METHODS OF A GEOPHYSICAL SURVEY FOR ROAD DESIGN

Pavel Bláha, Assoc. Prof. RNDr. D.Sc.  
GEOtest Brno, a.s. Smahova  
112, 659 01 Brno, Czech Republic  
blaha@geotest.cz

Roman Duras, Ing
GEOtest Brno, a.s. Smahova  
112, 659 01 Brno, Czech Republic  
duras@geotest.cz

Abstract: Geophysical methods are integral part of every extensive engineering-geological survey. Results of measurement provide information on the geologic structure of a studied environment, enable to obtain information on geotechnical properties of rocks needed for designing, and locate positions of future direct exploratory workings (boreholes, pits, etc.). An appropriate combination of geophysical work and other survey methods enables to achieve a high degree of the state of exploration of an area of interest, both a route and other objects. This approach of solution enables to give a designer a comprehensive solution and, at the same time, it holds true that such a maintained survey is financially the most effective.

Key words: geophysical survey, engineering-geological survey, effectiveness
1. INTRODUCTION

Geophysical methods for road investigation have the same task as for investigation for line constructions as well as for any other engineering-geological survey. The task of an engineering-geological survey is to identify the structure of a rock mass and to characterise its individual parts by geotechnical properties in order to apply physical and mathematical techniques enabling to ensure the proper and safe use of the construction during building as well as subsequent operation. In essence, we can say that we are searching for an answer to the behaviour of the ground during the construction of a work and after its completion, for changes in the stress state of the rock mass occur over this entire period, just as the way of groundwater circulation and the character of the original natural environment, where a line construction will be set, are changing. We must say that the structure of a rock mass and its behaviour are so much complicated phenomena that we may ask unending questions which will never be fully answered. But the point is that we solve all basic problems within given economic limits and at a given time so that a safe and functional construction can be designed and built in compliance with applicable standards and common national and international practice.

Parameters of every line construction are different just as the natural environment, into which they are set, is different. Neither can we consider foundation conditions of a construction as the same within the scope of one construction, nor even as similar ones in most cases; and every building in the route of a new road must be assessed individually. In order for us to successfully solve the basic model of the natural environment, into which a construction is set, we apply various exact methods, of which geophysics undoubtedly takes the front place.

Geophysics is a science that studies physical fields, natural as well as anthropogenic. Engineering geophysics deals with investigations for buildings, observes the extension and characteristics of individual types of the rock environment both in the axis of a route, and in the subsoil of significant buildings. To design appropriate survey methods and their applications requires a visualisation of a studied environment and of possibilities of implementation of particular methods. The evaluation of results of measurement presumes the knowledge of theoretical procedures enabling the interpretation of results from not only geophysics, but also other geological branches. The ideal approach, which leads to this objective, is direct cooperation of an engineering geologist, a geophysicist and other specialists over the whole time of a survey. This applies both to the preparation stage of work and to field measurements, and in particular to the geological interpretation of results of geophysical work.

The interpretation of measured values in relation to other characteristics and parameters obtained by an engineering-geological survey enables to develop a structural model of the studied belt along a line construction and, in case of buildings, the area in its vicinity. In both the cases, the model should be approximated to the reality as much as possible. Due to the complexity and heterogeneity of the natural environment, any geophysical method, even if chosen as appropriately as possible, leads only to approaching a reality. The quality of results of survey work depends on the appropriate choice of methods used, on the difference between the real geological environment and the theoretical model, an on the experience of the interpreter.

Geophysical methods always provide the basic information on the geologic structure of a studied area. Sometimes this information is precise and concrete, and at other times this result cannot be fully achieved. Due to the complexity of conditions in the basement and vicinity of a construction, or for financial reasons, it is only about general information. At any rate, it is possible to acquire data which will enable the configuration and direction of direct survey work (boreholes, pits, etc.) in further stages of a survey. Obtained information is always useful because it means the reduction of financial demands for costly field work, and enables the implementation of survey work in the most suitable places at the shortest possible time. Such application of geophysical work leads to the improvement in the quality of results of the entire engineering-geological survey.

The basic demand laid on an engineering-geological survey of line constructions is its effectiveness, while keeping the required quality of survey. When observing this condition, it is, however, necessary to obtain all basic data for the safe design and operation of a construction. Mistakes in initial phases of a survey recur in later stages of work and their elimination is extremely demanding in technical, time and financial terms. Geophysics, as a science discipline, is capable of yielding a great number of information within reasonable economic limits in all phases of a survey. In certain cases it also delivers basic data, which are otherwise virtually unavailable or which can be acquired for considerably higher sums.

It is possible to view the use of geophysical methods in investigations for line constructions from two aspects. The first one is the potential of individual geophysical methods arising from their physical
principle, and the second one is the capability to solve a required task according to the demands of an engineering-geological survey. The author of any publication on the use of geophysical methods in investigations for line constructions faces the essential decision about from which aspect to approach the creation of the document. As in the large majority of similar cases, each approach has its advantages and disadvantages. To develop a comprehensive synthesis of both the approaches is virtually impossible. The third way is a possibility to choose a non-traditional technique, which we will attempt in this paper.

2. TASKS OF GEOPHYSICAL INVESTIGATION

A geophysical survey for road routes can give information in the following spheres:
- a) Survey of the route of a line construction
- b) Survey of tunnels
- c) Survey of bridges
- d) Survey of slope deformations
- e) Survey of other future constructions
- f) Survey of material deposit sites

Work during the operation of a construction. It is natural that in the initial stages of a survey, not always all spheres of questions are being solved. It happens that all emphasis is laid only on the first problem, i.e. only on the study of a road route. In the early stages of a survey, it is possible to advantageously apply also remote sensing methods, which holds true particularly now when available are satellite images of great resolution, images with a wide choice of spectra as well as stereoscopic images. Also, it is possible to apply advantages of aerial geophysical methods, particularly in a survey in little explored areas. In a survey for a line construction, we determine especially the thickness of a Quaternary cover, the thickness and extent of the loosening of a rock mass, and basic lithological types along a road route. Another sphere of problems represent the delineation of zones of the weakening of a rock mass, including the identification of tectonic fracturing of rocks, for it is better to avoid such a place when siting facilities related to a line construction. Last but not least, it is also appropriate in this stage to detect the basic physical and mechanical properties of rocks needed for designing a construction.

In the next paragraphs we want to show a system of the use of geophysical methods in a survey for line constructions as used in the Czech Republic, notably in the company Geotest Brno. There, we have been dealing with the use of geophysical methods in engineering-geological surveys for more than 35 years.

3. SURVEY OF ROUTES

The first illustration is from a survey of the valley of the motorway route Brno – Uherské Hradiště in the bridging of the brook Syrovátká near Křenovice (Fig. 1). The surface layer with higher resistivities is interpreted as loess. In the floodplain, there is evident a near-surface layer with lower resistivities than loess loams have. This layer can be interpreted as a layer of flood loams. Valley gravels are probably absent; if they occurred, then they would heavily contain loams, and debris of solid rocks would not form the basic matrix of sediments. In the right slope, there is depicted a layer which is probably a stabilised slope deformation (layer E). By the course of apparent resistivities of symmetrical resistivity profiling (SRP) it is likely that the slope deformation is not active and only the shape of the boundary delimiting the base of this resistance layer indicates its existence.

Between the Quaternary and Neogene sediments, there is layer F (on the left slope) and layer K (on the right slope). Both the layers can include, according to the borelog, the eluvium of the original sediments and the highest layer of the Neogene. Their more detailed geotechnical characterisation is very difficult on the basis of geoelectrical measurements. It can only be deduced that the sediments are very clayey and the further decrease in resistivity is caused by higher moisture than that contained in the relatively unweathered Neogene sediments.

The Neogene sediments of the left slope are formed by layers G, H, and I. Layer H corresponds to the Neogene claystones, layers G and I to sandy claystones. The Neogene beneath the valley bottom consists of a discrete medium, which is denoted as layer J. Based on the geoelectrical measurements, it is not possible to determine its lithological composition because this belt of rocks is tectonically fractured and the fracturing conceals the effect of the original lithology on the interpreted resistivities of the medium. The Neogene sediments of the right slope are formed by two different units, layers L and M. According to the borelog of J64 and the size of resistivities, layer L was interpreted as sandstones, and layer M as claystones.

To compare the properties of the individual interpreted layers, we always determined an average value and the distribution of resistivity for the given layer. Based on this processing, we can mutually compare the individual lithological types and study
whether the layers which are not mutual neighbours have the same lithological composition, or whether they are tectonically fractured to the same degree. The eluvium of the left as well as the right slope have lower resistivities than detected in the underlying layers. This is given by several causes. The first of them is the strong weathering of the rock material, another one is the washing of loamy and clayey components from the surface layers into the free spaces of the eluvium, and the last cause is the higher moisture of the eluvium as compared to the underlying rocks. According to the size of resistivities it seems likely that the claystones of the left as well as the right slope have also other similar physical properties and that they belong to the same stratigraphic unit.

Based on such processed results, it was possible to describe the geologic structure of the area of interest more credibly. According to the findings detected during a tentative survey, it turned out necessary to pay increased attention to the closer vicinity of the brook in higher survey stages. The reasons are the tectonic fracturing of the rock mass beneath the valley bottom as well as on the adjacent slopes, and the existence of an old slope deformation on the left bank of the brook.

Another illustration is from the use of seismic methods in a survey of roads. In this case, it was not about a survey of a new route, but about a geophysical measurement along a road which begins to be affected by an ancient mining activity. By seismic refraction measurement complemented with gravimetric measurement, we detected those sections of the route where we could expect a fracturing of a rock mass (Fig. 2). The velocities of longitudinal waves change on a refraction horizon from 0.6 to 2.4 km/s. The average velocity is 1.45 km/s. From the beginning of the profile, the boundary velocity is dropping to the marked velocity minimum in the 25 – 80 m stationing. From this point, the velocities are growing with small variations until the end of the profile. The velocity of the direct wave is relatively constant and ranges around 0.55 km/s.

The measured values of gravity acceleration were limited by an interval of 637 – 850 µgal with an average value of 733 µgal. The gravity maximum (850 µgal) was found in the 190 m stationing, and the gravity minimum (637 µgal) in the 70 m stationing.
The resulting curve can be divided into two sections. The first is in the 0 – 150 m stationing and represents a large gravity anomaly with the above-mentioned minimum in 70 m. From 56 to 106 m, a local anomaly distinctly emerges, also comprising the above-mentioned gravity minimum. The average value of gravity acceleration in this local anomaly is $655 \mu gal$.

The second section starting with the 150 m stationing, represents a “positive” anomaly. The gravity extreme (850 $\mu gal$) in 190 m also represents the highest value of gravity acceleration in this point.

In this profile, after the interpretation of measurement by both the geophysical methods, a single place of the rock mass weakening was identified. The weakening, located between the 27th and 87th metre, was, however, denoted as significant. From the quantitative interpretation of seismic measurements by means of the method of critical distances, the base of the Quaternary soils and fully disintegrated bedrock was determined at a depth of 13 metres. The same depth was also detected by means of the plus-minus method. The disagreement in the precise determination of the fractured bed was caused by not so fully identical direction of the measuring profiles. Their position was given by the conditions of field measurement at the time of their implementation. On the other hand, we must state that there are known cases when the position of anomalous zones from gravimetry and seismics above weakened zones is not identical. This phenomenon has not yet been theoretically explained to full satisfaction.

The next two illustrations show the results of shallow seismic refraction (SSR) interpreted by the plus-minus method while considering the penetration of a seismic ray to below a refraction horizon. This method of processing considers a velocity growth below the main refraction horizon, which is mostly given by a geologic structure and the knowledge of which is a substantial matter for addressing engineering-geological problems. Results of the method give the thickness and velocity of the first layer and velocity changes in the basement. Velocity changes below a refraction horizon run in a different manner and they can be mathematically described in various scenarios, then we speak of different velocity laws. In literature, we can find references of linear, exponential and parabolic velocity laws. In our opinion, there is a certain disadvantage of the above-mentioned laws, which is a constant growth of velocities with increasing depth. However, to the present time, only the linear law of velocity growth gained ground in practice. Its advantage is relative theoretical simplicity and a possibility of its application by conversion into a computer solution.

In the practical part we want to present possibilities to use the method of penetration in little usual geological processes (Fig.3). At the Žamberk site in the Bohemian Cretaceous, a short profile was measured.
Its very interesting feature is a distinct velocity maximum in its right side. The maximum is induced by the heavy silicification of clayey sediments of the Cretaceous. The existence of the heavy silicification has been confirmed by drilling work as well. It can be proved by detailed analysis of velocity isolines that this belt is limited by a fracture zone at low depths. The question remains whether the silicification is not also bound to the fracture zone, or whether it does not form its part. Another possible scenario is that the original fault had been healed with quartz and during the renewal of movements the rock mass was fractured beside the healed zone. The problem could be solved only by other measurements if it was necessary to search for explanation. We cannot exclude the need of other direct survey work either. It is, however, necessary to decide whether to resolve this question is essential for the solution of the given problem. The depth of weathering varies around six metres.

In Figure 4, there is an example of seismic measurement, the purpose of which was to detect the velocity gradient of the rock medium near the ground surface. Field measurement was carried out with two "shots" outside the array of geophones. Velocities are displayed below a refraction horizon because the task of measurement was to provide a picture of velocity changes of the pre-Quaternary basement. In the velocity section, it is possible to observe the course of velocities of longitudinal waves and to interpret the fracturing of the rock mass according to it. Curves of the following form were interpolated through the individual values of seismic velocity:

\[ V = a_1 + a_2 h + a_3 h^2 \]  

We can see in the curves a difference in the rise of velocities in a block of intact rocks (the stationing of 30) and in a block of fractured rocks (the stationing of 75). It is, however, quite clearly evident that the use of the linear velocity law is not ideal. This picture as well as other results of survey practice show that it would be very appropriate to renew theoretical work on mastering the procedure of non-linear growth of velocities. Only after the derivation of suitable models, it will be possible to proceed to the conversion of the whole problem into computer processing and thus also into the routine survey practice. The implementation of multi-channel devices into field measurements ensures the demand for a larger amount of data for the solution and processing of new procedures.

The fifth illustration is from a relatively unique measurement, i.e. from the processing of surface seismic tomography from the Budimír landslide in the east of Slovakia. When constructing a road bed, open cracks were found. The task of the geophysical measurement was to contribute to the clarification of the geologic structure of this landslide and to explain the reason why the cracks appeared on the completed road bed. This example is thus from the version when the effect of the surface layer was eliminated by its excavation. The Budimír slope deformation lies north of Košice. The area is formed by the Košice Gravel Formation (KGF) consisting of Quaternary limnic-fluvial sediments. Sands, clays, loams and gravels rapidly alternate and very often form lenses. The KGF is underlain by Sarmatian clays. This entire area is susceptible to sliding. Tomographic measurement at the Budimír site was conducted in the version of non-longitudinal seismic
measurements between two profiles. The spacing between sensors was three metres and that between sources was 7.5 m. The results of seismic tomography show the rock mass fracturing by tensile cracks. It is known from seismic refraction measurements that although the measurement took place on the uncovered road bed, there is a refraction horizon there. Therefore, we must bear in mind that the plotted isolines characterise relative and not real velocities. The given velocities are the function of the size of the velocity of longitudinal waves of the direct wave, the velocity on the refraction horizon at a depth of about 5 m, and the precise depth of this horizon. This effect is roughly constant at the studied place and thus it is possible to deduce the relative magnitude of fracturing or to assess mechanical stress according to the size of velocities.

When interpreting seismic tomography, it is suitable to proceed from the comparison of results of tomography with SRP measured on an oblique profile. In Figure 5, besides the map of velocities from seismic tomography, there is also the course of apparent resistivities. On the graph of results of SRP, it is possible to document two distinct features. The first is a swift oscillation of apparent resistivities in the places where sand prevails. The second is the drop of resistivities in the places where clays prevail, and the relatively homogeneous course of apparent resistivity in such beds. From the map of relative velocities it is possible to distinguish four zones of different velocities, which correspond well with the results of SRP, where it is possible to identify 4 basic blocks.

From comparing all materials it is possible to infer that the rock mass on the road bed lies in the area of tensile stresses. The value of tensile stress is not the same everywhere. In certain places it is low and tensile stresses do not reach anomalous values. This is in those places where the velocities reach relatively high values (block 2). This block is disturbed by short cracks which are not persistent (see the crack occurring only in the centre of the picture). The firm contact of individual sandstone blocks guarantees relatively high velocities, and the presence of air on fissures results in high apparent resistivities. Suffosion phenomena emerge on some cracks. Another extreme is block 3. In this block, rocks underwent pronounced fracturing accompanied by their alteration. The origination of first tensile cracks at the time of the formation of the anticline of Sarmatian clays was facilitated by the intense weathering of the original rock material, which gradually assumed a clayey character. The full alteration of the original mass is not necessary for the resistivity to be lowered, but it is sufficient that an adequately strong conductive network of clays is created. This block has about five times higher resistivity than pure clays. According to the results of SRP (two spacings), this block has the sub-vertical and not the sub-horizontal delineation, as it is in the transition from sands to clays, which corresponds to the sedimentary boundary. The block is manifested not only by decreased resistivities but also by decreased values of relative velocities determined from seismic tomography.

The last type of fracturing affected blocks 1 and 4. The rocks there are intensely disturbed by tension. A part of tensile cracks is filled with clay. The considerable tensile fracturing of this block is also suggested by relative velocities which are distinctly lowered; more in block 1 than in block 4. Apparent resistivities are, however, fluctuating due to the existence of tensile cracks. According to the results of seismic tomography, it is possible to determine that block 1 is the equivalent of block 3. The values of relative velocities reach the same sizes in both the blocks. It is, however, interesting that in block 1 there are no visible cracks on the road bed. This fully confirms the theory on the alteration of the rock mass and on the movement of main tensile stresses into relatively little disturbed blocks. In the upper left-hand corner of the measured area, we can see how the individual cracks limit the block of relatively undisturbed sandstone.
4. SURVEY OF OBJECTS

Another illustration presents results of methods which are now used only in a survey for objects, not in the whole length of a route of a designed road. The first example is from seismic tomography (Fig. 6), which shows velocities obtained by the tomographic processing of the extended seismic logging of borehole J4 in the Strečno Ravine. The most marked feature is a distinct growth of velocities near the borehole bottom. This corresponds to the transition between little weathered and practically unweathered granodiorites. This boundary would be a refraction horizon in surface seismic measurement. Another distinguishing element is an anomaly of higher velocities with its centre being at a depth of about 15 m under the 10 m mark. This place with increased velocities represents a block of little weathered granodiorite. It is very likely that this block also juts out above the gravel base. Such a place is practically undetectable by a drilling survey. The interpretation of boundaries between individual media proceeds from a borelog and is further specified according to the course of velocity isolines. Findings on uneven weathering are very important for an engineering geologist and a designer of building work. If, for example, an unsuitable methodology of building-pit digging is chosen, great difficulties might arise in its implementation.

Certain special problems in civil engineering, geotechnics and an engineering-geological survey can be successfully solved by ultrasonic measurements. It is particularly about problems bound to small volumes of a studied environment. This limitation is given by the high attenuation of high-frequency elastic waves in the real geological environment, but also in the environments created by human activities. Ultrasonic measurements can be applied especially in detecting mechanical parameters of a studied environment. In this case, we can mention different samples of building materials, drill cores and, last but not least, the possibility of ultrasonic radiography of small-volume bodies.

The next illustration (Fig. 7) is from the radiography of concrete objects. Ultrasonic radiography was applied to concrete pillars of an overhead urban road in Ostrava. The velocity curves in three pillars show that the pillar concrete is isotropic and that the differences in the concrete quality between the individual pillars are not significant either.

The following two illustrations will be from areas which fall into a survey for tunnels and an inspection of their driving, respectively. An illustration in Figure 8 is now from the comprehensive documentation of a gallery as used in Czechoslovakia in the 1970s and 1980s. The illustration is from the Tereza gallery at the Malá Vieska site. A complex of methods, including a geoacoustic method and temperature measurement by a contact thermometer, was used for documentation. Both the methods were measured in short holes on the gallery bottom. A block of dolomites (to 210 m) and a block of limestones (the rest of the gallery) were delineated by the geological documentation of the gallery. Based on the comprehensive documentation of the gallery, the rock mass in its vicinity was divided into three basic blocks: A (0 to 115 m), B (115 to 210 m), and C (210 m to the end of the gallery), i.e. two blocks belong to dolomitic rocks and one to limestone rocks. Then, a more detailed analysis of all measured values enabled to delineate partial sub-blocks. Places of geotechnical tests were prescribed from such obtained basic data, and other derived parameters were acquired by calculations from geophysical
measurements (Poisson’s rate, moduli of elasticity, etc.). Interesting is a geoaoustic anomaly in the vicinity of 150 metres. Because this anomaly had no direct geological explanation at first sight, we repeated this measurement with another apparatus roughly after seven weeks. The existence of the anomaly was fully confirmed and we see its origin in a zone of concentrated stress above a thrust plane, along which dolomites were overthrust on limestones. A specific example of performance of geophysical tests is long exploratory workings or constructions operationally driven for the full profile by tunneling machines, where the testing activity gets into the conflict with the advance of a working/construction. On the other hand, this work technique provides better conditions for the geophysical documentation of workings/constructions. The results of such work show that particularly in the application of seismic methods it is possible to fully use not only longitudinal but also transverse waves. In Figure 9, there are results of measurement in such a working. In mechanical tunneling, the rock mass is not so much disturbed in the vicinity of the working as with the use of blasting work. When applying seismic methods, also transverse waves are successfully generated even with the use of standard seismic sources. The result is then the possibility to calculate Poisson’s ratio and shear moduli. In Figure 9, in the left-hand part, there is an illustration of measurement of a section in a tunnel in the Brno eruptive rock, and in the right-hand part, the summary of results, including calculations of other
parameters from the whole tunnel. In the event that we can manage to “continually” measure such a whole working, then we can further describe the rock mass by the statistical processing of obtained results and divide it objectively into quasi-homogeneous blocks or units. If we can manage to also use other fast methods in documenting a working, such a division will be still more objective. A separate sub-chapter will be devoted to the relationships between moduli.

Every object (building) inter-connected with the rock environment, located whether on the ground surface or below it, must be designed and constructed so that its life is maximal. This, among else, means that the design plans of an object must contain specific protective structural elements which minimise negative effects of the rock environment on the designed object.

The methods assessing the effect of the rock environment on objects include measurement of corrosive effects of stray currents. Figure 10 demonstrates measurement of corrosive effects on a pile of a road bridge. Geophysically, the aggressivity of the environment is assessed on the basis of the current density of stray currents and the size of apparent resistivity of the rock environment. The upper line graphs demonstrate measurement of apparent resistivity of rocks in the vicinity of the object of interest – the pile. Measurement is performed for two depth levels and the picture shows that thanks to the relatively high values of the measured quantity it is possible to classify the environment by the “very low aggressivity” degree. The graphs in the middle and lower part of the picture demonstrate the measurement of stray currents where particularly the middle graph documents a high variability of stray currents in time and space. The result of measurement was the construction of the resulting vector of stray currents and then the environment was assigned the category of very high aggressivity of environment.

An important part of an engineering-geological survey is boreholes and the other artificial exposures (dug pits, trenches, galleries, cuts and excavations). Direct survey work gives a possibility of detailed evaluation of drill cores and the description of walls of stripping work, and hence it becomes an important method for obtaining needed data on the geological conditions of the investigated territory. It also enables a detailed classification of rocks and soils, direct evaluation of deformation zones (inhomogeneities, discontinuity planes, etc.) and evaluation of their physical-mechanical properties. Drilling and stripping survey work enables not only sampling for laboratory investigation, but gives a possibility of direct in-situ testing of rocks and soils on or below the ground.
surface and their investigation by indirect survey methods, such as logging, TV probe, photo and video documentation of walls of boreholes and stripping work, inspection of their walls by a periscope, etc. If necessary, it is usually possible to suspend a compass below a camera and to determine with its help the orientation of linear and planar elements of a geologic structure (Fig. 11).

One of the greatest obstacles in the construction of roads is slope deformations. Therefore, greater attention is being paid to the application of geophysical methods in their survey. An illustration in Figure 12 is from the Ujala I landslide in northern Moravia. Four partial schemes are successively displayed on the graphic representation of the results of a survey of the landslide. The upper scheme represents a graph of results of measurement of SRP and velocities of longitudinal waves on the main refraction horizon. Two middle pictures represent the velocity fields both from seismic tomography and from SSR (velocities below the main refraction boundaries). The lower picture displays results of the quantitative interpretation of VES, SSR, logging and the overall geological interpretation of survey work. The landslide was divided into eight different geological units. Outside the landslide, the surface layer is formed by very variable loams. On RS30, there is an evident sunken block. On the plateau further to the north, there is a crack with the ground subsided by 20 cm. Above the landslide, the loess loams are underlain by a layer which is obviously formed by loamy glaciogenic sediments. However, we cannot exclude that RS15 and RS30 are also influenced by the groundwater table and the capillary fringe. The block subsidence just behind the scarp is also documented in the SSR results. The depth of the base of this layer determined from resistivity sounding (RS) and SSR is virtually identical. Low velocities of this layer, also evident from velocity isolines, rather indicate that this layer is formed by glaciogenic sediments than by the weathered Neogene.

The floodplain loams are underlain by a layer of fluvial sediments, sands and gravels. Based on the size of resistivities, we can state that the soils are highly variable and their composition ranges from loamy sands up to relatively pure sands and gravels. Beds with high resistivities may exhibit significant groundwater flow. The total thickness of the river Olšė terrace, geophysically identified in this place, is in good agreement with the results of archive drilling work. Interesting is the greater thickness of the terrace just at the toe of the slope. It can be caused by either the stronger erosion activity of the river Olšė in the post-glacial period or the smaller strength of the basement in this place. This is obviously caused
by the tectonic disturbance of Neogene claystones (see Fig. 12). Geodynamically most active is an upper slope deformation – a landslide. It is marked by a dense hatch in the picture. The landslide material consists of a mixture of all types of Quaternary soils and of underlying Neogene clays. All soils are remoulded and physically form a single layer. In the longitudinal direction, we may distinguish two partial landslides from geophysical measurements. The curves of SRP and the seismic measurements show that the rock mass in the proximity of the surface is under tensile stress from the scarp to SRS75. According to the results of seismic tomography, the active landslide is fully relieved, particularly in the upper part of the slope. Up to the stationing of about 70 metres, the velocities of longitudinal waves drop below 0.6 km/s. They suggest the low bulk density and high mechanical fracturing of the landslide material. Below the upper landslide, we can find other two storeys of slope failure caused by a deep slope deformation. Due to the marked minimum of velocities in the vicinity of the 50 metres stationing, it is obvious that there is a distinct tensile zone there. We can deduce from it that the middle storey of the slope deformation is in the active, though probably slight, movement. Only the lowest storey of the slope deformation can be considered as a currently steady structure. The middle and the lower storey of the slope deformation are marked by a thin hatch in the picture. The middle storey of the slope deformation cannot be distinguished by resistivity in a part of the
of penetration, velocities are determined mostly from measurements. The lowest shear plane was determined geoelectrically and, in the lower part of the landslide, also by the SSR method and hole logging curves too. The tensile fracturing of deep deformations near the scarp can be observed not only in the above-mentioned velocity field, but also in the quantitatively determined low velocities in SSR60, where a velocity of 0.7 km/s is documented down to a depth of about 17 metres from the interpretation of critical distances.

In the field of velocities from the tomographic processing of seismic radiography, we can see the interesting distribution of velocities. In the upper part of the landslide up to the stationing of about 70 metres, we can find low velocities of longitudinal waves. In the middle storey of the landslide, velocities drop below 0.8 km/s; in the lowest storey of the landslide, the detected maximum velocities reach up to 1.2 km/s. Such low velocities down to 15 metres are quite anomalous and indicate the pronounced tensile stress of all storeys of the slope deformations. Conversely, in the lower part of the slope, velocities increase up to 1.6 km/s. From velocity isolines, we can even see an inversion of velocities in a section of 80 to 100 metres. Anomalies of increased velocities are located around the centre of the shear plane. The increase of velocities in the lower part of the slope may be caused by either the increased stress of rocks due to friction on the shear plane, or the compression of material in the middle and the lower storey of the slope deformation. The changes in velocities according to seismic tomography are also in good agreement with the results of logging measurements. We can assume a possible explanation that the drop of velocities need not be caused only by rock fracturing, but is also given by the transition from the zone of increased tensions to that of normal tensions.

The comparison of velocities detected by seismic tomography and shallow seismic refraction informs us on their different values. Velocities determined by the plus-minus method are higher by values which could be explained by inaccuracies of measurement and interpretation. To explain this phenomenon, we must proceed from the principle of both the methods. When determining velocities by means of the method of penetration, velocities are determined mostly from rays parallel to the surface. Velocities determined from seismic tomography are the average value of velocities from all directions. If Figure 12 shows higher velocities from the method of penetration, then we must find out why the velocity in this direction is higher. The only possible fact which is capable of causing this situation is horizontal stress. If the ratio of velocities of both the methods is less than 0.8, then horizontal velocities are about 1.5 times higher than vertical velocities. Here, we must repeat that seismic measurements identify facts which are undetectable by classical engineering-geological surveys. In such cases, it is necessary to introduce the existence of horizontal stresses into stability calculations. New methods of stability calculations have already such capabilities.

In the post-glacial period, the river Olše has been deepened by erosion to the level of the base of the current terrace. As a result, the slope was undercut and slope deformation “B” has been formed. Due to the collapse of the slope, the river was forced away from its toe. The material of the slope deformation was gradually denuded by further erosion, hence the toe of the slope was again relieved. A new slope movement followed, resulting in slope deformation “A”. Materials of deep deformations (Neogene clays) are disturbed in two ways.

After glacier recession, the upper layer of clays was relieved, hence sub-horizontal cracks were formed. After lateral erosion had drawn nearer and after the first slope movement, clays were horizontally deformed together with the origination of vertical cracks. This was the way how the moisture of clays was increased. This, together with the deformation of clays by the slope movement, has resulted in the lowering of resistivities of deep deformations. Additionally, this was supported by released sandy intercalations, which have consequently served as suppliers of water to below the slope deformation, or directly onto shear planes. The resistivities of deeper deformations are then lower than those of upper landslides, the material of which is disturbed by sliding more than that of deep deformations. The fact that remnants of sandy glaciogenic sediments are “rolled in” them and that there are cracks filled with air in upper landslides participates in the increase in resistivity of upper slope deformations. Similarly, resistivities of deep landslides are lower than those of relatively less disturbed underlying clays. Vertical cracks were not formed there and, naturally, these slope deformations were not disturbed by a slope movement.

The bedrock of all above-mentioned geological complexes is formed by Neogene sediments. The lowest resistivities can be found at the toe of the slope in RS118 and RS148. It is likely that the Neogene sediments are tectonically weakened in this place. This is obviously also the reason why the lateral erosion of the river Olše has advanced up to these places. Near this zone of weakening, there is a layer with higher resistivities. We can express an assumption that this layer consists of firmer rocks than the Miocene claystones. It is either a sandier
bed or a bed with a higher admixture of a calcareous component. According to the results of seismic tomography, we can state the decrease in velocities at greater depths in the stationing of about 70 metres. The drop of velocities is also documented on logging curves and is obviously caused by the disturbed Neogene sediments underlying the landslide or the slope deformation. This supports an assumption that the origin of the slope deformation in this place is bound just to the disturbance of the Neogene claystones.

One of the important findings which we have obtained in surveys of slope deformations is the typical fluctuation of resistivity curves and the increase in values of apparent resistivity in the tensile zone of slope deformations. One of such measurements is presented in Figure 13, when four spacings of SRP were used on the Paskov landslide (the picture shows only two of them). The SRP curves in the landslide are relatively monotonous, particularly if the curves with greater spacing are considered. The curves of short spacing with a reach of about 2.5 and 5 metres, respectively, still depict the occurrences of the individual blocks of Quaternary soils in the landslide (23 – 35 m and 45 – 60 m metre spacings). According to the SRP, the boundary between the landslide and the zone affected by tensile stress is in the 75th metre. Another part of the slope, which is adjacent to the landslide crown, is markedly affected by tension, but a distinct movement has already occurred in it. These tensile changes appear not only on short spacings, but also on long ones, i.e. that the lower storey of the slope deformation is also affected by tension.

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**Fig. 13 Resistivity manifestation of a tensile zone**

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**Fig. 14 Geoacoustic measurements - shear plane determination**
In the past years in the Czech Republic, great attention was paid to the development of a geoacoustic method (rock noise), which was largely applied for determining the position of a shear plane and the activity of slope deformations. In Figure 14, there are two illustrations of such measurements. The first illustration is from borehole JS25A on the Harvelka landslide. The shear zone consists of two narrow shear sub-zones (or two shear planes) just one above the other. This fact, however, is not substantial because deviations in determining the depth of the shear plane, or the base of the shear zone, are less than 1 m.

The second illustration of geoacoustic measurements is from the Oravský Podzámok landslide and documents the seasonal character of the occurrence of acoustic emissions. In the winter season, both storeys of the slope deformation are stable. The upper part of the slope deformation is much disturbed in the period of the spring thaw, which is reflected in the high value of the relative amplitude to a depth of 15 m. The slope movement has affected loams above the old deposit of the river Orava. The lower storey is less active – roughly 6 times – and affects the lower part of loams and mostly a weathered layer of claystones. The lower part of slope deformations often escapes the attention of engineering geologists mostly because it has the character of creep. The evidence of its existence is one of the great successes of geoacoustics.

Another specific method used in Czechoslovakia was the method of magnetic marks. It was used in those cases when large deformations of a slope were expected (decimetres to metres). The method is based on the observation of the movement of permanent magnets placed into the body of a landslide. Magnetic marks can most often be applied to slope deformations of the type of flow. Permanent magnets are mostly penetrated down to a depth of five metres. The accuracy of locating the epicentre of the magnet is better than 10 cm. The method is mostly applied in such cases when due to a great movement of a rock mass, monitoring boreholes are being destroyed. The interpretation of measurement...
proceeds from the effect of the generally orientated magnetic dipole.

A practical illustration is from the Trinec landslide (Fig. 15). The Trinec combined landslide has in its upper part a torn-off block of cemented terrace gravels, which rotates against the slope. This upper part of the slope deformation "presses" against the upper part of the flow slide formed by older slides and weathered claystones. The pictures show that the vectors of displacement of surface points and magnets at a depth of 1 - 2.65 m are practically parallel. A detailed study of vectors of displacement shows that the landslide movement is uneven in both time and space.

Magnetic marks enable to obtain a good idea on displacements inside rapid landslides without the danger of breaking a measurement system by human malice or of destroying casings, wires, anchors, etc. Besides indirect survey methods, we can also apply direct survey methods to slope deformations (landslides, etc.), or to their manifestations and effects – e.g. optical documentation. Using optical documentation, we can observe overhead, ground and underground objects, which are affected by slope deformations. Figure 16 represents a static record (fragment) from a video inspection of an engineering-geological borehole designed for measuring by the method of precise inclinometry (PIM). The borehole is located on a slope deformation. The photograph shows a clear distortion of borehole casing caused by the movement of rock masses along a shear plane. The need of optical documentation was brought about by the sudden impassibility of the borehole for measuring by the PIM method.

The solution of the issue of slope deformations in a built-up area should always finish with their remediation and post-remediation monitoring. One of the effective remediation methods is to drain slope deformations and thus to reduce hydraulic upward pressure inside the mass. The drainage of the slope surface is usually made by a system of drainage pipes and troughs; the drainage of deeper parts of the rock environment at the level of the shear plane(s) is usually carried out by horizontal drainage boreholes. These boreholes serve for draining groundwater, for which the shear plane is one of the significant communication structures. The efficiency of drainage boreholes is assessed on the basis of the quantification of discharge and movement of the groundwater level in nearby observation boreholes. The optical inspection of boreholes is capable of recording the position of water inflows into boreholes and of giving the physical state of borehole casing – see Figure 17. Further work progress, including their potential cleaning, is recommended according to the detected state of boreholes.

5. CONCLUSION

The submitted paper gives a view of the use of geophysical methods for a survey of line constructions in the Czech Republic, particularly in the company Geotest Brno. The introduction presents general rules for the application of geophysical methods in engineering geology. The next chapter generally describes the tasks of geophysical measurement in a survey for line constructions. The tasks are further worked out in practical examples from surveys of routes and from surveys for objects. Results of common as well as specific geophysical methods are analysed. Special attention is paid to slope deformations.


