A methodology for geophysical investigation of track defects

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Abstract: This article presents possibilities of application of selected geophysical methods in railway engineering. Geophysical methods are used to observe a physical field. The measured data are interpreted in order to provide findings on geotechnical conditions of railway substructure and its surroundings. Geophysical methods have been unsystematically applied on European railways in the past. This paper's text is supported mainly by the measurements performed under the INNOTRACK projects at the sites in the Czech Republic, France, Spain, and Sweden. The geophysical testing has proved that the geophysical methods can reliably, quickly, in detail, and at a relatively low cost, inform about the problematic zones of the track. The effect of the geophysical application can be enhanced by long-term monitoring of track segments.

Keywords: geophysical investigation, geophysical method, resistivity tomography, seismic method, gravimetry, radar survey, modulus of elasticity

1 INTRODUCTION

The geophysical methods have a character of being non-destructive methods, which means that they do not disturb the environment. They are non-invasive (i.e. in performing investigation they do not interfere with the railway track structure). In principle, the measurements require no digging and excavations, no preparation of access roads for transport of instrumentation to the site, etc. Geophysical apparatuses are easily portable. The geophysical investigation can be organized to avoid railway traffic interruptions. It is of course an advantage if the geophysical investigation is organized to be included in the time schedule of railway track maintenance. In such cases, the geophysical investigation can be performed on a wider scale and further safety of operation is better ensured. Nevertheless, in principle, unlike other geotechnical tests and probes, the geophysics does not require traffic interruption. Using the geophysical methods, different physical fields are observed, and the measurement results may be interpreted to provide information of the geological setting of the area concerned or to provide findings on the geotechnical properties of the investigated place.

The geophysical testing measurements performed under the INNOTRACK projects were executed at the following sites:

Czech Republic:

Lipník nad Becvou
Polousí
Bechovice

Spain:

Lleida

Sweden:

Torp
Two sites near Borlänge

France:

Montmélian

The aim of the measurements was to test in different geological and organizational conditions possibilities of application of the geophysical methods in studying the geotechnical conditions of railway tracks.

2 THE APPLIED COMPLEX OF GEOPHYSICAL METHODS

On the basis of experience gained in previous projects [**1**, **2**] and general experience in qualities of the geophysical methods [**3–8**], basic geophysical methods were selected for testing within the INNOTRACK project. In particular, the methods concerned are the following:

(a) resistivity tomography;
(b) seismic methods;
(c) gravimetry.

It is known that also the method of geological radar has been tested and applied for a long time. This method was dealt with in the SAFE RAIL project (see references at the end of this text); therefore, radar was studied only marginally in the INNOTRACK project.

2.1 Resistivity tomography (multi-electrode system)

The method is based on the measurement of electric resistivity of the rocks. The basic measurement array is characterized by the use of two inner (potential) electrodes and two outer (current) electrodes. Resistivity magnitude rises with a decline of water content and a decline of its mineralization. Resistivity magnitude further rises in dependence on soil grain size curve (resistivity magnitude rises with increasing soil grains). For solid rocks it holds good that resistivity rises with rock strength.

The measurement in the variant of resistivity tomography proceeds using a computer, whose operational system allows to control mutual interconnection of tens to hundreds of electrodes. The measured data are recorded, and extensive and detailed databases of apparent resistivities related to the points in the studied medium are gradually produced. The database of apparent resistivities is further interpreted, which gives rise to a reliable interpretation model of resistivity conditions with much higher confidence level in comparison to simple resistivity profiling (only two potential and two current electrodes). The measured data are most often presented in the form of iso-ohmic vertical cross-sections. Certain special apparatuses allow three-dimensional interpretation, and iso-ohmic cross-sections then also have a form of horizontal cross-sections (plane in X and Y coordinates).

In the railway practice, the method can be recommended for detailed observation of resistivity conditions. In performing the measurement of railway tracks, the most often used distance between the electrodes is 0.4–4 m.

In engineering geological practice, the method can be used for a detailed study of the geological structures, for example, for the observation of incipient subsurface ruptures in connection with landslide movements, or in the mapping of already occurred landslide flows.

The method is also highly capable of detecting the existence of various covered or hidden construction elements. For example, it is possible to perform the measurement for the basement slab, prove the existence of hidden metallic reinforcement, etc.

2.2 Seismic methods

Seismic measurement is based on the observation of elastic wave propagation. Seismic impulses are most often excited by seismic hammer blows on a pad (blow seismics). As a source of seismic impulse also a vibrator can be used, which is able to excite different frequencies in a wide frequency range (vibrator seismics). If an observed seismic wave is only reflected from the seismic boundary, the reflection measurement is talked about. In performing refraction seismics, a seismic wave is refracted and slides for a certain time on the seismic boundary. A seismic wave propagates in dependence on geomechanical properties of the medium.

In the measurement, seismic sensors (geophones) interconnected with the apparatus are used. Most often, the distance between the geophones for the purposes of civil engineering ranges between 1 and 5 m. In principle, the velocity of seismic wave propagation declines with the level of disturbance of the studied medium. This allows to assess whether the medium concerned is disturbed or solid and whether it shows the character of rock or soil. The velocity of seismic wave propagation is dependent on bulk density and modulus of elasticity. With the rising values of modulus of elasticity, a medium showing higher solidity can be expected. The highest values of modulus of elasticity are shown by solid rocks. Low values of modulus of elasticity correspond to soils. A characteristic output of the seismic measurements is seismic cross-sections, in which the detected boundaries are depicted. Modern seismic apparatuses are easily portable in the field. Seismic records have a digital character, and the data interpretation proceeds by means of computer programs.

The measurement outputs have a direct link to the geotechnical properties of medium; therefore, the seismic measurements can also be included in the complex of the geotechnical tests.

The fieldwork with seismic equipment is shown in Fig. 1. The seismic apparatus is in the front. The vertical cylinder close to the sleepers is a vibrator exciting seismic impulses.

2.3 Gravimetry

The measurement is based on highly accurate observation of changes in gravity. To introduce topographical corrections, it is necessary to simultaneously perform accurate levelling. The works proceed at profiles (survey lines) and also in a grid. Solid objects, such as elevations of solid rocks, show positive anomalies. Deficits of mass (such as cavities and increased

Fig. 1 Seismic equipment McSeis 1600 OYO with seismic vibrator in the field

porosity of the medium) show a resulting negative anomaly. A characteristic output of gravity measurements are graphs with the course of the measured and corrected gravity values, or interpretation gravity models. The models express the measured distribution of mass in a way best fitting the measured values.

The measurement interval at the profiles on railway tracks largely ranges between 0.5 and 20 m. The measurement results have a direct relation to bulk density of the studied structures. This means that gravimetry can also be included into the complex of the geotechnical tests. The condition for successful resolving of the given tasks is to have a possibility of measurement, using a precise microgravimeter, whose repeatable reading accuracy reaches a value of about ±0.005 mGal. The advantage of the work with gravimeter is a relatively small effect of the presence of stray currents on the measurement. The final data processing requires to have available not only the gravity data but also precise hypsography of all measured gravimetric points and a topographic plan of the broader surroundings of the track.

The fieldwork with gravity equipment is shown in Fig. 2. The gravimeter is operated by one person. The measured data are stored in the gravimeter memory. Gravimeter can be connected with global positioning system (GPS).

3 RESULTS OF MEASUREMENTS AT THE INVESTIGATED SITES

In almost all of the measured localities, methods of refraction seismics, seismic tomography, resistivity tomography, and gravimetry were applied. The measurement was largely organized as follows: two basic longitudinal profiles along the railway track sides were laid out. At these profiles, all geophysical methods were applied. To identify the situation at a place of rails, the method of seismic tomography was used. At one of the pair of the basic profiles, seismic geophones were placed and at the latter one, seismic impulses were excited. In this way, the information on seismic velocities was acquired also from places that, for safety reasons, were inaccessible during trafficking. In the event of traffic interruption, one geophysical profile was situated also on the track axis. At this profile, the measurement proceeded using the gravimetric and seismic methods (mainly seismic refraction). All measurements were conducted by modern geophysical apparatuses; see the following:

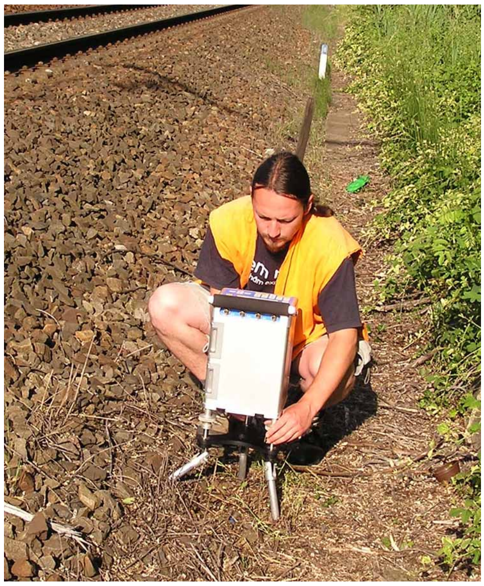


Fig. 2 Gravimeter CG-5 in the field

(a) seismic apparatus Terraloc Mk 6, v. 2.1, version 48 channels (ABEM, Sweden);
(b) multi-electrode resistivity apparatus ARS-200E (GF Instruments, Czech Republic);
(c) gravimeter CG-5 (Scintrex, Canada).

The processing of the acquired data was performed using mainly the following software:

(a) Reflex W (Sandmeier, Germany – seismic data processing);
(b) Res 2DInv (Locke, USA – resistivity data processing);
(c) MAG (Geofyzika a.s., Czech Republic);
(d) Excel (database administration);
(e) Surfer 9 (graphic processing);
(f) Grapher 7 (graphic processing).

As the extent of the article does not allow to describe in detail all the measured sites, typical examples illustrating the capabilities of geophysics in railway engineering are presented in the following section.

At the site near Lleida in Spain, the method of resistivity tomography was successfully applied in studying a railway embankment that got into a state of disrepair. The embankment was later remedied. One of the reasons for complications in embankment stability is intensive irrigation of agricultural land adjacent to the railway track body. Agricultural activities are shown by groundwater level fluctuations. An underground cut-off wall, which is to separate track bed subgrade from its surroundings, was probably failing to perform its function properly. In Fig. 3, examples of resistivity cross-sections are shown. They indicate the presence of the cut-off wall; however, cut-off wall condition changes with place. At the profile shown in the top part of the figure, the underground cut-off wall is clearly detectable. At the profile situated 50 m farther (bottom part of the figure), the cut-off wall is shown indistinctly, having probably given way to the degradation.

At the site of Lipnik nad Becvou (Czech Republic) there occur rail deformations (corrugation), particularly in the places where the track runs through a cut. The geophysical measurement using the method of resistivity tomography pointed out, in particular, the fact that the railway track runs through an area with loesses. Loesses show low resistivities (around 20 Ω m); they are frost susceptible and unstable in volume. Cut slopes were probably in the past built up by heterogeneous earths (backfills), which is demonstrated by the presence of higher resistivities. At places, cut slopes are susceptible to slope movements. The situation is documented by two resistivity cross-sections (the profiles were running transversely to the slope and perpendicular to the track) shown in Fig. 4. The resistivity tomography in Fig. 4 clearly proved the irregular composition of earths/soils in the final shaping of the slopes above the railway track body. At steep parts of the slopes, close to the track, indications of landslide movements can be observed (cylindrical shapes of contour lines indicate the presence of slip surface).

In Fig. 5, an example of seismic tomography application between two parallel profiles is shown. The profiles were running at left and right track margins. The measurement laid out in this way allows

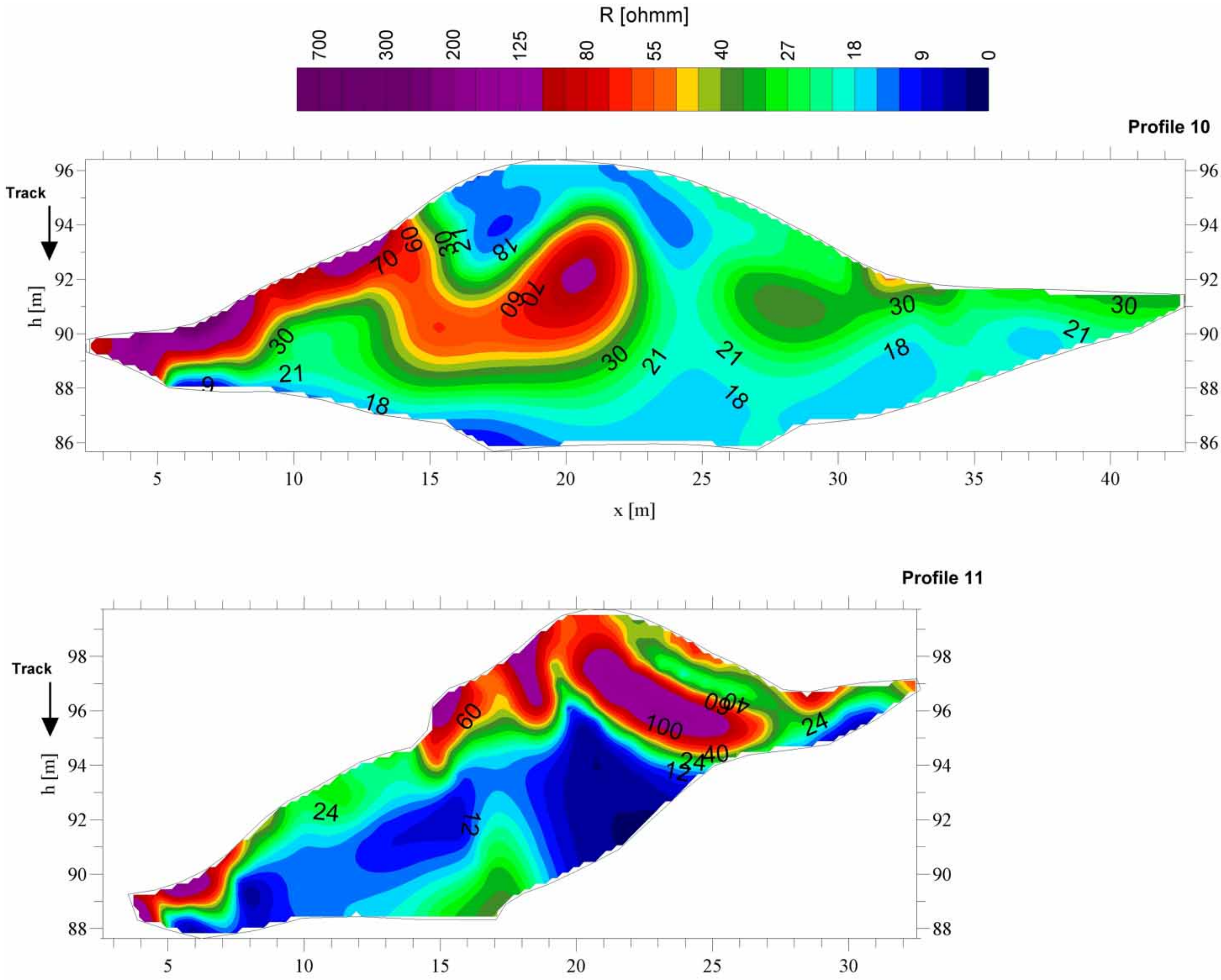


Fig. 3 Resistivity cross-sections from the profiles running transversely to the railway embankment. The locality of Lleida

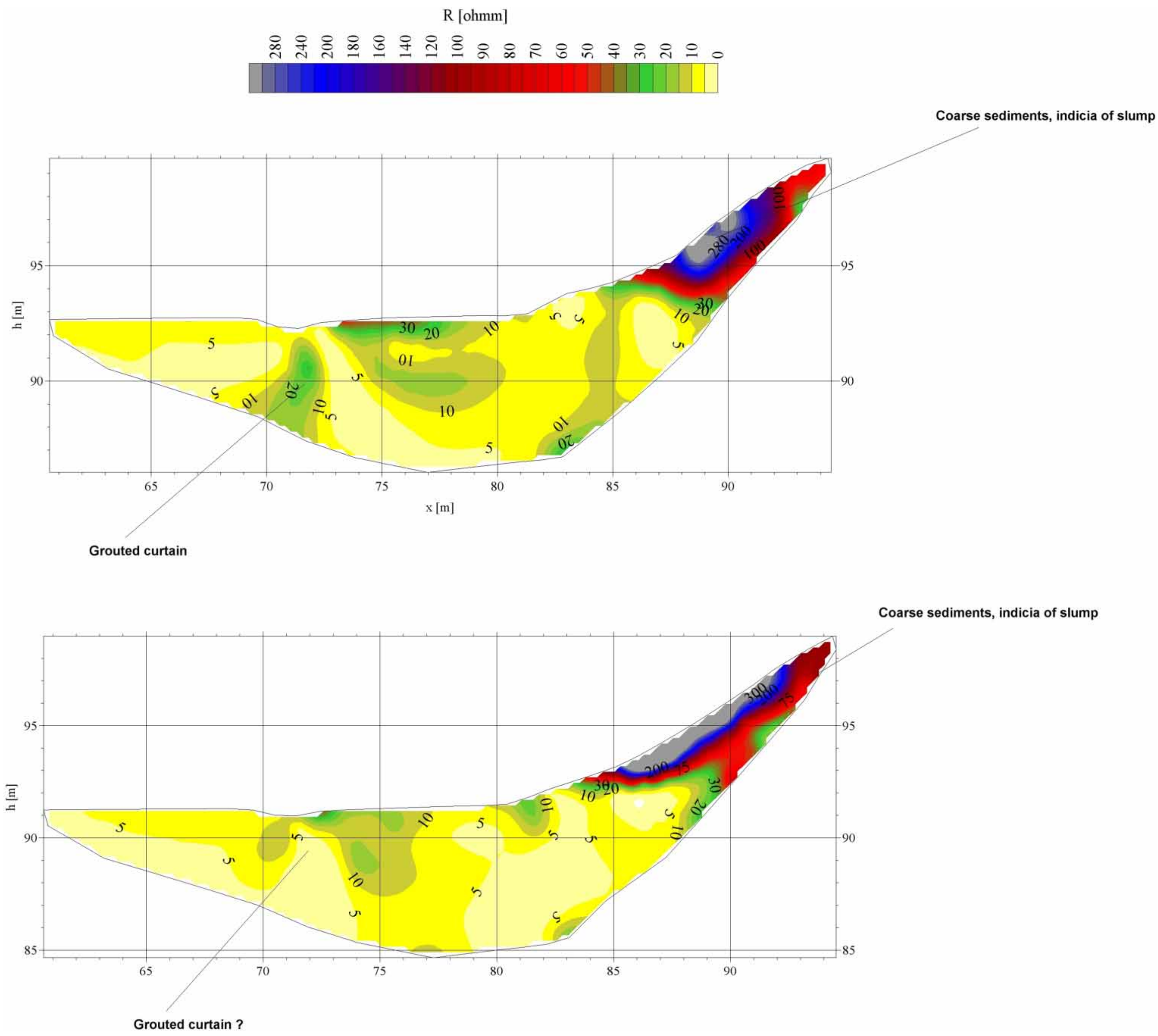


Fig. 4 Resistivity cross-sections from the profiles running transversely to the railway embankment. The locality of Lipnik nad Becvou

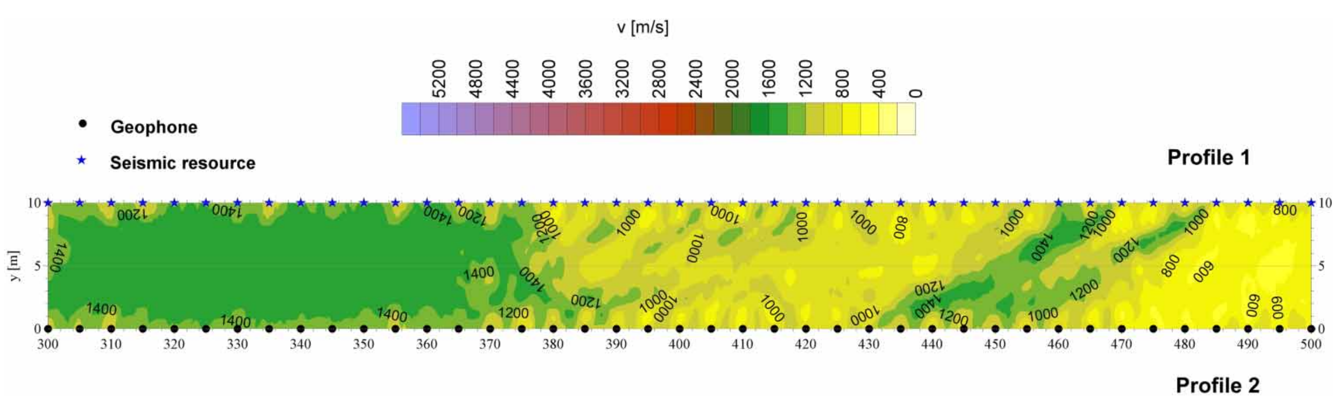


Fig. 5 An example of result of seismic tomography between two longitudinal profiles. The measured segment is located in a place without embankment, in a cut. The locality of Montmélian

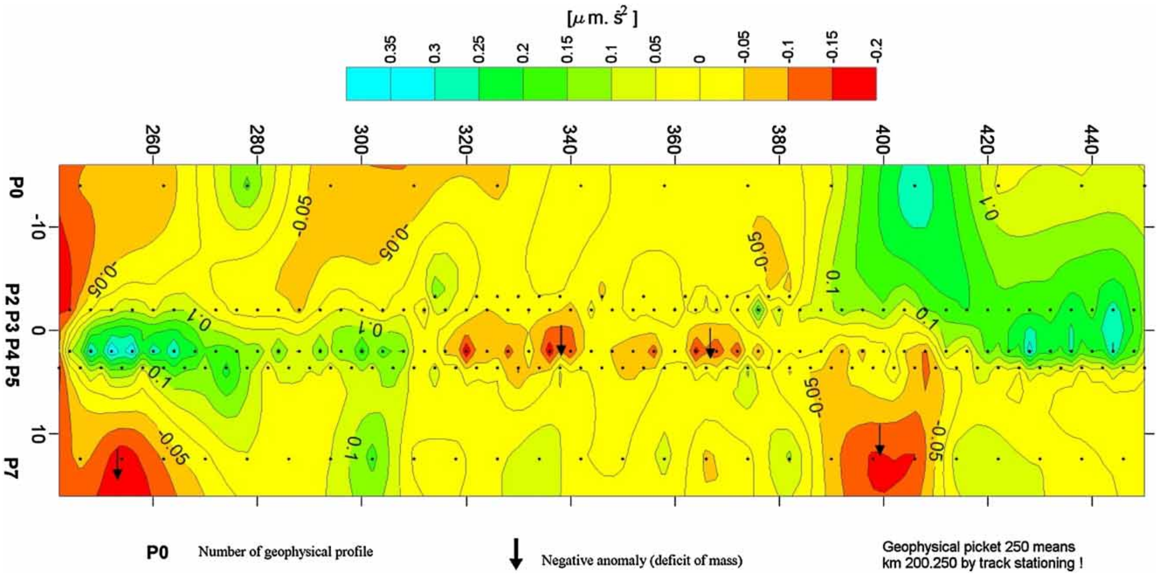
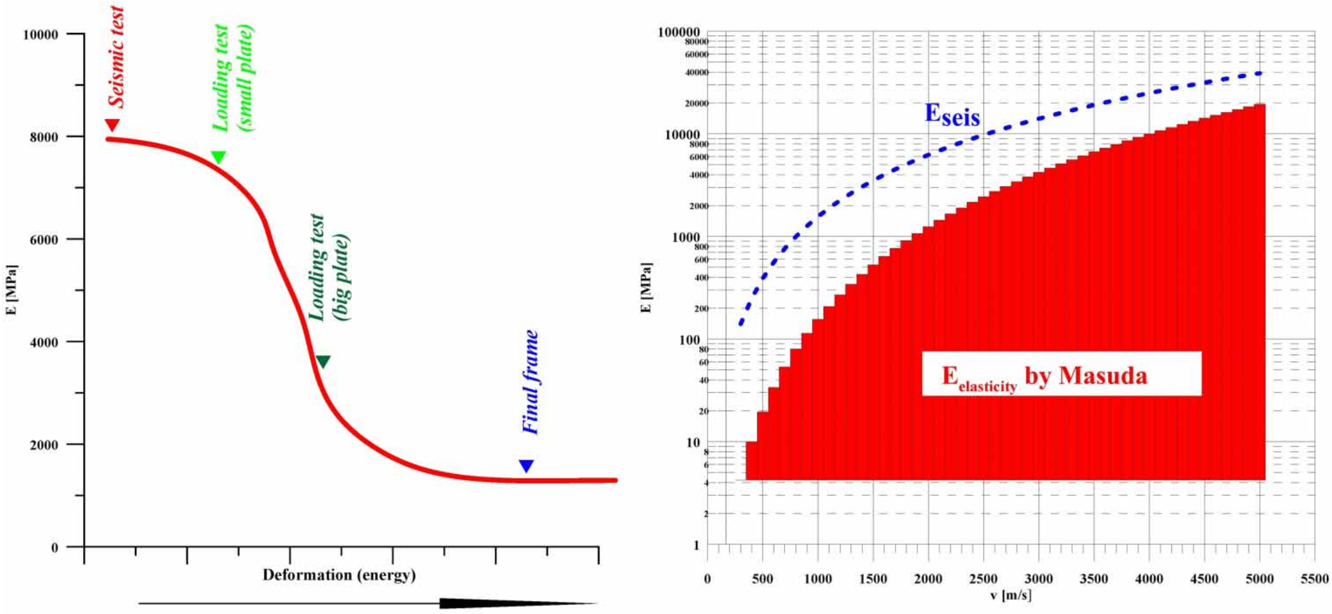


Fig. 6 An example of results of microgravimetric measurement at the locality of Lipník nad Becvou

to conduct the investigation also where trains run through. Such measurement layout allows to perform the measurement also at the places where traffic interruption is not possible. Figure 5 shows that in the segment of higher metres (from approximately 380 m) the seismic velocity declines, which gives evidence of partial reduction of subgrade compactness. The measurement was performed under the INNOTRACK project at the site of Montmélian in France.

Investigations conducted under the INNOTRACK project demonstrated the applicability of the measurement using the gravimetric method (strictly speaking, microgravimetry). Gravity measurements are able to primarily define places with lack of mass, for example, embankments with increased porosity or the presence of cavities. In Fig. 6, a map of contour lines of residual Bouguer anomalies from the locality of Lipník nad Becvou is presented. Areas with the negative anomalies mostly accord with the places where problems of rail deformations were identified. The measurement detected especially a significant anomaly in the surroundings of 400 m at a profile P7. This place accords with the place of frequent repairs of subgrade (rail bed underpinning). The resistivity cross-section



(a) (b)

Fig. 7 (a) The relation between deformation of a rock and modulus of elasticity E of a rock. (b) Conversion of the magnitude of longitudinal seismic velocities to the modulus of elasticity E_{seis}. This is followed by correction according to the Masuda formula running in this place shows indications of landslide movements in the slope cut.

An important result of the investigation performed under the INNOTRACK project was the conclusion that direct relation between the magnitude of propagation of the seismic wave and modulus of elasticity can also be exploited in practice. This relation is based on the fact that the velocity of seismic waves is a function of modulus of elasticity, bulk density, and Poisson's ratio.

In Fig. 7(b), an example of a graph of conversion of seismic velocities to the value of modulus of elasticity E_{seis}, using the basic formula for the velocity of propagation of seismic longitudinal wave v_P, is shown

$$v_P^2 = E_{seis}\rho^{-1}(1-\nu)(1+\nu)^{-1}(1-2\nu)^{-1} \quad (1)$$

where ρ is rock bulk density and ν is Poisson's ratio.

In the presented graph, the calculated values of modulus of elasticity E_{seis} are corrected by the Masuda formula to the values corresponding approximately to modulus of elasticity at a level of deformation reached in a load test using a big loading plate

$$E_{Masuda} = 0.5E_{seis}vv_{matrix}^{-1} \quad (2)$$

where v_{matrix} is seismic velocity in rock matrix and v is measured seismic velocity.

Conversion using equation (2) was used because modulus of elasticity also depends on the level of deformation of the studied medium, and engineering geologists largely experience values acquired through load tests that are performed within the geological investigations (see graphs in Fig. 7(a)).

It is possible to calculate rock bulk density refined by gravity measurement. The determination of modulus of elasticity can in certain cases be refined by using also the knowledge of velocities of propagation of transverse waves. Based on this, two equations are available, serving to determine both modulus of elasticity and Poisson's ratio. Nevertheless, knowledge of transverse wave motion in deeper depths below the ground surface is sporadic; therefore, Poisson's ratio is mostly determined using qualified estimation.

4 EXPLOITATION OF EXPERIENCE IN THE TESTING MEASUREMENTS FOR THE PRACTICE IN CONSTRUCTION AND MAINTENANCE OF RAILWAY TRACKS

From the preceding section 3 it results that the geophysical data provide information, which can be further interpreted for the purposes of geological, hydrogeological, and particularly geotechnical investigations. Deformations of rails as well as degradation of track ballast bed and other structure layers are primarily very frequently associated with underestimating of a complicated geological setting at a place in question. In this connection, the phenomena, such as the adverse effect of tectonic pattern, landslide evidence near railway track, or groundwater level fluctuation, can be talked about. Care for safe and trouble-free railway traffic is associated, among others, with conducting reliable geological investigation and subsequent geological surveillance. The complexity of the geological services also includes the geophysical measurements. The geophysical investigation is of particular importance in the following work phases:

(a) at the moment of starting to study the occurring difficulties when there is lack of essential information and when it is necessary to quickly gain, without larger financial and organizational measures, first findings on the geotechnical properties of the studied place;
(b) in the period after the standard geological investigation, when it is necessary to refine certain issues using detailed measurements;
(c) in the period after completing the remedial action it is recommended to apply the geophysical monitoring of the structure to ensure, in the event of repetition of adverse effects, the timely identification of these facts (at the beginning of the difficulties).

The measurements performed at the localities in Sweden, France, Spain, and the Czech Republic allowed to compare the application of geophysics under different conditions. By this, conditions of the geological setting and also the practice of railway traffic management by various European railway companies are meant. In none of the cases, the geophysical group encountered problems that would be specific to a certain territory. Applications of the geophysical methods were similar for all localities, and organization of work did not have to be much adapted to the local requirements. This means that the general applicability of geophysical methods in the European territory can be stated. An experienced geophysical group may perform work not only in domestic conditions but also elsewhere in Europe.

The measurements presented in section 3 have followed a certain basic model of how to proceed economically and effectively in organizing the geophysical measurement. This model can of course be modified and adapted to the needs of a specific situation. Nevertheless, it has been proved that initial work can largely be organized as follows:

1. If, from the area of interest earlier measured radar data are available [**9–11**], it is recommended to study and possibly reinterpret the data. A radar survey provides first information, on the basis of which it is possible to identify areas requiring more detailed investigation by means of other geophysical methods.

2. In the following phase it is advisable that a geophysicist should propose the extent of the area to be measured. The extent of the measured area generally exceeds by approximately two-thirds the extent of the place with the track defect itself. A common layout consists of two geophysical profiles running in parallel with the railway track. Measurements situated on profiles running beyond the track allow to conduct the geophysical investigation independently of traffic. In such case, traffic interruptions are not necessary. If it is possible to perform the geophysical works at the time of traffic interruption, it is recommended to situate at least one geophysical profile also in the track. As the basic complex of the geophysical methods, a combination of the seismic method, the method of resistivity tomography, and gravimetry is recommended. As an integral part of the seismic method, there has to be also a seismic tomography between the profiles running on the left and right sides of the track. In this way, also the information on the geotechnical conditions directly below the track is acquired.

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