Identifying Abandoned Mineshafts Near Railroads

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Abstract
The presence of the railroads affects the performance of standard geophysical methods to delineate abandoned mineshafts. This paper outlines the difficulties that geophysical techniques encounter when measuring at or close to the railroad track - in cutting or on embankment. All geophysical methods experience problems and some methods are even ineffective. The feasibility of some non-standard methods is reviewed. These methods have potential and field experiments are required to assess the full potential. In the short term, a field test will be conducted to verify some of the assumptions that have been made.

Introduction
The existence of cavities at a site constitutes a potential hazard. This is especially true for abandoned mineshafts in urban areas and near infrastructure such as railroads. In order to diminish the risk, it is essential that the abandoned shafts are located and stabilised.

It is estimated that there are still 30,000 out of 100,000 workings in the United Kingdom which are unrecorded. These workings date from the prehistoric times to late 19th century, but the larger part are from the last three centuries.

From desk studies the presence of a mineshaft in a certain area is sometimes known, but due to unreliable or incomplete historical data the exact location is often doubtful. If it is estimated that the actual location of the shaft is within 20 metres of the initial estimated point, then the probability of finding a mineshaft of 1 metre wide in an area of 40 by 40 metres by drilling - is very slim and also very expensive. Thus the usage of geophysical methods could be a better and more cost-effective method to delineate the shaft.

This paper deals with the problems that standard geophysical techniques encounter when surveying at and near railroads. Standard methods include the techniques that commercial geophysical survey companies are providing. In addition the feasibility of some other techniques will be reviewed - these techniques are currently developed, but little used.

The Mineshaft
Abandoned mineshafts can be found completely filled, partially filled, capped or sometimes even open. The fill itself can consist of local waste, timber, rubble, surface soils or anything that was

available. Deeper workings are unlikely to be filled completely. In order to seal off these shafts a platform made of wood, iron or masonry was placed on the rim of the remaining casing just below the surface or near rockhead. The platform is normally located between 5 m and 20 m depth. When the shaft was not filled at all, the shaft was often capped in some way. There is little consistency in the method of capping.

The diameter of the shaft varies between 2 m to about 5 m, but there are shafts known with diameters as little as 1.2 m. The size depends on the lining material available, condition of the surrounding rocks, the depth and the output of the mines (Culshaw, 1987). Generally the diameter of the shaft increased with the centuries. The lining used in the shaft depended on the availability of material. After the closure the lining was often totally or partially removed, which results in the collapse of the shaft in recent times. The drainage of the workings is usually halted and depending on the geology, the capped or partially filled mineshaft may well have flooded with water.

Most of the problematic mineshafts pre-date 1850. Unfortunately there is very little information available for such old abandoned shafts. Historical data is often incomplete or not available at all. In most cases the actual properties of the problematic shaft, such as size and lining are unknown and also the measures taken after the closure are rarely known.

Geophysical surveying near railroad

Geophysical techniques are routinely used to detect abandoned mine workings. The success of the applied geophysical methods depends on success of the detection of anomalies that are associated with the presence of a concealed mineshaft. The presence of an anomaly in the survey area depends on the physical dimensions, size and depth of the mineshaft, and the physical contrast of the shaft in relation to the surrounding material (McCann, 1987).

To ensure that the most suitable technique is used to delineate the shaft it is necessary to carry out a comprehensive desk study. Any *a priori* knowledge about properties of the shaft and the surrounding rocks can contribute to the success of the survey. After critical evaluation of the available information from the desk studies it should become clear which geophysical techniques could succeed. The next step is to evaluate the feasibility of each suitable method in relation to the survey area conditions: noise, obstacles, topography etc. The last step is to compare the cost-efficiency of the remaining methods.

The costs of a survey at the railroad are directly related to the possession management. When possession management is required the total cost of the operation increases dramatically. An expensive seismic tomography, which does not require possession management, may be more cost-efficient than any survey that requires possession management.

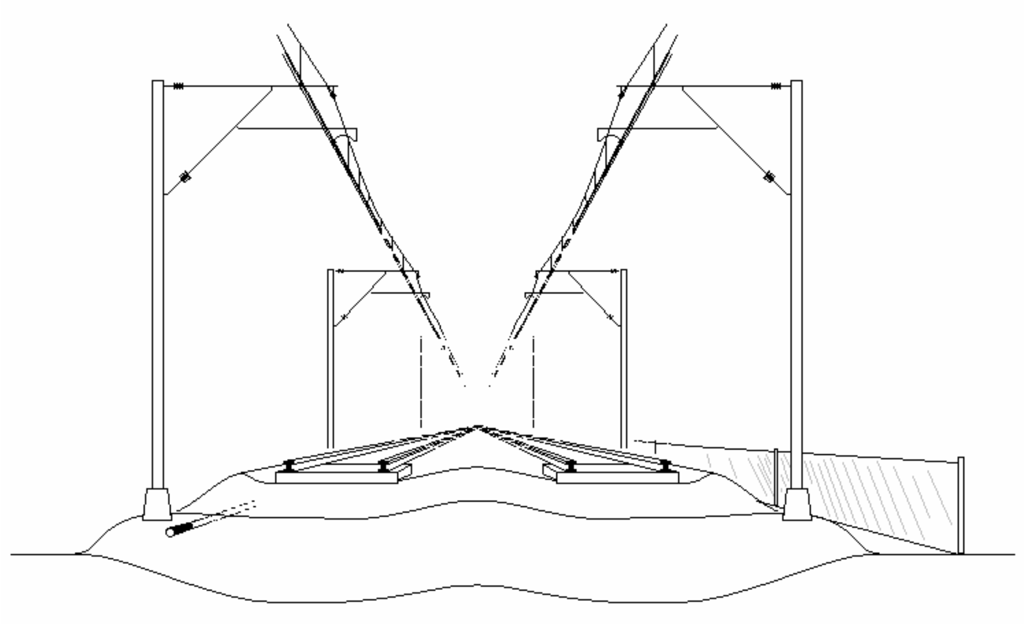

Figure 1: A cross section of a railroad embankment (not to scale).

Most surveys are executed at night, when there is limited or no traffic at all. On the other hand, working at night also increases the total costs significantly, because of higher wages and slower performance. The ideal geophysical method would be a survey technique that can be conducted during daylight and which does not require possession management. Because the possession management is an import issue, we will evaluate all geophysical methods in relation to the necessity of possession management.

Before the actual survey commences it is necessary to evaluate the feasibility of the proposed technique in relation to the survey site. The physical properties of the railroad embankment at a survey site can impose serious limitations on the feasibility of some of the methods.

A simplified cross section of a double railroad and its embankment can be found in Figure 1. The following elements are identified which could hamper the performance of the technique:

- *Embankment. The embankment supports the tracks and the sleepers. Major disturbance of the embankment is not permitted, hence no drilling.*
- *Ballast layer. The ballast layer consists of large aggregate that could affect the signal between the source and receiver placed in the ballast. The thickness of the ballast is often unknown.*
- *The rails. The rails consist of metal, which could interfere with electromagnetic fields and electric currents.*
- *Elevation variation. The embankment is not level, thus elevation correction may be needed.*
- *Overhead wiring. Safety regulations prescribe that the persons and equipment are permitted within 2.75 m of the wiring. Electromagnetic fields emanating from the wiring could interfere with geophysical data.*

- *Fences and other obstacles. The presence of fences and other obstacles could hinder the continuity of the survey lines and could also interfere with the geophysical data.*
- *Low voltage signal cables. The applied geophysical method must not produce any false signals.*

At this stage it is not know if any geophysical method could interfere with the signal cables, hence this has not been taken into account in the evaluation of each geophysical method.

Standard geophysical methods

In this section the feasibility of standard geophysical methods in relation to their performance at railroads sites are discussed. By standard methods is meant the commonly employed geophysical methods that commercial companies are providing. These include microgravity, magnetics, electromagnetics, electrical resistivity, ground-penetrating radar, seismic refraction, seismic reflection, surface waves and seismic tomography. All these methods have been able to detect voids, workings, shafts or other subsurface cavities at off-track sites with varied success.

Microgravity

The microgravity technique measures the vertical component of the local gravity which is the earth's gravitational field superposed with secondary fields, caused by anomalous densities. This method is one of the most used techniques to detect voids and shafts. Since a shaft produces very small anomalies in the gravity data, a micro-gravity survey requires high measuring accuracy. Accurate correction for the elevation, topography, tidal drift and instruments drift should all be taken into account.

The vertical gradient method is a variation of the microgravity method. This method is generally considered to provide better results for detection of shafts. The application of a 3 m tower as used by Fajklewicz (1976) is impractical and also expensive. A tower of 1 m could be more practical, but small measurement errors could result in a great error in the vertical gradient data. One of the difficulties that a microgravity survey would encounter near railroads is that elevation varies considerably, which makes it hard to level the instruments. Also the thickness of the ballast layer should be taken into account, but the exact thicknesses are rarely known in advance. Microgravity surveys are expensive and also require possession management.

Magnetics

Like microgravity, the magnetic method is a passive method. A bricklined mineshaft or a mineshaft filled with magnetic material can appear as an anomaly on the survey map. Problems arise when the magnetic properties of the shaft are similar to the surrounding rocks. The technique is highly sensitive to magnetic material, such as metals. The metal in the tracks and electricity posts will certainly have an influence on the measurements and therefore it is very unlikely that a shaft located directly below the tracks will be delineated by a standard magnetic survey.

Electromagnetics
The electromagnetic method measures the earth's electrical conductivity by metering the response to a transmitted EM field. The measured field is the primary field superimposed with a secondary field emitting from the subsurface. The secondary field should be small compared to primary field otherwise the secondary field generates its own secondary field. The problem that arises when surveying near railroads is that the metal in the tracks responds very strongly to the transmitted field and generates a second "primary" field. Also the EM filed emanating from the wiring interfere with the geophysical. Both effects are difficult to take into account and make the EM method not suitable for surveying near railroads.

Ground Penetrating Radar
The georadar is a very popular tool in engineering and environmental geophysics. A transmitter that is frequently co-located with a receiver generates an electromagnetic pulse and measures the response during a given time interval. The pulse reflects at the boundaries where a dielectric constant contrast exists. Although the mathematics of the electromagnetic propagation field is complex, the survey and the interpretation itself can be straightforward. This technique works well in low conductivity areas, but the penetration depth decreases rapidly in the presence of conductors such as clay or salt water.

The survey line at the railroad is limited to the space between the rails. The small penetration depth could also limit the performance. The method could be useful for detecting shallow mineshafts or for detecting secondary effects produced by the presence of the shaft (Leggo, 1983). The antennas have to be shielded from reflections from the tracks and other metal parts of the railroad. Possession management is required.

Electrical resistivity
This method determines the apparent resistivity of the subsurface by inducing an electrical current into the ground and measures the potential difference at two locations. By changing the electrode spacing an apparent resistivity profile can be created. An inversion algorithm can be used to calculate the actual resistivity profile from the apparent resistivity. The method is particular successful in detecting voids where the resistivity contrast is high. In general this is the case with water or air filled shafts. Shafts filled with rubble etc. are generally considered to be less suitable for this technique. Good results have been achieved in detecting water filled workings using borehole to surface resistivity (Maillol, 1999).

Difficulties could arise when measuring at the ballast, because of the expected bad contact between the electrodes and the ballast material. The presence of the rails could also affect the performance. Since the currents propagate in 3D, it is possible to detect objects that are not in line with the survey line. Hence it is theoretically possible to detect shafts below the railroad when measuring adjacent to the tracks.

Often an induced polarization profile (IP) is simultaneously acquired with the resistivity survey, because the acquisition and instruments are the same. The difference is that induced polarization measures the decay in the potential difference after the cut off of the current. Since the decay is not directly related to the resistivity, IP measures a different property, which is called the chargeability. A resistivity survey could fail where there is little resistivity contrast, whereas an IP survey could succeed at the same site. There is little argument for not doing resistivity survey simultaneously with an IP survey.

Seismic refraction

The refraction seismic method measures the travel time of an acoustic wave that has been refracted at a subsurface interface. The travel time data is used to acquire a velocity profile. This method is very commonly used in civil engineering to acquire the surface to bedrock depth, but there is very little reported success of the application of refraction seismics to delineating cavities, workings or shafts. This is because the wavelength of seismic waves normally used in practice exceeds the dimensions of the shafts.

Another problem is the poor coupling between the geophone and the ballast when measuring at the tracks. Possession management may not be necessary if the survey is conducted perpendicular to the railroad. This requires wireless seismic systems.

Seismic reflection

The probability to locate mineshaft by seismic reflection is related to the horizontal resolution. The Fresnel zone has been used to measure the horizontal resolution. Using the Fresnel formula and assuming that the top of shaft is located at depth of 8m and an average wave velocity in the overburden of 500 m/s, the minimum frequency required to delineate a 2m wide mineshaft is 400 Hz. The required frequencies are substantial higher than frequencies used in reflection seismics. Usage of high-frequency sources requires also different receiver concepts.

Due to the attenuation of the waves at high frequencies, the signal-to-noise ratio is very low. In spite of the problems, Miller and Steeples (1991) succeeded in locating voids in a seam at 7 m deep by using high-frequency waves. It is certain that shallow seismic reflection has some potential; however the reflection methods are expensive.

The poor coupling between the ballast and geophones could be a serious problem. This may be certainly true when using high-frequency waves. Possession management is required.

Seismic tomography

The use of high-frequency waves is commonly used in tomography. Typically the tomography technique consists of two boreholes. One contains receivers at fixed spacing and the other contains a source that varies with the depth. The travel time of the first arrival is used to produce a velocity profile of the subsurface. The disadvantage of this technique is that only heterogeneities between both boreholes can be detected. Borehole to borehole tomography has been very successful in detecting voids that have some horizontal extent. It is possible to use tomography techniques for borehole to surface and surface to surface configuration (Ditmar, 1999).

Borehole to borehole tomography requires no possession management, but the technique itself is certainly the most expensive. Since a mineshaft has a very limited horizontal profile it is very unlikely that tomography is useful for locating mineshafts themselves, but it may be useful to locate addits that are associated with the mineshaft.

Surface waves

The Spectral Analysis of Surface Waves method (SASW) is a relative new method (Froti, 2000). This method makes use of the dispersion behaviour of surface waves. A dispersion curve is obtained by transformation and processing of the surface wave data. This dispersion curve can be inverted to determine a shear-wave velocity profile. The inversion process is only suitable for horizontal layers and does not take into account lateral velocity changes. However it is possible to detect heterogeneities by looking at the change in the dispersion curve. The technique is reasonable robust and the data is easy to obtain, but it has not proven its usefulness for detecting lateral velocity changes.

When surveying near railroads, care should be taken when measuring close to the ballast layer, interference could occur between surface waves parallel to the ballast and the surface wave travelling through the high velocity ballast layer (Drossaert, 2001). Possession management is required.

Summary

The reviewed methods are briefly summarised in the Table 1 along with expected performance. The values for maximum depth of use are indicative. As can be seen non-of the techniques can be considered the golden solution to the problem, which is inherent to many geophysical problems. The tomography method seems to be the best method to delineate a shaft, but in order to detect 2 m sized mineshaft in an area of 40 by 40 m, at least 80 boreholes are required, which is impractical.

Technique	Difficulties	Max. depth of use	Possession required	Expected performance
Microgravity	Elevation, correction of embankment	20 m	Yes	Medium
Magnetics	Metal of the tracks, posts and fences	50 m	Maybe	Poor
Electromagnetics	Metal of the tracks, posts and fences	200 m	Maybe	Poor
GPR	Penetration depth	10 m	Yes	Medium
Resistivity	Bad contact	200 m	Yes	Poor
Refraction	Bad coupling, resolution	200 m	No/Maybe	Medium
Reflection	Bad coupling, resolution	200 m	Yes	Medium
Tomography	Spatial resolution	Depth of borehole	No	Good
Surface waves	Interference ballast layer, resolution	30 m	Yes	Poor

Table 1: Summary of the feasibility of standard geophysical method

Table 2 below gives an example of penetration of radar:

Depth (m)	Centre Frequency (MHz)
0.3 - 0.5	1500
0.5 - 1	1000
1- 2	500
2+	200
10	100

Table 2 - Antenna Frequency as a Function of Exploration Depth in Reflection Mode

Other geophysical methods

Other methods that have some potential include scattering of waves and thermal methods. Also the feasibility of some historical methods will be discussed, such as broadside refraction, fan shooting, seismic transmission method and seismic resonance method. Some of these methods may be more suitable for delineation of shafts then the standard geophysical methods.

Broadside and fan shooting

The fan shooting method has been developed to outline the shallow salt domes in Texas (Netteton, 1940), but the method can be modified to locate low velocity areas which can be associated with the presence of mineshafts. The geophones are placed in a fan pattern at various angles with respect to the source. When there is no velocity anomaly, the arrival times of the refracted wave will appear in a smooth normal time-distance curve whereas refracted waves travelling through the anomaly will appear off the curve. The anomaly can be roughly outlined by using overlapping fans.

A similar method is the broadside refraction method. The shotpoints and receivers are located along two parallel lines. Time leads are measured for each source-receiver combination. When there is no velocity anomaly between the source and receiver the time leads should not differ, whereas the presence of an anomaly will alter the travel time. The broadside refraction method is a very economical method for profiling (Telford, 1993).

The fan shooting and broadside refraction technique are both very robust, fast and the data is easy to interpret. Problems could arise when the refractor varies with the depth. Also weathering effects at the near surface could be a cause for local differences in the time leads. When the survey lines are chosen carefully it is possible to survey near railroads without possession management.

Scattered waves

Scattering or diffraction of waves is normally considered to be noise in the standard reflection and refraction surveys. Much effort has been expended to suppress the diffraction of waves, but as stated by Belfer (1998) diffracted waves can contain valuable information regarding the structure and composition of seismic media. Belfer used the information obtained from diffraction waves in combination with refraction data to locate a 5-m wide tunnel at 30 m deep.

As geophysicists recognise that scattered waves could be useful the number of researches to understand and model the scattered waves increased significantly. In a numerical research, Gritto (2000) successfully used an algorithm to invert synthetic scattered wave data to delineate the cavity. Herman (2000) attempted to separate scattered waves from the seismic data in order to locate shallow objects 10 m of the survey line. Although the target was not achieved, this study and Gritto's showed that scattering waves have certainly potential, but a practical method has still to be developed.

Thermal methods

Temperature is not a physical property that you would normally associate with the detection of mineshafts, but Donelly (2000) showed that there is a direct association between the surface temperature and the presence of shafts. It is found that the temperature at the surface is a function of the barometric pressure. A drop in the barometric pressure allows mine air to escape from the mineshaft and the workings. This process produces an increase in ground temperature in the order of a few degrees. Using infrared cameras could provide fast non-intrusive data about the temperature of the surface. Monitoring the temperature by IR over a period could be a cheap method to delineate the shaft.

The heat radiating from railroad traffic could possibly hinder the feasibility of infrared cameras.

Seismic transmission method

The seismic transmission method makes use of the fact the amplitude and main frequency of compression waves will be affected when a cavity is present between the source and the geophones. Dresen (1974) established that this shadow effect can be used to delineate a mineshaft. The acquisition and the interpretation of the data are reasonable straightforward.
An accelerator meter has been placed in a borehole at 19 m depth and the source was shifted in a fan pattern at the surface. By plotting the normalized main frequency versus the fan angle, the centre of the mineshaft could be located. By plotting the normalized amplitude versus the fan angle, the size of the shaft has been established. Although one borehole could be enough to locate the shaft, it has been suggested for the accuracy to use at least two.

A problem that could arise when conducting a seismic transmission survey at the railroad is that it could be necessary that the fan crosses the ballast layer. It is uncertain that the necessary high frequencies will be un-attenuated by the ballast. By carefully selecting the locations of the sources, it could be possible to avoid the ballast layer and the necessity of possession management.

It may not be necessary to use fan-like patterns, other patterns could be used, but the interpretation will become increasingly complex. Dresen (Owen, 1983) used a comparable method for surface waves, which worked well for near surface cavities. It also could be possible to apply the transmission theory of the seismic transmission method on the refraction fan shooting method.

Seismic resonance method

Resonance has been often observed when conducting standard seismic surveys over suspected cavities. The effect is probably a result of radial oscillations of the cavity walls. The resonance effect is approximately limited to receivers direct above the cavity. This can be used to locate a void. Fourier analysis and autocorrelation can further enhance the data.

This technique works well for voids filled with air or water, but voids filled with sediments etc. are unlikely to be detected by the seismic resonance method, because the resonant amplitude is considerably reduced. Although this technique has been used since the sixties it is still largely experimental.

In order to locate shafts below the railroad, it would be necessary to locate the geophones in the ballast layer. It is not unthinkable to use a passing train as a source to measure resonance effects.

Discussion of Current Techniques

The detection of abandoned mineshaft by geophysical methods is a difficult problem to solve. The presence of the railroad and the embankment makes it even more problematic. Although it is never measured, it is very unlikely that EM and magnetics are suitable to solve the problem due to the presence of metals. Seismic methods could experience coupling problems between geophones and ballast. Terrain correction could be difficult for microgravity. Resistivity measurements at the ballast are likely to fail and GPR lacks penetration depths. The responsible geophysicist has to satisfy himself with a geophysical technique that is the most likely to succeed.

Resolution is always a key feature of a geophysical survey - the detectable target needs to be related to the wavelength. It is essential to ensure that the iinput frequency is sufficiently high to identify the defect:

(a) Targets one half the minimum input wavelength are the often smallest detectable size

(b) $\lambda/2$ is the minimum depth of identifiable target

Beside the physical presence, the safety regulations and the necessity of possession management have to be taken into account. The cost-efficiency of a survey is directly related to the possession management. An expensive seismic tomography which does not require possession is still cheaper than any survey that requires possession management. Therefore our problem needs a different approach. Some techniques have been discussed that do not require possession management. These methods are currently under development or out-dated, but have certainly potential.

Planned Experimental Work

In order to validate some of the assumption that have been made in the paper, it is necessary to assess the feasibility of the techniques by field experiments. Up-to-now it has never been established what the effect of the presence of the railway lines is on the performance of geophysical methods. The University of Edinburgh possesses a 10m long full-scale model of a single track railroad embankment, which can be used for experiments (Figure 2). In the near future the following experiments are proposed to conduct at the embankment model:

- *Magnetics: The feasibility of magnetics near railroads will be assessed by burying a small magnet in the ground close to the tracks. The signature of the buried magnet is different from the rails, thus it may be possible be locate the magnet in spite of the presence of metals.*
- *Resistivity: The expected contact difficulties between the electrodes and the ballast will be estimated. Usage of contact improving means will be evaluated.*
- *Seismics: The attenuation of high-frequency waves by the ballast has to be assessed and means of improving the coupling between ballast material and geophones has be evaluated.*

After a careful assessment of the feasibility of geophysical methods in relation to their performance at and near railroads, field experiments are scheduled in long term. These experiments constitute of geophysical methods that are considered to have potential.

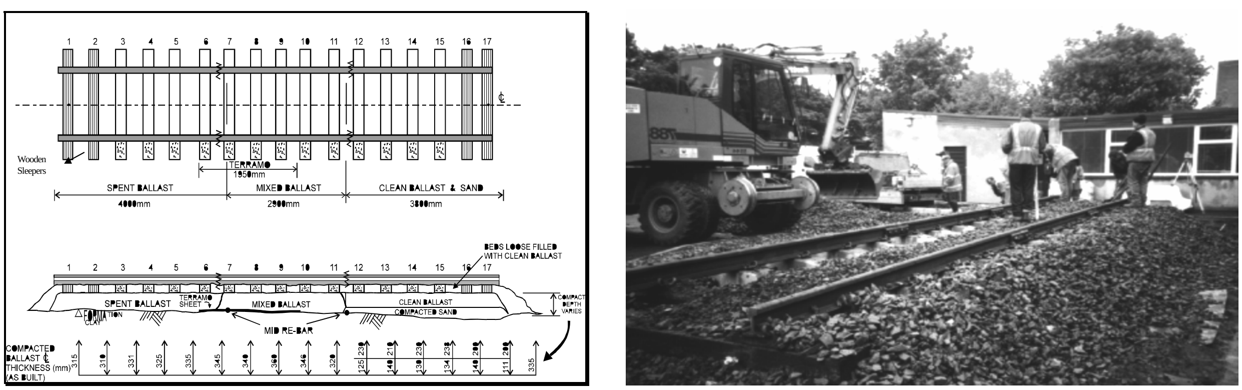

Figure 2: Illustration and photo of the full scale trackbed

Conclusions

It is certain that the presence of railway lines affect the performance of standard geophysical methods. Therefore the feasibility of some other geophysical methods has been discussed. These methods all have some potential. In the next few months a comprehensive report will be made, where the performance of geophysical techniques will be discussed. It should then become more clear where and when a method could work, why it could fail and what to do to make it succeed. Experiments are needed to verify some assumptions that have been made in this paper.

After the report, field tests will be conducted at existing railway track sites to estimate the feasibility of the techniques that are considered of potential.

Acknowledgements
The Authors wish to acknowledge the resources of the University of Edinburgh and the financial support of Network Rail Infrastructure Ltd.

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