Geotechnical modelling and monitoring as a basis for stabilization works at two landslide areas in Polish Carpathians

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ABSTRACT: The importance of detailed site investigation, monitoring and slope stability analysis is shown by means of the practical examples of two landslide stabilization projects in Polish Carpathians. Practical applications of geotechnical engineering monitoring methods were checked for public road authorities. Flysch soil-rock type deposits were difficult for in-situ and laboratory tests. Therefore they were investigated by different methods including core drilling, sampling, index, IL oedometer, triaxial and direct shear laboratory tests. Ground Penetration Radar (GPR) scanning, GPS-RTK mapping, instrumentation and slope stability analysis using FEM and LEM methods were also employed for the investigations. Extensive monitoring measurements conducted in 2006-2011, continuously every 1–1.5 month, provided data for slope stability analysis and enabled prediction of landslides behaviors before, during and after counteraction works. Monitoring network covered groundwater level, pore pressure and precipitation measures. It included also a new real-time monitoring system installed on one of the largest landslide in Gorlice region. Modeling of geotechnical conditions were used in the stabilization works. One of the landslides was fully stabilized. Another, partially remediated is monitored by real-time remote sensing system due to its activity and size. Research proved that chosen modeling and monitoring methods were helpful for mitigation measures and provided its control. Stabilization of active Carpathian flysch landslide is not an easy task. A more comprehensive monitoring and modeling before the design phase could lead to a safer and more economical solutions. It requires, however, respect to the landslide type, triggering factors, size and activity.

1 LANDSLIDE LOCATION

Investigated areas were localized in Beskid Niski Mountains, SE Poland, near to the city of Gorlice. Slopes in this region were characterized by high, in some places up to 30%, density of landslides. Sites were selected for investigations by the Polish Geological Survey. The research was conducted on nineteen landslides causing serious threats to the public roads. Stabilization and remediation works were performed in two landslide areas in Sekowa (1) and Szymbark (2). In area No. 2 only partial stabilization was decided. Due to landslide size and activity at these landslides the first in-kind in Poland real-time monitoring system was installed. Landslides location and instrumentation are presented on Figure 1.

2 LANDSLIDE GEOLOGY AND FIELD INVESTIGATIONS

The engineering geology conditions on landslides were complicated. Natural terrain relief was formed in Tertiary and Quaternary periods. Intensive erosion in river valleys and high groundwater level, during the Holocene era, characterized by thick weathering zones, activated huge number of landslides (Raczkowski 2002). Mass movements were reactivated in wet periods many times. Colluviums represent heterogeneous mixture of soils and rocks.
due to creep and geodynamic processes covered by weathering zones. Saturated claystones had mechanical parameters similar to weak cohesive soils. Sandstones usually occurred as thin layers with different degree of digenesis. It allowed water infiltration together with seepage rising due to many crack and joints. Landslides depths were changing from few to dozens of meters. Movements were usually localized on slopes with inclination varied from 15° to 35°. In some cases, active sliding zones were situated in lower parts of the landslides. Groundwater levels were very shallow and varied 0.5–2.0 m. Field investigations included 320 m of core drillings diameter of 132 mm, depths 9–30 m and NNS sampling. Project covered preparation of site conditions reports, slope instrumentations and recognition of counteraction possibilities. Mass movement area location, size, depth, failure mechanism, lithology, index and shear strength parameters were recognized. Monitoring network included ground movement, groundwater level and pore pressure measurements (Bednarczyk 2005–2011).

Geological stratification was recognized by boreholes and by 4500 m RAMAC/GPR scanning (Fig. 2). Results of GPR calibrated by boreholes had fairly good correlation with monitoring results. For landslide mapping GPS-RTK profiling with vertical and horizontal accuracy up to 1 cm was used.

3 LABORATORY TESTS

Geotechnical laboratory tests included 66 sets of index tests (grain size, moisture content, Attenberg limits, bulk density, density of soil particles, content of organic/bituminous material), 16 direct shear tests and 3 (IL) odometer tests. Soils used for these tests represented silty loams, silty clays to claystones (rock). Moisture content was high 19–35%, liquidity index 0.1–0.8, cohesion 6.5–10 kPa, angle of shearing resistance 11–15°. Soils had very high compressibility. Results of index test indicated that the highest values of moisture content and plasticity index were observed in samples taken near the sliding surface (Fig. 3).

At lower part of landslide area No. 1 in Sekowa, active slip surface was localized at the depth of 2.4–5.4 m. It was characterized by high values of plasticity and moisture content. For both landslide areas slip surfaces were in good agreement with index test results. On landslide No. 2 in Szymbark, active slip surface was at the dept of 2.5–16.0 m depending on location (Figs. 3, 4 and 6).

4 INSTRUMENTATION AND MONITORING

Landslides instrumentation included 80 meters of 70 mm ABS inclinometer casings equipped with special moving joints for settlement measures. Standpipe, pneumatic and automatic vibrating wire pore pressure transducers were used (Fig. 4). The groundwater table locations and the pore pressures values were measured in order to estimate effective stresses. Subsequent surveys, every 30–45 days were performed by the period of 5 years. (Figs. 5, 6). They allowed recognition of movements in the ground profile.

![Figure 2. Ground Penetration Radar (GPR) scanning profile.](image1)

![Figure 3. Results of index tests, landslide area No. 2 Szymbark.](image2)

![Figure 4. Szymbark landslide slope instrumentation scheme.](image3)
and determined the magnitudes, depths, directions and rates of landslide ground displacements using equation described by Dunicliff (1988). Cumulative displacements varied from several up to 180 mm and depended on landslide activity and size. At landslide area No. 1, the largest monthly movements of 12 mm in May–June 2006, corresponded with a record monthly precipitation of 230 mm and high pore water pressure of 45 kPa. (Fig. 7). Movements in both areas occurred when the pore water pressure reached 45–65 kPa on the slip surfaces. The largest ground movements were usually observed in some time after these conditions. The pore pressure values had better correlation with displacements than groundwater level depths.

At landslide area No. 2 in Szymbark, standard inclinometer casings were damaged by cumulated displacements of over 150–180 mm at the depth of 11 m. Comparison of displacements, groundwater pore pressure, temperature and precipitation shows that the largest displacements occurred when the pore pressure lowered after high value periods in May–June 2006 (9.6–11 mm) and during stabilization works in Dec. 2006 (49 mm) and May–June 2010 (Figs. 7, 8). At landslide area No. 1, the largest displacements occurred in May–June 2006 (11.2 mm), March 2007 (15 mm) and April–May 2009 (54 mm).

The first in Poland, real-time monitoring system was installed in May 2010 at the landslide area No. 2, just before record precipitations of 100 mm/m² in 3-hour time. System was financed by EU funds. Three field stations were installed (Fig. 9). They included two 3D inclinometers (12 m and 16 m with 66 tilt sensors), one in-place inclinometer (14 m with 3 IP uniaxial sensors), automatic pore pressure and groundwater level transducer and automatic weather station. Continuous measurements have started and they will be conducted for the next two-year time (Figs. 10–12).
5 LANDSLIDE STABILIZATION

The basic landslide remediation questions were addressed to the effective mitigations methods needed to maintain stability. The monitoring results allowed interpretation of landslide triggering factors. It included landslide activity, groundwater level depth and pore pressure parameters. Different remediation methods were used for every landslide. At the landslide area 1 stabilization project included gabion wall length of 200 m along the river. Gabions were founded on 300 micropiles foundation to the depth of 6 m. In central part above the road another retaining wall, consist of 60 micropiles to the depth of 11 m were installed. Micropiles, diameter of 300 mm, were designed in three rows at the length of 30 m. First row was inclined by 30 degree and two other were vertical. Upper parts of micropiles were connected in reinforced concrete construction. Drainage systems, total length of 300 m, lead down groundwater to the river and to a new culvert under the road. Large displacements of 60 mm were observed during stabilization works. However, after remediation they were reduced to +/-5 mm/36 months. The pore pressure value of 45 kPa before remediation was lowered to 30 kPa after it. Groundwater level depths were lowered from 1.3–1.8 m to 2–2.2 m. At landslide area No. 2 several options of stabilization were considered including no any improvement of stability as a preferable to the status quo. Finally, marginal stabilization at front part of the landslide was decided. It included gabion walls along the river, surface and internal drainage system, two new culverts under the road, horizontal drainage boreholes with filters, anchors 20 m long to the bedrock, and Geobrugg high tensile wire mesh (Fig. 13). The pore pressure values after counteraction dropped in both areas (to 30 kPa at Sekowa and 15–50 kPa at Szymbark). At Szymbark, displacements of 13–20 mm were still observed after remediation works especially after record precipitation in May–June 2010 that had caused food in adjacent regions.

5.1 Slope stability analysis

The slope instability was activated by flysch sediments nature, slope geometry, river erosion factors.
and changes in groundwater regime. These processes increased the disturbing weight, decreased the effective stresses and finally decreased the shear strength in the slopes. In some cases, landslides were activated by external factors, such as undercutting of their lower parts during the road construction together with the land exclusion from agricultural production. Slope stability calculations based on assumption of rotational failure by LEM Janbu, and Bishop methods were compared with results of methods of arbitrary sliding mechanism.

The applied approach allowed analyzing influence of high pore water pressure on the shear strength reduction. Proposed counteraction methods were tested using classical LEM methods, based on relative factor of safety. At Sekowa landslide, values of relative factor of safety Fs, calculated by Bishop method, were slightly above Fs = 1.13 before stabilization and Fs = 1.58 after it (Figs. 14 and 15). On both landslides, after remediation the most preferable rotational slip surfaces were localized outside public roads. Expected displacements were calculated also by FEM methods using SOILVISION codes and linear elastic models. Monitoring data were included in boundary conditions definitions. The exemplar results of stress analysis and expected displacements on Sekowa landslide are presented on Figures 16 and 17. The final FEM mesh indicated that the landslide was active and dangerous for the public road.

5.2 Mitigation measures control

Monitoring measurements detected that remediation methods lowered landslide risk and safeguarded roads. However, in some cases displacements during and after counteraction works were recorded. The values of observed movements before counteraction works varied from 26 to 138 mm. In some cases they increased to over 60 mm during remediation, but after they usually were lowered to +/- few mm (Fig. 18). On landslide area No. 2, where partial stabilization was decided displacements were up to 10 mm, but after record precipitations it increased in some unstabilized places up to 18 mm, what was detected by real-time early warning system.
The conclusions from monitoring and stabilization control are presented in Tables 1 and 2.

**6 CONCLUSIONS**

The results of research indicated that selected monitoring and modeling methods helped in control and preparation of counteraction projects. Proposed stabilization methods were fully effective on landslide area No. 1. In two years time there after remediation displacements only of several millimeters were observed. However, ground movements of over 60 mm were recorded during remediation. That was caused by weather conditions characterized by high autumn precipitation and undercutting of the lower part of the landslide. At large and dangerous landslide area No. 2 only partial stabilization was decided. Displacements during 48 months period of time had very different magnitudes from 13 mm to over 180 mm. Slip surface depths varied from 2 m to 16 m, mainly due to the flysch sediments nature. The remediation works limited displacement ranges. However, it is to short time to fully prove effectiveness of the stabilization works. The results of the study reveal that large flysch landslides were difficult for counteraction and remediation methods should be considered very carefully. Time of stabilization works should be planned to avoid heavy precipitations periods. Remediation of active Carpathian landslides were not an easy task and required good quality geological data. Types of instrumentation and minimal time of monitoring should be chosen carefully. Research methods have to be selected with respect to landslide type, size and activity. However, caution should be paid in monitoring results interpretation.

**REFERENCES**


