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APPLICATION OF GEOPHYSICAL METHODS IN THE STUDY OF LANDSLIDE MOVEMENTS, TAKING INTO ACCOUNT GEOLOGICAL CONDITIONS IN THE SUDETY MOUNTAINS

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ABSTRACT
Geophysical department of G IMPULS Praha systematically deals with the issues of landslide movements and possibilities of their detection by geophysical methods. The geophysical measurement is able to inform both about common geological condition and about geotechnical features of an area. We want to call your attention to the fact that these methods can be useful also in systematic investigation (including the monitoring) in the Sudety Mountains and adjacent areas.

KEYWORDS: geophysical measurement, geophysical method, landslide

Geological conditions in mountainous areas are often complicated by landslide movements which may be of fossil or recent origin. As it is generally known, landslide movements are often activated in connection with torrential rains which in some regions of the Czech Republic last occurred in 1997 and 2002. Landslide movements largely occur repeatedly in old landslide regions. An experienced mapping geologist is able to easily identify areas in which the presence of old landslides is indicated by morphological features. On the other hand, it is difficult for a geologist without technical instrumentation to demonstrate that an old landslide is really present at a given location, to identify its basic characteristics and the level of potential risk posed by such landslide. In this respect, a geologist can be assisted by a well organized geophysical survey. The advantage of geophysical survey is in its nature of nondestructive investigation which can be conducted at the locations where survey drilling encounters with disapprovals of the property owners. The geophysics allows us to acquire at the geophysical profiles practically continuous information, a change of which can be monitored in time. Geophysical survey can be employed not only within the framework of common geotechnical investigation, but the practice has shown that it is useful also in the cases of emergency where sudden landslides pose risks to the line structures, buildings, etc.

Landslide movements have a character of an anomalous effect which can be observed as differences in physical properties of a medium. We know from experience that these differences can particularly be found in behaviour of elastic (seismic) waves, in the presence of residual gravity anomalies, in a change of electric resistivity or natural electric field. Changes in the character of magnetic field can only marginally be expected. If geophysical logging methods or a complex of logging penetration methods are applied, it is possible to detect changes in density indirectly by means of a gamma-gamma method, to detect changes in moisture content by means of neutron logging or to demonstrate changes in physical properties by means of dynamic or static penetration.

SEISMIC AND DYNAMIC TESTS:

The velocity of propagation of seismic waves depends directly on mechanical properties of a medium, which for a longitudinal (formula (1)) and a cross wave (formula (2)), respectively, can be expressed by the following formulas:

$$V_p = \mathrm{E}_{seis}.\rho^{-1}(1-\nu)\cdot(1+\nu)^{-1}\cdot(1-2\nu)^{-1} \qquad (1)$$

$$V_S = 0.5\cdot[(\mathrm{E}_{seis}\cdot\rho^{-1}\cdot(1+\nu)] \qquad (2)$$

where E_{seis} is Young´s modulus of elasticity determined by a seismic way, ν is Poisson number and ρ is bulk density of a medium. The formulas show that the seismic measurements allow us to identify, among other, significant geotechnical quantities, i.e. modulus of elasticity and Poisson number.

As deformation rate in a seismic wave energy effect on the rock environment is low, we recommend, based on investigation conducted by us, to use for conversion of modulus of elasticity a correction formula (by Masuda), see formula (3(:

$$\mathrm{E}_{Masuda} = 0.5\cdot E_{seis}\cdot\nu\cdot\nu_{matrix}^{-1} \qquad (3)$$

where, v is seismic velocity of a medium and v_{matrix} is velocity in matrix corresponding to a given rock type. By using formula 3, E_{seis} is converted to E_{Masuda} value which can be expected for deformation corresponding to a classical loading test.

For a medium showing variable porosity (particularly sandstones) or variable jointing, we have elaborated an application of formula (4) (Hőschl and Bárta, 1989). The formula indicates a porosity P value. By this term we understand all free space in the block of a rock massif, i.e. we take into account both free pores and jointing:

$$P = 50 \cdot \Big[(v_m \cdot v_w) \cdot (v \cdot (v_m - v_w))^{-1} - v_w \cdot (v_m - v_w)^{-1} + \\ + (\rho - \rho_m) \cdot (1 - \rho_m)^{-1} \Big] \tag{4}$$

where, v is velocity of a studied medium, v_m is velocity in matrix and v_w is velocity of a seismic wave propagation in water, ρ is bulk density of the rock environment and ρ_m is bulk density of the matrix. Bulk density of a medium is determined under optimal conditions as weighted average from the results of gravity measurements because the results of laboratory measurements are often not objective (difficulties with collecting of undisturbed samples, taking into account the effects of wider tectonic zones, etc.).

In the application of seismic measurements, a simple geometric view is mostly used for the interpretation of seismic cross-sections. It is represented for example by calculation programmes based on a known t_0 method. This method assumes linear propagation of a seismic ray of a direct wave, which is refracted at a distinctive refraction boundary. However, landslide areas in fact represent a complicated velocity medium. The character of velocity gradient both in vertical and horizontal directions is rapidly changing. It is therefore recommendable to check the basic interpretation also by some type of software based on ray analysis of seismic waves. As a basic velocity model, positive vertical velocity gradient with propagation of a seismic ray following approximately parabolic trajectory can be accepted. Areas showing irregular velocities (over 10 000 m/s) are an unmistakable sign of diffraction of seismic waves (tectonics, inhomogeneities, etc.).

Recently, experts of G IMPULS Praha have been experimenting with the application of vibrator technology used for exciting of seismic impacts, and also with the interpretation of geotechnical properties of a medium by means of a frequency analysis of Rayleigh´s waves (SAW, MASW methods). The work results have been published in the literature, for example (Bárta et al., 2003; Vilhelm et al., 2003). The fundamentals of this new methodology are well described in the literature (Socco and Strobbia, 2004). The method is promising particularly for the monitoring in the areas of potential zones of separation as repeated measurements can be conducted under identical conditions and the measured primary data can be subjected to highly objective statistical comparison.

GRAVITY MEASUREMENTS

Gravity measurement forms an integral part of a package of geophysical methods. Current level of instrumentation allows us, assuming good knowledge of morphological features of the terrain in question, to detect not only basic geological structures but also to characterize changes in porosity or in jointing. Gravity measurement results are also used for the calculation of porosity according to equation 4 (see above).

Solid objects such as rock elevations show positive anomalies. Lack of mass (for example cavities, increased porosity of a medium) is shown by a resulting negative anomaly. Characteristic outputs of gravity measurements are formed by diagrams showing the measured and corrected gravity values or by interpretation gravity models. The models indicate the calculated distribution of masses best fitting to the measured values.

As highly promising can be considered the application of gravity measurements in the monitoring of landslide areas, particularly in the period of expected (potential) increase in the slope activities. Our opinion is supported for example by the result of test measurements conducted at a landslide close to Vsetín (Bárta, 2003). The accuracy of modern gravimeters (sensitivity around 0.002 mGal) allows to expect that in a residual gravity anomaly also showings of changes in stress of a rock massif or significant changes in the water regime of an investigated location can be detected. A major advantage of the monitoring work is in the fact that the measurements can be repeatedly conducted at an identical profile (area). In such case, practically no necessity of perfoming exact topographic corrections is required as of crucial importance are relative changes in the primarily measured data.

NATURAL ELECTRIC FIELDS

The method of natural electric potentials is a field-tested method intended for the groundwater flow observation. In the case of the issues connected with potential water flow, particularly so-called filtration potentials and diffusion-adsorption potentials have to be taken into account. Filtration potentials arise due to higher mobility of positive-charged ions in a capillary (quasicapillary rock system). Diffusion potentials arise due to differing concentrations of water solutions separated by a membrane. Adsorption potentials arise in connection with differing porosity of a medium. Theoretic fundamentals of the applied method are described in detail in the literature [Semyonov, 1968]. Semyonov was the first to notice the fact that Quaternary water flow through a slope was

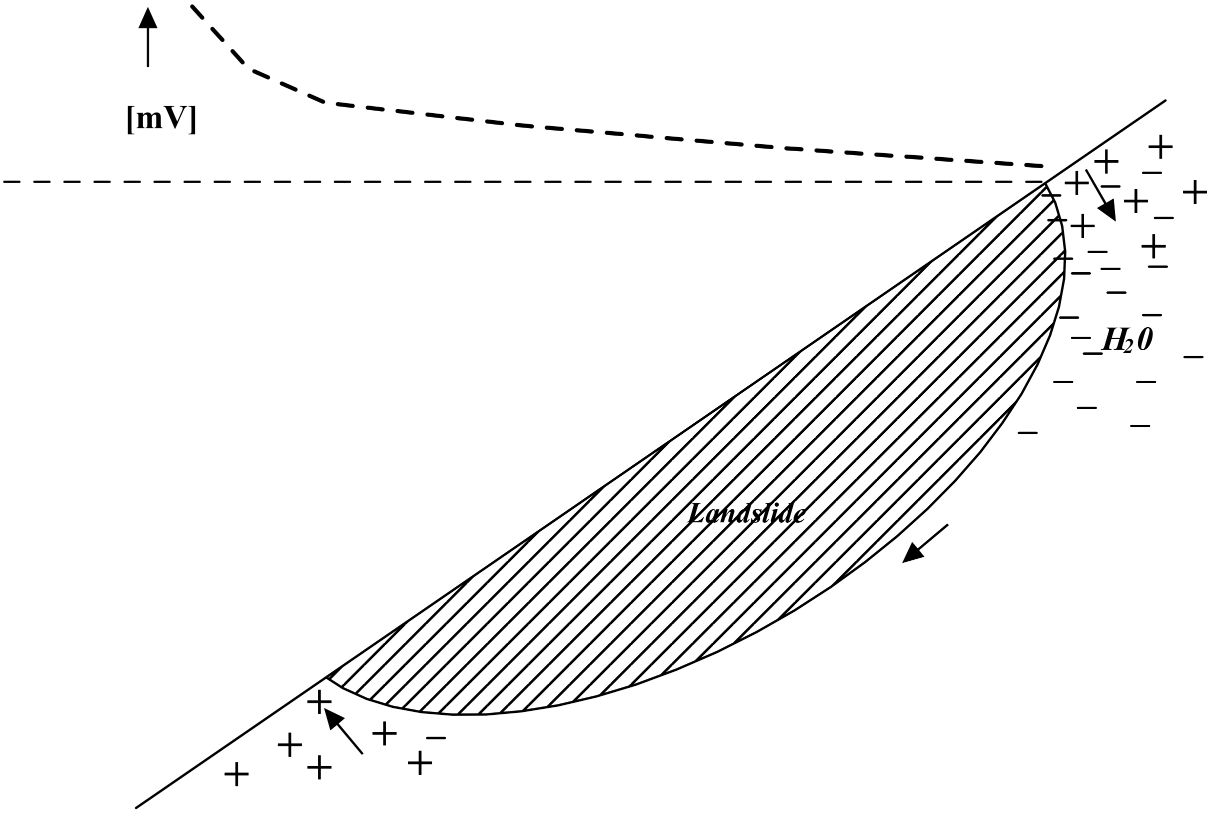

Fig. 1 Creation of filtration potentials (model of typical condition for landslide area)

accompanied by an increase in natural electric potential downgradient of a slope. As demonstrated later, it is possible in this way to detect gradual moistening of a slope resulting in a landslide shear plane saturation with water, or to observe gradual occurrences of seepage in dam/dike structures.

On Fig. 1, a scheme explaining occurrence of a potential difference between a zone of separation and landslide foot is shown. On the territory of the Czech Republic, the monitoring of landslide movement activities by means of measurement of natural potentials was first conducted in 1964. The measurement was performed within the framework of geotechnical stabilization of Nechranice water structure (Bárta, 1966). The work demonstrated that the landslide which after a winter period showed a slight movement (on order of centimetres per month) also showed an increase in potential differences (on order of milivolts).

The method of monitoring of electric potentials was successfully applied also in the observation of landslide above a railway line close to Vsetín. A change in electric potentials successfully indicated a sudden increase in activity in spring 1998 and gradual stilling of a landslide relating to its drainage.

RESISTIVITY MEASUREMENTS

The magnitude of electric resistivity particularly depends on a grain size of the rocks, contents of water and its mineralization. Electric resistivity decreases with increasing contents of water in the rock and with increasing mineralization of water. On the other hand, resistivity increases with an increasing grain size of the rock. This means that resistivity measurements allow us to well separate individual structural elements of the rock massif and to observe changes in time. As varying with time there may be a factor of moisture content. The water gradually infiltrates into a medium and reduces its resistivity. Examples of resistivity measurements in landslide areas occur frequently in the literature as so far these measurements were relatively simple, based on four-electrode measuring systems. However, with the development of advanced computing techniques it is possible to use also multielectrode systems allowing the application of various arrays of electrodes and interpretation by means of sophisticated software. For example, the team of authors of this paper tested a possibility of application of resistivity tomography in a landslide area at a location close to Vsetín (Bárta et al., 2003). The interpretation was made by means of a licence

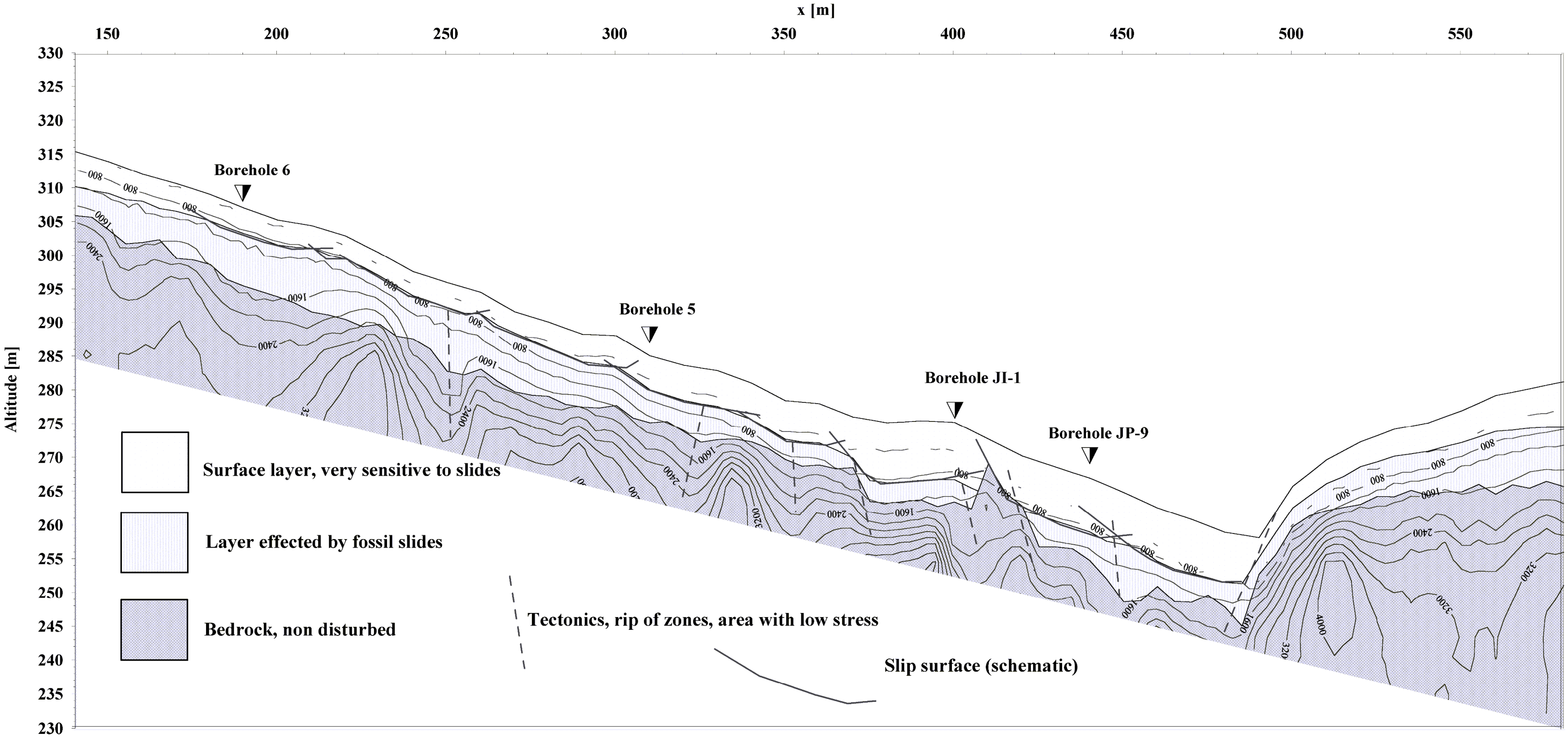

Fig. 2 Seismic cross section supplemented by contour lines of velocities [m/s] and by interpretation of slip planes. Profile P2. Halenkovice

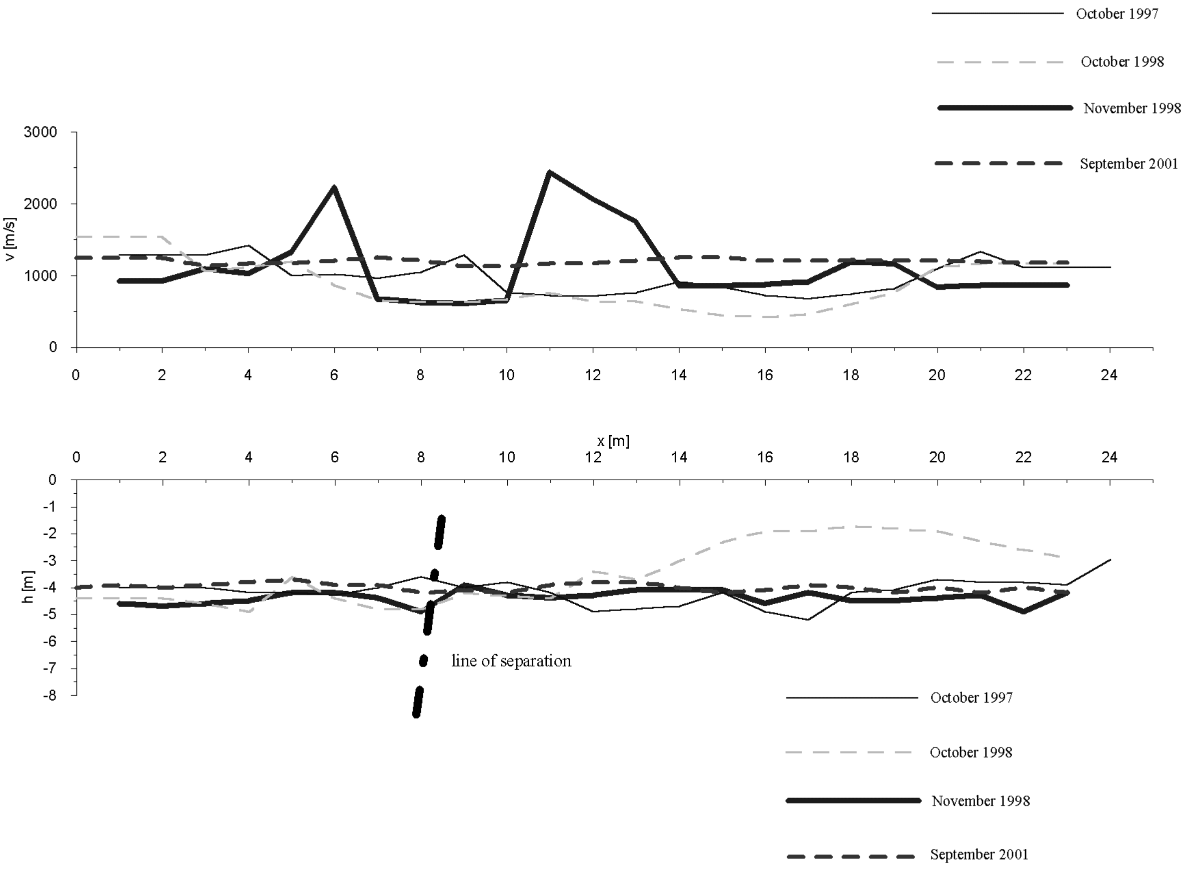

Fig. 3 Seismic cross section and graph of velocity. Line of separation, Bystřička. Monitoring since 1997.

software Res2Dinv. The programme has turned out to be reliable for complicated geoelectric conditions, without any reservations for the zone between the ground level and bedrock (or reaching a depth of around 30 m below the ground level). Deeper areas below the ground level are screened by near-surface effects and the imaging of bedrock changes is therefore somewhat simplified. The multielectrode systems show rather high productivity of work and can also be applied at the locations preventing the drilling rigs from the use. The above mentioned statements apply to the work conducted in 2D regime. The team of authors and their co-workers also tested a 3D variant of measurement and interpretation. The entering of the third dimension inadequately increases the requirements on computer capability and on the correctness of the starting resistivity model (i.e. correctness of geological concept). For this reason, for the current technological level it is optimal in landslide areas to take into consideration particularly the measurements conducted in line profiles and to prepare models on order of max. 2.5 D.

GROUND PENETRATING RADAR MEASUREMENTS

Relatively limited in studying landslides is the application of geological radar (GPR). In preparing a project of GPR application it is important to take into account that landslide areas are largely characterized by lower values of resistivity. This results in lower penetration depth of GPR measurement (an optimum is 5 metres). Also manipulation of an antenna system in a complicated terrain affected by landslide is demanding, not always guaranteeing good reproducibility of the data.

On Fig. 2 through Fig. 5, characteristic examples demonstrating effectiveness of geophysical methods are shown. The examples have been selected in order to show similarity of geological-physical conditions to those in the Sudety Mountains area, therefore, they may be an inspiration to new geological projects in this area.

In eliminating consequences of disastrous floods (particularly in Moravia, 1997), field measurements demonstrated a relation between the state of stress of

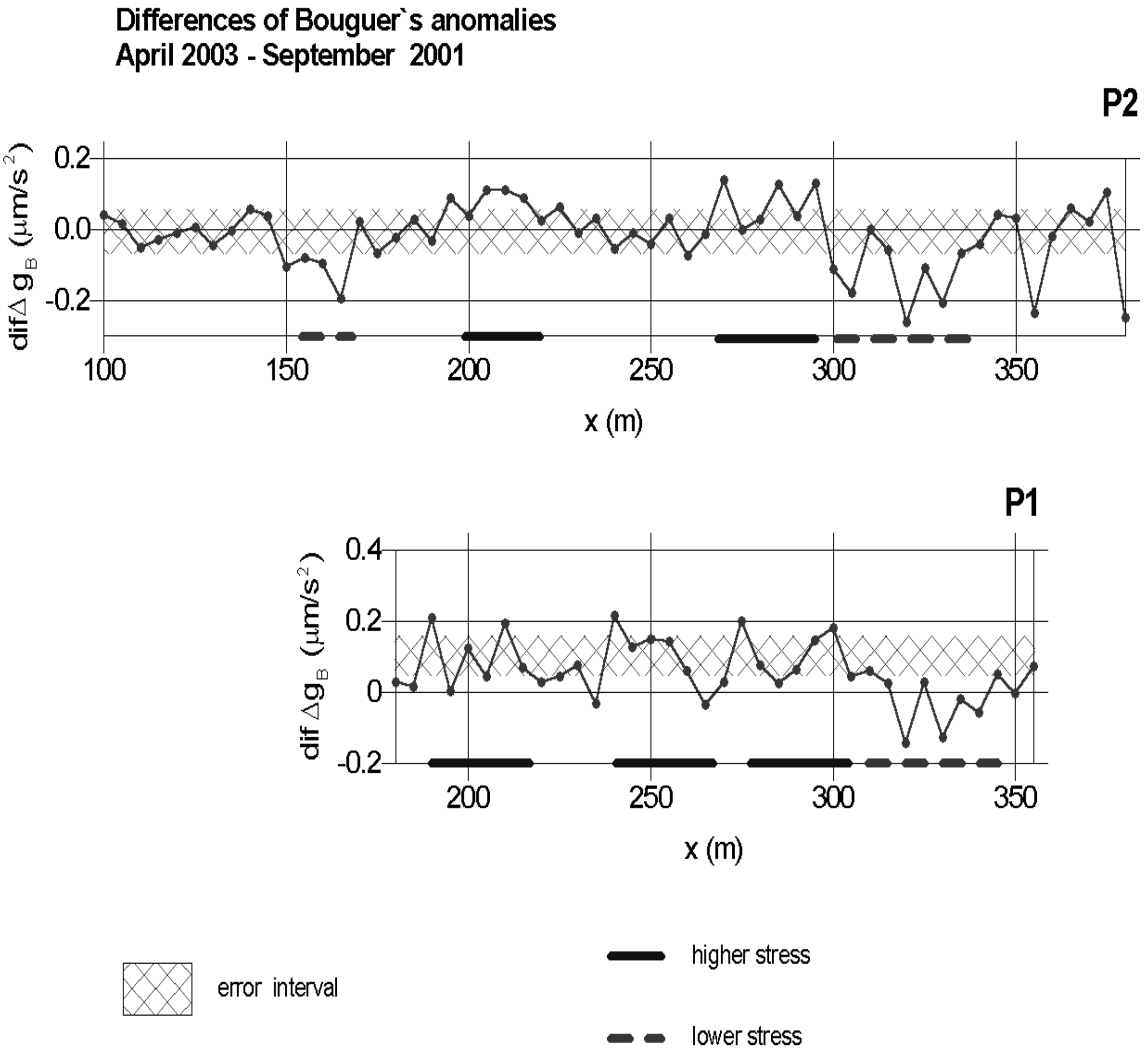

Fig. 4 Gravity monitoring of landslide area. Landslide above a railway line close to Vsetín

the rock environment and the magnitude of seismic waves propagation (particularly Bystřička, Mikulůvka, Halenkovice and Soláň locations in northern Moravia). A surface layer which was affected by landslide movement or which is vulnerable to such movement, can be very well detected by seismic investigation. As relatively sharp there appear reflection planes that are of quasicylindrical shape and most probably represent fossil slip planes (see Fig. 2). In the crack areas, velocity (stress) changes can be observed, and their activation and stilling can be monitored (see Fig. 3).

In the areas of stress changes there occurs a decrease or on the other hand an increase in density of the rock environment. These changes that are characteristic of landslide areas, are detectable by means of precise gravity measurement (Bárta et al. 2003).

Very good experience was gained in application of resistivity tomography (multielectrode system of measurement). At Bystřička location (Bárta, 2003), a large landslide area was monitored. Resistivity cross-section (see Fig. 5) trends approx. 50 m from a railway body located in the valley. The cross-section documents complicated geological conditions of flysch nature. The main solifluction hit a sandstone block (higher resistivities between the pickets Nos. 277 through 309), thus having changed its direction and failed to pose risk to the railway track located at a slope heel. On the other hand, a minor landslide (see low resistivities) around picket No. 317 trended directly towards the railway body, having seriously endangered it. Resistivity cross-section presents structures showing distinctive resistivity differences, whose potential development in time can be well monitored by means of resistivity tomography.

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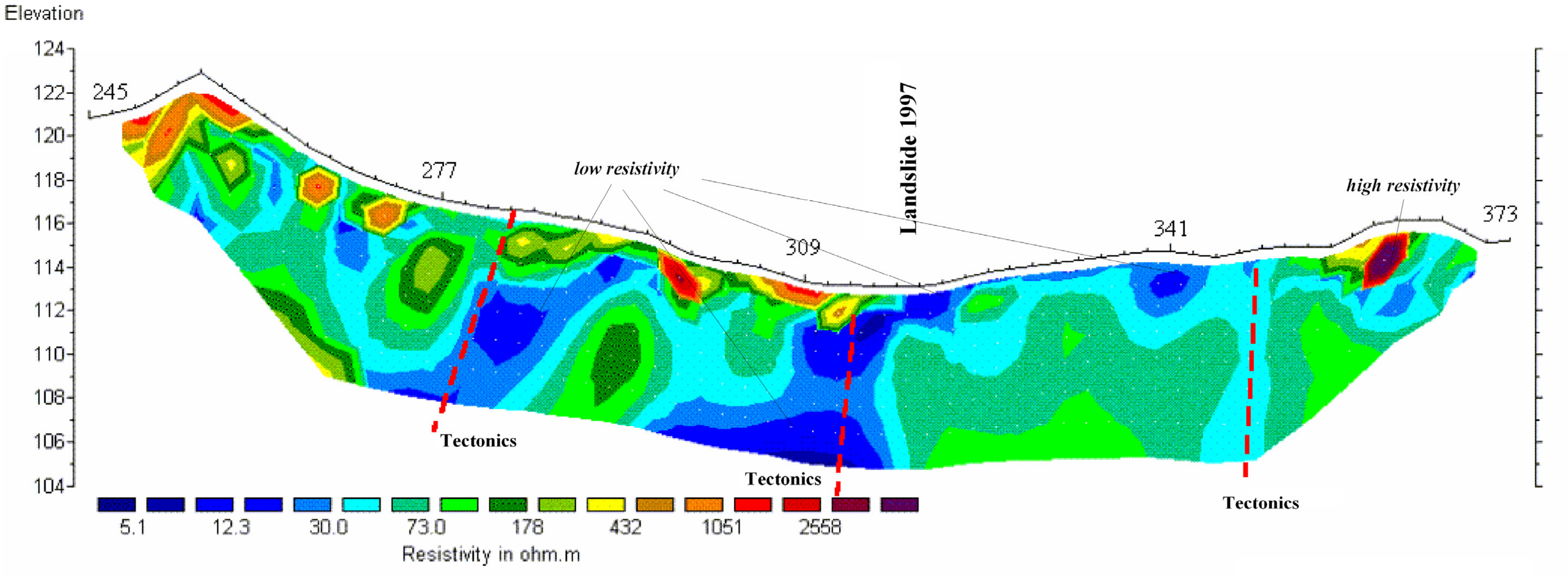

Fig. 5 Resistivity cross section of the landslide area in parallel with the valley (Bystřička near Vsetín). (All pickets in the Figure are in metres).