

Methodology of geophysical investigation of track defects



INNOTRACK GUIDELINE

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1. Executive Summary

Instructions and information presented in this document make a reader acquainted with the 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 condition of railway substructure and its surroundings. Geophysical methods used to be unsystematically applied on European railways already earlier. The presented guideline is intended to provide sufficient knowledge for railway engineering specialists to allow them to get acquainted enough with when the application of the geophysical methods is effective and what outputs from such geophysical measurements can be expected. The text below is supported mainly by the measurements performed under the INNOTRACK projects at the sites in the Czech Republic, France, Spain and Sweden. Helpful as well in preparing the text was an extensive database of the geophysical measurements which is available in the archives of the Czech Railways. This database was already used for the preparation of internal binding guideline which has been in force since 2006 in the Czech Republic, namely: Guideline for Application of Non-destructive Geophysical Methods in Diagnostics and Investigation of Railway Track Substructure. Experience related to the issues of georadar (GPR) measurements was drawn, inter alia, from the task executed under the SafeRail project of the Sixth Framework Project of the EU. The guideline presented herebelow summarizes all the essential by what the geophysical investigation may contribute to timely and cost-effective detection of defects associated with the geotechnical conditions of railway track structure.

2. Geophysical methods

2.1 Introduction

Geophysical investigation is based on observation of changes in physical fields. According to the character of the detected fields, geophysical methods are divided into the following groups:

geoelectric methods,
seismic methods,
gravimetry,

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*magnetic survey,
nuclear physics methods (radiometry).*

Research and retrieval of information from archival reports enabled to set an optimal complex of geophysical methods which is effectively applicable for the diagnostics in railway engineering. Based on the problem nature, methods listed below are used in full complex, incomplete complex or separately.

Complex of selected geophysical methods:

- *GPR (geological radar),*
- *resistivity profiling,*
- *multielectrode (resistivity) measurements,*
- *blow seismics,*
- *vibrator seismics,*
- *gravimetry.*

2.2 Digest

GPR (geological radar)

Similarly to classical radar, electromagnetic waves are transmitted and reflected from geological boundaries. Penetration depth is directly dependent on the magnitude of frequency applied, permittivity and conductivity of the medium. On radar records, changes in intensity of reflections are observable, in different times (in different depths). Radar records are presented in the form of recording the course of amplitudes, or the magnitude of reflection is transferred into a colour scale. The records are further interpreted. The method allows very rapid measurement. Antenna system can be installed, for example, in track recording car or on a specially adapted rail trolley (see Fig. 1). GPR is the only method which is able to cost-effectively provide the basic information from the routes exceeding a length of more kilometres. Usual penetration depth in performing measurement beyond track skeleton is max. 8 m, on track skeleton max. 2.5 m. The relation between the geotechnical quantities and the measured data is indirect only.

In certain countries, GPR is used on railway tracks as standard method. The measurement documents especially the course of subgrade layers and trackbed layers. From GPR records there may also be identified cavities, covered or hidden construction elements, the level of wetting or landslide indications. In the Czech Republic, GPR method is obligatory in the

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regulations governing the final acceptance procedure for opening of reconstructed tracks. The basic radar record acquired at the time of opening of the respective track segment is filed in the SŽDC/Railway Infrastructure Administration database and, where necessary, it is later compared with the records acquired in control measurements during the track maintenance or repairs.



Fig. 1: GPR apparatus with antenna systems on rail trolley CRAB. The same apparatus can be installed in track recording car or on engine front.

Resistivity profiling

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 (symmetric resistivity profiling - SRP). To detect thin conductors, one additional distant current electrode is used (combined resistivity profiling - CRP). In carrying out the profiling, the array of electrodes remains constant, and thus also penetration depth during the measurement remains constant. In performing the measurement, the magnitude of current between the two current electrodes (I) is observed and, at the same time, potential difference (ΔV) between the two potential electrodes is determined.

Resistivity magnitude rises with a decline of water contents and a decline of its mineralization. Resistivity magnitude further rises in dependence on soil grain size curve (resistivity magnitude rises with increasing soil grains). The measurement proceeds in profiles/survey lines. The lines, if allowed by the field conditions, are laid out in parallel with one another. The measured data are largely presented in the form of graphs. In the

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event that the measurement covers a more extensive area, it can be processed also in the form of resistivity contour lines.

The method of resistivity profiling is used, for example, to differentiate clays from gravels or to follow the course of bedrock. The method may also be applied to observe intensively water-bearing areas and to detect tectonic lines (thin conductors). In the railway practice, it is recommended to use this method to observe the geological conditions close to the railway body or changes in embankment composition. Usual measuring interval at a profile is 5 or 10 metres.

The method is quite undemanding as regards the instrumentation and shows high working productivity. In a shift, the geophysical group of 4 persons is able to complete the measurement for 2 to 6 km of profiles (based on the character of the landscape and the array of the measuring electrodes). A disadvantage of the method is potential measurement interference caused by stray currents and by the presence of artificial conductors in the ground. The effect of stray currents can be eliminated by disconnecting the electric energy source in traction mains. A reduction of stray currents can also be achieved by working with the geophysical apparatuses that operate not with direct-current source, but with atypical current source, for example, 2.5 Hz.

For basic orientation we mention that clays show the resistivity values of around 5 Ωm (clays of marine origin) to 25 Ωm (clays of freshwater origin). Solid rocks show the resistivities exceeding 1000 Ωm .

Multielectrode method (resistivity tomography)

Again, the method is based on the measurement of electric resistivity of the rocks. In this case, the measurement 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. 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 with the resistivity profiling. The relations between resistivity magnitudes and petrographic properties are identical with those for classical resistivity profiling. The measured data are most often presented in the form of isoohmic vertical cross sections. Certain special apparatuses allow three-dimensional (3D) interpretation

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and isohmic cross sections then also have a form of horizontal cross sections. An example of measurement using multielectrode apparatus is shown on Fig. 2. The apparatus is fully portable and may be situated at a larger distance from railway track.



Fig. 2: Apparatus controlling a multielectrode system during fieldwork.

In the railway practice, the method can be recommended for detailed observation of resistivity conditions. In performing the measurement on railway tracks, most often used distance between the electrodes is 0.4 to 4 m. The acquired volume of information is manifold higher than if GPR, SRP or CRP methods are employed. A disadvantage of this method is its relative labour intensity, higher price of the geophysical apparatus and interpretation software. For the relations between the resistivity magnitudes and petrographic properties of the rocks the same holds good as for other resistivity methods (see the section above - Resistivity profiling).

In engineering geological practice, the method can be used for 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.

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

Seismic methods

Seismic measurement is based on observation of elastic waves propagation. Seismic impulses are most often excited by seismic hammer blows on pad (blow seismics). For the variant with penetration depth of more than 30 m, explosives are often used as a source of seismic impulses (dynamite seismics). As a source of seismic impulse also 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 seismic boundary, we talk about reflection measurement. In performing refraction seismics, a seismic wave is refracted and slides for certain time on 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, whether it shows the character of rock or soil. The velocity of seismic wave propagation is dependent on bulk density and on 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 are 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 programmes. A view of seismic apparatus in the field is shown on Fig. 3.



Fig. 3: Seismic apparatus during the measurement in the field.

The measurement outputs have a direct link to the geotechnical properties of the medium, therefore, the seismic measurements can also be included in the complex of the geotechnical tests. It is recommended to include seismics especially to detailed measurement phases, where shorter track segments are examined (track segments reaching a length of max. several hundreds of metres, longer segments are exceptional). A disadvantage of the seismic measurements is their relative labour intensity and processing intensity. High-quality multi-channel seismic apparatuses with 24 to 48 seismic channels including the cabling and geophones are quite costly

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, increased 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. Field measurement using gravimeter is shown on Fig. 4.

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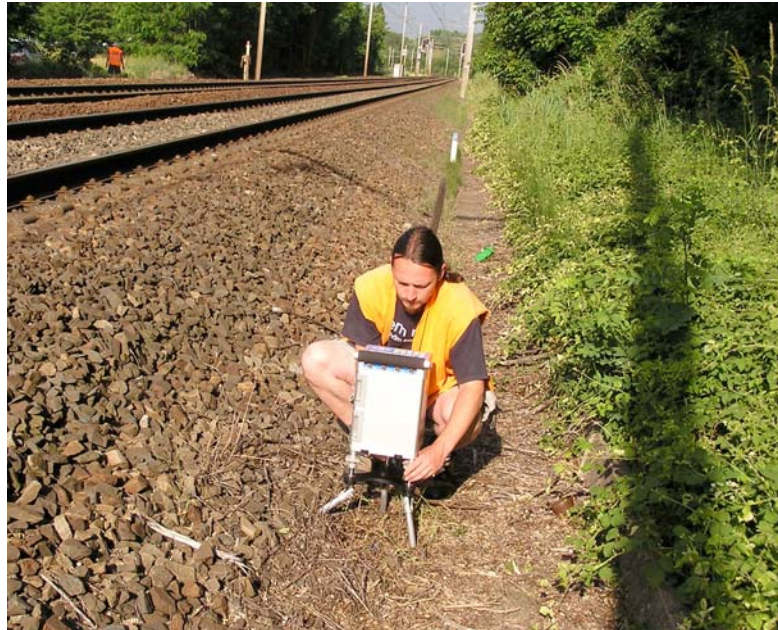


Fig. 4: Gravimeter during the measurement in the field.

The measurement interval at the profiles on railway tracks largely ranges between 0.5 and 20 metres. 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 precise microgravimeter, whose repeatable reading accuracy reaches the value of around $\pm 0,005$ mgl. 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 topographic plan of the broader surroundings of the track.

Work stages and sequence, and optimized selection of geophysical methods

Every prepared project of the geophysical works has to be first confronted with the results of possible geophysical measurements which might have already been performed in the area of interest.

For the initial stage of any investigation it is recommended to have available, in particular, information database containing also regular track

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measurements by the GPR method (radar). GPR measurements provide initial findings on anomalous spots on the track, and if the measured data are available in a time series (systematic monitoring), time development of potential defects can be estimated.

If the segment intended for investigation is relatively extensive (on order of between 1 and 10 km), the next geophysical works are commenced by the resistivity profiling (SRP or CRP variant). Resistivity measurements provide the basic information on the development of the geological conditions, and also the information needed to refine places of interest for situating further detailed measurements. We note that the variant of the resistivity profiling may sometimes be also complemented by the measurement using the method of vertical electric sounding (VES). In this case, again resistivity measurement is concerned. The measurement is performed in every point with multiple spacings between the electrodes (with the differing penetration depths).

If the area of interest for the geophysical measurement is smaller (on order of hundreds of metres), the application of resistivity measurements is not strictly required and the task is solved by another appropriate geophysical methods. If allowed by the issue in question, it is possible, for the sake of economic efficiency, to reduce the complex of methods. The optimal selection of the geophysical methods is recommended by a geophysicist.

The advantage of the geotechnical quantities acquired by the interpretation from the geophysical (especially seismic and gravimetric measurements) is that they bring continuous information on the studied medium in situ. Nevertheless, similarly to all tests, they are influenced by the measurement conditions. Optimal can be considered the condition, if at a location of the geophysical measurements there were also performed, for example, static load tests. The data gained in complex then may be assessed together, mutually compared, and characteristic values of the geotechnical quantities determined with full responsibility.

2.3 Geophysical methods and their parameters (review)

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Investigation method	Range of application (frequencies, distances, types of materials etc..)	Measured parameters	Mechanical parameters obtained	Classification parameters obtained
Geoelectrical	Geological and geotechnical investigations on the track sections from tens metres to many kilometres. Distances between geophysical sensors mostly from 0.5 metres to 10 metres. Electromagnetic methods work with continual measurement.	Resistivity [Ωm], relative permittivity and additional electrical parameters	Geotechnical interpretation is possible (stiffness, consolidation, compatibility, fracturing)	Classification of rock quality. Soil grain-size Hydrogeological parameters.
Seismic	Geological and geotechnical investigations on the track sections from tens to hundreds of meters and sometimes to many kilometres. Distances between geophysical sensors mostly from 0.5 metres to 5 metres,	Velocity [m/s]	Geomechanical interpretation is possible (modulus of elasticity, Poisson number)	Classification of rock quality.

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	maximum to 10 metres.			
Gravimetric	Geological and geotechnical investigations on the track sections from tens of metres to many kilometres. Distances between geophysical sensors mostly from 0.5 metres to 20 metres.	Density [mg/l]	Geomechanical interpretations are possible (differential density of geological structures). Indication of cavities.	Classification of rock quality.

2.4 References for the purpose of detailed study

The above mentioned information provide only a brief overview of the geophysical issues to the extent required for experts from non-geological fields. In case of need to acquire in-depth information or get answers to intricate questions we refer to the SEG (Society of Exploration Geophysicists) publication from 2005:

Butler Dwain K., et al.: Near – Surface Geophysics.

The book comprehensively describes the geophysical issues from the viewpoint of the need to measure in first tens of metres, i.e. in the zone, which also the investigation for railway tracks falls within. We further refer to the entire bibliography presented below in chapter 4.

The author of the present text is prepared to consult any special questions arisen. Contact address:

3. Implementation of the geophysical measurement

This chapter summarizes the issues of the preparation and implementation of the geophysical measurements especially from the viewpoint of the client (railway infrastructure administration) and is particularly based on experience gained in the measurements for Innotrack Project. It allows railway infrastructure staff members (who are not geophysicists) to form a picture of what they can expect from the geophysical measurements, what questions can the geophysicists be sensibly asked, and what organizational measures are required for the measurement.

3.1 Detection of geotechnical problems on track with uninterrupted traffic

3.1.1 SCHEDULE OF GEOPHYSICAL MEASUREMENTS

No	Requirement to be met	Remarks
1	Study of archive documentation, field reconnaissance	Participation of the representatives of railway infrastructure is desirable. Of crucial importance in this phase of preparation is exploitation of the

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No	Requirement to be met	Remarks
		GPR (radar) database, if available for the given site.
2	Preparation of technical project of works A geophysicist proposes the extent of area to be measured. The extent of the measured area always exceeds by approx. two thirds the extent of place with track defect itself. It is usual to lay out two geophysical profiles (survey lines) running in parallel with the track. Measurements situated at the profiles (survey lines) running beyond the track allow to perform the geophysical investigation independently of traffic. Traffic interruptions in this case are not necessary. If it is possible to perform the geophysical work in the time of traffic interruption, it is recommended to situate at least one geophysical profile (survey line) also in trackage.	The design work has to be performed by a geophysicist-designer with the relevant certified professional qualifications.

3.1.2 OPTIMIZED SELECTION OF GEOPHYSICAL METHODS.

No	Requirement to be met	Remarks
1	Selection of methods from the viewpoint of physical conditions of the site Physical conditions of the studied medium and the character of the task determine the optimal selection of a complex of the geophysical methods. As the majority of questions associated with the geotechnical conditions can be concentrated to the issues of delimitating solid, partly disturbed and disturbed structures, for most of the tasks there can be recommended a complex of survey methods comprising the seismic measurement, multielectrode measurement and gravimetry. For the regional investigation (segments long 1 km and more), which is to	The geophysicists with the relevant professional qualifications are required for this work

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No	Requirement to be met	Remarks
	delimitate anomalous places for more detailed measurement, it is recommendable to start with the GPR method or the method of resistivity profiling.	
2	Selection of methods from the viewpoint of field conditions Transport conditions of access to the track and elevation conditions on the track significantly influence the progress of work.	The geophysicists with the relevant professional qualifications are required for this work
3	Selection of methods from the economic viewpoint The extent of the geophysical works has to be proportionate to the expected benefit of the measurement results.	Cooperation with the client's economic department is required. The geophysicists with the relevant professional qualifications are required for this work.

3.1.3 REQUIREMENTS ON GEOPHYSICAL GROUP EQUIPMENT.

No	Requirement to be met	Remarks
1	Geophysical group executing the respective task has to be equipped entirely with modern apparatuses which from both the technical and safety viewpoints comply to the European standards. All the measured data have to be acquired in such a way allowing them to be reliably stored in digital databases.	Work is performed solely by geophysical team with certified professional qualifications

3.1.4 WORK SAFETY AND SURVEILLANCE

No	Requirement to be met	Remarks
1	Geophysical investigation usually requires the presence of several persons at the site. In most	Activities require cooperation with

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No	Requirement to be met	Remarks
	cases this means 4 to 6 persons. The work performed by geophysical group has to be, with exceptions, supervised by railway infrastructure administration staff member. Geophysical group members have to be instructed and take over the working site by protocol. The character of activities related to the geophysical measurement is shown on Fig. 5 below.	supervisor appointed by railway infrastructure administration

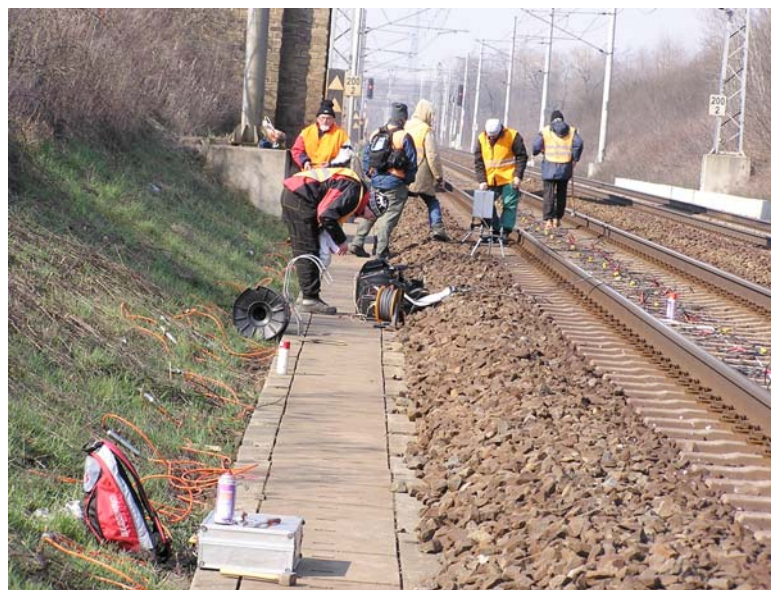


Fig. 5: Preparation of geophysical group for measurement

3.1.5 INTERPRETATION OF THE MEASURED DATA. DELIVERABLES.

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No	Requirement to be met	Remarks
1	The measured data first go through the phase of data processing, which means to arrange the data into an easy-to-survey form (tables, first graphs, etc.). This is followed by evaluation phase. Using various, largely highly sophisticated computing programmes, it is possible to compile physical models reliably approximating the real situation in the field. Physical models inform, for example, on the distribution of resistivities of the rocks, on the distribution of heavier or lighter masses in the rock massif, or provide information on the distribution of seismic velocities. These physical images have to be further evaluated, in order to provide the geotechnical information. Such final conclusion to be provided by every geophysical report is possible through exploiting the findings from boreholes, cooperation with the responsible geologist, and the use of information database from the preceding similar tasks. Examples of deliverables are shown on Fig. 6 and 7 below.	Work is performed solely by geophysical team with certified professional qualifications

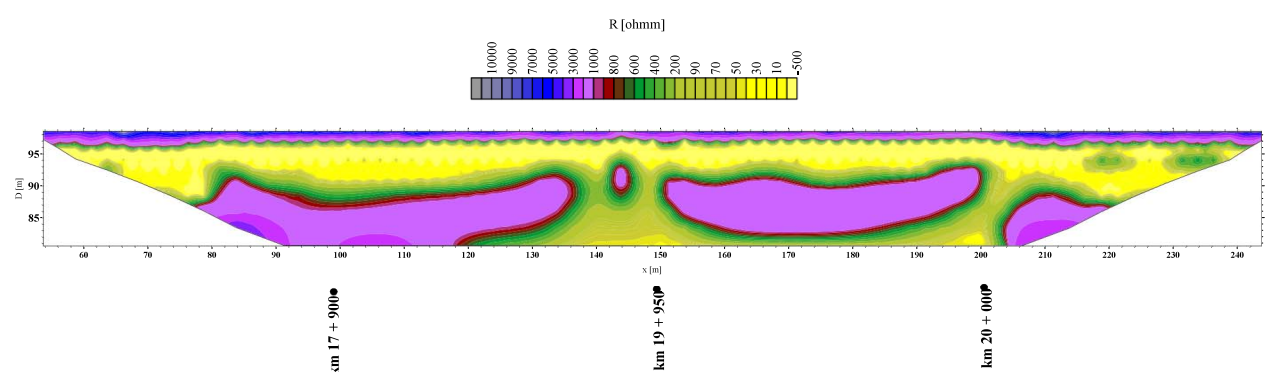


Fig. 6: Example of deliverable – resistivity cross section produced by multielectrode method on track near Borl nd

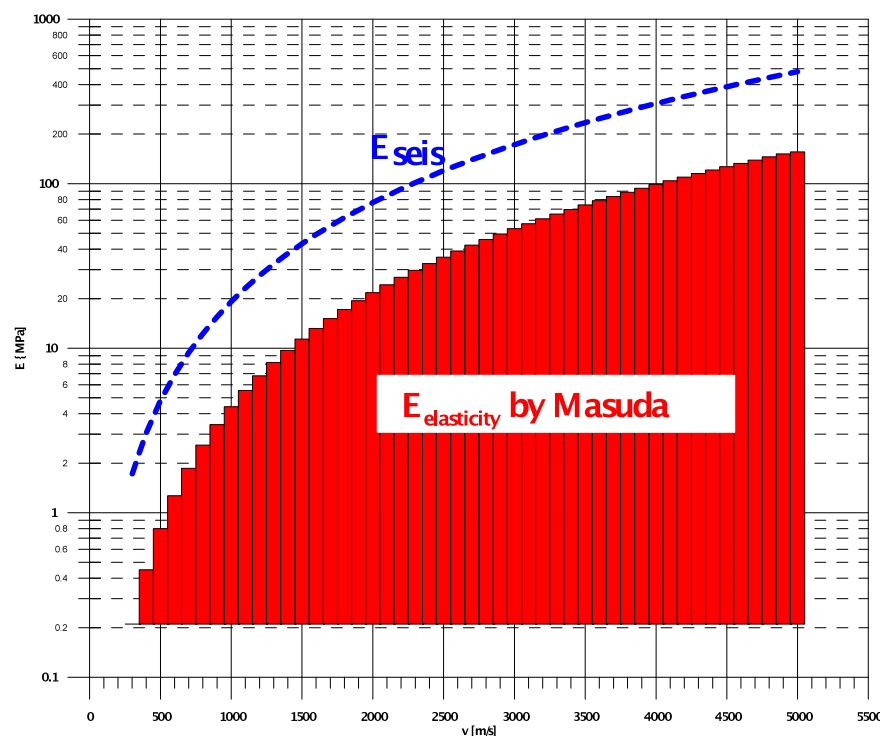


Fig. 7: Example of deliverable – conversion of magnitude of seismic velocities to modulus of elasticity.

3.2 Monitoring on the track with uninterrupted traffic

Most of the principles for the monitoring of the geophysical quantities on railway tracks are identical with the above mentioned principles for the basic geophysical measurement (work safety, selection of the geophysical methods, etc.). In this chapter, therefore, attention is only paid to the questions that are characteristic of or essential for the monitoring works.

3.2.1 SCHEDULE OF GEOPHYSICAL MEASUREMENTS

No	Requirement to be met	Remarks
1	Study of archive documentation and field reconnaissance	Participation of the representatives of railway infrastructure is desirable.

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No	Requirement to be met	Remarks
2	Preparation of technical project of works A geophysicist proposes the extent of area to be measured. The extent of the measured area always exceeds by approx. two thirds the extent of place with track defect itself. It is usual to lay out two geophysical profiles/survey lines running in parallel with the track. Measurements situated at the profiles/survey lines running beyond the track allow to perform the geophysical investigation independently of traffic. Traffic interruptions in this case are not necessary. If it is necessary to perform the measurement also inside the track, it should be organized to allow the work performance in the time of traffic interruptions. In certain cases, such as the seismic measurement, seismic sensors can be permanently placed in trackbed ballast and the monitoring can be performed as necessary. For the placing of seismic sensors at Běchovice site, the time of the entire track reconstruction was used. The placing of seismic sensors, see Fig. 8.	The design work has to be performed by a geophysicist-designer with the relevant certified professional qualifications.



Fig. 8: Building up the seismic monitoring base at Běchovice site in the time of track reconstruction

3.2.2 OPTIMIZED SELECTION OF GEOPHYSICAL METHODS.

No	Requirement to be met	Remarks
1	Selection of methods from the viewpoint of physical conditions of the site Physical conditions of the studied medium and the character of the task determine the optimal selection of a complex of the geophysical methods.	The design work has to be performed by a geophysicist-designer with the relevant certified professional qualifications.
2	Scheduling of the monitoring measurement frequency. The measurement frequency has to be higher than expected frequency of changes in the character of the geotechnical conditions of the site. For example, at Běchovice site in the Czech Republic, the seismic measurements and measurements using TDR method were set at a frequency of approx. once a month, and the works proceeded in the period of 16 months. This period of time allowed, with sufficient accuracy, to monitor and characterize the behaviour of the structure layer (soil + 2 % lime). The task was solved under the project INNOTRACK, SP2.2.	The design work has to be performed by a geophysicist-designer with the relevant certified professional qualifications.

3.2.3 INTERPRETATION OF THE MEASURED DATA. DELIVERABLES.

No	Requirement to be met	Remarks
1	The measured data first go through the phase of data processing, which means to arrange the data into an easy-to-survey form (tables, first graphs, etc.). This is followed by evaluation phase. Using various, largely highly sophisticated computing	Work is performed solely by geophysical team with certified professional qualifications

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No	Requirement to be met	Remarks
	programmes, it is possible to compile physical models reliably approximating the real situation in the field. These physical images have to be further evaluated, in order to provide the geotechnical information. An example of deliverable is shown on Fig. 9. Here are the results of the seismic tomography in subgrade at Běchovice site. Changes in the velocity image give evidence of gradual changes in the structure layer due to lime reaction with soil. Behaviour of the layer is also influenced by penetrating moisture content into the studied layer. Penetration of moisture content has to be reduced to the maximal possible extent in the future. From the evaluation of the data in Fig. 9, the following practical conclusion can be drawn: In the period of first two months after the formation of the structure layer, 2% lime admixture reacts very intensively with soil which leads to what is the purpose of the action, i.e. the consolidation of the structure layer. This is followed by steadying down the reaction, nevertheless, even then minor velocity changes in the structure layer can be observed. In our case, these changes can be mainly attributed to moderate infiltration of surface water into the structure layers. The fortification of the layers using the method of lime admixture is efficient, but, in this case as well there may occur gradual degradation of the structure layer, if water penetration to the fortified layer is not fully avoided.	

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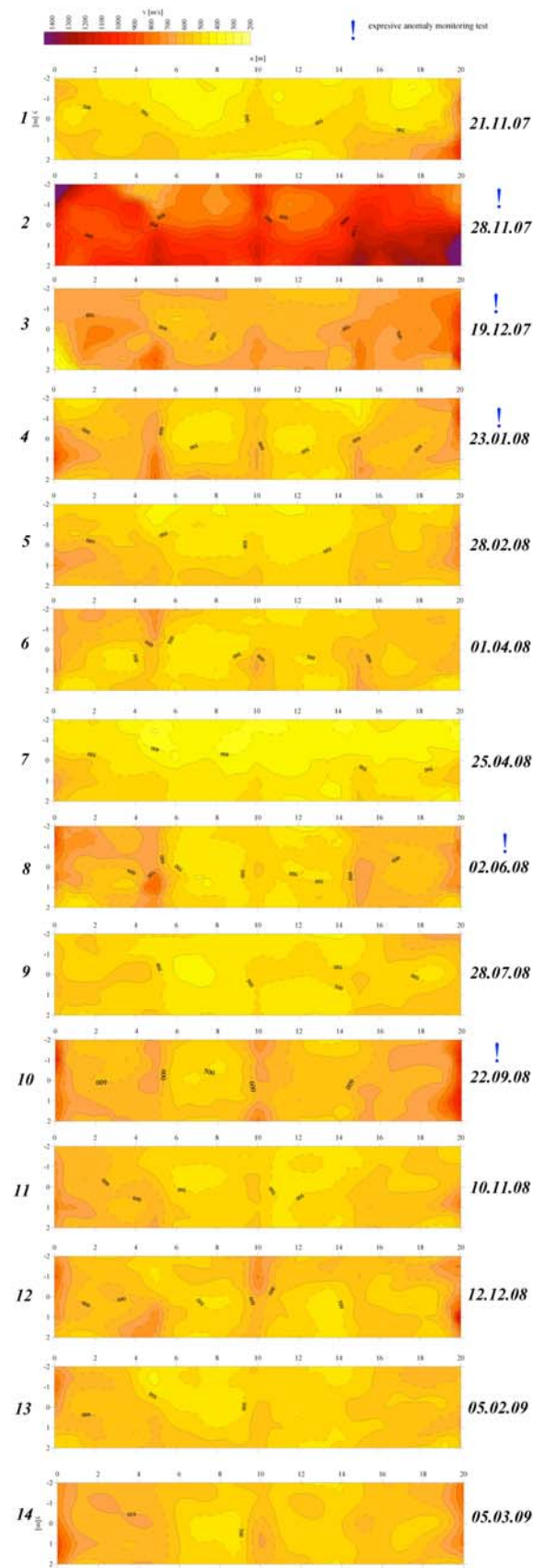


Fig. 9: Results of the monitoring - seismic tomography. Běchovice site.

3.3 References to complex examples of the application of the geophysical methods in railway engineering

The presented text has the character of Guideline and, therefore, it cannot contain extensive examples of how to apply the complex geophysical measurement to the particular railway site. It is especially the Report on Innotrack Project, where it is possible to get acquainted with detailed examples for the application of the complex of the geophysical methods to resolve the issues related to railway engineering:

D 2.1.15 Non-destructive geophysical methods.

This report is included in the official documents of the Innotrack Project and the Guideline presented here is based on experience gained especially in the measurements that were performed in the Czech Republic, Sweden, France and Spain.

We further refer to the Innotrack Project Database, which is the result of the work performed by colleagues from Institut für Bodenmechanik und Felsmechanik (IBF) Universität Karlsruhe (TH), and which is available after getting the access code.

The particular sites subjected to the measurements in the Czech Republic, Sweden, France and Spain were further discussed at workshops dedicated to the project part WP 2.1. From these discussions, presentations are available and accessible in Innotrack Project documents.

4. Conclusions and recommendations

From the preceding chapters and following up with the experience gained through investigations performed under the Innotrack Project (see Report *D 2.1.15 Non-destructive geophysical methods*) it results, that the geophysical data provide information which can further be 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. We talk about phenomena, such

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as the adverse effect of tectonic pattern, landslide showings near railway track or groundwater level fluctuation. 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:

- 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.
- in the period after the standard geological investigation, when it is necessary to refine certain issues using detailed measurements.
- In the period after completing the remedial action we recommend 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, we mean conditions of the geological setting and also the practice of railway traffic management by various European railway companies. In none of the cases, the geophysical group encountered problems which 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. Experienced geophysical group may perform work not only in domestic conditions, but also elsewhere in Europe.

The measurements presented in chapter 2 have ensued 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:

- if from the area of interest earlier measured radar data are available, we recommend to study and possibly reinterpret the data. A radar survey provides first information, based on which it is possible to delimitate areas requiring more detailed investigation by means of other geophysical methods.

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- in the following phase we recommend 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 we recommend a combination of the seismic method, the method of resistivity tomography and gravimetry. As an integral part of the seismic method there has to be also a seismic tomography between the profiles running on left and right sides of the track. In this way we acquire also the information on the geotechnical conditions directly below the track.

The monitoring of hazardous events potentially endangering railway tracks can be considered a very significant part of the application of the geophysical measurements. The monitoring is also advisable in testing of new construction (structure) elements, whose behaviour in the railway track body has not been sufficiently examined yet. The monitoring contribution to improvements in economy of railway track operation can be demonstrated, for example, in the application of GPR method (radar). We recommend that every significant segment of a newly constructed or reconstructed railway track is subjected to the measurement using GPR method. The basic radar record has to be filed in a properly administered database. In the event of any doubts about the track condition, or in case of intervention in the railway body it is possible to perform control GPR measurement. By comparing the original record (acquired at the time of final acceptance procedure) with the record detecting changes caused by potential adverse intervention in the railway body it is possible to easily identify the differences in the course of radar reflections and to correctly interpret such differences. Similarly, the monitoring can be performed, using the seismic method, gravimetric method or method of resistivity tomography. Any monitoring measurements facilitate the interpretation of the geophysical data by the following: the monitored object (or structure, layer, etc.) which in static image may appear less distinct, will be accentuated by its changes (shift, bend, change of physical properties) occurring in time. The main result of the geophysical monitoring is a possibility of early warning against serious railway track defect. In other

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words, it is necessary to capture in the development of the monitored condition the moment when minor quantitative and by geophysics observable effects may transform to a qualitative change of permanent character.

5. Bibliography

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