Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-2-7

Near-surface geophysical scanning for exemplar landslide projects in Poland

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ABSTRACT: The paper present usage of shallow geophysics in landslide investigations. The GPR method carefully scaled by others geotechnical engineering tests were useful for recognition of landslides and its internal structure to the depths from few to even 18 m. Totally over 27 km of scanning was performed on 24 landslides. The investigations were conducted for protection of public roads and infrastructure. The depth of scanning was depended on types of equipment used and local soil conditions. The best scanning results were obtained with 100 MHz antennas. Caution was paid to proper calibration of GPR results because in this method detected stratification is interpretation result. Therefore the GPR was carefully calibrated by the boreholes. In the paper conclusion from usage of this method is presented. Near-surface geophysical scanning was very effective, low cost and fast method of investigations. However, due to same limitations, caution should be paid in geotechnical interpretation of the results, its careful calibration by monitoring measurements.

1 INTRODUCTION

Landslides became a serious problem in southern Poland. Its density is there the highest in the country. According to the newest data of Polish Geological Survey (PGI), 60 000 of landslides were registered in Polish Carpathians (Chowaniec et al. 2015). High economic losses, damaged roads together with different types of infrastructure and private buildings are reported in Poland every year. In May-June 2010 after the flood its costs reached 2.9 bln EUR. (Chowaniec et al. 2015). Author of the paper had opportunity to perform same of these landslide investigations and counteraction projects for public roads and local authorities. These works financed by Polish State budget and loan from the European Investment Bank were conducted in years 2006-2015. The main objective of the research was to define possibilities and methods of landslide remediation. Landslides built from soil-rock type flysch deposits, were difficult for in-situ and laboratory tests. Complex and effective techniques of investigations were required. Some types of in-situ tests proper for soils were not always useful. The site investigations required core impregnated boreholes. These were very important but time consuming, costly not always answering all the geotechnical questions. The near-surface geophysical and geotechnical methods delivered valuable data for slope stability analysis. The Ground Penetration Radar scanning were found to be a one of very useful methods in conjunction with other in-situ and laboratory geotechnical tests. It was very effective, low cost and fast method of investigations. However, it had also same limitations connected with forest areas, powers supply lines and specific soil conditions. Caution was paid in geotechnical interpretation of the GPR results, its careful calibration by boreholes and in-situ monitoring.

2 LANDSLIDE CHARACTERIZATION

Investigated 24 landslides were localized in three regions located in Beskid Niski Mts. (No 1-20), Beskid Sredni Mts. (No 21-23) and Carpathian Foreland (No 24). Exemplar landslides are presented on the map (Fig. 1). List of investigated landslides and its parameters are presented in Table 1.

Figure 1. Investigated landslide localization

Table 1. Landslide parameters and GPR scanning length

Location No	Inclin. deg	Volume mln m^3	Depth m	Type *	GPR length m
1-6. Szymbark	6-18	2.2	1.3-15	R	2170
7-8. Szymbark	6-12	0.5	6-13	R	940
9-11. Bystra	6-9	2.5	2.7-5	R	2240
12-14. Bystra	9-12	1.3	2.5-9	R	2400
15. Szalowa	6-12	10.8	9-16	R	990
16. Sekowa	6-12	0.4	2.7-5.1	R	1257
17. Wapienne	6-9	1.9	2.5-9	R	6155
18. Strzeszyn	9-16	0.3	1.4-10	R	460
19. Sitnica	6-9	0.1	1.2-5	R	360
20-21.Tarnawa	6-12	0.9	10-15	N 2006/R	2795
22. Sitarzowka	6-19	1.6	10-12	N 2010	3520
23. Zarebki	8-10	1.8	2-13	R	1845
24. Strachocina	5-18	0.6	10-12	R	2130

* R – reactivated N-new formed.

Investigated landslides occurred at specific mountain locations under certain morphology and geotechnical engineering conditions. Its volume varied from 0.1-2.2 mln m^3. Mass movements were localized on mountain slopes dip from 5^o to 19^o. Landslide depths varied 1.0 m to 16 m. The most active zones were usually situated at landslide tongues. Colluviums were built from shale's and sandstones. Flysch layers involved in slides represent Neogene marine clastic sedimentation folded during Alpine Orogenesis. Intensive erosion in river valleys and high groundwater level, during the Holocene era, characterized by thick weathering zones activated huge numbers of landslides (Raczkowski 2002). Deposits were built from many thin layers of flysch type marine sandstones and claystones. Colluviums represented soil-rock type of landslides (Cruden 1996). Saturated claystones in colluviums had mechanical parameters as a weak cohesive soils. Sandstones interlayer's allowed water infiltration. Failure occurred as a combination of different mechanism and was depend on hydrology, geology and topography factors. Low friction angle, cohesion high moisture and variation of pore pressure values often influencing the slope stability (Rybar at al. 2002). On slopes built of clayey deposits failure developed over periods of months as a creep process. Clayey soils with very low geotechnical parameters were often interbeded by medium stiff to stiff rocks such as claystones or sandstones with different degree of digenesis. The groundwater levels were 0.5-1.5 m bellow the natural terrain level. Groundwater regime conditions had a dominant influence on landslide activation. Intensive rainfalls together with floods, erosion in river valleys, snow melting and pore pressure fluctuations inside soil layers were enhancing the sliding activity (Bednarczyk 2004-2015). The previous studies (Starkel 2011) shows that the activity of the landslides were increasing after long-term precipitations in 20-40 days, which exceeds the sum of monthly rainfalls of 400-550 mm. Especially, if the rain in a few days exceed 250 mm. Three of investigated landslides No 20, 22, 23 were new formed others twenty one landslides were reactivated in wet periods many times.

3 GEOPHYSICAL SCANNING PRINCIPLES

Landslide slopes internal stratification and colluvium depths were detected using 2D GPR RAMAC scanning. It allowed more accurate measurements of changes of colluviums and bedrock layers dielectric properties between the boreholes. The GPR scanning is based on the Electromagnetic Reflection Theory (EMR). In this method pulses of ultra high electromagnetic frequency waves were transmitted down from transmitter (T) into the landslide body through antennas (Burton 2009). Part of the GPR waves were reflected from flysch sediments layers boundaries, while the rest of the waves passed through to the next layers or contacts between landslide colluviums and bedrock layers. Reflected signals returned and were received by the digital control unit – receiver (R) which registered the reflections against two-way travel time in nanoseconds and then amplified the signals. The data control unit allowed generation of radar energy coordinates together with displaying and recording the time of received reflections returns. The speed of the electromagnetic energy travelling trough the colluviums and bedrock layers was directly related to its dielectric properties. The lower the dielectric, the faster waves travel. More precisely, data logger registered returned reflections of the radar waves. The depths of GPR survey with100 MHz antennas were as deep as 10-18 meters depending on the local conditions. Scanning usually had not very high resolutions at depths below 15 m but allowed general landslide depth and internal structure recognition. Lower frequency 100 MHz unshielded antennas allowing relatively deeper penetration were chosen for the scanning of 23 landslides (Fig. 2).

Figure 2. GPR, 100 MHz unshielded antennas, landslide No 21

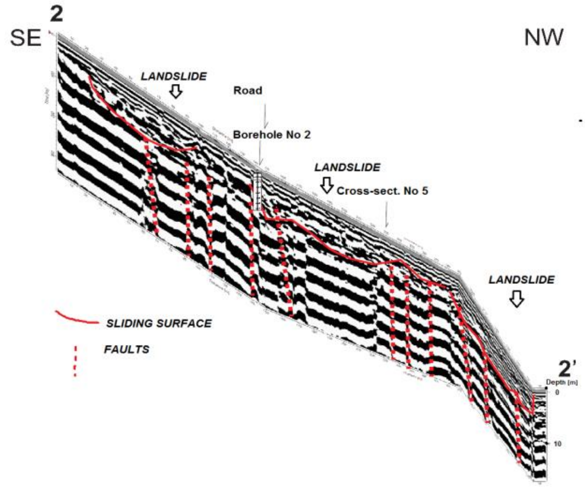

Figure 3. GPR longitudinal scanning profile, landslide No 23

Figure 4. GPR scanning close to the borehole, landslide No 23

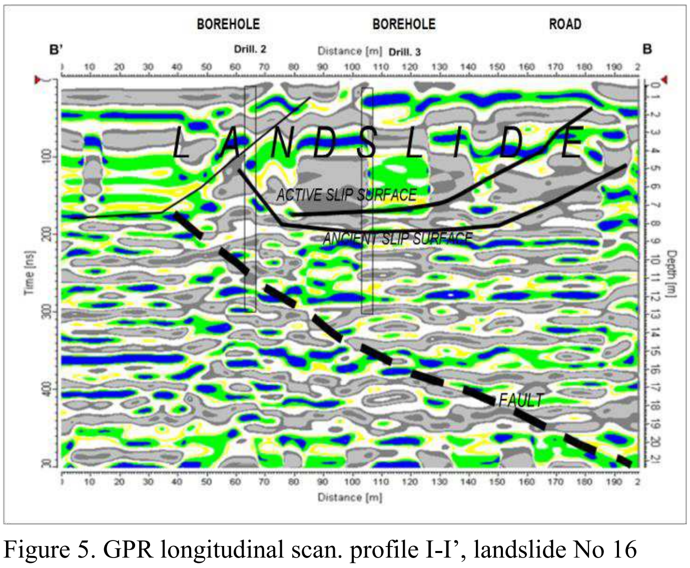

Figure 5. GPR longitudinal scan. profile I-I', landslide No 16

On one landslide No 23, 100 MHz shielded antennas were used (Figs. 3 & 4). For shallow parts of the landslides 3-5 m depth, better resolution had 250 MHz antennas. The post-processing and interpretation Ground Vision software was used for data interpretation. The output signal voltage peaks were plotted on the profile as different colour bands by the digital control unit (Fig 5).

The calibration of the depth scale was calculated after boreholes data: thickness of colluviums and type of bedrock below. It was necessary to include in the interpretation software dielectric parameters for different types of soils and rocks. For colluviums, built from clayey wet deposits, the attenuation (dBm^{-1}) as 6, relative permittivity range as 30 and relative permeability 30. For dry claystones, the attenuation (dBm^{-1}) as 10, relative permittivity range as 9 and relative permeability 9. For fine sandstone, the attenuation (dBm^{-1}) as 10, relative permittivity range as 5 and relative permeability 10 (see: Daniels 2004, Bednarczyk, Szynkiewicz 2008). The GPR raw data was processed in program. On scanning results interpreted colluviums depth, faults and folds were indicated. As a result of scanning, two dimensional images of the landslide colluviums, calibrated by boreholes were indicated on the cross-sections. Obtained results were corrected for slope morphology. On the cross-sections geographical directions, control points, boreholes, faults, colluviums depths were marked. The georadar cross-sections showed that colluviums had approximate depths of 1-15 m. The GPR profiling was essential for construction of geotechnical cross-sections. It allowed recognition of landslide colluviums and inclinations of layer and faults. For example, on landslide No 16, under the public road, the colluviums were recognized to depths of 2.8-4.5 m (Figs. 5-6). The total length of GPR profiles was over 27,2 km on 24 landslides. It varied from 360 m on landslide No 19 to 6150 m on landslide No 17 depending on the mass movements size and slope accessibility. Interpreted by GPR method and boreholes sandy and clayey layers was helpful in identification of water infiltration prone zones.

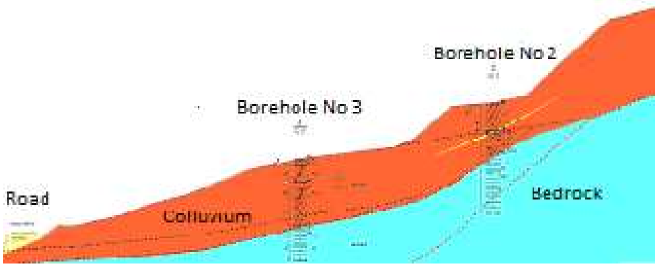

Figure 6. Geotechnical cross-section I-I', landslide No 16

4 CORRELATION WITH OTHER METHODS

4.1 *Calibration by core boreholes*

In GPR method the interpreted layers depths are affected by included in the software rocks and soils dielectric input parameters. Therefore the detailed profiles of new drilled boreholes were used for GPR surveys calibration and scaling. The oldest GPR profiles didn't included morphology.

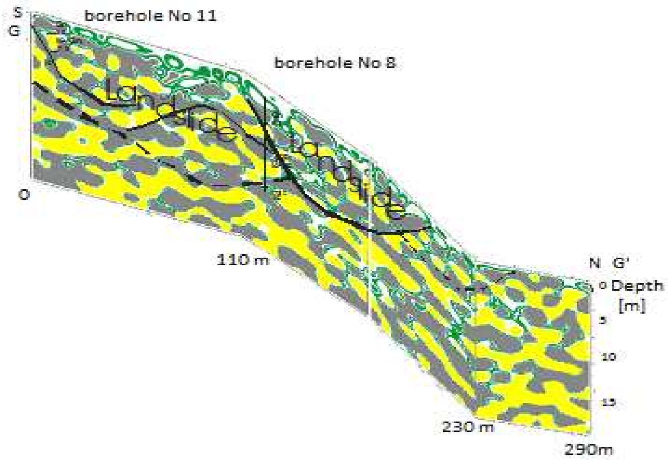

Figure 7. GPR longitudinal scanning profile, landslide No 18

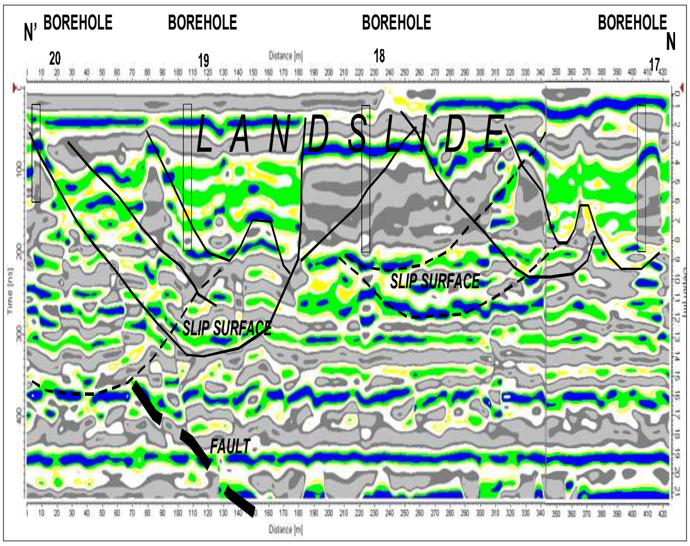

Figure 8. GPR transverse scanning profile, landslide No 15

More recent scanning profiles were corrected for slopes morphology (Fig. 7). In same cases faults inside the deeper parts of flysch sediments were detected (Fig. 8). The GPR method helped in identification of slope internal stratification in areas where no any other geological data were available. In many cases it was also valuable for initial identification of slip surfaces depths. In the most cases on the scanning results colluviums were characterized by "mixed" not regular areas. These interpretation were compared with detailed geotechnical description of core from the boreholes. In same cases it was possible to recognize slip surfaces in the core. However, in same cases it required complex comparison of different geological data including reference monitoring results. In order to facilitate the interpretation the GPR surveys were located between the previously drilled boreholes located 50-200 m one from the other. The obtained data were used for construction of geotechnical cross-sections. The georadar scanning interpretation was always based on few longitudinal and transverse cross-sections. On every landslide, depending on its size 6-10 longitudinal and transverse GPR survey were performed. To eliminate the fault scanning results in same cases the same scanning works were conducted twice, for example in W-E and E-W directions. The locations of the profiles in the field and on the map were compared to normalize scanning profiles to the real distances in areas of variable morphology. The longitudinal scanning were performed with slope inclination. These profiles were conducted from area above the main landslide scarp downhill. The crossing of longitudinal and transverse scans were indicated at the field and measured by GPS.

4.2 *Calibration by monitoring and in-situ tests*

The GPR surveys were also compared with the different types of in-situ measurements and tests. Inclinometer and piezometer monitoring was performed at 30 monitoring locations. The measurements started depending on the location 2006-2008 and are conducted till now (Fig.9).

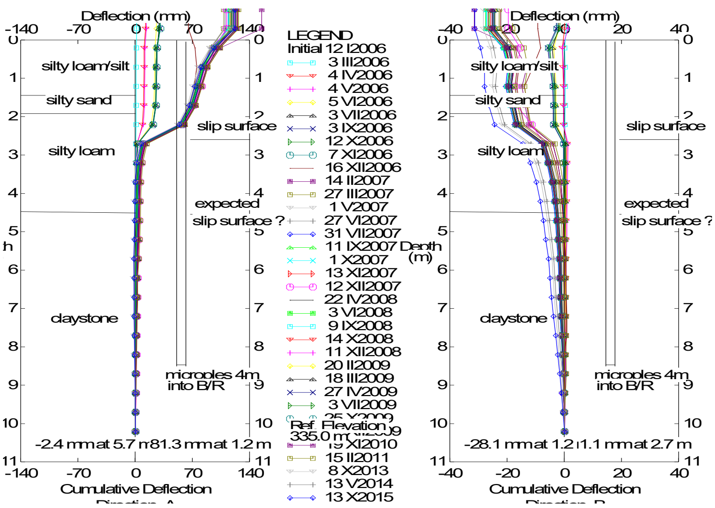

Figure 9. Inclinometer measurements, landslide No 16

The changes in ground profile were measured every 0.5 m by inserting an inclinometer probe into vertical ABS inclinometer tube and recording how far out of vertical the probe was at various depths within the tube (Dunnicliff 1993). It allowed detection of sliding surfaces depths and ground movement size with accuracy of 0.05 mm. Together with pneumatic and automatic VW pore pressure and groundwater level depths monitoring it delivered detailed data for comparison with GPR scanning results. The GPR survey on landslide No 16 detected that the main active slip surface under the public road was at depth of 2.4 m while another at the depth of 4.7 m below the natural terrain level (Fig. 9). Inclinometer measurements detected that second deeper surface was not active. The GPR results together with monitoring measurements were included in slope stability analysis for this landslide. It allowed to lower up to 30% the costs of remediation works using more effective design of micropiles lengths. At landslide No 17 (Fig. 8) the slip surfaces were detected at different depths of 2 m and between 7.2-9.0 m bellow the natural terrain level. The results of drillings and GPR profiling on this landslide indicated that few slip surfaces had complicated shapes. The monitoring measurements and slope stability analysis detected that remediation of this landslide will be not possible due to economical reasons. Exemplar instrumentation on landslide No 1-6 is presented on figure 10. Monitoring measurements on these landslides reported slip surface at the depth initially detected by GPR. The pore pressure values of 14-98 kPa were reported at the sliding surface. The values of pore pressures rose over 90 kPa after high precipitation in July 2008, May-June 2010 and May 2013. The groundwater level was usually very shallow and varied mainly between 0.8-1.5 m below the natural terrain level. The ground movements occurred at the different depths and they varied in magnitudes due to the flysch lithology nature. In same colluviums built of clayey soils in-situ vane tests were performed in boreholes every 1 m depth. For example on landslide No 20 the values of shear strength in vane tests reported in stiff clays of 0.67 MPa was decreasing to 0.037 MPa at the slip surface depth.

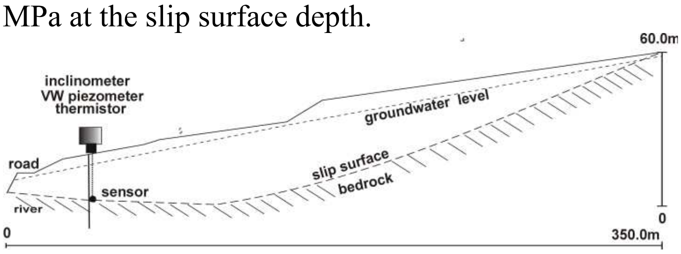

Figure 10. Localization of monitoring landslide No 6

4.3 *Correlation with the laboratory results*

The recognition of geotechnical engineering conditions by laboratory tests allowed better identification of landslide zones. Geotechnical laboratory tests included index tests (grain size, moisture content, liquid and plastic limits, unit weight, and soil particles unit weight), direct shear tests and incrementally loaded (IL) odometer tests. Flysch soils used for these tests represented silty loams, silty clays to claystones (rock). Soils inside the sliding surface usually had very high moisture content 20-36%, liquidity index up to 0.5, cohesion from 6.5 kPa, angle of shearing resistance 9-11 degree. Very high values of soil moisture and plasticity index up to 50% were usually recognized at the sliding surface depths. Soils were characterized also by high 2-10% content of organic (bituminous) material. Results of oedometer consolidation tests detected high compressibility of clayey soils at the slip surface. Index laboratory tests results indicated that on landslide No 1-6 sliding surface depth of 10.5 m detected by monitoring measurements and GPR was in quite good relation with the highest values of moisture content and plasticity index of 15-40% (Fig. 11). At landslide No 16 similar conclusions for two slip surfaces at 2.8 m and 4.5 m depth were obtained (Fig. 12).

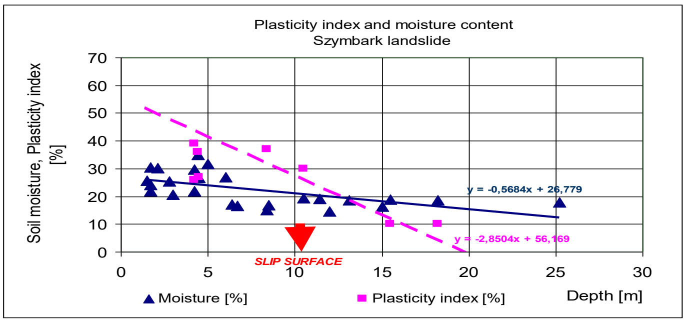

Figure 11. Plasticity index and moisture, landslide No 1-6

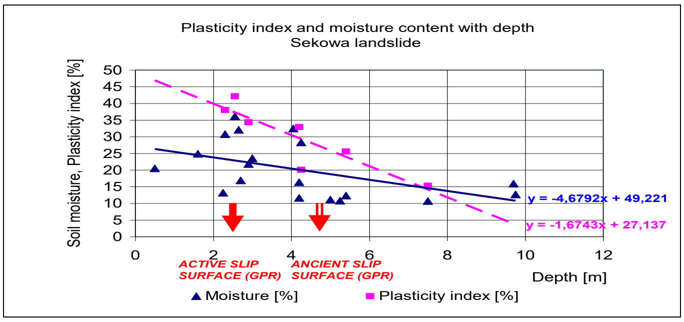

Figure 12. Plasticity index and moisture, landslide No 16.

4.4 *Implementation of GPR results in slope stability analysis and remediation works*

The GPR scanning results were the basis for construction of landslide geotechnical engineering cross-sections. Together with monitoring and laboratory results it delivered valuable data for slope stability LEM and FEM analysis. For example on landslide No 16, values of relative factor of safety F_s, calculated by Bishop LEM method, were slightly above Fs=1.13 before stabilization and 1.58 after it. Using FEM methods and linear elastic model it was predicted that expected displacements of 120 mm and could be dangerous for the public road. Proposed counteraction method was checked by LEM method, included 60 piles length of 11 m, gabions retaining walls on 300 micropiles foundation length of 6 m, culvert and surface draining system length of 300 m. These works safeguarded the public road. This was confirmed by the monitoring measurements conducted up to 9 years after remediation (Fig. 9). After the remediation displacements were reduced to +/-5 mm. The pore pressure value of 45 kPa before remediation was lowered to 30 kPa after it. Groundwater level depths were also lowered from 1.3-1.8 m to 2-2.2 m.

5 CONCLUSIONS

The Ground Penetration Radar method carefully calibrated by boreholes and others methods was quick and inexpensive way of landslide investigations. Together with other geotechnical engineering methods it made possible recognition of mass movement's areas. It allowed delivery of detailed site investigation reports to the depth of 5-18 m. One of the main advantages of GPR was its efficiency. It allows recognition of geological stratification and tectonic structures. The results indicated that GPR scanning with proper correlation by other geotechnical engineering methods could help in recognition of internal landslide geology and was used for slope stability calculations. Interpretation and calibration of GPR results is very important. In same specific soil conditions and due to others external factors this method could not deliver high quality data. At any new landslide site it is important to know what natural undisturbed slope geological stratification looks like. Therefore scanning should be performed also in the nearest to the landslide border areas. Then it is easier to identify colluviums layers which are not ordinary for natural slope stratification and often characterized by "mixed" structures. The most crucial practice is careful interpretation and calibration by other methods including core drillings to gaining experience in each investigated landslide area. Landslide monitoring helped in precise mass movement's prediction for civil engineering landslide remediation projects. One of the main advantages of the GPR method was its ability of data collection. On some landslides over 2 km of GPR scanning was performed in one day time. Limitations were connected mainly with the penetration depth and resolution, which depended on the ground conditions. On some landslides due to the electric power supply lines or in the forest areas some difficulties were also observed. The obtained results indicated that with proper interpretation and correlation by other methods GPR could detect colluviums and bedrock depth. This method also allows recognizing many internal geological structures together with faults and folds. Calibrated by core drillings, inclinometer measurements, pore pressure monitoring and laboratory tests the GPR method allowed indication of failure zones between the boreholes and was used for slope stability calculations for landslide stabilization projects. However, not every research method is suitable for every landslide type. Caution should be paid in type of the equipment and the antennas used for the scanning, correct interpretation of the GPR results. Very important is careful calibration of GPR results by the boreholes and in-situ monitoring results.

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