Polish Geological Institute Special Papers, 15 (2004): 19–28
Proceedings of the Conference "Risks caused by the geodynamic phenomena in Europe"

LANDSLIDE INVESTIGATIONS BY STATIC SOUNDING WITH PORE PRESSURE MEASUREMENTS (CPTU), GROUND PENETRATION RADAR TECHNIQUES (GPR) AND OTHER CHOSEN METHODS

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Abstract. The main subject of the paper is the practical application of the existing geotechnical and geo-environmental engineering techniques for the purpose of ground characterisation in landslide areas. Special interest is given to the landslide issues in difficult geotechnical and geological conditions and evaluation of soil design parameters by *in situ* tests. In the paper, usage of CPTU connected with reference laboratory tests, GPR and other monitoring techniques in landslide and potential landslide areas are presented. Research was based on investigations in Polish opencast mines, Carpathian flysch sediments and Norwegian clays. Presented data are based on the exemplar landslide projects. The background of presented CPTU studies is slope stability evaluations of the Polish opencast brown coal mines undertaken during a research stay at the Norwegian University of Science and Technology (NTNU) with support of the Norwegian Research Council and NATO Advanced Fellowship Programme. Landslide investigations by GPR and GPS technique were performed on Carpathian flysch sediments in Lachowice and Wapienne (Poland).

Key words: landslide investigations, geotechnical *in situ* and laboratory tests, CPTU, GPR, GPS.

Abstrakt. Głównym tematem artykułu jest praktyczne zastosowanie badań geotechnicznych i geo-środowiskowych do charakteryzacji rejonów osuwiskowych. Specjalną uwagę zwrócono na osuwiska o skomplikowanych parametrach geologicznych i geotechnicznych oraz na sposoby określania ich parametrów za pomocą testów *in situ*. Omówiono zastosowanie CPTU w połączeniu z laboratoryjnymi badaniami parametrów wytrzymałościowych gruntów, profilowaniem georadarowym i innymi nowoczesnymi technikami, które mogą być użyte do charakteryzacji rejonów osuwiskowych. Zaprezentowano projekty wykonane w polskich kopalniach odkrywkowych, we fliszowych osadach karpackich oraz w norweskich iłach. Dane te pochodzą z przykładowych rejonów osuwiskowych. Przyczyną wykonywania zaprezentowanych badań CPTU były problemy stateczności występujące w polskich kopalniach odkrywkowych, które analizowano podczas stypendium w Instytucie Geotechniki Uniwersytetu Trøndheim (Norwegian University of Science and Technology-NTNU) finansowanym przez Norwegian Research Council i administrację programu stypendialnego NATO (NATO Advanced Fellowship Programme). Badania osuwisk za pomocą georadaru (GPR) i GPS-u wykonano w osadach fliszu karpackiego w Polsce w miejscowościach Lachowice i Wapienne.

Słowa kluczowe: badanie osuwisk, testy geotechniczne, testy *in situ*, testy laboratoryjne, sondowania statyczne CPTU, badania georadarowe, pomiary GPS.

INTRODUCTION

Economic damages due to landslide movements in last years became a significant problem in many places in Europe. As results of extreme precipitation which are decreasing the rock strength many new landslides have been developed. One of the main problems in landslide phenomena prediction is poor knowledge of soil strength parameters as well as a not good enough geological characteristics. Usage of *in situ* tests and reference laboratory testing together with different monitoring techniques in every case should be adequate to the type of the landslide. Some of these techniques were used in the Polish open-cast mines. It includes groundwater monitoring (groundwater level, pore water pressure measurements),

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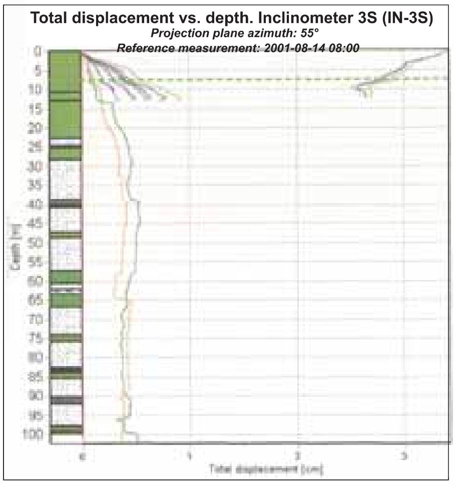

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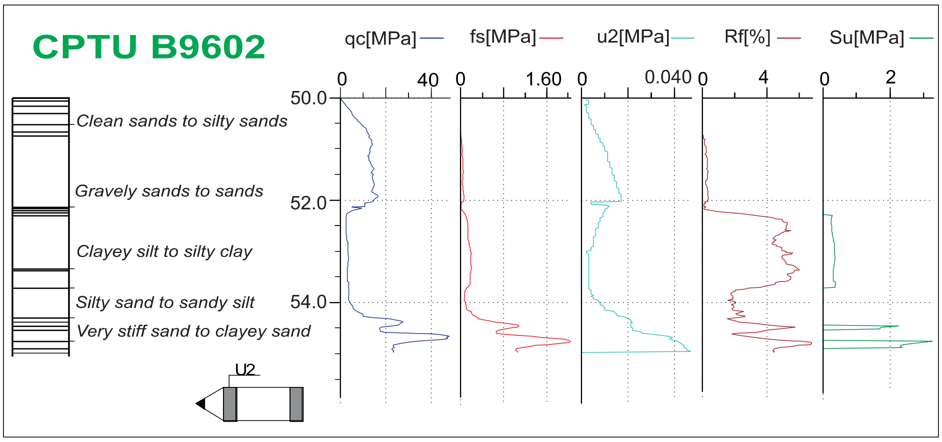


Fig. 1. Landslide investigations in Bełchatów open-cast mine (Poland)

A — CPTU tests on landslide 20S, **B** — inclinometer measurements, **C** — CPTU profile used for correlation with laboratory tests: qc [MPa], sleeve friction-fs[MPa], pore pressure-u2[MPa], friction ratio Rf [%], interpreted undrained shear strength Su[MPa] and soil type

ground movement observations (inclinometer and variation measurements), geotechnical laboratory tests (index, oedometer and triaxial tests), field *in situ* tests (CPT, CPTU) and slope stability analysis. Ground movement monitoring, based on measurements of surface and subterranean displacements together with pore pressure monitoring, *in situ* and laboratory tests results were the base of geotechnical data bases creation. In open-cast mines landslides are one of the main threats for exploitation effectiveness and safety. In the largest Polish open-cast mine in Bełchatów, due to exploitation needs, *in situ* tests with pore pressure measurements were performed up to 200 m below the terrain level (Bednarczyk, 1997) (Fig. 1). High landslide risk is also observed on mines slopes (Fig. 2B). In Turów Open-cast Mine high landslide risk was reported on external waste embankments (Fig. 2A). The largest reported landslide there reached volume up to 6 mln m^3.

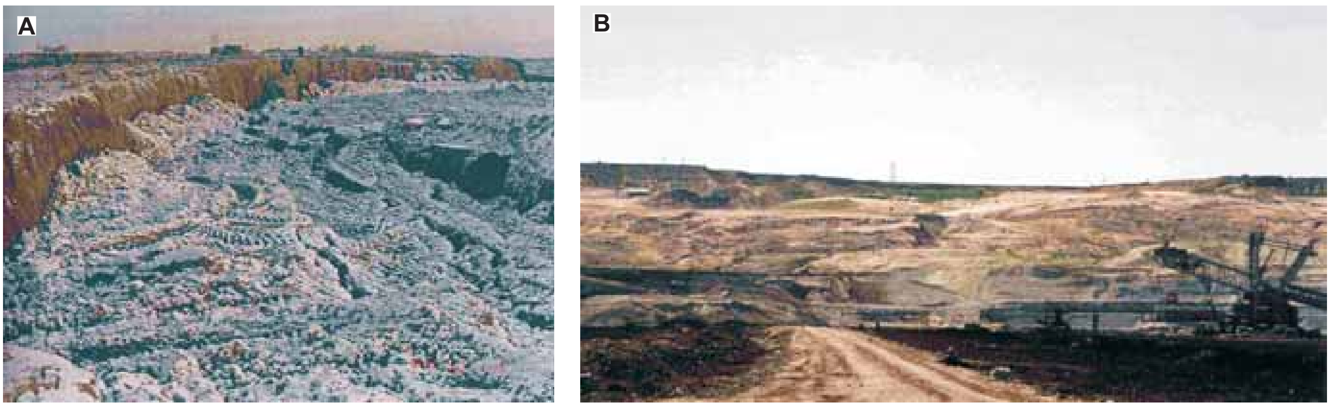


Fig. 2. Landslides in Polish open-cast mines

A — landslide on external embankment of Turow mine — 6 mln m^3 (southwest Poland); **B** — south slope of Bełchatów mine 2 mln m^3 (central Poland)

Fig. 3. Landslide in Stjordal, Norway (2002) near the E-6 road Trøndheim–Narvik

In Norway, different types of landslide monitoring measurements including CPTU are in use as methods for landslide investigations in sensitive clays (Sandven, Watn, 1997). For example, in Røesgrenda, international Japanese-Norwegian consortium conducted landslide monitoring including movements control, meteorological station control, conventional soundings, undisturbed soil sampling, *in situ* tests such as CPTU, miniature CPTU, total sounding, piezometer monitoring, melt water gauge measurements, tensiometers, extensometers, soil temperature sensors, geophysical survey using electrical methods, oedometer and triaxial tests. Sensitive clays (quick clays) are considered as a national hazard in Norway because they are very soft and liquefy easily when disturbed. A number of landslides and deaths have been attributed to them not only in Norway but also in Canada and Sweden. Landslides in quick clays exhibit a number of enigmatic features: high values of factor of safety at failure, sudden development without warning, ability to transport afloat large flakes of dry crust over long distances, extremely rapid movement. A possible mechanism of landslides in quick clays suggests that they are the result of the action of a suspension force and caused by friction between sinking solid particles and immovable water. Quick clays were disposed in sea water where ions played dominant role in blinding their particles during sedimentation. Due to different geological processes these ions were removed. Increase of groundwater level or human activity could very easily involve these clays in landslides and turn to liquid soil mass. In Norway every year 1–2 people are killed by the slides according to the statistics. The largest reported landslide in Trøndheim region reached volume 55 mln m^3, length over 6,000 m, and killed 111 people (Follodalen, Verdal, Nord-Trøndelag, 1893). In the city of Trøndheim (out of 140,000) forty thousands inhabitants live on the quick clays. On figure 3 some examples of Norwegian landslides in Trøndheim region are presented. Very dangerous are also coastline slides (Fig. 4) and large submarine slides which involve the costal areas.

During research stay at the Geotechnical Division at the Norwegian University of Science and Technology, methods used for Polish *in situ* test interpretation were compared with Norwegian interpretation methods (Bednarczyk, Sandven, 2004). Special interest was paid to CPTU test interpretation. This type of *in situ* tests is very popular in Norway. In Poland, CPTU tests are performed in open-cast mines, post floating tailings near the city of Lubin, metro in Warsaw and some other places.

Fig. 4. Landslides SW from Trøndheim (2003) and Røesgrenda (1998)

PIEZOCONE TEST INTERPRETATIONS

Piezocone tests in Polish open-cast mines are performed since early 1990s. They were localised in landslide and potential landslide areas. At the beginning, tests with mechanical cone (CPT) were used especially for the embankments. Piezocone with electrical cone enables measurements of cone resistance qc [MPa], sleeve friction-fs[MPa] and generated pore pressure at different filter locations (Fig. 5). In tests performed in Polish opencast mines, pore pressure just behind the cone u2[MPa] was measured. Tests results are used for soil type interpretation and with reference laboratory tests are very effective and inexpensive methods of soil investigations comparing with traditional core borings and laboratory tests on large numbers of specimens. This type of tests allows predicting soil type and soil design parameters. Using this method of investigation, it is possible to penetrate 100–150 m per day in not heavily cemented or consolidated soils.

Piezocone tests are widely in use in Norway. CPT test were carried there since early 1950s for offshore foundation design. In this country, first cone penetration tests with pore pressure measurements — CPTU was made. At the Geotechnical division NTNU Trøndheim, special method and software for CPTU test interpretation have been developed. Using this method soil design parameters characterisation could be obtain by CPTU tests correlation with reference laboratory results. This type of correlation was performed in presented project for Polish and Norwegian cohesive soils with high landslide risk (Bednarczyk, Sandven, 2004). Laboratory test program conducted at the NTNU included general index tests (density relations, water content, Attenberg limits, classification shear strength, grain size distribution), strength testing in high capacity triaxial apparatus (total and effective shear strength parameters, stress-strain relationships and pore pressure parameters), deformation testing in IL and CRS oedometer cells for determination of deformation and consolidation characteristic (deformation moduli, preconsolidation stress, overconsolidation ratio). Interpreted CPTU tests were compared to laboratory test results relating various selected soil parameters. Interpretations of CPTU tests made for selected sites in Poland and in Norway showed that reasonably good comparison between field and laboratory test data could be obtained by using NTNU interpretation method. It allowed soil type predictions from CPTU in addition to mechanical parameters of the soil, such as shear strength, compression moduli, and preconsolidation stress. To compare soil design parameters, obtained from piezocone and laboratory tests, two research sites in Poland and in Norway were selected. The Norwegian research site was situated in Stjørdal, close to Trøndheim. Norwegian CPTU tests were made in moderately overconsolidated, non-sensitive, low plastic Glava clays. In Poland, piezocone tests were performed 50 m below the surface, in the tertiary clays from south slope of the Bełchatów open-cast mine (central part of Poland, 44 km south of the city of Łódź). The clays were situated over upper calcareous marl detritus, north of the tectonic border of Kleszczów Rift Valley. This place was located above the landslide 20S founded in clay deposits. Soil in this part of the mine could be described as a low plasticity (CL), clays, silty clays and clayey sands. The clay minerals content in clays ranges from 35–40% (<0.002 mm). Interpretation of CPTU recordings was made using special NTNU software and Microsoft Excel spreadsheet software. Selected CPTU profiles from Norway and Poland were processed and prepared for further interpretation.

Laboratory test programme for Polish soils designs parameter characterisation included 20 sets of index tests, 12 triaxial, 24 oedometer tests and 10 uniaxial compression tests.

For presentation of the study results, some comparisons of the same choosen soil design parameters received from CPTU tests and reference laboratory tests are presented bellow.

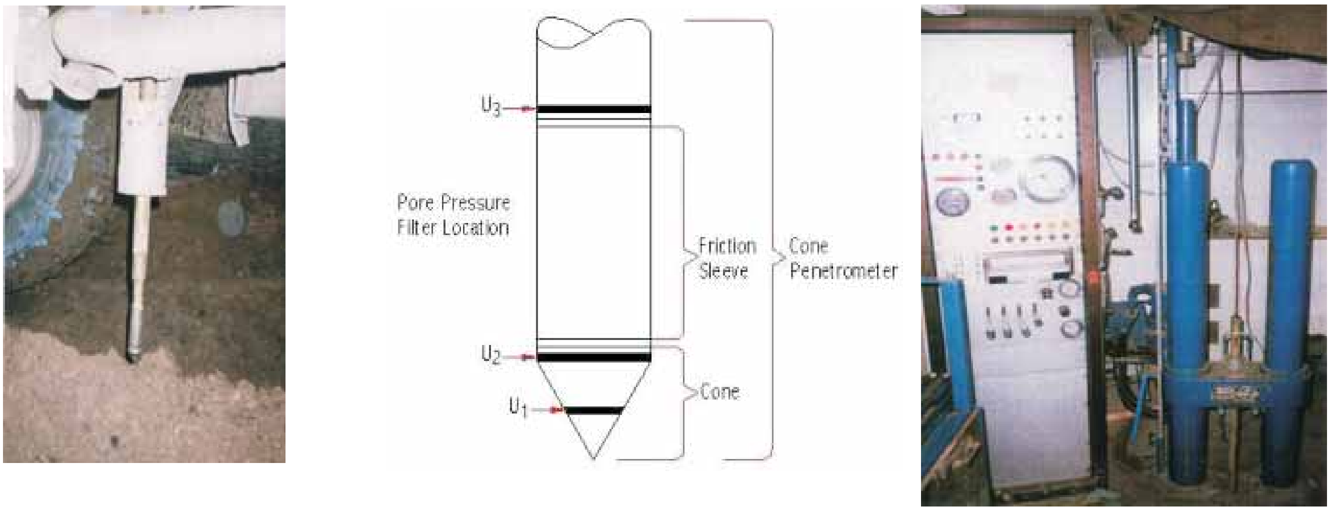


Fig. 5. Piezocone test equipments (A P Van den Berg penetrometer Hysson 200)

Undrained shear strength S_u from CPTU tests was calculated using equation

$$S_u = \frac{q_c - \sigma_{vo}}{N_c}$$

where:
q_c — cone resistance [kPa]
σ_{vo} — initial *in situ* total stress (vertical) [kPa]
N_c — theoretical bearing capacity factor (corresponds approx. to values 6–10).

Undrained shear strength S_u from the laboratory tests was calculated using three different methods:

1. Equation

$$S_u = \alpha_c (\sigma_c' + c)$$

where:
α_c — factor dependent of tan ϕ (and could be establish using interpretation diagram, $\alpha_c \approx 0.22$–0.28)
σ_c’ — preconsolidation pressure [kPa]
c — cohesion [kPa].

2. The peak shear stress τ_{max} from consolidated triaxial test (to maximum previous stress level).
3. Uniaxial compression tests.

On Figure 6, undrained shear stress S_u for Polish and Norwegian clays interpreted from CPTU data for two different values of Nc (Nc = 6, Nc = 9) is plotted against depth and compared with reference laboratory values.

Preconsolidation pressure from laboratory tests was predict using 24 oedometer tests (4 IL tests — 11steps every 24h, 8 IL tests — 9 steps every 1h, 12 CRS tests) and three different interpretation methods (Moduls M, Janbu — Creep resistance, Taylor coefficient of consolidation method). It varied in most cases from 400 to 500 kPa. Using Taylor method preconsolidation pressure had values 500–750 kPa. Clays were overconsolidated, OCR was between 6 and 8.

Comparison of preconsolidation pressure interpretation (Fig. 7) and compression moduli in overconsolidated stress range M_i (Fig. 8) from laboratory tests have a good agreement with CPTU. Only values of friction angle (Fig. 9) received from CPTU were significantly lower compared with the laboratory test results.

For prediction of friction angle and cohesion, triaxial CID and CIU tests were performed. Five isotropically consolidated drained tests (CID) and seven undrained tests (CIU) with pore pressure measurements were carried out on 100 × 54.30 mm cylindrical specimens trimmed from the 75 mm diameter samples. Specimens of the same type of the soil were tested at different cell pressures, isotropically consolidated and saturated in steps to 300, 400, 500, 600 kPa. In undrained tests, high backpressure (70–360 kPa) was used for saturation of the specimen. Each step of consolidation was continued until no significant change in pore water volume was observed. An obtained value of friction angle and cohesion in undrained tests for clays was: ϕ = 21.3°, c = 8.56 kPa (in drained tests values of friction angle varied from 8.1° for clays, to 25.1° for sandy clays).

Interpretations of CPTU tests made for the selected area in Poland and Norway showed that reasonably good correlations between field and laboratory tests results could be obtained (Table 1).

Nearly all values of mechanical parameters obtained directly from the CPTU results for Polish soils were two times higher compared with the Norwegian soils. Only interpreted friction angle was lower, mainly due to the choice of input parameters. Parameters obtained from CPTU (with some remarks) gave approximately the same results as laboratory tests (good prediction or just small difference). Polish clays were taken from a very different environment compared with the Norwegian clays. Tests in Poland were made 50 m below the ground level in the Bełchatów open-cast mine. Soil specimens were taken from this depth and were partly unsaturated due to the mine water pumping system. Testing of partly satu-

Table 1

Comparison of soil design parameters prediction from CPTU and laboratory tests for Polish and Norwegian clays

Parameter	Norwegian clays	Polish clays
Soil type	stiff clay, silt, good prediction	stiff clay to hard stiff soil, good prediction
Undrained shear strength	80–100 kPa good prediction	250–500 kPa good prediction
Preconsolidation pressure	200–300 a little lower values-CPTU	500–600 kPa good prediction in test b9602 in test b9603 lower values
Overconsolidation ratio	5–4 lower values – CPTU	6–8 good prediction
Compression moduli in overconsolidated range	7,000–8,000 kPa a little higher values – CPTU	20,000–30,000 kPa lower values – CPTU
tan ϕ	0.6–0.7 good prediction	0.2–0.4 lower values – CPTU

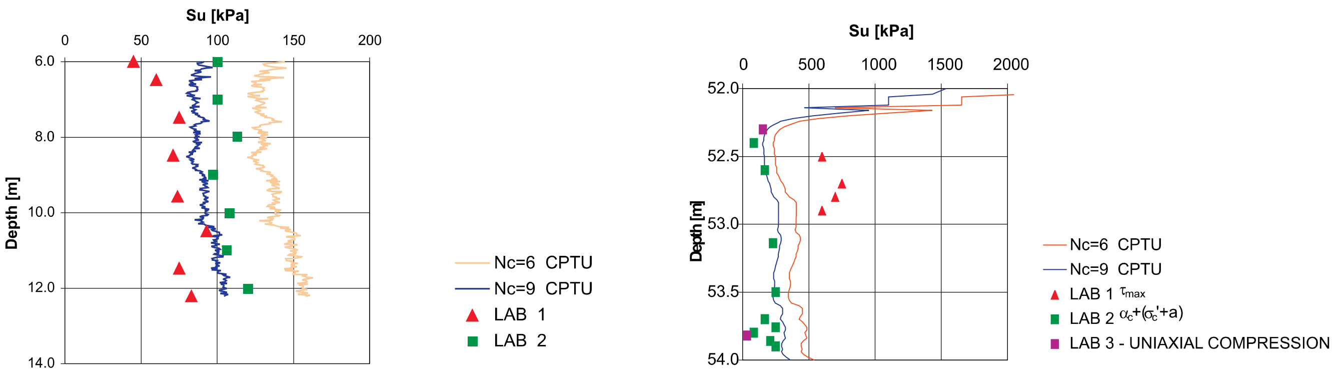


Fig. 6. Prediction of undrained shear strength for Polish and Norwegian clays using bearing capacity theory (N_c = 6–9).

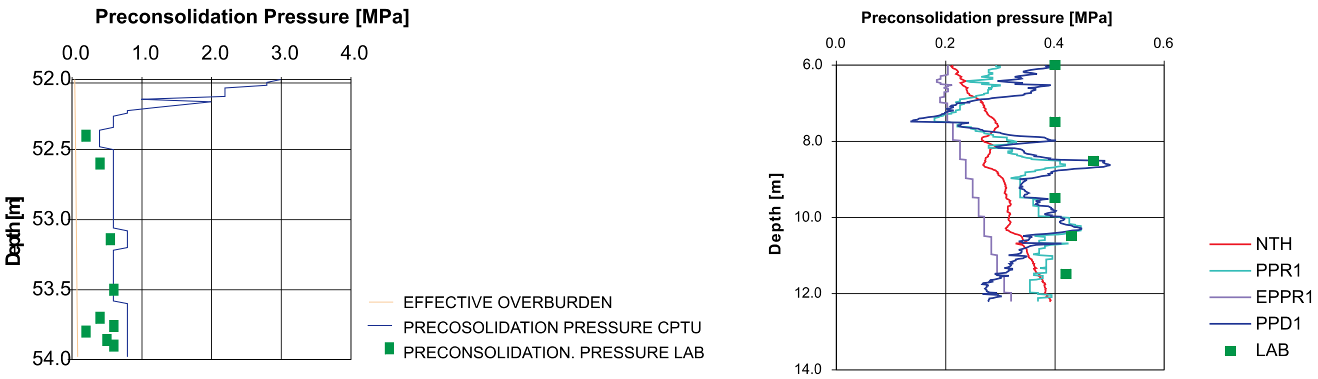


Fig. 7. Prediction of preconsolidation pressure for Polish and Norwegian clays from CPTU using different approaches and laboratory tests

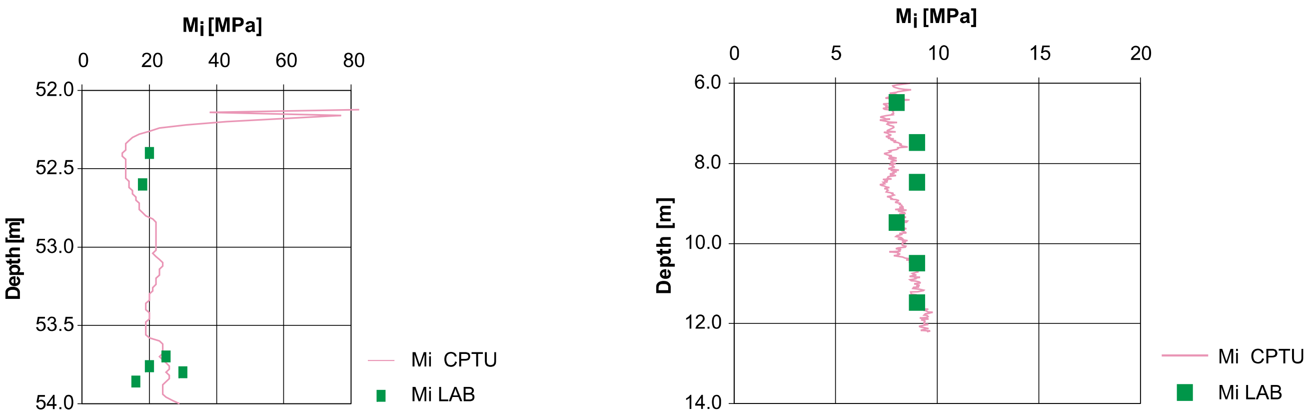
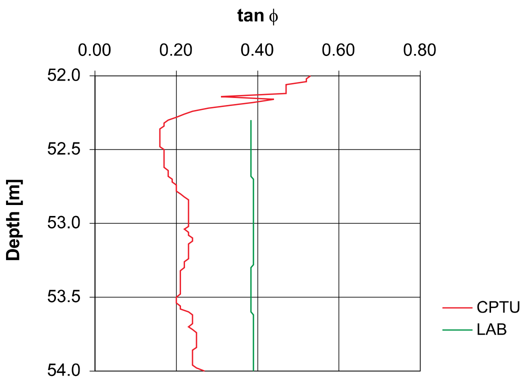


Fig. 8. Prediction of compression moduli in overconsolidated stress range for Polish and Norwegian clays from CPTU and laboratory tests



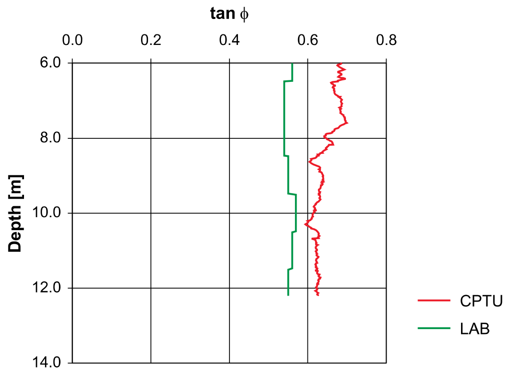


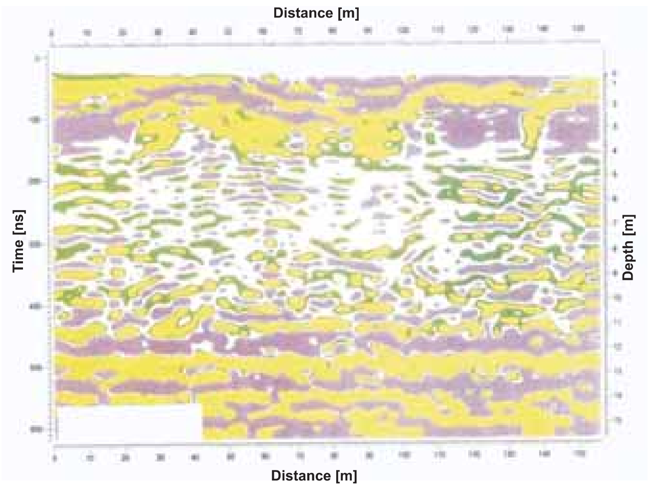
Fig. 9. Prediction of friction angle tangent for Polish and Norwegian clays from CPTU and laboratory tests

rated specimens, however, requires special type of triaxial apparatus with possibility of air pressure measurements inside the sample during shearing. Research works are in progress but fully acceptable testing procedure for this type of unsaturated soils has not yet been developed. This study based on the NTNU interpretation models shows that CPTU in combination with laboratory testing could be used to estimate soil parameters under the prevailing geotechnical conditions. Caution should, however, be shown since the interpretation methods are sensitive to the choice of input parameters.

GROUND PENETRATION RADAR AND GPS MEASUREMENTS

Ground penetration radar (GPR) scanning is a very quick and effective method for high-resolution images of subsurface conditions. The system receives reflections from the layers boundaries objects as changes in electrical properties of materials, which are displayed as a continuous profile on a PC monitor. The system measures the time it takes for the pulse to propagate down to the reflecting interface and back up again, the so-called two-way travel time. Electromagnetic waves reflected from the layers boundaries are stored by the data logging system. The measured time is depending on the depth to the layer interface and the velocity of which the wave propagates. Hence, in order to conduct accurate depth determinations from radar diagram, it is necessary to calibrate the ordinary GPR measurements with velocity measurements or coring. The measuring speed and high-resolution capabilities of the GPR method make it well suited for landslide monitoring. However, GPR is not suited for determining stiffness and soil design parameters. Therefore, other methods as *in situ* tests and laboratory tests or borings are necessary compliments to GPR. This method could be used for landslide investigations, especially in mountain areas built of different types of sediments and rocks where conventional methods (borings, vertical shaft, etc.) are very expensive and not effective.

Usage of GPR techniques was successfully tested on landslide in Carpathian flysch sediments in Lachowice and Wa-



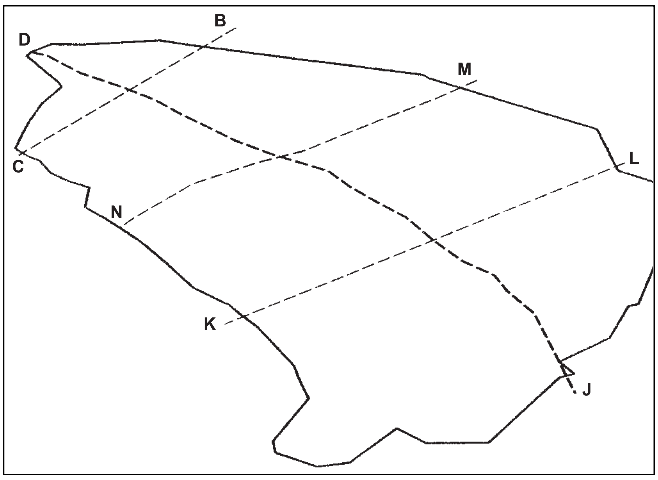


Fig. 10. GPR measurements, Lachowice, Carpathian Mountains

A — GPR longitudinal cross-section (K–L); **B** — model based on GPS, localisaton of cross-sections

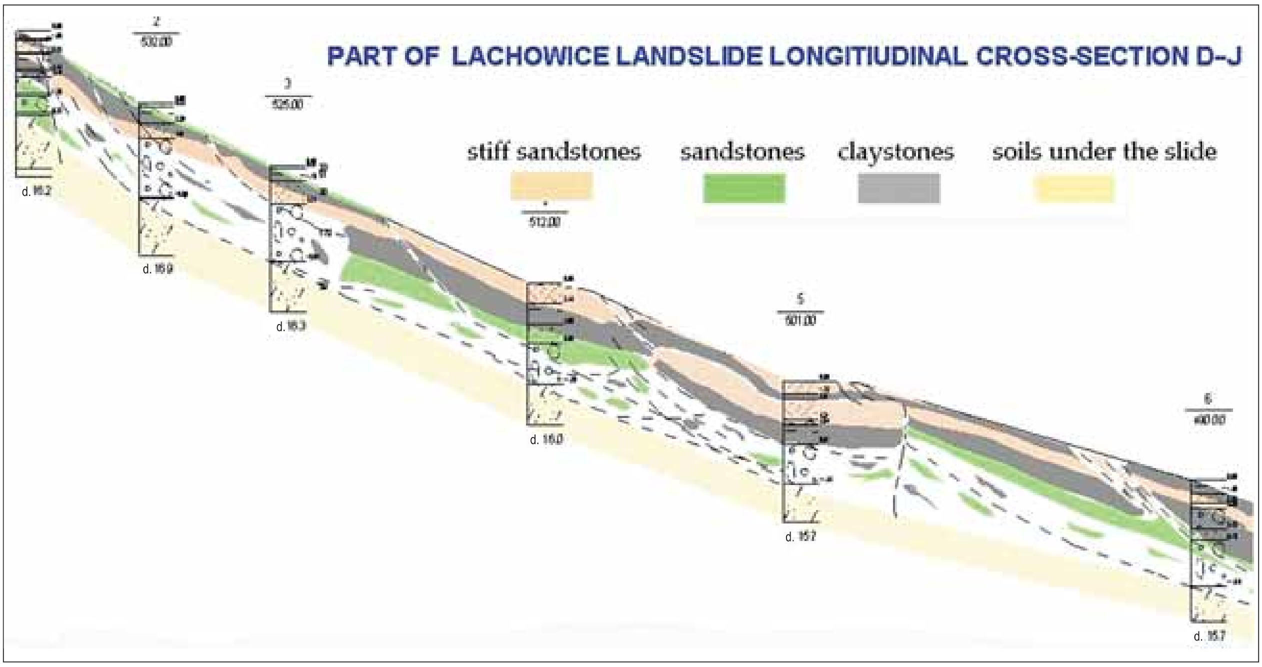


Fig. 11. Ground penetration radar interpretation, Lachowice landslide

pienne (Poland) (Bednarczyk, 2002). These sediments are built of the layers of mudstones, sandstones and clay-stones with different degree of digenesis. In Lachowice slide surface was observed in soft layers under very stiff sandstones on the surface. GPR measurements (total length 1200 m) were performed on longitudinal and transverse lines across the landslide body (1.3 mln m^3) with penetration depth up to 16 meters. Georadar measurements were operated by a high performance GPR system with 50 MHz antenna and penetration depth up to 18 meters. The frequencies used for investigation depend on the specific site conditions. Using GPR scanning, maximum depth of sliding activities (10–12.5 m) was detected. Presented method allows to follow in detail main and minor slide surfaces and soils recognition in the landslide body. Filtrated by special software GPR measurements data were the basis for geological cross-section construction. Waves reflected from different deposits boundaries were filtrated to obtain landslide stratification (Fig. 10). Results of ground penetration scanning were used for geological interpretation of landslide area (Fig. 11). Inside the landslide body, layers of stiff sandstones (yellow colour), sandstones (green colour), claystones and mudstones (gray colour) were detected. White colour represents mixed soils. Because GPR scanning did not include slope inclination, all received data were corrected and adjusted to the landslide slope profile obtained by GPS measurements and usage of existing geodetic network.

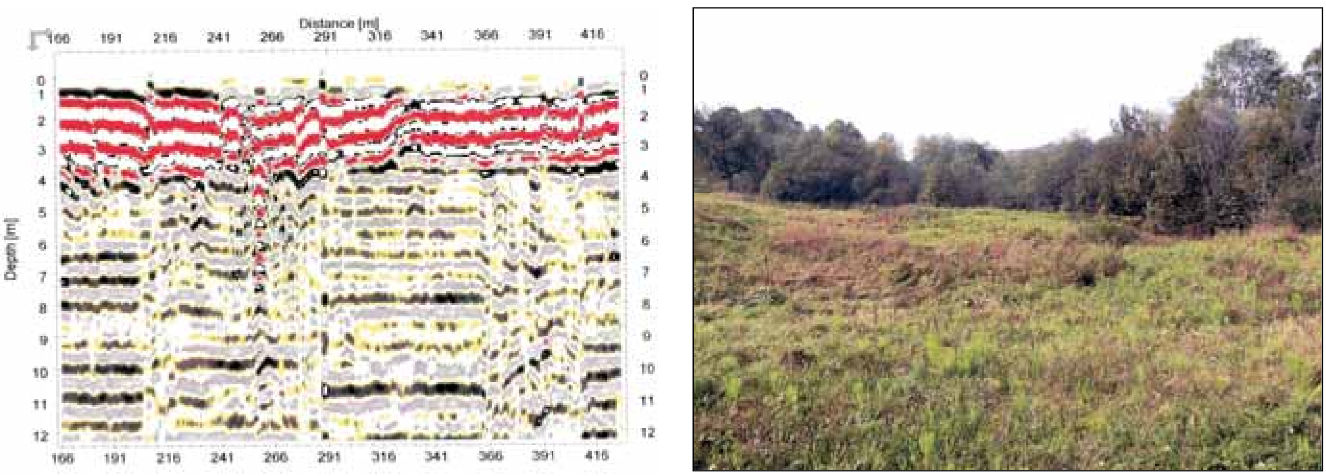


Fig. 12. Landslide in Wapienne, results of ground penetration scanning

Ground penetration radar testing was also successfully tested on Wapienne landslide (Fig. 12). On this landslide using 100 Hz antenna over 3000 m of GPR scanning was performed. Using this scanning, soil types inside the landslide body as well as depth of sliding surface (4.5–6.5 m) were detected. Landslide is founded in claystones and sandstones with different degree of diagenesis.

AERIAL PHOTO INTERPRETATION

Aerial photo interpretation in potential sliding areas could deliver different data including landslide shape, disturbance and cracking and water flow directions from the sliding body (Fig. 13).

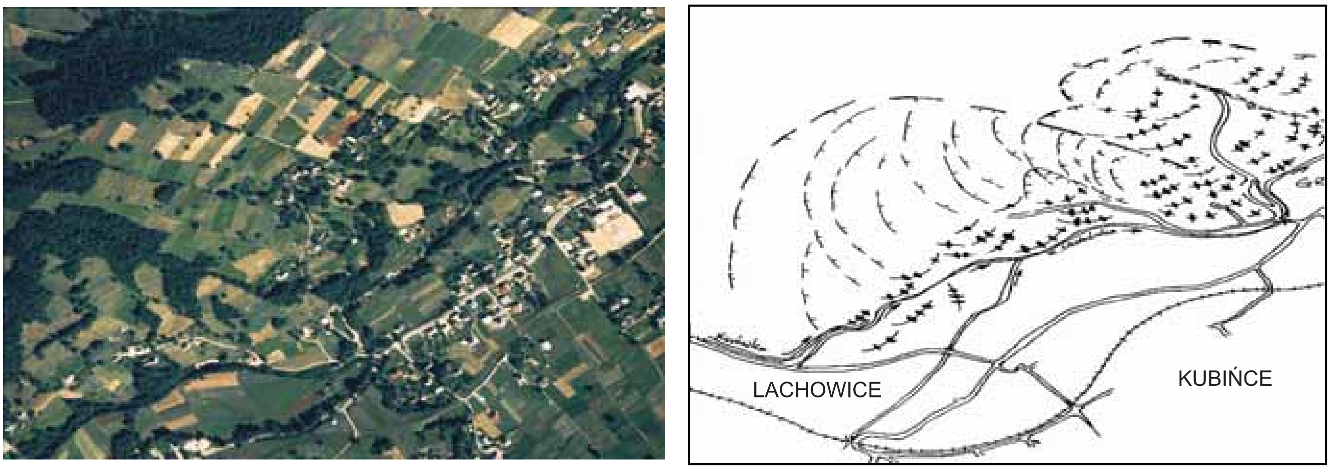


Fig. 13. Lachowice landslide aerial photo (1998) before the main slide occured (2001) with sliding area interpretation

GPS MEASUREMENTS

For better characterisation of the Lachowice landslide sliding body also GPS measurements were performed. Investigation was performed with 218 measuring pickets and usage of existing geodetic network. Using GPS data, Lachowice landslide slope profile was measured (Fig. 14). Obtained data allowed also 3D model construction (Fig. 15).

Involving georadar scanning together with GPS measurements could provide complex landslide characterisation, including coherent data along prospecting lines. However, for better measurements quality, GPR measurements should be always completed with limited drilling works for obtaining geological and geotechnical data of rock samples.

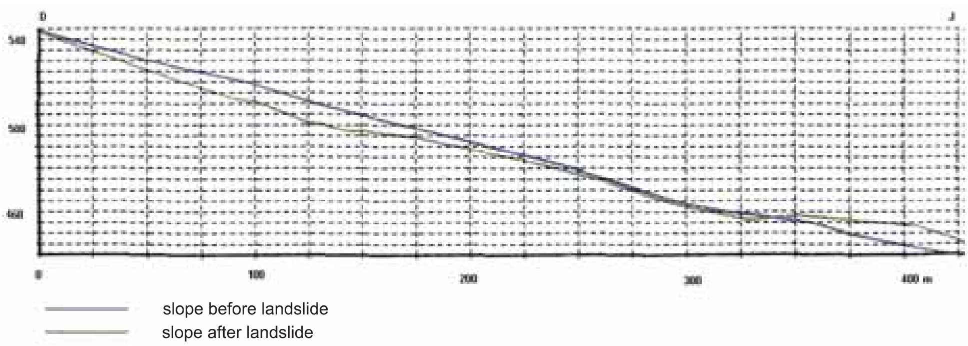


Fig. 14. GPS measurements on Lachowice landslide, comparison of slope profile before and after the main slide

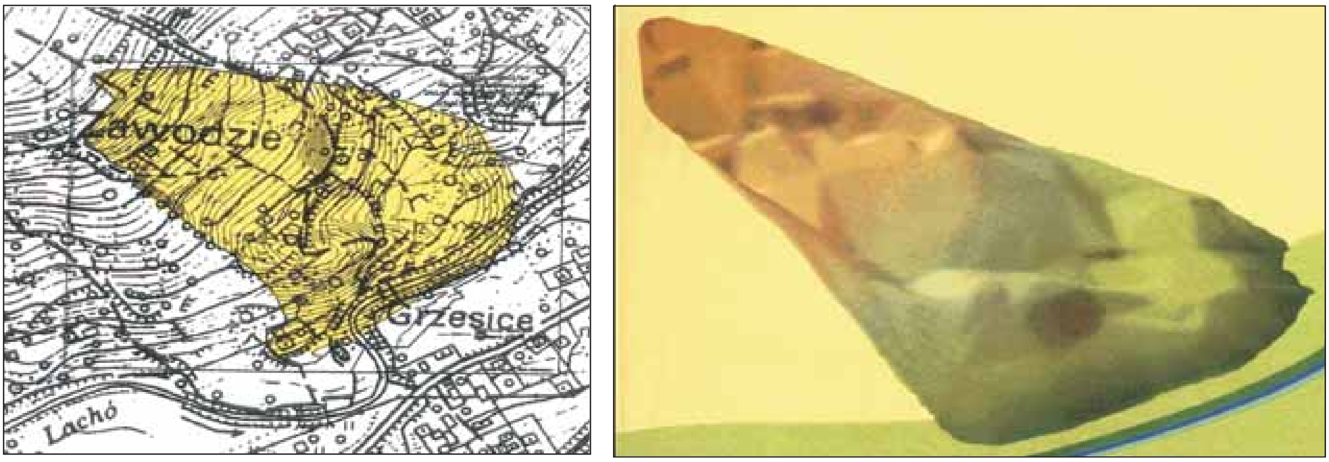


Fig. 15. GPS measurements on Lachowice landslide, 3D slide model

SUMMARY AND CONCLUSIONS

Landslide investigations require quick, efficient and relatively inexpensive system of investigations. Experience from Polish opencast mines could be used also in other areas, though types of investigations in every case should be adequate to the type of the landslide. The presented GPR and GPS measurements together with CPTU tests fully meet these requirements, however, CPTU is suitable method only for cohesive soils or sands and it is not proper method for employment in rocks and rock detritus where conventional borings and sampling should be used. Usage of these techniques was successfully tested in presented landslide projects, however types of investigations in every case should be adequate to the landslide type. Presented *in situ* tests together with reference laboratory testing could provide all necessary data for designing stabilisation measures. Detailed knowledge of landslide internal structure, depth of sliding surface, type of soil and rocks and its geotechnical parameters and pore water pressure inside the landslide body allows to start landslide area remediation in a relatively short time to limit potential damages caused by the landslides.

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