COUPLED APPLICATION OF GEOTECHNICAL AND GEODETICAL SLOPE MOVEMENT MONITORING

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Abstract: Based on our previous activities in highly exploited tertiary brown coal basin a monitoring project was started in 2002. The site is located in Chabarovice open cast mine near the town of Usti on Elbe in the north Bohemia. Unstable area takes about 25-30 hectares. Coupled geotechnical and geodetical monitoring was focused on determination of above- and in- ground displacements. Selected results of the project "Research and Verification of Methods of Slope Movement Monitoring" executed during the years 2002 – 2004 and further extended in 2005, which were used for stability assessment, design of remedial measures and for risk analysis are discussed in the paper. The unstable area characterization and reliability of the monitoring system together with remedial measures are discussed in the paper with summaries of risk analysis.

1. Introduction

The whole area of interest is strongly disturbed by mining - underground formerly and open cast till now. Prior to any instrumentation an archive search, observations and site investigation were made in the area of interest [1].

Excepting the unstable site the mine is in reclamation process, now. A large lake is located in the centre of the mine surrounded by side slopes. The unstable site Rabenov (local name) is presented in the Figure 1 and it consists of two parts, (Fig. 2). Upper part with very small ground inclination is unstable and not directly affected by open cast mining. A long distance drinking water supply is located very close to the top boundary of the unstable area in the forest below the hill. Lower part formed by mining activities is partly backfilled by internal waste dump. Because of the instability of the upper part and not completed backfilling in the lower part, the lower part is unstable, too.

2. Geology of the Rabenov site

The site is located on the north side slope of the excavated mine. In general the recently highly exploited tertiary brown coal basin is composed of clays, sedimentary / volcanic complexes, coal and Quaternary overburden – loess, gravels, sands and regionally metamorphosed rocks under Tertiary fill and coal seams. Huge waste dumps made mostly of stripped clay and loess on one side and side slope of the large pits are often unstable. High frequency of slope movements not only due to mining activities but also natural slope structure and site conditions occur often in the brown coal basin.

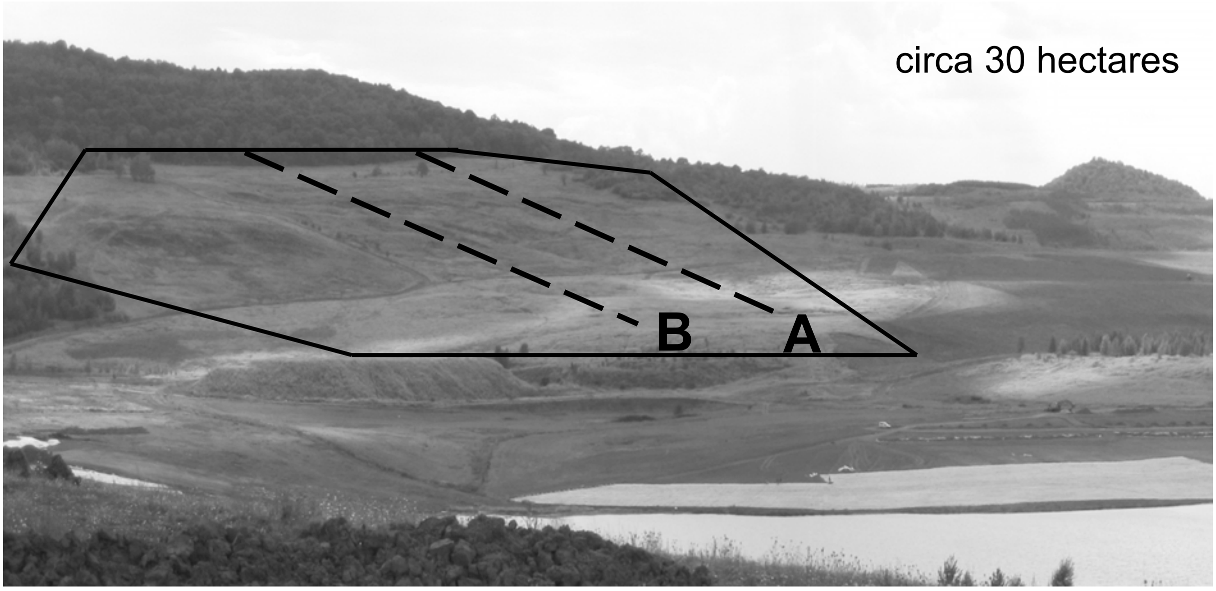

Figure 1: Photo of the Rabenov unstable site

The upper part of Rabenov area is more or less "virgin" ground and it is known by a lot of springs, which are indicated by an old local name "Wasserberg". Lower part of the site is formed by internal waste dump located on an overconsolidated inclined clay base underlying mined coal seam.

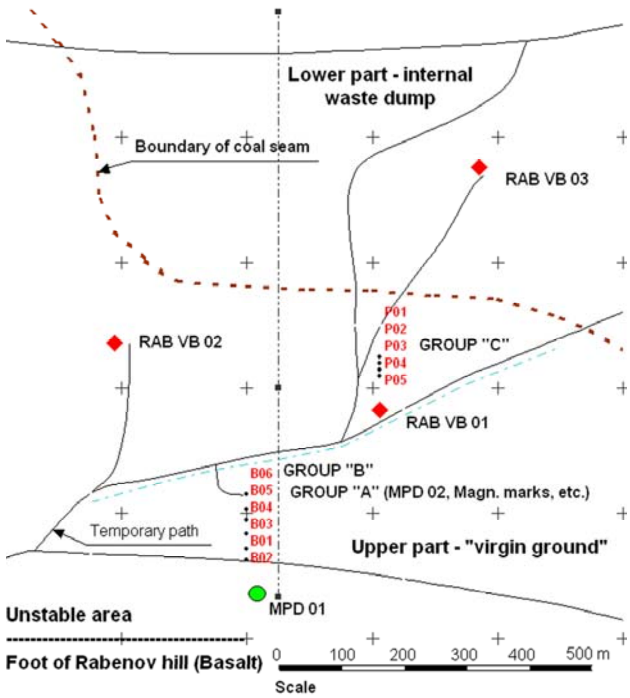

Figure 2: Simplified site plan of the Rabenov area

3. Site instrumentation

Monitoring was designed to cover different levels of requirements, with different monitoring equipment, indication of stable and / or unstable area by geodesy and radar interferometry, above ground determination of displacement range and velocity, indication of slip surface location in sliding mass, determination of displacement along slip surface, identification of contractile and / or dilative behaviour by shearing, spatial mass displacement vectors and pore water pressure distribution [1]. The most important and further presented monitoring instrumentations are:

- Local geodetic network was established in the first monitoring stage with below mentioned geotechnical instrumentation.
- Application of Swiss line-wise 3-D displacement monitoring in boreholes using high precision combined casing and sliding micrometer for establishment of reference points VB 01÷03 and or application of sliding deformeter (both with modified inclinometer) for measurement of displacements in sliding mass.
- Pore water pressure monitoring using Swedish BAT system of filters and intelligent sensors installed usually in clusters by static / dynamic penetration.

4. Local geodetic network and selected results of measurements

The network of the Rabenov area was founded in 2002 with reference points VB 01÷03, because an available set of reference points was several kilometres outside of the area. The points were established with use of combined casing for sliding micrometer and high accuracy inclinometer measurements in boreholes circa 24 m deep. The casings are embedded in overconsolidated clay base. Another auxiliary reference point VB 04 is located inside the sliding area in the upper part on large square pad footing of former column of high voltage line. VB 01 and 03 are placed along more or less horizontal line splitting the area in two parts with significantly different slope angle. The system of reference points is composed of two triangles with common side VB 01 and 03 and it is presented in the Figure 3. The side lengths vary from 400 to 600 m.

The points VB 01÷03 are located in stable parts outside the area of sliding. High accuracy connection of geotechnical and geodetical measurements is provided with special insert tool placed in high precision combined casing [3]. Horizontal and vertical shifts of the top of the casing (insert tool) are measured and calculated with the use of geotechnical equipment and transmitted to geodetical team. The accuracy of shifts x, y, z determination is high at least 0,1 mm [4].

Location of the auxiliary reference point VB 04 is measured by total stations from VB 01 and 02 at the beginning of each surveying phase.

In the sliding area, there are located 23 discrete measuring points. Iron bars of diameter 0,06 m and length 1,25 m were inserted in the ground with the use of dynamic penetration equipment and there are re-installable. The heads of the bars are equipped with an internal thread and protective caps. The measuring points covered by different species of grass and weeds are temporary extended with a special reflecting instrument. The instrument of length about 2,2 m is equipped with two omni-directional reflecting prisms of electro-optical distance meters of the Leica GeoSystems. Individual dimensions - the distances from geometric centres of the upper and lower prisms to the instrument foot with the thread for fastening to a bar - are precisely known [5].

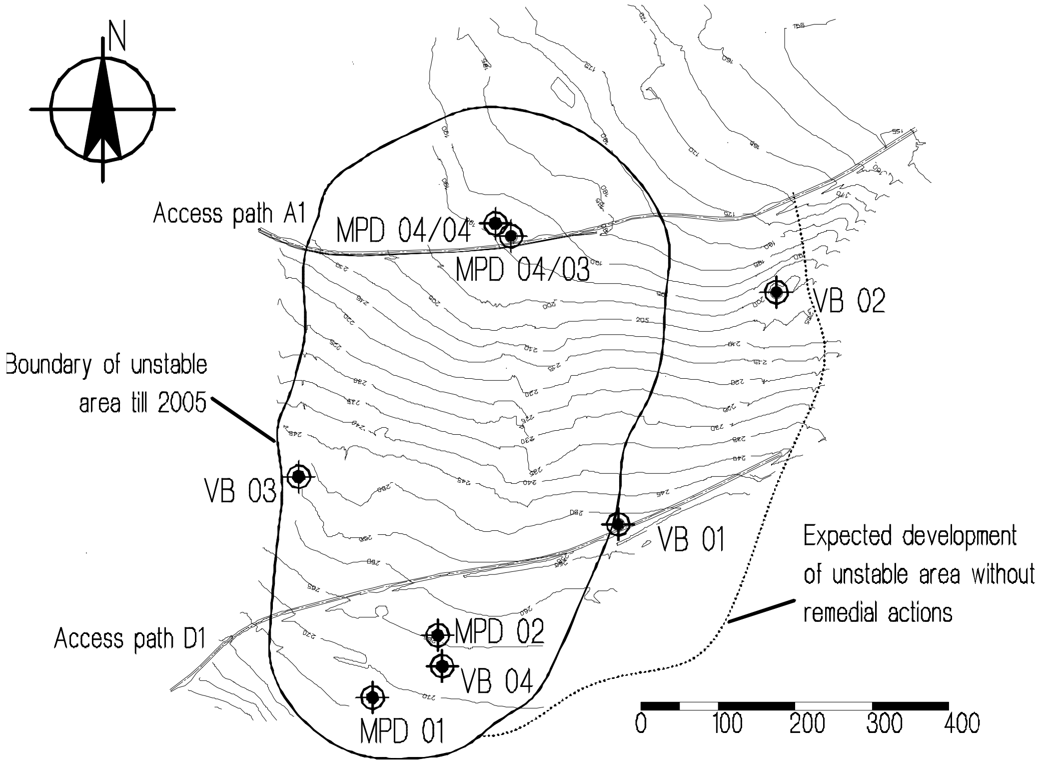

Figure 3: Site map and reference points VB 01÷03 with high precision combined casing

4.1. Selected equipment and methods of measurement

Stage terrestrial measurements are carried out by means of two total stations Leica TC1700 and one station TC1800, standardized according to the standard ČSN ISO 8322. The measuring equipment and accessories are identical at each survey point during each stage of measurement; tripods with the centring plates, well balanced and centred, are not moved during measuring. In this manner the influence of the systematic errors in the apparatus is minimised. The same apparatus is in turns placed at points VB 02 and 04.

Seven stages of measurements (0 - 6) took place during the years 2003-2005. During the stages 0 through 4 the full extent of the survey network was spatially observed. Observation was carried out in two turns of horizontal directions using the double sighting. Zenith angles and inclined distances were measured in opposite directions implementing physical corrections and characteristics of the prisms; differences in elevation were registered for control purposes. Measuring points on the ground were sighted mostly from two survey stations with one position of the apparatus scope targeted the additional reflecting instrument described above. Known dimensions of the instrument enable, by means of the calculated coordinates of the prisms, the determination of the coordinates of a ground level point (otherwise invisible) and the change of inclination of each measuring point.

A simplified measurement of the survey network was tested in stages 5 and 6 during the year 2005. This variant consists in sighting only from points VB 01 and 03 in two sets of horizontal directions and zenith angles; inclined distances were measured four times. The network measurement was twice repeated; points VB 02 and 04 were fitted with the precise or omni-directional prisms Leica (following analyses proved an uncertainty in determination of heights in value of approximately 3 mm with omni-directional prisms). Points on the ground were not measured during that year.

Stage GPS measurements by the fast static mode were carried out from the 3rd stage onward, i.e. from the second half of the year 2004. Geodetic NAVSTAR-GPS Trimble 5700 system was applied; the setting of the elevation angle was 13° for the base station and 5° for the rover station; the PDOP parameter was less then 6. The system was tested on the survey network in the Central Bohemia during the year 2003. The observations serve for monitoring of the stability of reference points and proposed connection of the local network to the national coordinate systems (position S-JTSK and vertical Baltic Vertical Datum – after adjustment). Identical positions of tripods and centring plates were used for both GPS and terrestrial measurements so that the influence of centring errors following the change of position between individual measurements was minimised [6].

4.2. Evaluation of measurements in the local network

The terrestrial network is evaluated with respect to the local coordinate system with the origin at the reference point VB 01 and the axis +X passing through the reference point VB 03. It can be stated for stages 0-4 that the mean value of error of the station coordinate adjustment ranges between 0,0 and 2,5 mm.

Geotechnical measurements in the reference point high accuracy casings VB 01÷03 showed interesting results describing 3-D shifts with respect to time (see part 5.1). The obtained accuracy checked by surveying was acceptable. The accuracy would increase, if the shifts would be taken into account.

The mean coordinate error of station points measured by GPS mode is within 0,7 – 35,0 mm for position and 0,7 – 43,9 mm for altitudes. Differences of space coordinates of points among stages satisfy the GPS accuracy described above. GPS is also used to verify the assumption of fixed toe of combined casings comparing results with geotechnical monitoring.

Several procedures and programmes for coordinate transformations of reference points in a precise local terrestrial network and the measuring marks on ground sighted from these station points into national systems determined by less precise GPS procedures were tested. CTU Prague freeware product called Rosinanta was applied. In case of using the simplified survey method (stages 5 and 6) the mean coordinate error of the points VB 02 and 04 after consecutive transformation to the values of GPS mode is increased by up to 55%.

4.3. Measured on ground shifts

An average theoretical limit of a clearly proved shift is 26 mm implementing the confidence coefficient 2,5. Mean shifts of surveyed points, re-calculated to one month, are shown in the Table 1. Shifts slow down in the course of winter months.

Shift [mm]	Stage			
	1.-0.	2.-0.	3.-0.	4.-0.
Y	42	10	53	49
X	0	-2	4	-7
Z	-17	-11	-36	-31

Tab. 1 Mean shift per mensem

The sighting of all the measuring points on ground was also carried out during the 3rd stage by means of Trimble 5700 system applying RTK method (denoted by R) and by means of Trimble GeoExplorer XT device satisfying GIS accuracy employing the post-process DGPS method (denoted by D). Mean differences in coordinates of measuring points on ground between the data obtained individually by the before mentioned methods with respect to the terrestrial mode (T) are shown in the Table 2.

Difference [mm]	Methods	
	R - T	D - T
Y	34	131
X	70	118
Z	61	623

Tab. 2 Mean differences according to the methods used

These measurements were carried out within the framework of postgraduate (doctoral) and undergraduate work at the Departments of special geodesy and mathematics FCE CTU in Prague [7].

5. Geotechnical instrumentations and selected results of monitoring

A typical section through the unstable site is presented in the Figure 4. Numbers in boxes represent the depth of sliding zone below ground, symbols MPD indicate boreholes instrumented with combined casing for line-wise 3-D displacement monitoring and BAT installations of pore-water pressure measurement.

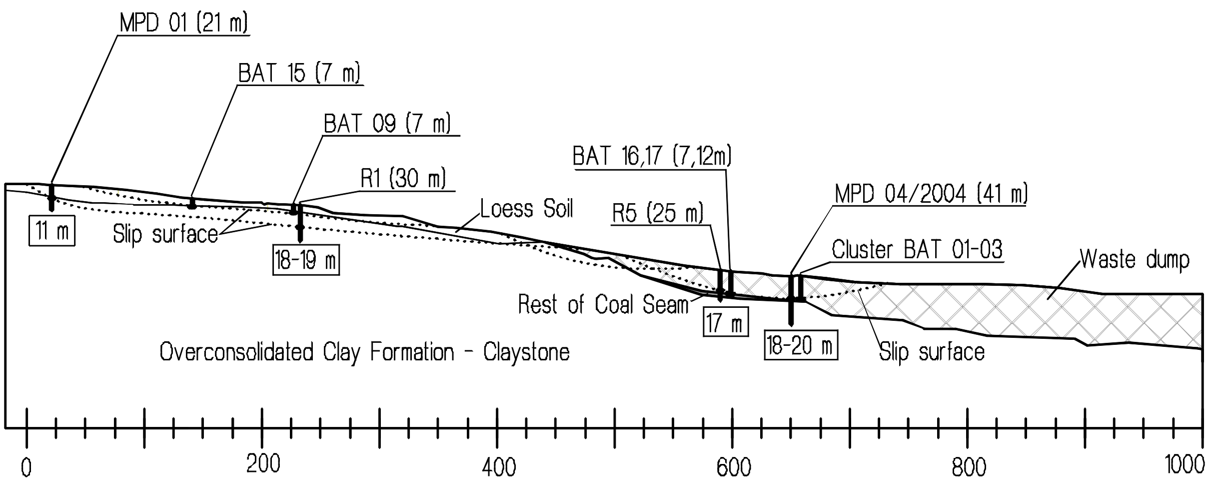

Figure 4: Section B with selected elements of instrumentation

The lower part of the site with X coordinate (horizontal distance from local origin) higher than 550 ÷ 600 m (Fig. 4) was considered as stable from the point of view of long-term observations. Borehole MPD 04/2004 was instrumented by combined casing for 3-D line-wise displacement monitoring in summer 2004.

In the upper part of indicated area, there were expected slides in shallow zone up to 6 m at the maximum. To be sure to describe the whole sliding activity here, the MPD 01 borehole 21 m deep was instrumented with combined casing close to the Rabenov hill toe (Fig. 4).

5.1. Selected results of displacement monitoring

Determination of Δx, Δy, and Δz shifts of reference points VB 01÷03 using sliding micrometer and modified inclinometer brought following important results in 2002-2005:

- VB 01 - vertical heave Δz up to 4,0mm, slope down Δx up to 4,0 mm,
- VB 02 – vertical heave Δz up to 16,0mm, slope down Δx up to 1,0 mm,
- VB 03 - vertical descend Δz up to 50,0mm, slope down Δx up to 12,0 mm.

Presented vertical shifts were caused by volume changes of local clay. In case of VB 02 ground water level rise resulted in swelling of clay within upper zone of about 5 m. On the other part in VB 03 settlement occured in the same zone because of local lack of water and clay shrinking. Horizontal displacements in the same zone were caused by creep with high probability.

Selected results of monitoring of horizontal displacement in unstable mass are presented in the Figure 5. Monitoring in MPD 04/2004 showed plastic displacements of the waste dump in the first phase followed by a shear displacement at 18 ÷ 20 m depth being contradictory with respect to before stated assumptions of waste dump stability. The sliding deformeter measurements approved the expected contractile behaviour of the waste dump mass - mostly stripped clay placed by stackers.

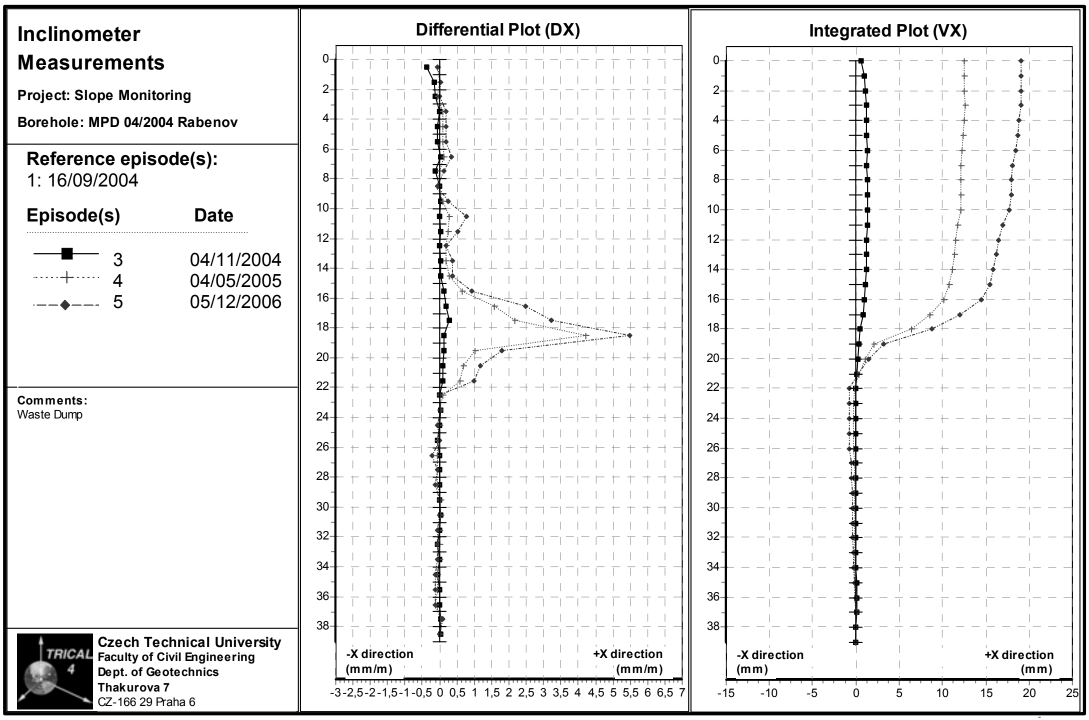

Figure 5: Horizontal displacements in the waste dump

In the borehole MPD 01 there was recognized another independent slip zone located in the virgin clay base (firm to hard clay) at 10 to 11 m depth below the zone of plastic soil formation. The horizontal displacement in the discrete shear zone was 10 mm within 1,5 year and the movement continues. The axial strain measurement by sliding deformeter brings another complementary result connected with horizontal shifts. Due to high accuracy of strain and integrated axial deformation determination it is possible to evaluate the character of soil behaviour with respect to contraction / dilation along slip surface. In this case firm to hard clay was compressed nearly 2 mm within 10 to 11 m depth. This particular case is probably a result of an inclined slip zone, [1].

5.2. Results of pore pressure monitoring

Pore water pressure has been monitored in the lower part of the slope since 2003 using separate clusters of BAT piezometers installed at different levels up to 20m below the ground. A nearby boring (in Fig. 3: MPD 04/2003) was stopped at depth of 27m below the ground and it was transformed into an open standpipe piezometer. Selected results of the measurements in the BAT 01÷03 filters and theoretical hydrostatic pressure assuming water table at the surface are presented in the Figure 6.

Measurements of pore water pressure using multilevel piezometers helped to identify important features of mechanism of the sliding of the slope such as existence of separate hydraulic horizons and occurrence of temporary artesian water at certain depths.

Artesian water has negative effect on slope stability and may occur due to shear deformation of the saturated soil with contraction behaviour or existence of isolated aquifer of limited drainage capacity. Between several factors significant increase of pore water pressure and temporary artesian water occurrence can result in triggering effect of the slide.

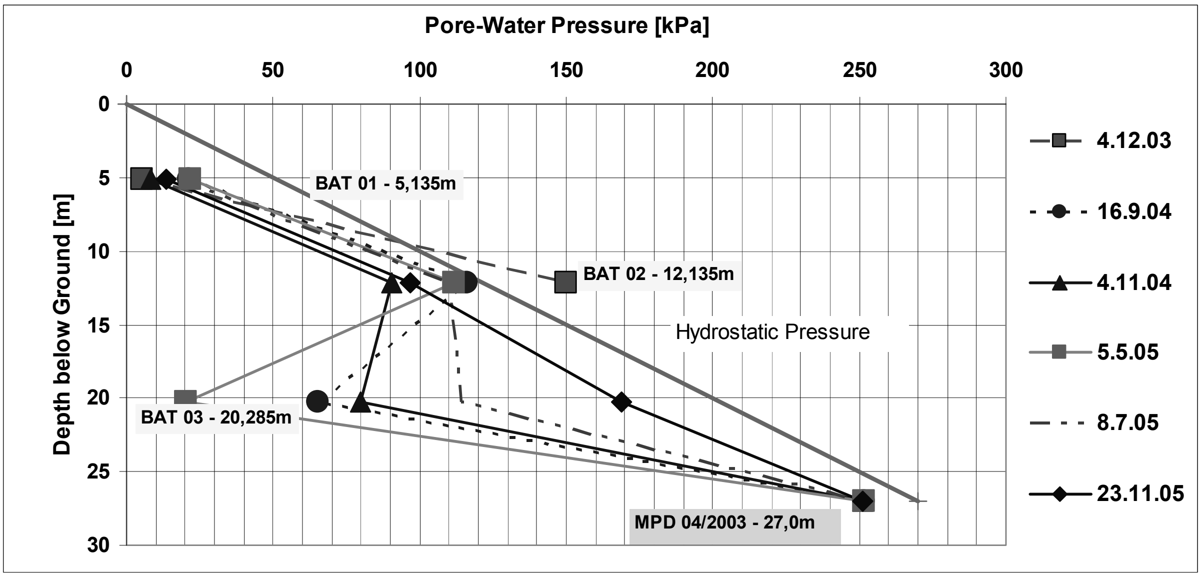

Figure 6: Pore pressure development in the waste dump

Artesian water has been also observed in other parts within the mine dump and in the virgin soil section of Rabenov site. In the virgin soil section pore water pressure is monitored, eg. in filters BAT 09 and BAT 15 located in the section B. Both are installed at depth of 7m but with significantly different ranges and trends of pore pressure development with time, Fig. 7. Where as pore pressure in filter BAT 15 maintain more or less constant value of around 60 kPa, filter BAT 09 located approx. 100 m down the slope exhibits significant decrease from initially artesian water, three times higher then possible hydrostatic pressure, to almost the same value as in BAT 15. It means in the location of BAT 09 the minimum vertical effective stress reached – 70 kPa. It is obvious the pore overpressure shall have a local effect and a spatial impact of soil mass confines local stability.

Pore water pressure measured for three months in the autumn at a group of two piezometers BAT 16 and 17 installed within the mine dump indicated stable artesian water of pressure up to 187 kPa at depth of 12m, where as almost zero values (slightly negative) were picked up at level of 7m below the ground. This is an important finding as the pore water pressure distribution present at this location is completely different from presumption of hydrostatic pressure in the lower part of the waste dump.

6. Risk analysis of remedial measures design

Former assumption of ensuring stable side slopes of the mine by internal waste dumps support was unreal because of stopping of mining activities by governmental regulation. To stabilise the side slope it was decided to prevent soil movement within the range of X about 0 ÷ 400 m by an anchored pile wall and to increase stability of the waste dump by a new embankment construction. Complementary drainage systems were designed to lower pore water pressure together with re-shaping of the slope in X = 250÷600m to speed up precipitation dewatering and to contribute to overall stability.

The analysis was used to assess three alternatives A to C of active remedial measures design and to compare these ones with “zero” action. The A was designed with the highest costs, the B with medium ones and the C was the cheapest alternative. The A alternative was not selected as the optimum one. There was recommended a combination between the A and the B with respect of more intensive drainage and a modified pile wall [8]. Because of high risk of remedial measures with the application of the anchored pile wall (critical in the section B due to the pore water pressure and the slip zone location) the modified design of remedial measures is under development, now. Extended monitoring was recommended with respect to pile wall load and anchors activation by soil mass movement.

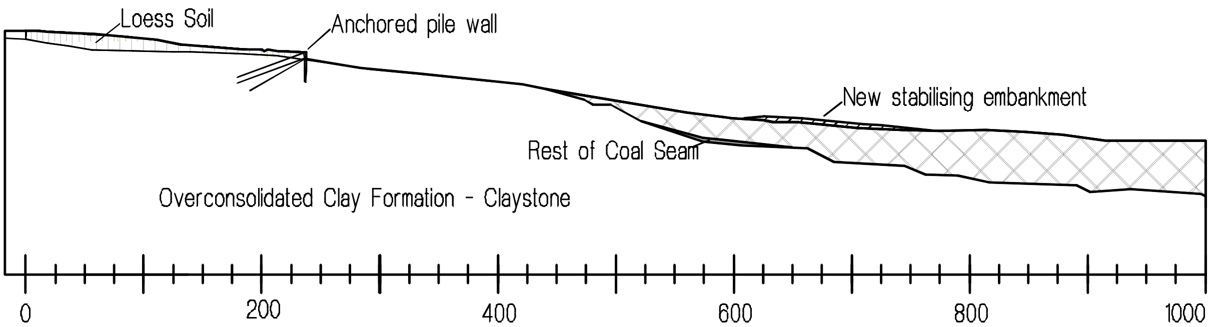

Figure 7: Slope section with pile wall and stabilising embankment

7. Conclusions

In cases of a very complex soil section with respect to a natural geological structure and or the ground affected by large human activities the monitoring plays a significant and a very important role in development of a reliable geotechnical site model, in characterisation of soil / rock mass and in possible discovery of its unexpected behaviour, in calibration of computational models and in verification of analyses together with safety approvals. It is obvious that following items will increase significantly reliability of our understanding of factors of slope stability and if not taken into account could be critical:

- Periodical visual inspection

- Application of combination of geodetic and geotechnical monitoring methods – especially for surface displacement determination and possible duplication and cross-comparing of results brings more reliability to site models
- Indication of zones of shear displacement development by 3-D measurements at variable depth taking into account not only shallow instabilities but also deep ones probably not discovered till present day, all with respect to the time stages and evolution trends
- Determination of artesian water effects development using pore pressure monitoring and recording significant changes with the time, tracing and locating of possible excesses with the high negative impact on slope stability

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