landslide head area is quite obvious. In this area (Fig. 8.4), in observation wells J-16, J-17 (Fig. 8.8), J-18, J-11B, J-11A the groundwater level is increasing for long time period, in the case of J-11A the groundwater freely flows out of the well as from artesian well. Inspection of the horizontal drainage boreholes was made with use of camera (Fig. 8.9). The largest throughput was observed only up to 30 m. In most cases the camera got only a few meters away from the HDBs mouth. The inspection results have pointed out that the broken HDBs should be either cleaned or replaced by new HDBs.

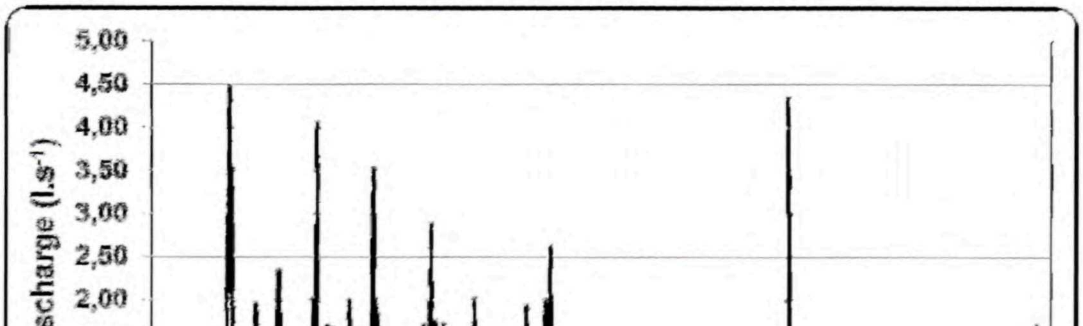

Fig. 8.7 Downward trend of the total discharge from all HDBs on the Veľkomarský landslide

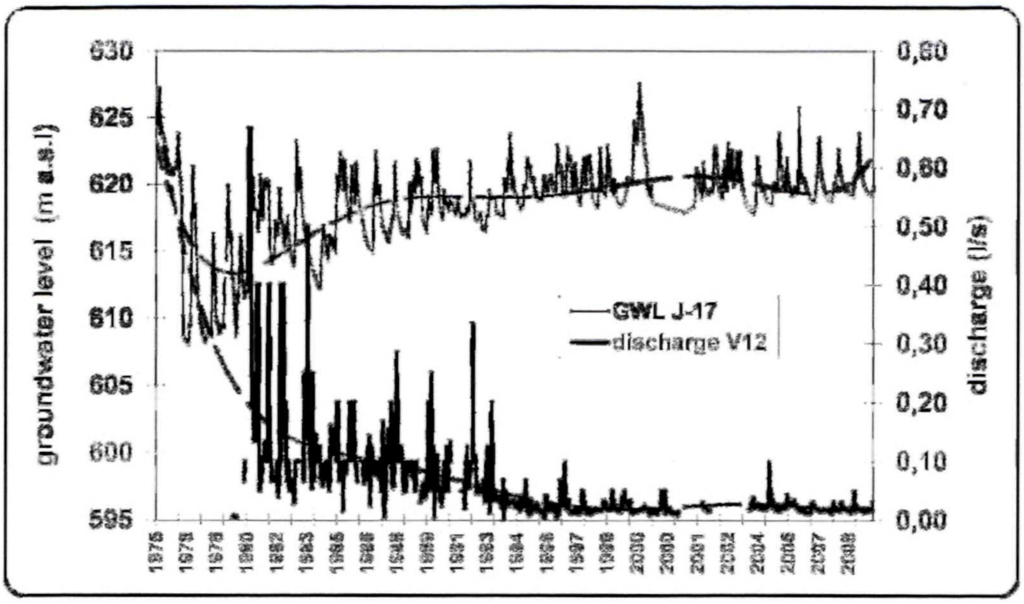

Fig. 8.8 Decrease of functionality of HDB V-12 and GWL rise in observation well J-17

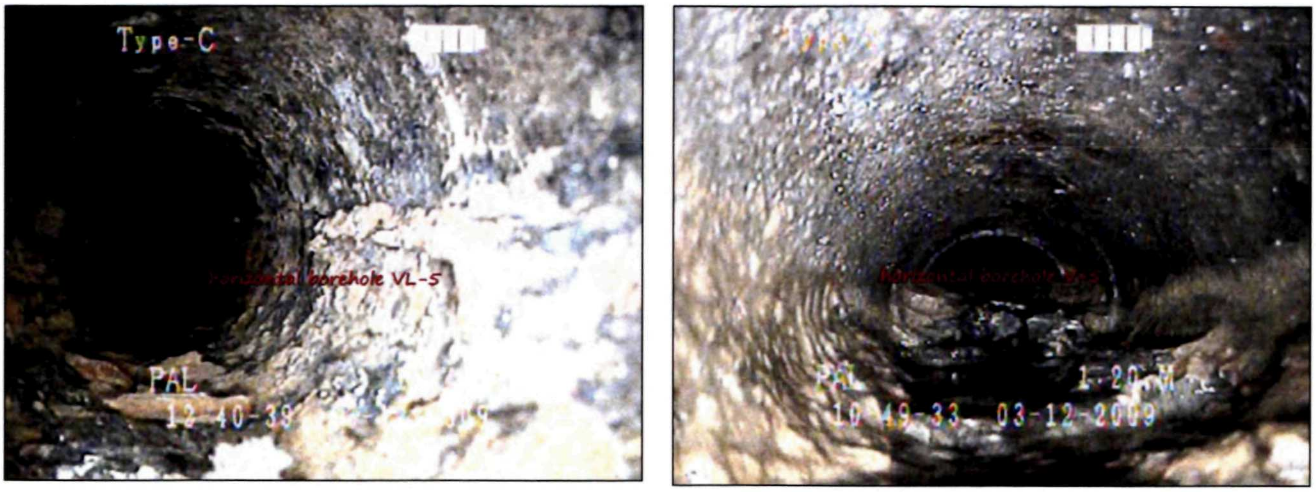

Fig. 8.9 State of the HDB casing after 38 years in operation revealed by the camera inspection

8.2.4. Proposal of design and maintenance of the monitoring network of the Veľkomarský landslide

The proposal of the complex monitoring of the landslides on the right-side of the dam body of the WR Liptovská Mara was designed in such a way that its results were:

- determination of the landslide recent activity,
- forecasting the future development of the stability,
- setting the critical values for need of implementation of additional remediation measures.

The proposed measures were split in to 3 stages – Tab. 8.1. Emphasis is placed especially on the building of inclinometer boreholes and reconstruction of network of geodetic points, because stability (or better dynamics) of any slope can be judged the best way by combination of geodetic measurements of the surface movement with inclinometric measurements of movement below the surface. It will be also necessary to clean the existing HDBs. If such measures prove ineffectiveness, it will be necessary to proceed with a construction of new HDBs.

Even during the renovation and reconstruction of new elements of the monitoring network it is necessary to continue with monitoring measurements on both landslides. However, gradually it is necessary to upgrade the system to automatic data acquisition in order to determine the threshold conditions for a possible activation of the landslides. Only then it will be possible to implement necessary measures in time and to provide a safe operation of the WR Liptovská Mara.

8.3. Landslides at the Dam Nová Bystrica

The reservoir Nová Bystrica is located in the northern Slovakia, about 6 km south of the border with Poland on the river Bystrica (Fig. 8.1). It is used to supply the population with drinking water and was put into operation in 1989 (Bednárová et al., 2010).

Tab. 8.1 Proposed measures on the Veľkomarský landslide in 3 stages

Proposed measures	Purpose and output of the measures
1st stage - specifying and obtaining additional information on landslide area	
a) **Geodetic survey** of existing monitoring elements and important elements of the landslide areas	Creating a representative model of slope deformations + positioning of the network elements
b) **Geophysical measurements** – 4 profiles with total length of 2,380 m	Determination of surface and depth extent of the landslide area + precising the location of new inclinometers
2nd stage - building of new elements of the monitoring network	
a) **Building inclinometer boreholes** – total 7 pcs - 200 m	Observation of movements in depths of the massif. Determination of residual shear strength parameters of soils from samples taken during the drilling
b) **building new piezometers** - total 4 pcs - 100 m	Measurement of GWL in the vicinity of inclinometer boreholes + installation of automatic piezometers
c) **new geodetic points - 5 pcs**	Measurement of surface movements of landslide area – movement of blocks in the upper part of the landslide area.
3rd stage - reconstruction of the current monitoring network elements	
a) **geodetic points** – rebuilding all 22 pcs	Rebuilding of geodetic points in their original places and adjusting their surroundings for measurements by methods of very accurate leveling and GPS
b) **piezometer** - reconstruction of approximately 11 pcs - 265 m	Reconstruction of the broken wells
c) **horizontal drainage boreholes – about 2 000 m**	Cleaning those HDBs which show long-term decline in yield and those in which there is a rise of GWL (Fig. 8.5). In a case of inefficient cleaning new HDBs will be necessary to build

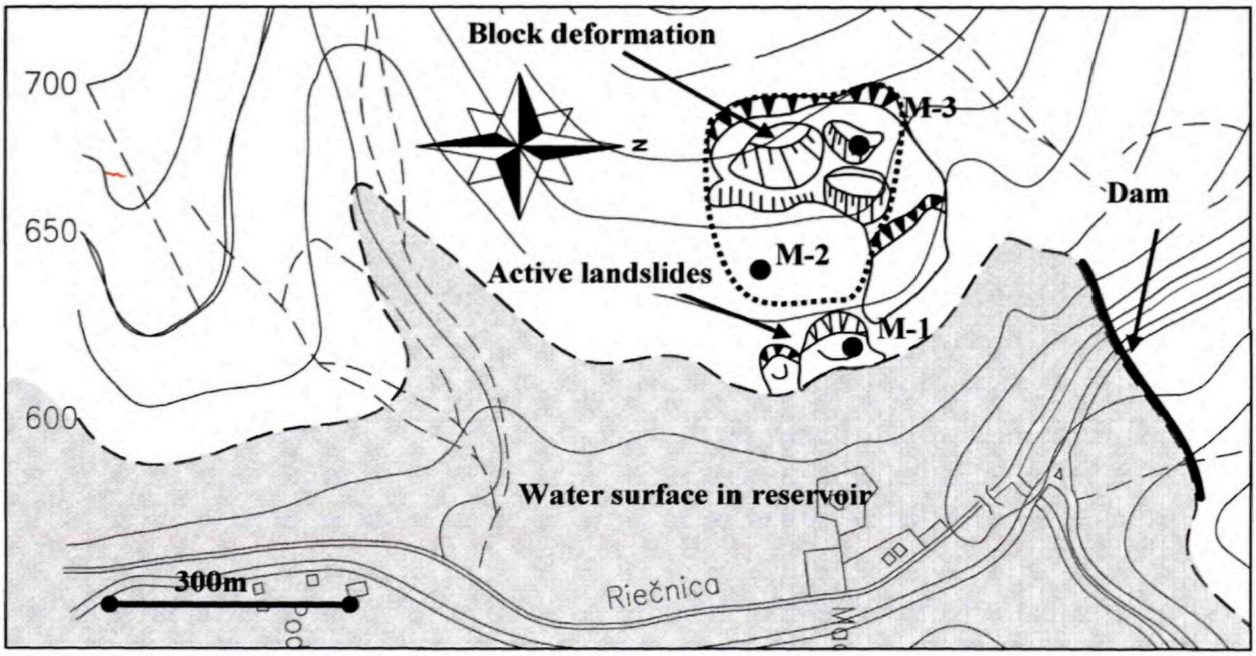

Fig. 8.10 Scheme of the landslides at the slope located on the dam left-hand side

Rock environment of the area consists of rocks belonging to Outer Flysch Zone. The flysch formation is characteristic by the alternation of pelite (claystone, marlite and siltsone) with sandstone. The most dominant strike of the flysch layers is E-W, while their dip is almost vertical (80-90°). The formation has due to multiple folding of the area complex overthrust structure.

Even before the construction of the water reservoir Nová Bystrica, during the implementation of a detailed engineering geological survey (Nevický et al., 1977), the presence of slope deformations was observed at the slopes on the left side of the designed dam (Fig. 8.10), which are located above the maximum shoreline. Two slope deformations of varying activity are located on the slope. In the area between the reservoir shoreline and the forest road there are active landslides with overall area of about 120x60 m. The landslides were probably caused by improper intervention during construction of the forest road. Active landslides are bound only to the slope debris containing coarse fragments from 40 to 80% and the slip surfaces were detected by the inclinometric measurements at depths from 3.5 to 5.0 m. In the higher part of the slope (in the range of about 630-690 m above sea level) there is a block deformation (Fig. 8.10). Based on initial investigation works (Jadroň & Fussgänger, 1993) its dimensions were estimated to approximately 100 x 140 m. According to our latest knowledge, this could be up to 220 x 140 m (dotted line in Fig. 8.10). Block deformation is result of gravitational movement of relatively rigid sandstones over the layer of plastic claystone. During the movement from the main scarp zone the sandstones were disintegrated to individual blocks. The maximum depth of the slip surfaces was detected by inclinometric measurements at a depth of 34.0 m below the surface (Figs. 8.11 and 8.13).

8.3.1. Landslide activity - monitoring and its results

In 1993, investigation boreholes (Jadroň & Fussgänger, 1993) were equipped for the combined observations of groundwater levels (GWL) and movements on the slip surfaces (7 pcs). Four of them, which were placed in the active landslides, become inoperative since 2001. In 2002 there were made 6 new inclinometric boreholes (without possibility of measuring GWL) in the active landslide on the forest road. Furthermore, in 1995 there were built 4 drainage fans (each with 3 horizontal boreholes), and their discharge is monitored. These drainage wells are the only remediation measure performed on the landslide up to now.

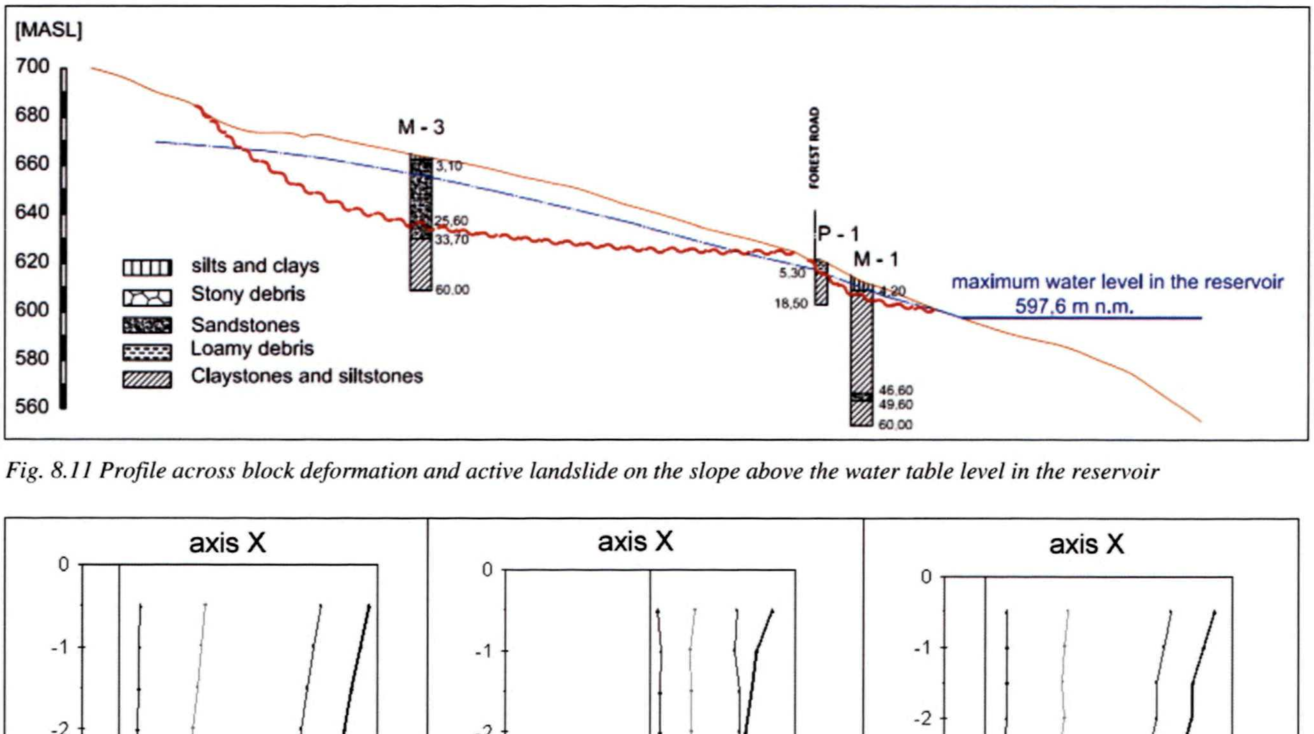

Fig. 8.11 Profile across block deformation and active landslide on the slope above the water table level in the reservoir

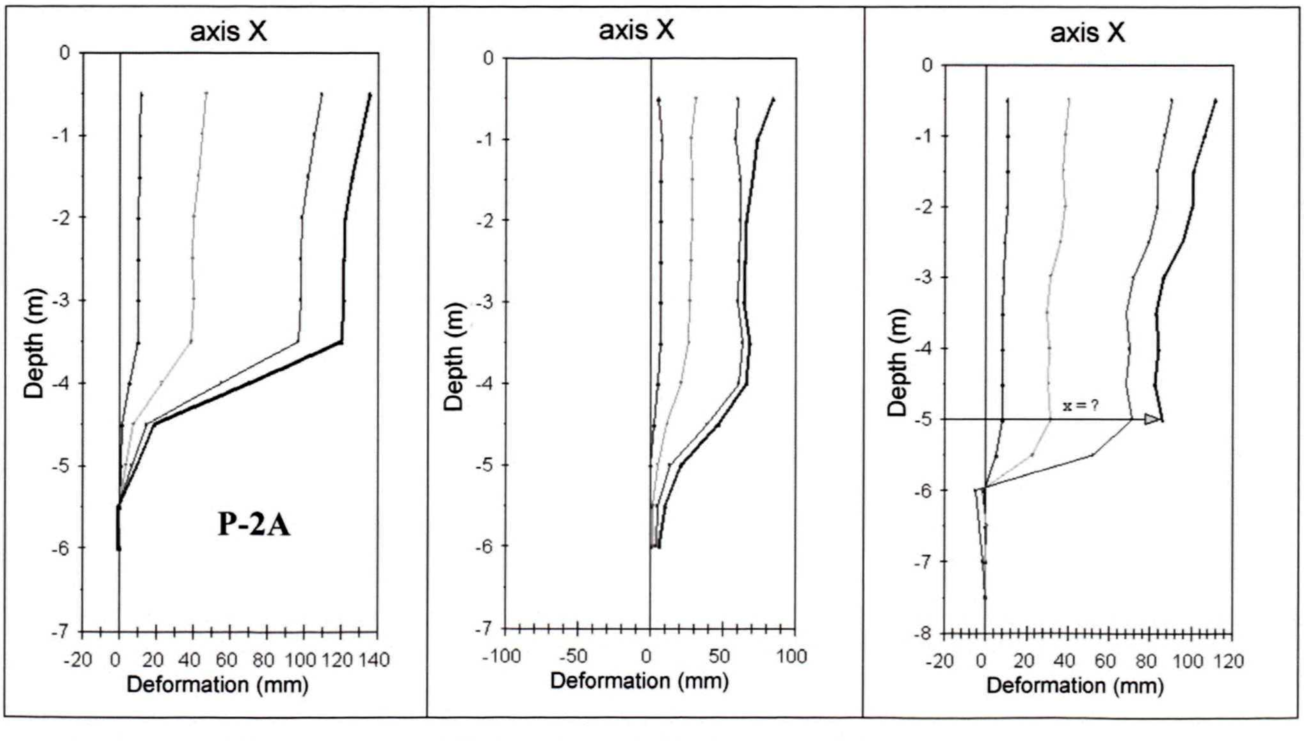

Fig. 8.12 Movements in three inclinometers, including P-2A, located in the active landslide on the forest road

At present, GWL can be measured in 3 wells and movements on the slip surfaces in 5 inclinometric boreholes (of which 3 are in active landslide and 2 in the block deformation).

The analysis of measurements of movements in the inclinometric boreholes is the most important. Due to the nature and depth of the measured movements it was necessary to assessed independently the active landslides at the forest road and the block deformation.

Active (little) landslides

In the landslide area with the forest road it has been confirmed that the activity of the movement still persists. The maximum deformation observed from 1993 to 2006 was 300 mm (sum of deformations from two inclinometers - the second one replacing the first one damaged). The movement is probably not continuous and uniform, it occurs only under extreme climatic conditions (excessive rainfall and snow melting). The depth of the slip surface of the active landslide on the forest road was found 3.0 - 5.5 m below the surface (Fig. 8.12).

Based on the analysis of the inclinometric measurements it was found in 2 inclinometric boreholes located outside the presumed area of the landslide active in 1993 that since 1999 there was gradual expansion of the landslide and significant distortion of the forest road (Fig. 8.13).

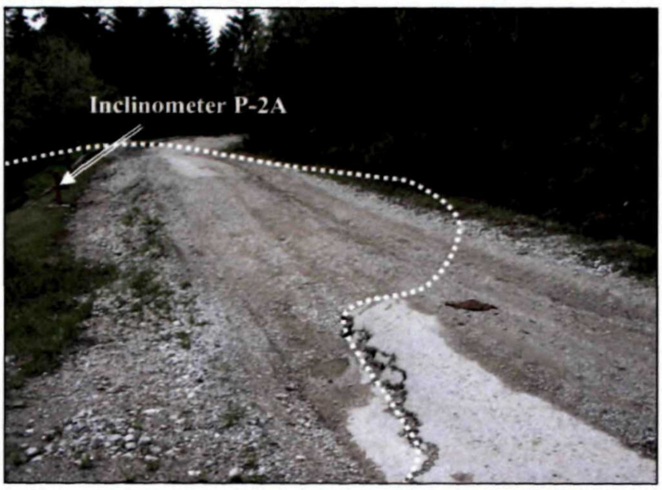

Fig. 8.13 Main scarp area of the active landslide in the body of the forest road with inclinometer P-2A

Block (large) deformation

The block deformation, which is situated in the slope above the forest road, there is a gravitational movement of relatively rigid sandstones over the surface of a plastic claystone. Inclinometric measurements under the main scarp zone of the block deformation (borehole M-3 - Figs. 8.10, 8.11) confirmed the existence of a relatively thick slip zone (about 7 meters), along which there is a movement of the block of sandstone up to 34 meters thick (Fig. 8.14).

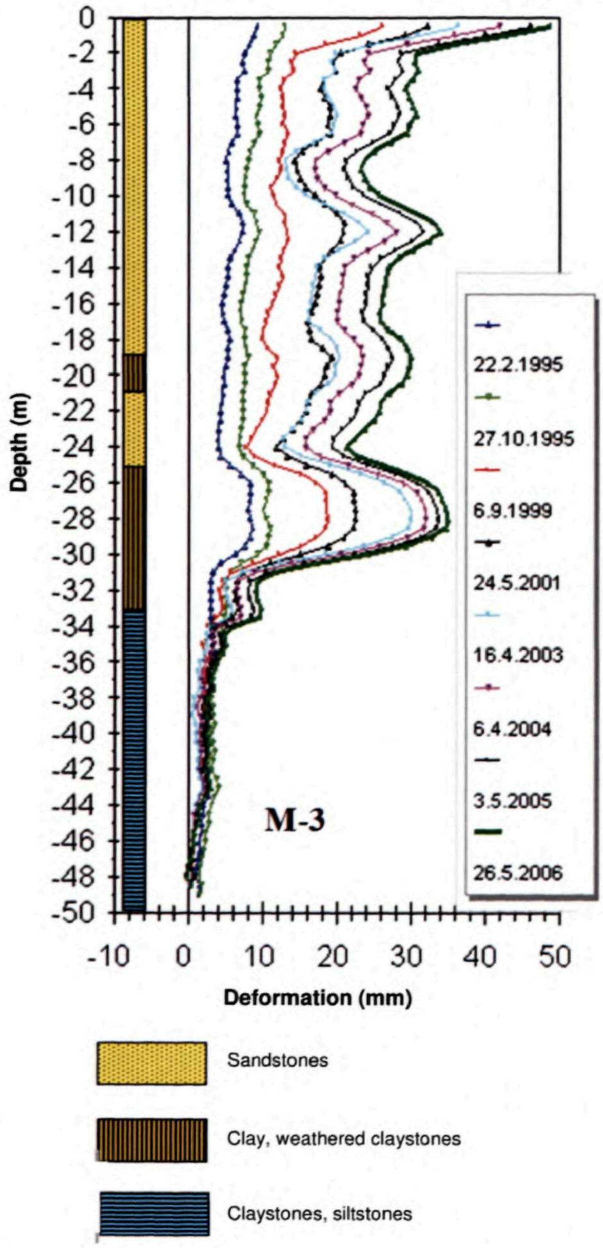

Fig. 8.14 Inclinometric measurements in the borehole M-3 located in the block deformation

Total movement of 47 mm during 15 years was detected. However it is important that the movement at a depth of about 28.0 meters is relatively uniform up to now (Fig. 8.15).

Borehole M-2 (Fig. 8.9) was situated on morphological platform about 60 meters above the forest road, and it was assumed (Jadroň & Fussgänger, 1993), that the platform was not the result of the slope movement. However, subsequently realized inclinometric measurements showed quite a clear movement on the contact between sandstone and claystone (13.0 meters below the surface). The total resultant movement in this depth is almost 98 mm for 15 years. These findings led us to an opinion that the areal and depth extent of the block deformation is greater than it was originally anticipated.

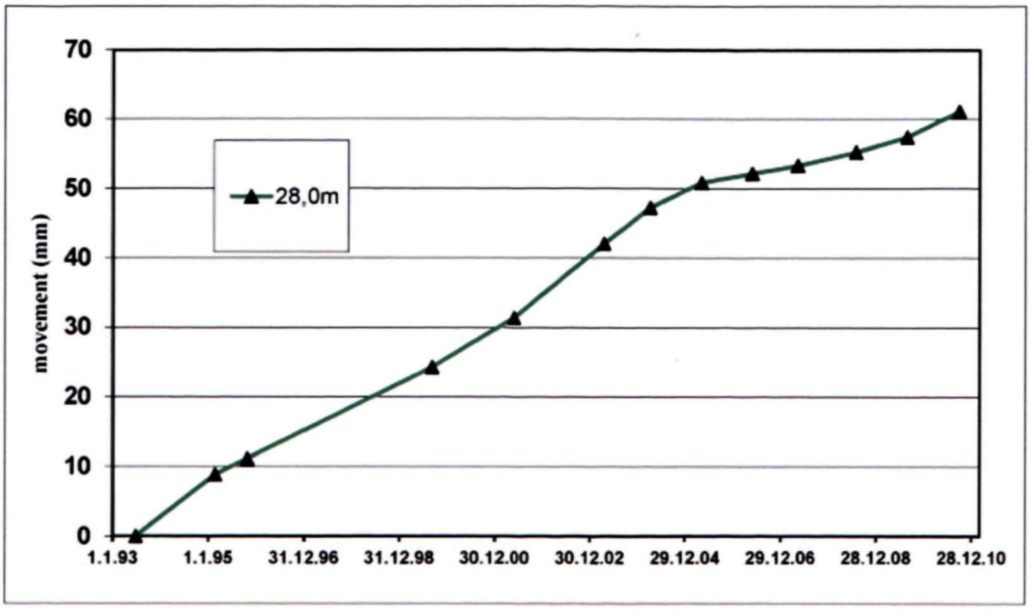

Fig. 8.15 The curve of movements vs time in depth 28.0 m in the borehole M-3

8.3.2. Forecast of development of the slope deformations and their influence on the operation of the water reservoir

Development of the existing slope deformations and their potential impact on the operation of the water reservoir can be forecasted based on the measurements of the monitoring network (especially in inclinometric boreholes), and also calculations of slope stability (Kopecký & Hruštinec, 2006). Results of the calculations of the slope stability showed that the most important factor affecting the stability of the slope deformation is the groundwater level in the slope. This fact will have to be taken into account when designing remediation and stabilization measures.

8.3.2.1. Active (small) landslides

It is obvious that, provided no remediation works will be made on the active landslide area with the forest road (Kopecký & Hruštinec, 2006), than in some time there will be an absolute destruction of the slope and sliding of the deluvial sediments to its lower part and partially into the water reservoir. About 55,000 m^3 of debris can be mobilized. However, we assume that in this process there is no threat to the inflow waterworks facility remote about 150 m from the accumulation of the active landslides. On the other hand, removal of rock masses from this area can cause acceleration of movements of the block deformation situated above the forest road.

8.3.2.2. Block (large) deformation

Based on the inclinometric measurements a link between deformations in an area of borehole M-2 and the deformations around the borehole M-3 cannot be ruled out. The knowledge of the fact whether there is accelerated motion or movement is steady is crucial to the prognosis of further development of the movements (Fig. 8.15). However, as the inclinometric measurements are carried out only once a year, it is not possible to determine the nature of the movement reliably.

If there are demonstrably accelerated movements in the area of the block deformation, it will be necessary to proceed to remedial or other measures, because at certain acceleration it will not be possible to stop the given movement. The subsequent movement of the rocks would likely jeopardize the operation of the water reservoir.

8.3.3. Recommendation for the following monitoring

Assessment of the stability of the slope on left side of the dam Nová Bystrica and forecast of its future development with respect to the operation of the water reservoir were based only on pre-existing knowledge, where the inclinometric measurements play the critical role. Assumptions obtained by calculations and analyses correspond to the accuracy of all existing data.

For clarification of existing knowledge (especially in the area of the block deformation) the further works recommended are summarized in Tab. 2.

8.4. Conclusion

Based on the monitoring we assume that the landslide at the WR Liptovská Mara is temporarily calming; the movement has slow creep character. The only activation was recorded in the spring 2006, when there was a downturn in the crown zone of the landslides. The stability of the landslide slope described in this paper is primarily a function of groundwater levels and water level in the reservoir.

On the WR Nová Bystrica the stability calculations demonstrated instability of the shallower landslides

Tab. 8.2 Recommended remediation works on the Nová Bystrica landslide

Recomended works	Purpose and output of the works
Geodetic survey of the terrain morphology	Creating a representative model of slope deformations (active landslides and block fields)
Installing surface geodetic points and measuring their movement	Understanding the relative speed and direction of the movement of blocks on surface (forecast of their future development)
Inclinometric measurements (twice a year) Construction of 2 pieces of new inclinometer boreholes in the block deformation Restoration of functionality of inclinometers P-5 and M-1	Determination of the depth and size of the deformation in the rock environment – prediction of further development of the movements with identification of critical values of their velocities
Groundwater level (3 new piezometers with continuous measurement of GWL), discharge of horizontal drainage boreholes	Optimization of boundary conditions for stability calculations and determination of the critical levels of GWL
Geophysical measurements	Determination of areal and depth extent of the block deformation + specification of location of new inclinometers

threatening the forest road, what was subsequently proven by measurements of the movements in boreholes equipped with inclinometer. The movement was more than 30 cm in 15 years. More dangerous for the operation of the water reservoir may be activation of the block deformation above the shallow landslides. The movement of the blocks occurs along slip surfaces in greater depth (34 m and 12 m below the surface). The movement is uniform and is about 3-5 mm per year. Acceleration of this movement could have disastrous effects on the safe operation of the water reservoir.

On the WR Liptovská Mara, the only representative measurements proving the actual movement of the landslide are measurements of elevation changes on geodetic points. Positional changes of geodetic points are irrelevant because unstable are even the reference points. It is necessary to rebuild a network of the measured geodetic points. It is also necessary to build several boreholes to monitor movement within the soil mass (inclinometer boreholes). Only then we can determine the critical groundwater levels and predict the actual development of the landslide slope. With respect to poor condition of the monitoring elements after 40 years of their operation it is necessary to build new or refurbished the old monitoring elements.

In turn, on the WR Nová Bystrica there are quite good data on the movement of the landslide slopes, however less satisfactory there are data on groundwater levels and particularly there is a lack of data on the extent (area and depth) of the block deformation.

The output of the article is therefore not only information about the current stability of landslide slopes, but especially the proposal for their continuing monitoring, enabling reliable prediction of their further development and hence it is also the proposal of measures ensuring long-term trouble-free operation of the referred to water reservoirs.

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