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A new methodology for assessment of railway infrastructure condition

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Abstract

The majority of the railway infrastructure in Croatia is over one hundred years old. In common with many other EU member states, a lack of investment in maintenance and renewal projects in over the last 30 years has resulted in generally poor track conditions. As a result traffic speeds are often restricted with some important operating with speeds limited up to only 20 km/h.
This work describes a joint initiative between researchers and infrastructure managers (IM's) to revitalize risk assessment associated on ageing infrastructure, with the aim of increasing safety and reducing the costs of remediation. In order to achieve this, a new methodology for assessment of railway condition is developed. In this paper the use of phased investigation involving electromagnetic ground penetrating radar (GPR), seismic refraction, drones and in-situ geotechnical investigation to determine parameters affecting the track performance are presented. The features considered include ballast fouling, anomalies in railway embankments (including burrows), boundaries between layers, substructure condition, the water content of the soil, the slope geometry and drainage condition. The work constitutes the first step in a Decision Support Framework for IM's, being developed through the Horizon 2020 Project Destination Rail which will help to identify potential hot-spots on the rail network. By early identification of these locations low-cost remediation can be applied and thus costs can be reduced and failures avoided.
In this paper the use of custom-made cart which allows acquisition of data along the three axes of railway rail cross-section and an innovative interpretation methodology is described. Based on GPR data, visual assessment and on photogrammetry images made using an unmanned aerial vehicle (UAV), a categorization of critical infrastructure data is collected to a quantitative risk assessment procedure. This provides a basis for preliminary design solutions as well as for establishment of detailed programme of investigation works and monitoring on sections where it was shown as necessary. A next step is implementation of this

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methodology into geographic information system (GIS) which would additionally fulfil the needs of decision-makers in railway sector.

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Keywords: GPR; unmanned aerial vehicle; railway infrastructure; embankments; risk assessment

1. Introduction

The work described herein forms part of the Horizon 2020 project DESTination RAIL. The overarching aim of the project is to provide solutions for a number of common problems faced by EU infrastructure managers. Novel techniques for identifying, analysing and remediating critical rail infrastructure will be developed. These solutions will be implemented using a decision support tool, which allows rail infrastructure managers to make rational investment choices, based on reliable data. At present Infrastructure Managers make safety critical investment decisions based on poor data and an over-reliance on visual assessment. As a consequence their estimates of risk are sometimes highly questionable and large-scale failures are happening with increasingly regularity. The project (safer, reliable and efficient rail infrastructure) will be achieved through a holistic management tool based on the FACT (Find, Analyse, Classify, Treat) principle.

- **Find –** Improved techniques for the assessment of existing assets will be developed.
- **Analyse –** Advanced probabilistic models fed by performance statistics and using databases controlled by an information management system will be used to determine the level of safety of individual assets.
- **Classify –** The performance models will allow a step-change in risk assessment, moving from the current subjective (qualitative) basis to become fundamentally based on quantifiable data. A decision support tool will take risk ratings and assess the impact on the traffic flow and whole life cycle costs of the network.
- **Treat –** Novel and innovative maintenance and construction techniques for treating rail infrastructure including tracks, earthworks and structures will be developed and assessed by whole life cycle assessment and impact on the traffic flow.

The paper considers work related to the objective Find and in particular how we might locate potential hot-spots on the rail network in a more reliable manner.

2. Current practice – condition assessment and remediation measures for railway embankments in Croatia

Safe and efficient transport infrastructure is a fundamental requirement to facilitate and encourage the movement of goods and people throughout the European Union. There is approximately 215,400 km of rail lines in the EU which represent a significant asset. Many of the rail networks in Eastern Europe and in parts of Western Europe were developed more than 150 years ago. These networks were not built to conform to modern standards and suffer from low levels of investment and in some cases poor maintenance strategies. In the current economic climate it is vital that we maintain and develop our transport network and optimize the use of all resources. The Croatian railway network has 2604 km of railway lines. The majority of the railway infrastructure in Croatia is over one hundred years old. In common with many other EU member states, a lack of investment in maintenance and renewal projects in over the last 30 years has resulted in generally poor track conditions. As a result traffic speeds are often restricted with some important operating with speeds limited up to only 20 km/h. Main railway international and national lines are shown in Fig. 1.

Fig. 1. Railway network in Croatia.

2.1. Typical problems of the embankments instability

In common with many rail networks there is a wish to increase capacity on the network while infrastructure managers (IM's) are dealing with the effects of climate change which can result in catastrophic failures. For example, longer duration and more intense rainfall is causing increased incidence of shallow landslides across the EU, see Figure 2. Earthworks (cuttings and embankments) on old railway networks are particularly prone to failure (Reale et al. 2015) as their side slopes tend to be much steeper than modern highway slopes made in similar soils and drainage is often in poor condition.

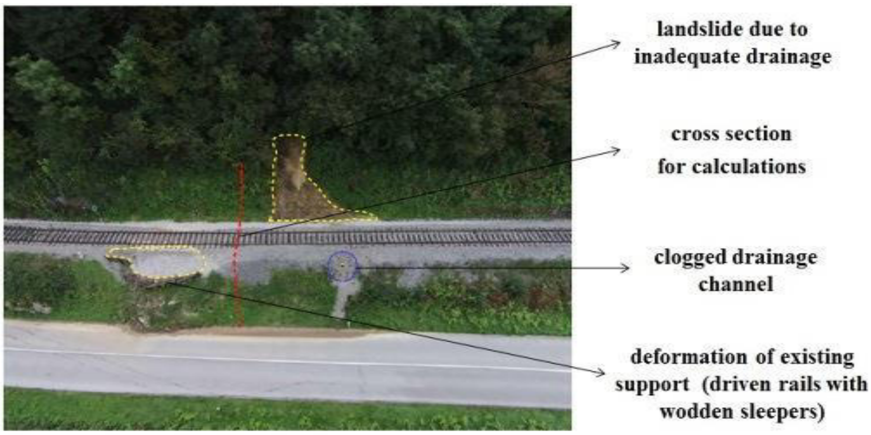

Fig. 2. Typical problem of embankment instability – image recorded with UAV, as a part of the repair project on railway track in Croatia.

The Croatian rail network crosses may areas where near surface soils consist of soft clay and loose sand which are relatively poor founding soils. Typical problems associated with these soils relate to their low bearing capacity and tendency for the accumulation of long-term settlements. With a move to increase train speeds these problems can accelerate. Typical problems associated with weak sub-soil or poor drainage and remediation measures are considered in Figure 3.

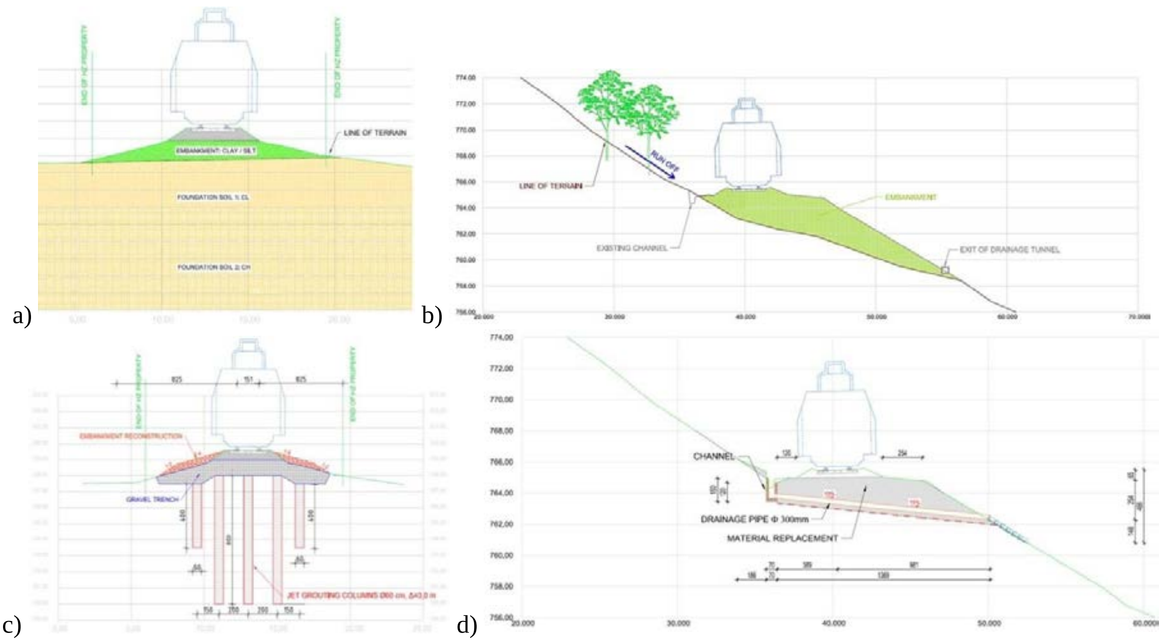

Fig. 3. Examples of typical problems a) cross section of the embankment with soft soil, and b) instability problem due to the lack of drainage system, c) remediation measure for the case a); d) remediation measure for the case b).

As noted the risk of failure of earth structures is often primarily based on hazard assessment determined from a visual assessment. These assessments are conducted periodically and are unlikely to observe key mechanisms which might lead to failure occurring (e.g. poor subsoil conditions are broken drains) and cannot account for the temporal nature of, for example rainfall events on the safety of an element. Therefore most IM's recognise the need to move away from over-reliance on visual assessment.

3. New assessment methodology

The incidence of major failure of critical sections on rail infrastructure is increasing. The current response is reactive i.e. when failures occur they are fixed. The location of the failure then becomes a hot spot on the network. Forensic analyses of these failures often note that indicators of distress were ignored due to lack of understanding or absence of a proper framework for decision-making. Since the railway network in Croatia is experiencing fundamental revitalization in recent years, the owner, Croatian Railways (HŽ Infrastructure) has recognized the need for the planned condition assessment of the existing railway embankments in order to get the risk assessment of potential excessive deformation and stability problems. The intention is to develop a long-term strategy for railway maintenance works, for which the background information is needed in order to prioritize the maintenance and repair works at critical sections. The aim of new assessment methodology is to identify hotspots on the network before an asset failure, allowing for preventative measure to be taken. The overview of existing measurement techniques that will be applied during the assessment of earthworks are presented in Table 1.

Table 1. Overview of measurement techniques which can be used for embankment assessment.

Instrument / measurement technique	Observed physical parameter	Usage	Disadvantage	Speed
UAV / drone	Topography	Collection of 3D coordinates – geometry and detection of settlements, soil movements, …	Cannot detect anomalies and potential failures located in in embankment and subsoil (subgrade) composition	Depends on capacity of batteries and distance from operator. Up to 20 km/h
GPR	Relative dielectric permittivity Electrical conductivity Magnetic permeability Electromagnetic wave velocity	Trackbed structure determination Ballast depth variation Trackbed condition Identifying fouling Intermixing between the ballast and subgrade material Subgrade material condition Relative degree of moisture within the ballast	Cannot detect the level of the problem	Up to 70 km/h
Seismic refraction	Longitudinal wave velocity	Trackbed structure and subgrade material determination Modulus of elasticity profile of trackbed and subgrade	Longitudinal wave velocity must increase with depth (subgrade must be weaker than trackbed)	1 km per day
SASW/MASW	Shear wave velocity	Trackbed structure and subgrade material determination Shear modulus profile of trackbed and subgrade	Generation of frequency spectra depends on surface condition and material characteristics	1 km per day

In order to perform condition and risk assessment of the existing railway embankments, the following activities should be performed:

1. Collection and systematization of existing data. In order to assess the condition of the railway substructure and superstructure and to design the rehabilitation measure all the available data for the observed section has to be collected, these include; (i) existing project documentation (including geotechnical studies); (ii) information about the traffic load and the type of trains that operate on this section, (iii) information about the maintenance measures implemented to date and (iv) Specialized visual inspection, by using unmanned aerial vehicle, so called drones.
2. Assessment of the substructure condition with ground penetrating radar (GPR). Measurement should be performed along at least three axes of the embankment cross section, with the maximum distance of 20 cm in the longitudinal direction and minimum depth of 2 m.
3. Geotechnical categorization of the railway substructure (including embankment and subsoil), based on the results from first two points and recorded irregularities.
4. Development of the detailed investigation program and monitoring project.
5. Development of the remediation and repair strategy for different risk categories.

Finally the risk assessment and ranking methodology has to be developed in order to provide risk maps with the critical railway sections. The railway owner, namely infrastructure managers should then develop the maintenance plans based on the provided risk maps. In the next chapters each of the steps will be explained in more detail.

3.1. Collection of data using unmanned aerial vehicle

Since the railway embankments are linear structure which can be long dozens and even hundreds of kilometres, there is a potential problem of the performance and quality of the visual inspection. Standard visual inspection consists of personnel walking along the track which is being assessed. In some cases the track is located on high and/or steep embankments, and very important information can be missed. To achieve high quality visual assessment of the condition of existing railways the use of unmanned aerial vehicle (UAV), known also as drones is being investigated.

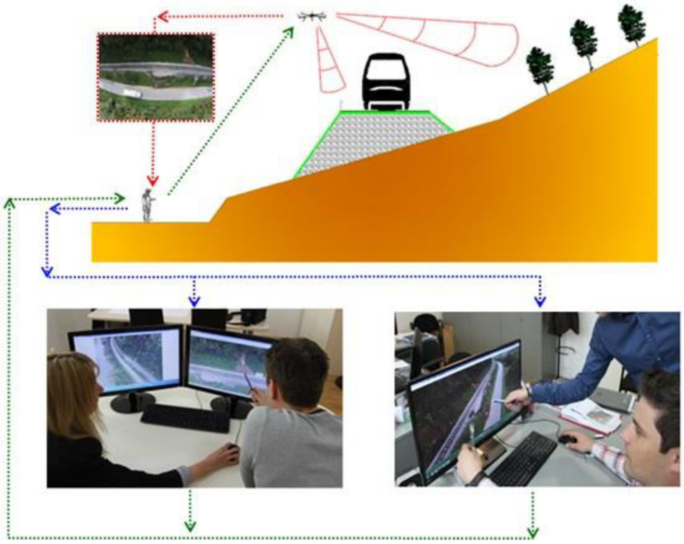

Fig. 4. Interactive procedure of visual assessment using UAV.

A drone or UAV is a small aircraft that can be remotely controlled or can fly autonomously based on a pre--programmed route using complex autonomous dynamic systems (Kovacevic et al., 2014). Drones are nowadays used in many different public or research applications, because of their simplicity and there potential for gathering useful information at high speed. An additional benefit of using drones for rail inspections lies in the reduction of time necessary for inspectors to be in the vicinity of a live railway, which reduces accident risks.

A UAV's imaging is controlled by a person on site, located at one fixed point. The distance between the operator (pilot) and drone can reach between 1 and 10 km. UAVs are divided into micro/mini, tactical, strategic and UAVs with special purposes categories. In the case of railway inspections micro/mini UAVs will be used, due to their design, movability and instantaneous data collection. One of the main advantages of the UAVs application is the interactive assessment of the infrastructure objects, as shown in Fig. 4. Namely the operator on site has on the screen the real image from the UAV, and transmits it in the real-rime to the experts at other locations (e.g. offices, laboratory), who can see the condition of the railway infrastructure and interact with the assessment procedure, influencing the locations which should inspected in more detail.

In Fig. 2 the results of the UAV application can be seen, where the landslide in the length of 50 m was recorded. By the application of UAV phenomena typical for the landslide could be detected more accurately, such as deformed temporary supporting structure (inclined track and sleepers), instability of the embankment, clogged drainage system and landslide above the track, as shown in Fig. 2.

3.2. Combined GPR and seismic methodology

Information about the railways substructure is mostly based on the geotechnical investigations, namely drilling the boreholes. This investigation method provide good informative, however, it is very expensive and time consuming and usually also requires the closure of the track section for a relatively long time period. As a result only very limited information is therefore available along the network. Donohue et al (2011) describe a case history on the Irish Rail network which illustrates that the relatively small volume of soil tested in a borehole may miss the main structural features of the problem being considered. In order to decrease the costs and increase the efficiency of the investigation works, or test a much larger volume of soil the application of non-destructive measurement techniques such as geophysics is recommended. Ground penetrating radar is a rapid and non-destructive technique, which can be applied for the evaluation of key substructure condition indicators (Olhoeft and Selig, 2002). A typical configuration for the railway substructure testing by ground penetrating radar is shown in Fig. 5. The application of different antennas (different frequencies) depends exclusively on the phenomena which should be monitored. Usually one antenna is located in the axes of the track and then two antennas outside of the rails, as it can be seen in Fig. 5. Antennas operating at different frequencies allow variable depths of penetration and different resolution of the images to be achieved.

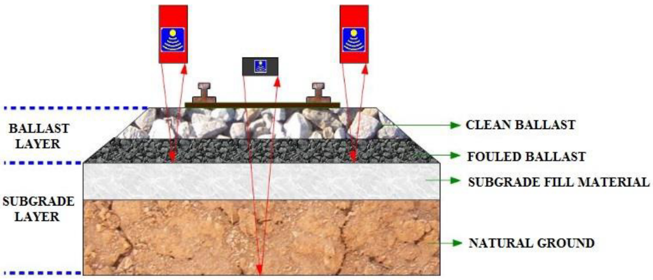

Fig. 5. Typical configuration of the GPR testing applied on the railway infrastructure (Bekic, 2015).

Fig. 6. Multichannel GPR system installed on the special vehicle.

Reflections of the GPR pulse occur at boundaries in the subsurface where there is a change in the material properties, usually described with dielectric constant. Large difference in the dielectric constant between two materials will result in higher reflection in the GPR profile (Kang et al. 2010, Selig et al. 2006). Many studies have been conducted in order to determine the railway substructure conditions (Donohue et al. 2011; Leng & Al-Quadi, 2010; Selig et al. 2006). GPR data are now routinely measured over significant portions of the rail network. In this project a multi-antenna system will be mounted on track and will provide three dimensional data acquisition so that better insight in integrity of embankment and sub-soil can be obtained. This will allow detection of anomalies such as animal burrows, pipes, ballast, depression sections, etc. These will indicate as a first-pass, potential hot-spots which require further investigation. In second phase the seismic geophysical methods will be performed at site identified as potential hot-spots. This will provide correlation between measured parameters, so that conclusions on physical-mechanical parameters can be made. If the 2nd phase assessment suggests that a hot-spot is likely, then standard in-situ geotechnical (e.g. boreholes and in-situ testing) will be undertaken to verify the ground model and provide specimens for laboratory testing. This methodology was applied to two sections of the Croatian Rail network.

During 2014, two rehabilitation projects have been designed and performed for the improvement of embankments stability at railway tracks in Croatia (FCE – 1 2014, FCE – 2 2014). The investigation works comprised of geodesic survey, geotechnical boreholes, laboratory testing and non-destructive geophysical, GPR and seismic refraction measurements. In Figures 7 and 8 the results of seismic refraction and GPR measurements are presented for both locations.

Investigation works carried out at track R202 have established that the railway embankment is located on soft soil, with the seismic refraction survey identifying soils of very low stiffness in the area directly beneath the embankment. A remediation method consisting of the installation of 0.6 m diameter, 4 to 8 m long jet grouted piles see Fig. 3c. was adopted. It is also proposed to strengthen the embankment body by execution of gravel trenches on the longitudinal distance of 3 meters (above the jet grouted piles). Finally the slopes of the embankment will be reduced to between 1:4 and 1:2.

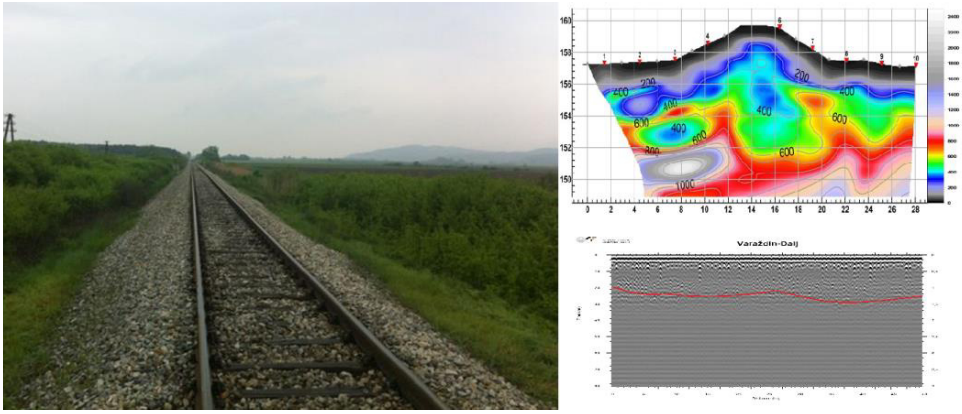

Fig. 7. Unstable embankment at km 132+200 till km 133+000, railway track R202 in Croatia, with belonging refraction profile and GPR profiles recorder during the assessment stage.

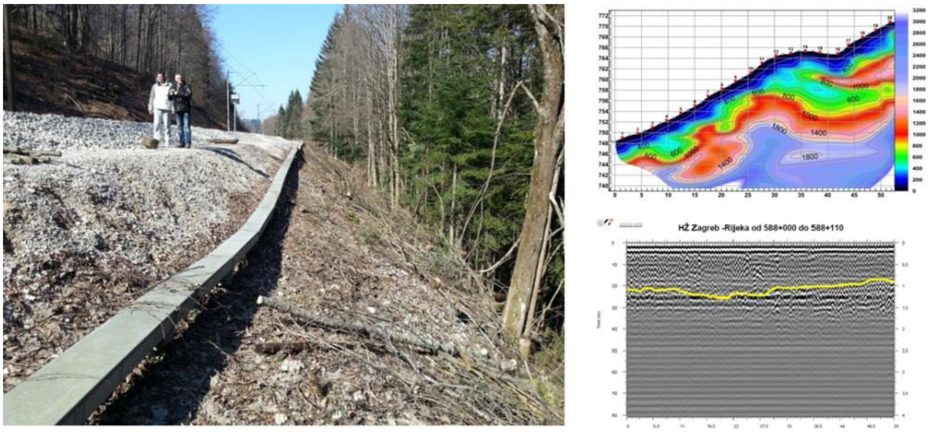

Fig. 8. Unstable embankment at km 588+000 do km 588+110, railway M 202 in Croatia, with belonging refraction profile and GPR profiles recorder during the assessment stage.

Another case study is the rehabilitation of the instability of embankments in km 588 + 000 to km 588 + 110, 202 track M 202 (FCE-2, 2014). At this location investigation works included also the implementation of geodesic survey, geotechnical drilling, laboratory testing and geophysical methods of GPR recording and seismic refraction. The results of testing are presented in Figure 8. Based on the investigation works it was shown that a major cause of instability was poorly maintained or absent drainage. The flow of water from the slope located above the track (Fig. 3b and Fig. 8) caused the retention of water in the embankment, primarily because of an inadequate drainage system. In order to improve the current situation, 22 drainage canals were designed where drainage pipes will be installed and will collect water from the embankment body and from a new concrete channel that will be located at the bottom of the upper slope (Fig. 3d). This improved design will greatly increase the safety of the embankment and improve its performance.

Despite these efforts, it is obvious that many problems persist along the network and similar problems can occur at any time at any other sections of the network exposed to similar conditions. The current practice is that rehabilitation measures are not considered until visible instabilities appear. In order to take into account the possible risks of instability, it is necessary to have a broader picture of the situation of individual sections along the network. The phased investigation approach proposed in this study could identify many of the underlying causes of these instabilities before the situation becomes critical and failure occurs. Increased investment in monitoring the current conditions (FIND) is likely to result in overall savings for the network operator as failures will decrease.

4. Conclusion and future developments

Today, the evaluation of transportation infrastructure is done through implementation of largely visual assessment. Where instabilities occur investigations often involve fragmented methods covering various disciplines such as geophysics, geotechnics, transportation engineering. Since there is no consistent collaboration between different experts, this leads to a fragmented and incongruent decision-making processes which infrastructure owners need to deal with. The need for unified methodology which would give straightforward answers on integrity of transportation infrastructure is necessary. Traditionally, the most widely used tool for investigation of embankments in order to detect surface cracks, shallow and deep cavities and inhomogeneity was visual detection. The problem with visual inspection is that hidden effects can be overlooked and that the result is subjective and any statement regarding stability is applicable only to the time at which the inspection took place. Another widely used method is destructive drilling, which gives unique information on parameters of the sub-soil, but only for a relatively small volume of the embankment section, thus extrapolating the data is challenging. Electrical methods are used for detection of layer boundaries, the GPR method is also used for detection of defects (such as voids) in embankments with relative accuracy. Seismic methods can additionally be used for obtaining velocities which can then eventually correlate with mechanical characteristics, and in-situ measurements and give information on parameters which affect the behaviour of embankments. However, by overlapping the images obtained from each method, a better insight can be obtained providing more reliable conclusions and significant savings of finances, time resources and ultimately safety. In this paper the proposed phased methodology to be developed as a part of the H2020 project DESTination RAIL (www.destinationrail.eu) is described and the implementation along the Croatian Rail network is described.

Acknowledgements

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