Technical Sciences, 2017, 20(2), 111–129

Quarterly peer-reviewed scientific journal
ISSN 1505-4675
e-ISSN 2083-4527
TECHNICAL SCIENCES
Homepage: www.uwm.edu.pl/techsci/

# LIDAR AND GROUND PENETRATING RADAR DATA IN DETERMINING ROAD SURFACE CONDITIONS AND GEOLOGICAL CHARACTERISTICS OF UNSTABLE SOILS

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Received 31 March 2016, accepted 23 February 2017, available online 27 February 2017

Key words: road investment, laser scanning, geophysics, ground penetrating radar.

Abstract

Within the road investments the very important element determining repeatedly the success of the whole project is an adequate information about the characteristics of the site, its load capacity, stability and the possible impact of geological characteristics that may interfere with subsequent service life, not only for the road surface itself, but also for the surrounded objects. The surface is incessantly influenced by geological characteristics, determining its durability and functional usefulness. The main aim of this paper is to answer the question how by the usage of modern technics for obtaining data it is possible to find a link confirming the characteristics of land on which the specific road projects are supposed to be carried out, or where these projects have already been accomplished, concerning their requirements with high accuracy of location and also the stability and durability of the ground. This article makes also an attempt to answer not only the question how to identify the construction of road surface, but also how to locate underground cavities, created or influenced by the flow of water, or due to geological structures characterized as an inconsistent ground. The results were supported with geophysical researches using GPR method, and also data collected with laser scanners.

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## Introduction

Due to rapid development of remote methods of obtaining data for certain areas and the imagery from the aerial and satellite altitude, and also further development of digital technologies of their processing, integration and visualization, the possibilities of generating the various sets of results are still growing. Every day they are becoming more useful for creation of various databases and information systems, thereby causing a steady growth of range of their users. A completely new situation arose upon the occurrence of airborne laser scanning methods with very high resolution. In terms of basic performance parameters, these methods slowly but steadily and quite effectively find the right place in market applications (KURCZYŃSKI, WOLNIEWICZ 2002, 2005, KURCZYŃSKI 2005, Spaceimaging.com.). LIDAR data, obtained on the basis of the results of the scan area provide rich and real information about the interested areas, and it may be also a valuable component of information systems, and due to their combination of geophysical methods can create an interdisciplinary space for their adoption (HOWARD 2009, SANDERS 2000). An example of such use is the collection of data about the terrain model, which, together with geophysical data, provide information and evidence of existence of variety of geological structures, and thus the heterogeneous characteristics of the land. These techniques also give an opportunity to achieve information about changes and defects in the structural layers. In addition, the efficiency and quality of such kind of data made them one of the basic methods of assessing the structural condition of road surface, together with providing data about the terrain profiles and their physico-chemical composition. This in turn gives an opportunity to create geo-referenced GIS databases that allow to conduct multivariate and multi-criteria statistical and space analysis.

## Aim of the study

The lack of adequate investment for safety in area of geological protection quite often results with the inappropriate quality parameters of the implemented project, both during construction stage and during its operating time. The overall aim of strengthening the subsoil is adjusting its parameters to the operational requirements of installed facilities. Before we determine the necessity of strengthening the ground we should acquire an adequate engineering-geological conditions introduced by the study of the inconsistent ground presented i.e. in the form of geological and engineering documentation of the interested area. As the contrast to typical practice, the range of research should also include investigation of layers properties usually and generally referred as unstable – these effectively always should be strengthened. Their physical and mechanical properties (before and after amplification) are, after all, not only the basis for the design or a choice of how to strengthen the ground, but also the choice of how to implement the entire project and its cost calculation (JERMOŁOWICZ 2013). Some of the European legislation in terms of designing routes imposes very specific conditions. If it is possible, it should be avoided to project driving routes through the areas of peat bogs, silt and other highly irrigated unstable soils. These are constantly wet, hard and poorly penetrable surfaces, covered with marsh and marshy-meadow plant communities, extremely valuable in terms of natural heritage. Apart from aspects of nature, the construction of roads through the area of wetlands always brings increased costs because of the use of very expensive engineering solutions. The costs of maintaining such a route are usually much higher than the route carried out in normal water and groundwater circumstances. The unstable grounds are not suitable for direct foundation of engineering structures. Road embankments, in turn, set on weak soil grounds may be affected by the significant deformations due to its compressibility and plastic deformations. Methods of road designing on unstable soils are extremely invasive and can be used only on land of low thickness and playing no significant role from the point of view of natural heritage. Setting roads over peat bogs and other wetlands or high ground water level should be preceded by a thorough examination of geological and geophysical terms (SISKOM, http://www.siskom.waw.pl).

Second approach taken in this article, is the quality checking of the correctness and "honesty" of the execution of the road surface, which must deal not only with the requirements of quality, but also must contain a cross-section of all (required by the regulations) layers of road, in addition with complying the project thicknesses. It is, or rather should be, in a way a control parameter, not only during the construction phase of the road, but also as a part of control measurements, giving a rise to the approval by the client the correctness of the execution of works. Lack of adequate quality information, both in respect of the surface layers and the land can seriously interfere with the subsequent service life of not only for the same road, but also for the objects within its course. The paper presents a case study how by the usage of modern techniques for obtaining data is it possible to find a link confirming the characteristics of land on which the specific road projects are supposed to be carried out or were already carried out, concerning their requirements in high accuracy in regards of location and also the stability and durability of the ground and secondly correctly identify the structure of the road surface. Both factors play a significant role in determining a possible opportunity to perform (in a given place) the planned investment or later to affect its durability. Complementing the LIDAR – detailed information together with the Ground

Penetrating Radar (GPR) technique data, we are able to get a reliable image of the geological structures and road layers running through the site, which allows, for example to choose correct location of future roads, or to indicate incorrect location of future structure.

## Methods

Point cloud gathered with LiDAR gives information about the topography of the terrain, what is also the most common reason to use scanning technology. Analysis of LIDAR signal, reflecting from various surfaces, allows us to do more. Special raw data processing algorithms are able to determine the physical properties of these surfaces or their movement. When the surface is covered with objects partially transparent for the laser beam (eg. vegetation or snow) it can also gather information about their structure. The signal emitted during the measurement is partially disturbed by the atmosphere – in connection with the LIDAR data it also gives information on its characteristics. LIDAR has already found its place in optimizing the use of wind energy with for example control system (built by engineers from Stuttgart) that measures wind speed and direction before it reaches the turbine blades (Optic.org. The business of photonics. http://optics.org/news/3/6/16).

The base for correct interpretation of the obtained measurement data is the clarity of the resulting material. The raw data without proper processing cannot meet its role, if chosen (depending on the usage) accuracy is poor – the obtained image clarity is also not satisfying. It is necessary to consider each point obtained with LIDAR technology, so the capacity of data required equipment with high computing power. For example, in an area of about 100 hectares are collected more than 4 million laser points (in *.xyz format), of which nearly 2,5 million are points containing valuable information. Selection of the suitable GRID resolution is also very important in the process of interpretation. Figure 1 shows one of developed mosaic of established GRID with resolution of $0.5 \times 0.5$ m with usage of the "Surfer" software. It enables to distinguish changes in topography, providing the potential risks of instability and incoherence of the ground (Fig. 2). "Surfer" allows to create grids of values used to produce maps of land surface, three-dimensional representation of triplets (*XYZ*) type of data, which can be exported to several different formats (*.dxf, *.kmz, *.kml etc). It allows both creating simple maps of the baseline, as well as more complex spatial maps of the surface, also vector maps, relief shaded maps, map of single points, overlaid maps and others. The program has a rich computing capabilities, enabling an automatic calculation of surface projected data using *XY* plane, the curve surface, volumes and distance between points. Specialized procedures allow to generate cross-sections along an arbitrary broken line. The data is calculated by a regular grid of values, on the basis of which the special type of map can be created. Thanks to its capabilities this program is used to visualize data in various fields, including geophysical data and geography. The built-in wide range of interpolation methods for generating regular grid of values, allows to choose the optimal algorithm "gridding" to the nature of the input data (Gambit Centrum Oprogramowania i Szkoleń Sp. z o.o. http://www. gambit.net.pl).

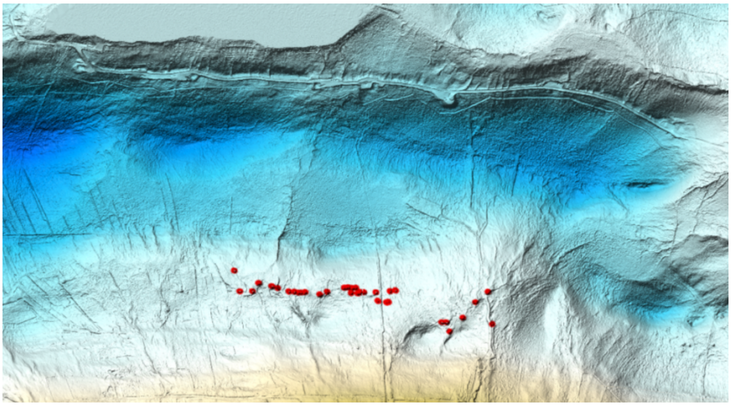

Fig. 1. The GRID of 0.5m size with the presentation of swallow holes (red); mosaics made using "Surfer"

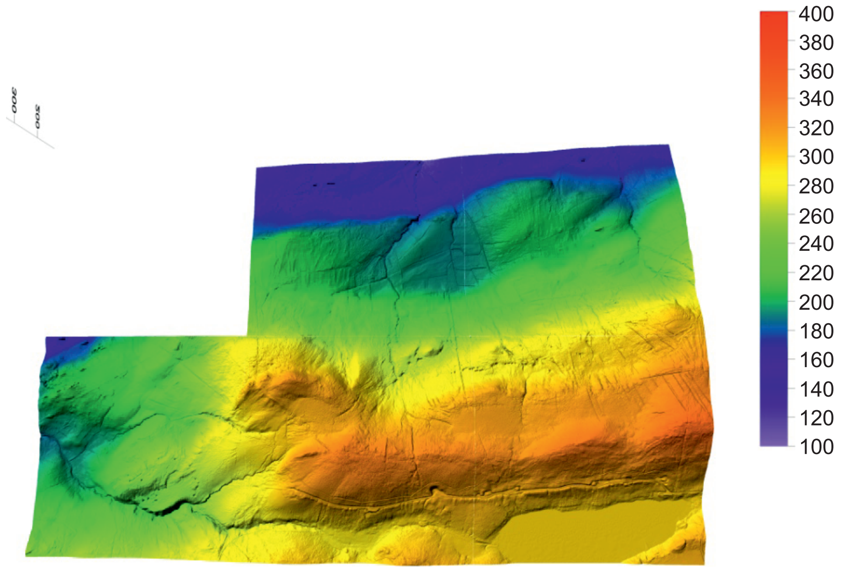


Fig. 2. The range of colors for the height of the tested terrain (in meters)

Visible to the naked eye, regular depressions in the ground can foretell the location of underground space, created or by the flow of water, or due to geological structures characterizing the ground as inconsistent. The confirmation of the assumptions can be supported by geophysical investigation of land using three methods:

– Electrical Resistivity Tomography – ERT,
– GPR method,
– Seismic method.

Based on data obtained from laser scanning, some methods of land survey were selected to confirm suspicions of the content and carrying capacity of land for road construction. Finding the most appropriate methodology is the basis for all research, primarily to determine exactly what type of investigations should be taken into account for economic reasons, as well as external factors (accuracy, size of objects etc.). After an appropriate analysis, some of the methods can be eliminated in order to provide very accurate results without unexpected time investments.

During determining geotechnical conditions of foundations of linear objects such as roads and railways it is imperative to reach a compromise between the amount of field research and the accuracy of geophysical investigation. GPR technique is used for instance in continuous monitoring of the road surface condition or railway subgrade (Geopartner. http://www.geopartner.pl). An important advantage of geophysical survey is non-invasive cappability of determining structures invisible to the eye, sometimes assisted with geological surveys (i.e. trial pits, borehole drilling) confirming data obtained from field measurements. In case of linear objects related to public transport on-going work do not cause any disruption to traffic.

Data obtained with GPR give the ability to identify sub-surface structures, providing information about the uniformity of the structural layers and geology. Proper identification of the layer types ensures quality of the assessment of objects being under investigation and underlain soils. GPR provides continuous information about the type of surface structure, thicknesses of layers, homogeneous sections and existing changes and anomalies (MASER, SCULLION 1991).

The principle of GPR is based on the generation of electromagnetic wave and sending it into tested ground, rock or material. This is accomplished by transmitting antenna (Tx) that generates a signal at a given frequency (<20 ns). The wave passes through objects, where is refracted and reflected of the surface, but encountering objects, infrastructure or other heterogeneities the wave is being diffused. Some of the energy carried by these waves is transmitted to greater and greater depths, while some of the energy is reflected back towards the surface receiver (Rx) whenever a contrast in dielectric properties is encountered. Both antennas are connected to the central unit, which manages the generation of wave and recording its reflected digital signal. The penetration depth achievable depends on the nature of material (especially its electrical conductivity), the location of the water table and on the frequency of transmitted wave. Researches at Lund University in Sweden by ULRIKSEN (1980, 1982, 1983), BJELM, ULRIKSEN (1980) and BJELM (1980) investigated such factors as the effect of frequency of the transmitted wave, the transmission velocity and the technique used for moving the antenna over the ground on the measured results. This work also showed that, not only the material layer thickness could be estimated accurately but also some information about the material situated beneath can be obtained. The receiver measures the variation in the strength of the reflected signals with time (Figs. 3, 4). The resulting profile is called a "scan" and is a one-dimensional representation of the subsurface beneath the antenna. The example is visible on Figures 5 and 6 (RSK Geophysics Mapping the unscene. http://www.environmental-geophysics.co.uk).

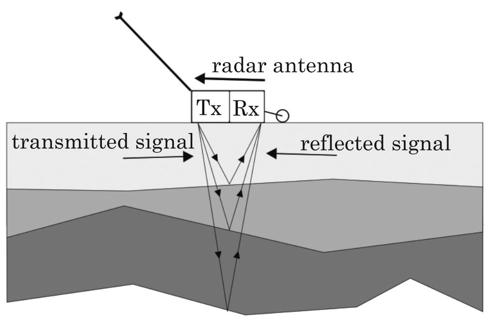


Fig. 3. GPR Principles
Source: RSK Geophysics Mapping the unscene. http://www.environmental-geophysics.co.uk.

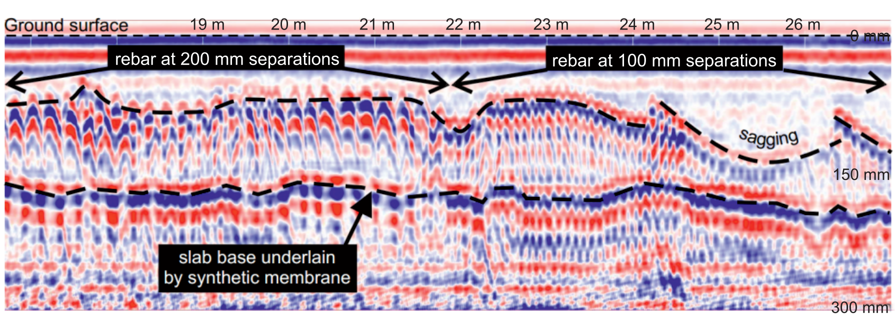


Fig. 4. An example of high frequency (1.5 GHz) radar data collected over a concrete slab
Source: RSK Geophysics Mapping the unscene. http://www.environmental-geophysics.co.uk.

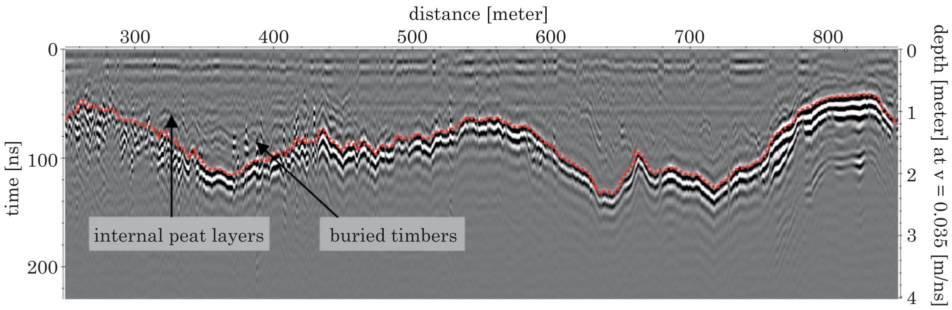


Fig. 5. Example of GPR data: processed section
Source: Near Surface 2009 – 15th European Meeting of Environmental and Engineering Geophysics.

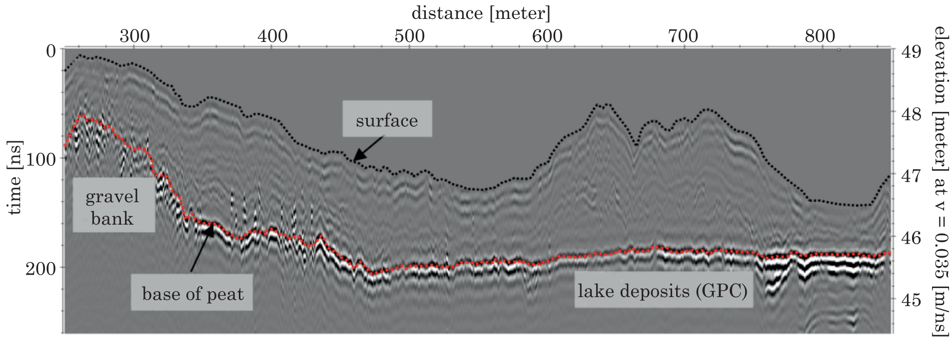


Fig. 6. Example of GPR data: topographically corrected section
Source: Near Surface 2009 – 15th European Meeting of Environmental and Engineering Geophysics.

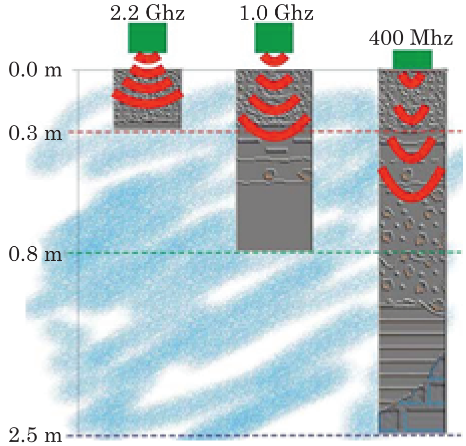


Fig. 7. The range of terrain penetration depending on the frequency of the antenna
Source: SUDYKA (2006).

The accuracy and range of a GPR method depends primarily on the frequency of the emitted electromagnetic signal that ranges from 10 MHz to several GHz. This frequency range causes that the GPR method is provided from a few centimeters to tens of meters (Fig. 7). While the resolution, which means the expected vertical accuracy tests varies from a few millimeters to a few meters. Resolution and coverage dependency is inversely proportional, which means that the higher the frequency of the generated wave is the better resolution is expected, but the range is decreasing (GeoSpectrum. Nowoczesne techniki badawcze. http://www.geospectrum.pl/).

## Tests

As part of the research the chosen section of road with a length of 3600 m, running along the geologically diverse area, located on the borders of Northern Ireland was analyzed (Fig. 8).

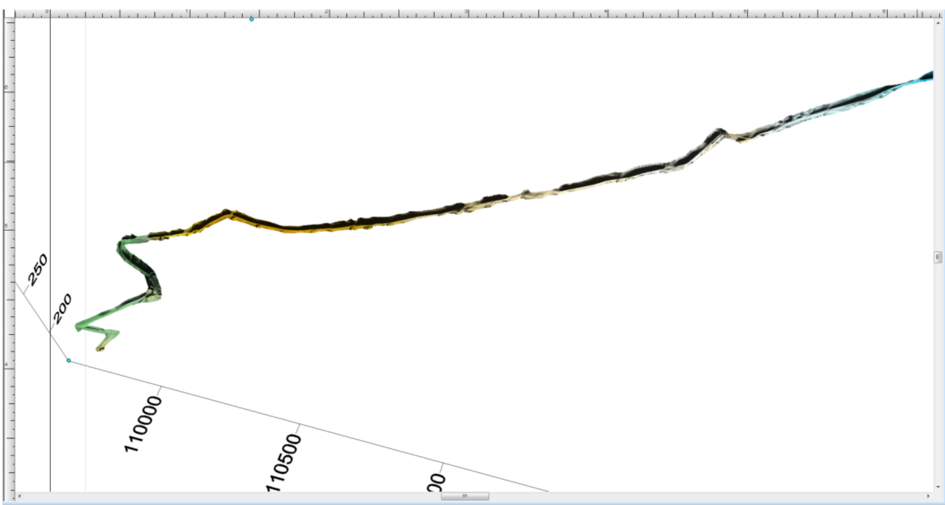


Fig. 8. Analyzed section of the road, cut out from a point cloud using Surfer application

Driving and utility parameters of described road section have significantly degraded. Clearly visible are the structural damages in the form of sinks and surface subsidence, as well as the linear and transverse cracking. In the presented case the proposal provides analysis of the road subsurface intended for modernization, as well as areas in its surroundings, where variety of structures could be built in the future. An investigation has been undertaken to explain the current situation, with the assumption that responsible for the road surface damage are geological structures running under the road, as well as inadequate technical parameters of the road layers, including their layout and thickness. The study was based on data obtained from laser scanning, supplemented by a GPR survey of the investigated road section.

As the first stage of work LIDAR data was used in order to create three-dimensional terrain model, which allowed the insight into the shape of the surface of the considered section. At a later stage LIDAR data was processed using the "Surfer" software. LIDAR data was used to assign an altitude for each one of thousands of the analyzed with GPR method points. Prior to survey appropriate density of readings should be chosen as well as the interval between signals sent by the antenna into analyzed area. It was agreed that for analyzed section the required resolution should be equal to 10 mm, what meant that study of the considered area in a straight line would be investigated at that given density. Antenna was placed under the vehicle (Toyota HiLux 4×4) and set up for simultaneous transmission and collection of reflected signal. The vehicle has been appropriately modified so that at a speed of (not exceeding) 30 km/h the analysis could be carried out smoothly, without requirement for stopping on the road and blocking any of ongoing traffic. Each of the antennas used for the survey was part of Swedish MAL3 X3M™ SYSTEM, which connected with the rear wheel of the vehicle, after proper calibration, allowed to run a survey with a given density (Figs. 9, 10). The X3M is an integrated radar control unit, fitted directly on a shielded antenna and powered externally. No antenna cable was required since the control unit was

Fig. 9. 400 MHz MAL3 X3M™ SYSTEM antenna used during the measurement


Fig. 10. Custom modified vehicle allowing GPR measurements without stopping road traffic at analyzed road sections

mounted directly on top of the MAL3 shielded antenna (in our research up to 1.5 GHz). It communicated directly with the XV11 GPR Monitor that was running GroundVision2 acquisitioning software (Fig. 11). MAL3 allows to gather information from a range of depths (base and sub-base thicknesses) for the entire road construction, for example pavement, supportive layers and base layers, including also evaluations of the asphalt thickness (MAL3. World Leading Ground Radar Solutions. http://www.malagpr.com.au).


Fig. 11. XV11 GPR Monitor with results of the measurement

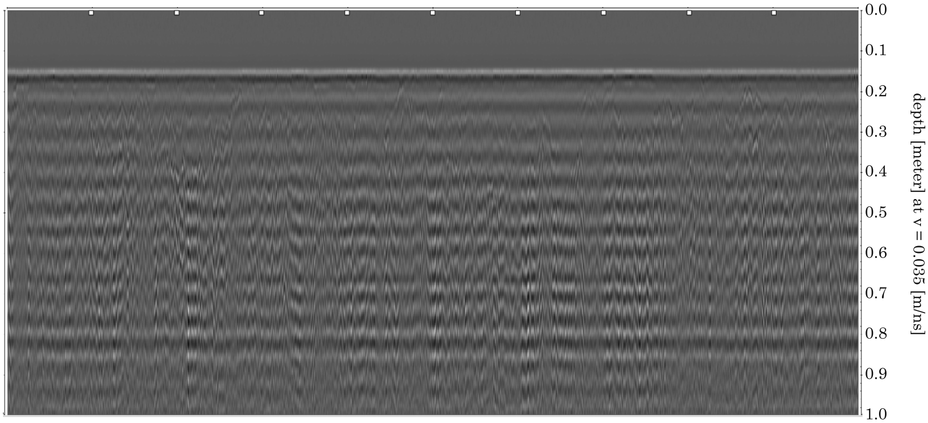


Fig. 12. Raw data in *.DAT format from 400MHz antenna, without implemented filters which allow proper interpretation

For the section of 3,600 m 360,000 signals were sent, each one of them during processing received *X* and *Y* coordinates, together with the elevation. Each analyzed depth – i.e. layer of bitumen or thickness of certain surface had exactly associated *XYZ* value. GPR work is now usually linked to an accurate GPS system which allows spatial relocation to GPS co-ordinates as well as providing topographic information. For the purpose of determining the exact location and correlation between LIDAR data and carried out measurements, on the investigated sections, GPS base stations at distances of 200 m have been placed, measured using GPS Trimble Geo7x with the accuracy of 1 cm. Thanks to laser scanning precision in determining road surface changes or specific characteristics of the analyzed area, allows very accurate indication of road defects that are not visible to the eye ball. Antennas which have been used for the measurement of the section have different frequencies, ranging from 100 MHz up to 1.5 GHz. The lower frequency values allow the analysis of deeper layers of road surface, however resolution decreases with depth, and the possibilities of interpretation are dependent on environmental conditions as well as the characteristics of the terrain. The antenna with a frequency of 1.5 GHz enables very thorough and accurate investigation of shallow surface layers, thus reducing the frequency decreases the resolution of the analyzed object. The research was carried out by analyzing the same road section with each antenna separately, stopping only at the base stations, for which coordinates have been measured earlier. We handled and interpreted all data using MALÅ ObjectMapper software. MALÅ ObjectMapper includes the visualization of several radar profiles simultaneously, robust filtering, capabilities including time gain, band pass, background removal and a report editor to mark and visualize objects on a map. Several different types of markers can be defined to illustrate the position of pipes, single objects etc. Built in data collection management in the MALÅ XV11 GPR Monitor that was used in the experiment allowed to select the base stations, which were presented in the form of white squares on the upper part of Figure 7, that represented the raw data from survey with 400 MHz antenna. Afterwards (in ObjectMapper software) it was automatically adjusted to the baseline and thus aligned for profile to profile target picking.

## Results

Before undertaking the process of interpretation the appropriate filters should be applied, which affect the "readability" of data obtained from the field of measurements (IBDiM 2010). A significant factor is the experience of person responsible for work with the data, lack of knowledge of the rules related to reflecting and refraction of waves could have a negative impact on the interpretation results. It is worth remembering that the value of the analyzed data becomes increasingly important in places where the location due to construction defects, or a complicated order of geological layers is an extremely important factor in determining the further decision-making processes. The interpretation process was extremely time-consuming, any breakdown in the image of such high detailed data is linked with the existing situation in the field. The interpretation process is unfortunately not automated – all kinds of changes in the road surface are "outlined" by the interpreter using the mouse. Of course, each of the layers is peeled and marked individually, colors are assigned for easier interpretation of the results, thanks to the perfect matching filters the image becomes clear (Fig. 13).

Interpreted data have been converted to graphs created in spreadsheets using written macros, appropriately modified in a way that fully illustrates the developed interpretation. The determining factor in this case was the appropriate collection and tabulation alignment of measurement figures, so that the result of study is clear, and the interpreter has the ability to see requested data (Fig. 14). It has become apparent that a great deal of information on the sub-peat soils can be determined from the GPR data. It is possible to determine the type of sub-peat deposit and depositional history of an area from the assessment of the GPR response. Different reflection characteristics from within the peat layers can also provide information on the origin and composition of the peat layers.

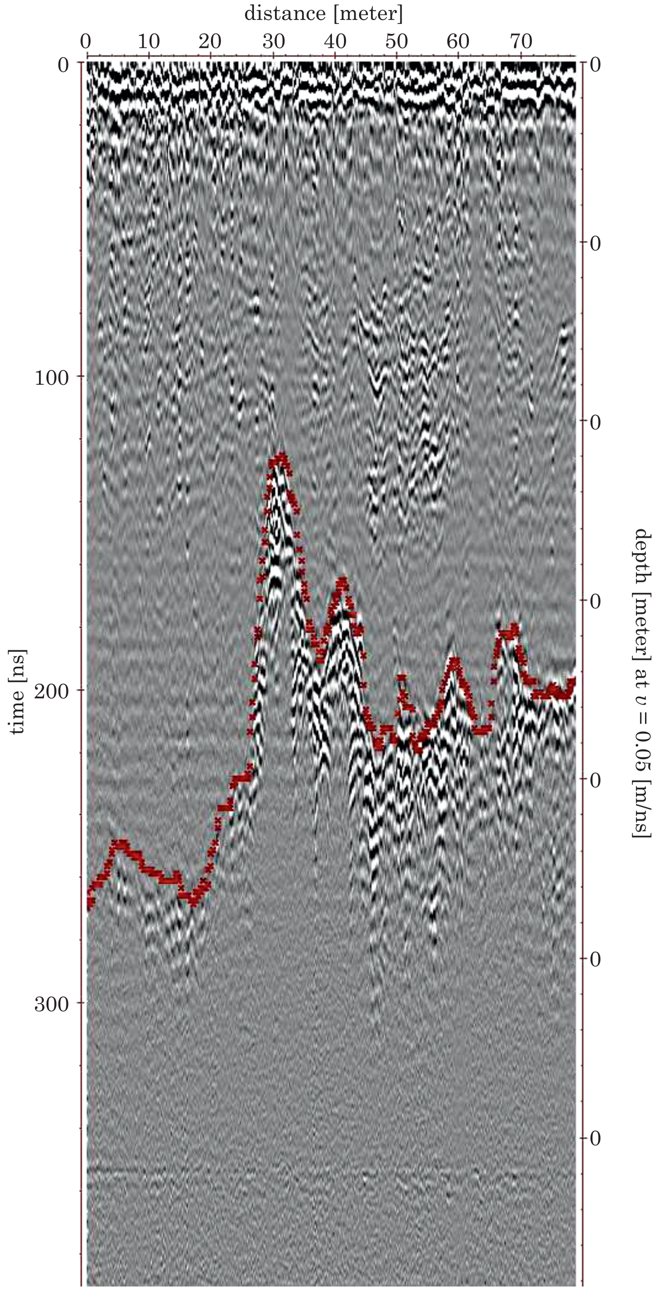


Fig. 13. Data from 400 MHz antenna presenting a 80 m section of road, after applying filters and processes of relocation, with sketched interpretation of Peat Thickness

Sample pavement construction summary table

| Chainager | Coordinates | | | Bituminous material | | | Subbase material | | | Peat subgrade | | | Section |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Start (m) | end (m) | easting | northing | min. depth [m] | max depth [m] | avg. depth [m] | min. depth [m] | max depth [m] | avg. depth [m] | min. thickness [m] | max thickness [m] | avg. thickness [m] | |
| 0 | 125 | 123456 | 370810 | 0.107 | 0.224 | 0.167 | 0.398 | 0.998 | 0.689 | 0.16 | 2.06 | 1.27 | Section A |
| 125 | 217.5 | 123457 | 370811 | 0.111 | 0.226 | 0.198 | 0.313 | 0.521 | 0.401 | | | | Section B |
| 217.5 | 281 | 123458 | 370812 | 0.084 | 0.171 | 0.133 | 0.313 | 0.474 | 0.395 | – | – | – | Section B |
| 281 | 467 | 123459 | 370813 | 0.056 | 0.137 | 0.095 | 0.276 | 0.499 | 0.387 | | | | Section B |
| 467 | 600 | 123460 | 370814 | 0.058 | 0.165 | 0.084 | 0.272 | 0.554 | 0.346 | | | | Section B |
| 600 | 644.5 | 123461 | 370815 | 0.061 | 0.277 | 0.177 | 0.363 | 1.718 | 0.594 | 0 | 0.74 | 0.4 | Section C |
| 644.5 | 875 | 123462 | 370816 | 0.039 | 0.184 | 0.096 | 0.328 | 0.633 | 0.505 | | | | Section C |
| 875 | 1024.5 | 123463 | 370817 | 0.108 | 9.197 | 0.141 | 0.425 | 0.722 | 0.569 | 0.13 | 0.83 | 0.42 | Section D |
| 1024.5 | 1100 | 123464 | 370818 | 0.098 | 0.192 | 0.131 | 0.522 | 0.831 | 0.677 | 0.31 | 1.72 | 1.02 | Section E |

Fig. 14. Spreadsheet view with evolving data

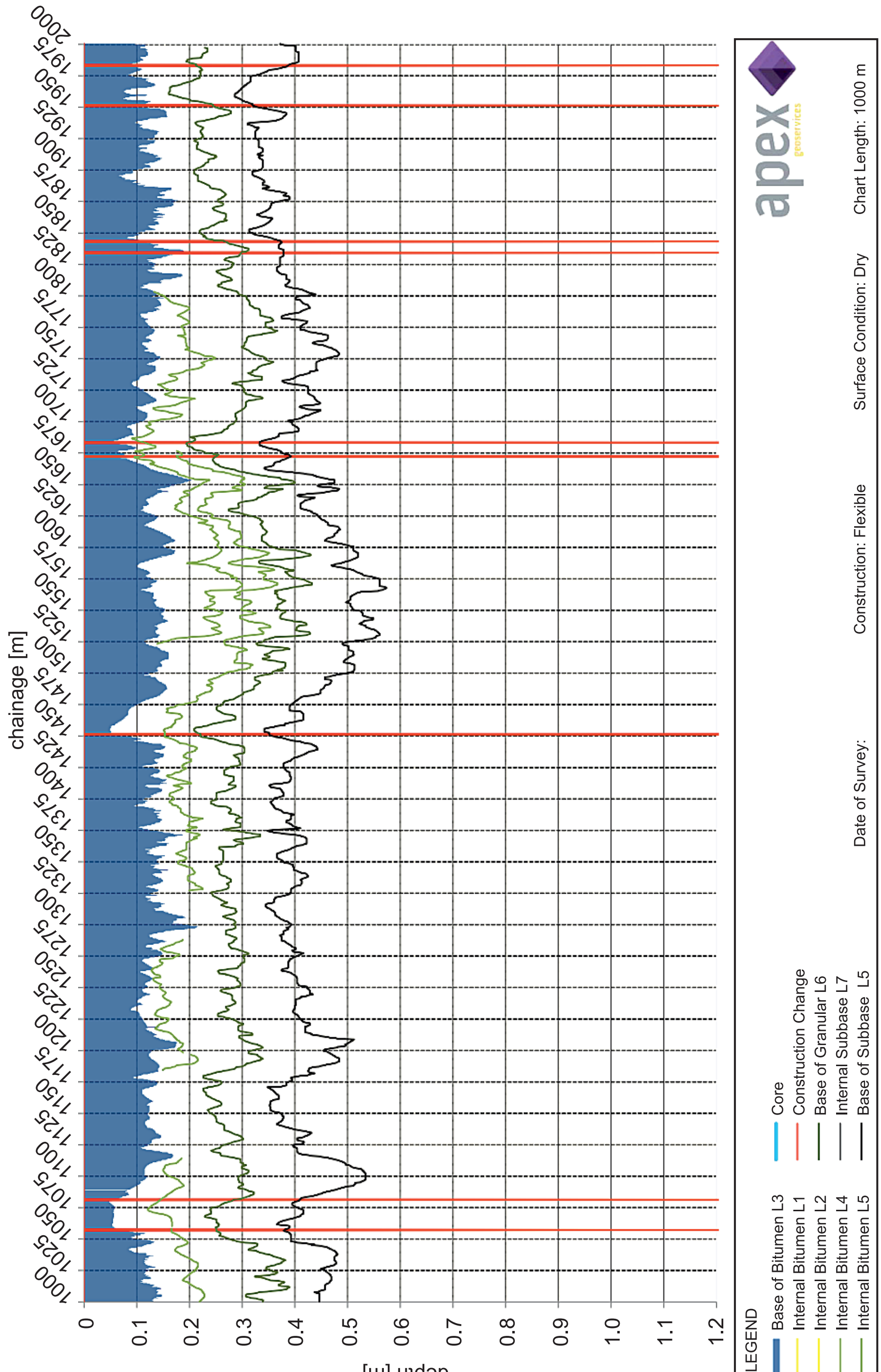


Fig. 15. Graph created with excel macros based on data obtained from the measurement and interpretation process for considered section

Above listed part of final report of surveyed section presenting part of road with selected layers of bitumen (Fig. 15) is also enclosed the aerial view of road where investigated was peat thickness with cross-section for the same area (Figs. 16, 17) – elevation data taken form LIDAR.


Fig. 16. Aerial imagery with overlaid layer of Peat Thickness created in "Surfer" based on GPR Investigation data

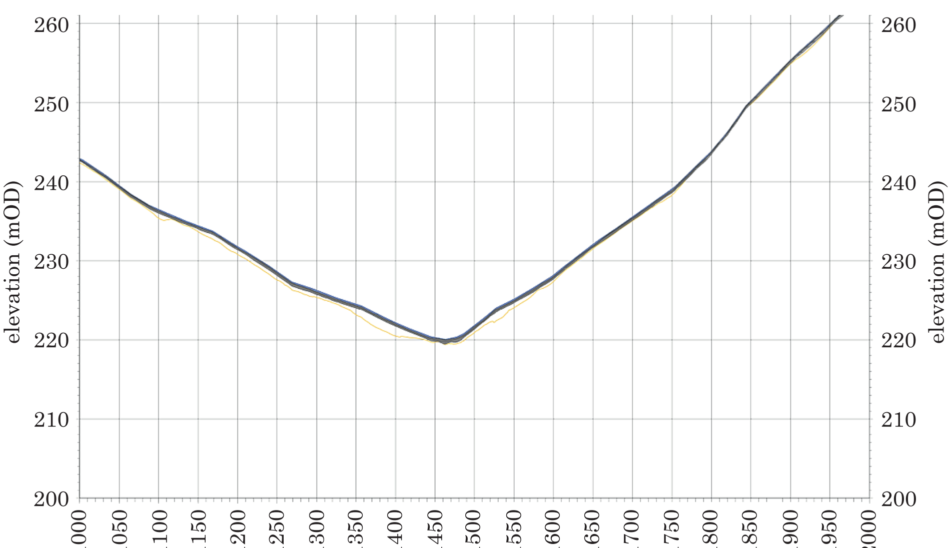


Fig. 17. Cross-section of considered area

## Conclusion

Radar technology presented and demonstrated in this article, mainly because of its effectiveness and quality of obtained data, makes it one of the main methods of assessing the structural condition of road surfaces now and in time of near future – especially as currently the determinant of use of specific technologies is the cost factor. Thus, searching for cost-effective and efficient technologies for renovation of the existing road surface by GPR methods seems to be indispensable. The results of research and analysis are based on achievable results, enabling a thorough and honest assessment not only of structural, but also geological layers. GPR measurements should be widely used not only as a complementary element of developed projects, but most of all from the point of i.e. confirmation of structure of newly made roads prior to their release to public. An important advantage of radar systems is their effectiveness, performance and relatively low cost of the research. No interference with the road surface and speed of the measurements cause that radar techniques to be used in a number of so-called measuring circuits, allowing accurate identification of the surface structure also in cross-sections. In addition to the standard information about layer thicknesses it is also possible to assess other parameters of construction such as i.e. layers connection status and their homogeneity. Main factor influencing negatively in the considered solution is the fact that despite of the advanced technology and high quality of the data, problem of automatic processing and interpretation of received data is not yet fully solved. Still, the vast majority of processing and interpretation of the data must be controlled by an experienced engineer. Nevertheless, it is hoped that this new technology will gain a proper place in the area of engineering applications.

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