A BETER UNDERSTANDING OF TRACKBED FAILURE MECHANISMS THROUGH A HOLISTIC APPROACH TO TRACKBED INVESTIGATION

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Introduction

The importance of trackbed investigation in the planning and management of ballasted rail systems has been known for many years. It is however sometimes overlooked and not properly understood leading to abortive track renewal works and increased maintenance liabilities. The failure of the underlying support to the track structure can ultimately result in speed restrictions, delays to service and occasionally to catastrophic failure of the rail system.

UK practice has improved on the national rail network in recent years. After decades of renewals undertaken with no coordinated and consistent approach to trackbed investigation across the network, trackbed investigation and design has now been implemented as part of a national strategy. Scott Wilson’s Trackbed Technology team has worked with infrastructure owners in developing this national strategy and acts as preferred supplier for these works across the entire UK rail network. A similar approach has also been developed with London Underground with Scott Wilson working on a framework contract delivering trackbed investigation and design for the current financial control period.

Historic UK Practice

The recognition that trackbed condition is a major factor influencing track quality deterioration and ongoing maintenance is not new. In the early 1900s trackbed construction good practice was well understood. The following extract from ‘Railway Maintenance Problems’ by Lt-Col H. A. Hull (District Engineer, Northampton, LNWR and LMSR, 1918-33) shows an important understanding of the factors above. “The foundations to carry permanent way have developed from solitary stone blocks to the present standard of crushed stone or slag. A layer of clean sand beneath the ballast, especially where the formation is of clay, is to be recommended. Where clay works up through the ballast, thus making it difficult to maintain a good road, the trouble can be cured by taking out the impregnated ballast, excavating the clay formation to a depth of 9 in. or 1 ft., and filling in with clean sand. Of course the drainage must be overhauled at the same time”.

Whilst developments have been made in formation treatments, this historic good practice has remained relatively unchanged as the chosen method of remedying poor formation sites. This is demonstrated in many international track construction standards. Ballast and sub-ballast depths are specified, appropriate to line speed, axle loading and underlying formation conditions. Minimum requirements for lineside drainage are also recommended along with optimised material specifications for the prevalent environmental and loading conditions.

Although the above is well known in the permanent way discipline, application of this good practice cannot always be achieved in the time and physical restrictions of an operational railway. Add to this the ever increasing demands on the network with more traffic, heavier axle loads and higher line speeds related to the modern railway and the determination and delineation of trackbed failure mechanisms becomes of paramount importance. Without this the designer cannot determine remedial solutions that are practical, have a long term positive effect on line and level, and target where they are needed.

In the past the trackbed was often designed according to tradition. No trackbed evaluation or remedial treatment was normally considered until the track quality began to deteriorate, by which time urgent action was required. A detailed investigation was seldom undertaken. Where they were undertaken, the trackbed investigations consisted of shallow depth trial pit excavation at set 100m intervals with the aim of providing an assessment of contaminated ballast and suspected subgrade problems. This non-targeted and generic approach to site investigation could lead to significant costs later if failure mechanisms were misunderstood or missed, and chosen renewal types were inappropriate. This would occasionally cause long term maintenance liabilities and a requirement to return to site to renew the track again, long before the intended design life had elapsed. Examples include pitching stones (laid historically at poor formation sites) being removed, or exposed cohesive layers not being blanket ed, if these risks weren’t identified until the construction stage.

Trackbed Investigation – Holistic approach

It is reasonable to say that the UK’s current drives for efficiency and cost savings mean that a standard approach to all trackbed designs would be desirable. The reality is however that every site needs to be
treated on its own merits in terms of both investigation and design. The physical and time constraints of accessing the rail network and ultimate client deadlines however often mean that we cannot gather all of the information that is desired. For the Permanent Way Engineer to maximise the engineering value of any investigation this has to be designed carefully, to ensure that the right information is obtained with the appropriate level of detail. Ultimately, the suite of techniques, laboratory tests and sampling schedule will need to be designed as the first phase of any scheme in accordance with the scope of works and client driver. As an example, the site investigation scope will be very different for a route upgrade using modern high output plant where buildability will be the primary focus, or a standard plain line/switches and crossings renewal.

Experience, Research and Development over the last 10 years has greatly enhanced the thought process behind trackbed investigation. This has given rise to a staged approach that relies on well timed investigations and strict adherence to the process before the investigation is undertaken and also in interpreting the results of the investigation. Figure 1 shows the stages of trackbed investigation now used in this standard approach.

The following sections provide further details referring to each stage of the approach detailed above.

**Desk Study and scope of investigation**

It is essential that the clients’ reasons for undertaking the trackbed investigation are fully understood at the start of the process. The investigations may be required for a variety of reasons, for example to provide data to be entered into an asset management tool, to understand the implications of lowering the track to increase clearance to overbridges and tunnels or to understand why a particular section of track is proving hard to maintain. The majority of the trackbed investigations however are undertaken where the site has already been identified as requiring renewal as part of an annual track renewals strategy.

On the UK national network the site is located by referencing using a mileage system on particular lines Engineers Line Reference (ELR) and the site is also given a unique identifier (UID) that all data can be referenced to at a later date. The current and proposed line usage in terms of tonnage, traffic type and line speed are required to understand the Track Category and any proposed increases in line speed or annual tonnage are also recorded. It is also normally possible to gain an understanding of the primary driver for the renewal (age of materials, known defects, difficulty in maintaining adequate track quality) and the proposed renewal method. The proposed renewal method will often be driven by high level constraints such as route strategies, budget, available plant and the physical and operational constraints of a particular site. For example the renewal method for a section of plain line track in a single bore tunnel will be different to that of a Switch and Crossing (S&C) unit of a major junction.
Once all of the above are understood it is possible to start to undertake a desk study and gather information that will help to better understand the engineering problems and intricacies of the site.

**Geological records**

Geological records provide an essential source of information relating to the materials underlying the site. These materials will normally have a direct impact on the way the railway was constructed and also how it performs under traffic and a variety of environmental conditions. An understanding of the engineering properties of the underlying materials is essential in any trackbed investigation, but particularly where the track is at grade or in cutting. The local geological records can also often provide an insight into the likely construction of any embankment, with locally won materials often being redistributed as part of the original railway construction process.

Information about localised faults that may affect the railway construction and the interfaces between different strata are useful. It is often at these interfaces that there is a direct influence on the track as water moving through a permeable material meets the impermeable strata and is shed into the track system.

Sources of solid and drift deposit information include both geological maps from the British Geological Survey (BGS) and extracts from infrastructure owner’s own records.

**Track Quality records**

Track Quality records are available for the majority of sites on the UK network, with regular measurement being undertaken using specialist trains (referred to in the UK as the New Measurement Train (NMT)). On the more heavily trafficked lines this can be as often as twice a month due to the requirement to identify track quality problems early on.

Experience has shown that with all of the necessary supporting information track quality data can be used as a good indicator of trackbed condition. There are basically three elements that determine the geometrical retention properties of track, i.e. the ballast, the formation and the track components. The condition of the track is relatively easy to assess since it can be done largely by visual inspection from the surface and direct measurement (e.g. of weld straightness). However the ballast and formation cannot be adequately evaluated by observation. It is of course possible to observe some advanced symptoms of trackbed deterioration, (e.g. wet spots at the surface), but the majority of trackbed problems are buried and therefore only manifest themselves as poor quality track.

Track quality can be assessed in two ways. The first method requires the collation of historical records, so that seasonal trends and the track's ability to maintain good track quality after maintenance intervention can be assessed. In the UK this is done by considering the standard deviation of track quality for a given 1/8th mile (200m) of track. The patterns of track quality deterioration for each 1/8th mile can be assessed to highlight locations of concern requiring intervention from maintenance and further investigation.

Figure 2 shows an example of historic track quality records for half a mile of track (4 no. 1/8th mile sections). The track quality bandings are categorised as good, average, poor, very poor and super red with threshold values set in relation to the line speed and traffic levels of the line. These track quality bandings are colour coded for ease of understanding with good track quality shown as green, through very poor and super red track quality represented as red and turquoise respectively. Asset data and records of where intervention work has been undertaken are also recorded and available as part of the desk study process.

![Figure 2 – Example of historic 18th mile track quality records](image-url)
Going into more detail, the rate of track quality deterioration for each individual 1/8th mile can also be assessed to identify sections of track were more persistent work is required to ensure that the track quality is maintained at acceptable levels. The example of data given in Figure 3, shows how the rates of track quality deterioration can be assessed before and after a renewal is undertaken. In this example the track quality was deteriorating at a rate of 1.4mm/year before the renewal was undertaken which improved to a rate of 0.4mm/year following the renewal works [Sharpe et al 2005].

The second method of assessment of track quality data is used to pinpoint problem locations and requires analysis of the raw track quality data collected by the NMT. Data can be plotted from the latest NMT run to assess the current track quality. As noted above the fact that track quality can be closely linked to trackbed and formation condition means that in locations where poor track quality is apparent in the raw data and the influence of other factors can be removed, it is now possible to pin-point locations where it is though that the trackbed may have failed and detailed investigation is required.

Figure 4 below shows an example of the raw NMT data plotted for half a mile of track. A site schematic has been superimposed above the data so that site features can be aligned to the data to aid in interpretation. Simplistically peaks in the NMT data relate directly to locations of poor track quality, which in return can be related to site features or locations of poor track condition. In the example shown below, the track quality had become such a problem for this site that a temporary speed restriction had been enforced at the time of the investigation.

The relationship between track quality and trackbed stiffness is discussed further later in this paper and further examples of data collected from the site shown above are presented.
Video survey / aerial photography

It is also possible to view the majority of the UK network via digital imagery collected from train mounted videos (provided to Network Rail by Omnicom Engineering Ltd). This allows a coarse level of “visual survey” to be undertaken without having to visit the site in question. It is possible to highlight site features and provide relatively accurate positional data from the system. Global Positioning Systems (GPS) and Internal Navigation Systems (INS) on the train allow all of the images collected to be spatially positioned and it is also possible to scale off still images to provide approximate offsets to site features from the running rails.

Figure 5 below shows some typical images obtained from the system. The primary benefit of using the video survey data is to recognise site features, such as structures and drainage and locate them in relation to the track quality trace (as detailed in the previous section). This can be done without putting staff at risk of working in the live railway environment. “Seeing” the site before it is visited also gives the site engineers a good understanding of what to expect and reduces the risk of any unforeseen conditions or features.

Combining these images with aerial photography (easily obtained by using web sites such as Google Maps™) also allows for the surrounding topography to be assessed. This can be influential in better understanding the contribution to the track system of the underlaying and surrounding geology and also the likely drainage conditions at the site.

Visual Survey

It should be noted that there is great value in visiting the site to be investigated as part of the scoping process. This allows the trackbed engineer to start to understand the potential trackbed failure mechanisms that may be occurring at the site. The visits are normally undertaken after the desk study and when as much data as possible has been collated and aligned to the track chainage system. The trackbed engineer can then focus his or her attention on the areas of poor track quality (as seen in the raw NMT data), or at areas where the track quality has deteriorated rapidly over time (by using the historic track quality data plots).

Visiting the site also allows the trackbed engineer the opportunity to meet the local maintenance engineer on site and talk through their experiences of particular problems that have taken place over the years. Even if the local maintenance engineer does not attend site they are normally contacted as part of the scoping process to ensure that any valuable local knowledge from the ground is taken into account.

A full understanding of the drainage conditions of the site is also essential when considering the performance of the trackbed and the track system. The site visit is an excellent opportunity to undertake a condition survey of the lineside drainage (if it exists) although certain safety limitations on individuals working alone on the UK rail network mean that detailed measurements may not be possible at this stage. Details of pipe invert levels, pipe dimensions, condition and outfalls can be taken during the later more detailed trackbed investigation.

The visual site inspection should also include observations relating to environmental contamination of the ballast and trackbed materials. An important aspect of the whole trackbed investigation process is the assessment of the materials that will eventually be removed from site in terms of contamination that may require disposal as special waste. The visual inspection will highlight areas of suspected contamination so that a full suite of chemical testing and analysis can be undertaken on samples recovered from the detailed trackbed investigation.
Ground Probing Radar data

Ground-penetrating radar (GPR) is the most widely used geophysical technique on the UK network. The radar signal – an electromagnetic pulse – is directed into the ground by a transmitting antenna. Changes in electrical properties caused by such features as subsurface objects or stratigraphy (layering) cause reflections that are picked up by a receiver (the travel time being indicative of the depth).

The inspection of trackbed using ground probing radar is well practiced and can be applied in several ways. For more detailed site assessments, ground coupled hand held antennae should be used, to give optimum data quality and signal penetration. Alternatively as a more general low cost alternative, high speed GPR surveys using horn antennae mounted on vehicles/trains can be used for route based assessments. These high speed surveys are undertaken on the more strategically critical routes such as main lines and primary freight routes in the UK and the resulting data is available to the trackbed engineer undertaking the desk study and investigation scoping process.

GPR can be used to give an indication of condition of ballast and the formation, as well as ballast depth. The example presented in Figure 6 has again been aligned with the associated schematic site diagram. The ½ mile of data presented, shows a variety of features within the GPR data that require calibration with intrusive investigation, but are very useful in delineating trackbed problems.

There is normally a strong reflection from the base of the ballast layer in the trackbed. Variations in signal reflection within the ballast and at interfaces can relate to a variety of trackbed problems. For example, if the ballast has deteriorated or become contaminated, this can reduce the penetration of the radar waves, so the strength of reflections from the base of the ballast may be low. If there is a distinct layer of contamination within the ballast (e.g. clay slurry) this can produce a distinctive strong reflection from its upper surface. A variety of material variations will often be present along any one site, particularly problematic ones.

The disadvantages of GPR should also be mentioned. In less-than-ideal conditions such as wet clays and silts, high attenuation can cause losses of signal strength; and granular materials can scatter the GPR signal. Nevertheless, provided the limitations of this technique are known and other data sets are used to support GPR analysis [Chrisp et al 2007] it provides an excellent cost effective method of making a first assessment of the underlying ground conditions. The use of other geophysical techniques in understanding the trackbed construction and failure mechanisms is discussed later in this paper.
Other data sets

In addition to the data sources and information described in the sections above it is also important to identify all the structures that may influence the track quality (for example level crossings and under track bridges) or create physical obstructions to the trackbed renewal works.

Buried service information must be sourced and checked at an early stage of the trackbed investigation process to ensure that there are no conflicts with proposed intrusive investigation locations and the necessary Health and Safety considerations are taken into account.

The national Hazard Directory, signal diagrams, line diagrams and other information are also sourced to provide details in preparation for site teams to visit the site and ensure that all operational aspects of the trackbed investigation can be properly planned and executed during the course of each stage of the process.

Scope of detailed investigation

The collation of all of the available data, information from the visual inspection of the site and any historic trackbed investigation reports allows the trackbed engineer to make informed decisions about planning the trackbed investigation. The level of detail into which the investigation can go, will be limited in most cases by budget. The cost benefit of the work will, however often justify a thorough investigation that will ultimately reduce the risks and overall costs of a project.

It is important that the whole site is covered in some way. If GPR data is available this will provide a picture of the underlying conditions throughout the site, but it is essential that this is always calibrated by some form of intrusive investigation. Where GPR data is not available the intrusive investigations would normally be planned with a maximum spacing of every 50m. The value of the desk study and scoping process is that additional intrusive investigations can be targeted at known locations of poor track quality (from the raw NMT data), and where the trackbed condition is thought to be directly influencing the performance of the track.

Specific features in the GPR trace (if available) should also be targeted by intrusive investigation to confirm their nature. The trained eye of a geophysicist can often interpret the nature of any GPR anomalies or interfaces, but it is essential that this is backed up with “ground proof”. It is also necessary to undertake physical works to accurately define the depth of any interfaces at material horizons as these depths are important in the trackbed design.

The usefulness of GPR in determining failure mechanisms is more apparent when analysis is considered with the other available data sets combined with the visual survey. An example of this can be seen in Figure 6 where there is a ‘trough structure’ evident in the GPR trace. This is indicative of deeper seated underlying subgrade problems, leading to the need for continual topping up of ballast to maintain track geometry. This was confirmed when speaking to the local maintainer during the desk study stage at this particular site and the intrusive investigation was planned taking this into consideration.

In general the detailed investigation will predominantly involve intrusive investigations with the Automatic Ballast Sampler (ABS) supplemented by trial pits. Further specialist investigations will be also be scoped where the desk study indicates that the site conditions and trackbed condition require more scrutiny. The intrusive investigation techniques employed and other specialist investigations are described in the following sections.

Intrusive Investigations

The preferred method of intrusive trackbed investigation is the ABS. This equipment consists of a steel sampling tube with cutting shoe, as shown in Figure 7. This is driven into the trackbed using a hydraulically powered hammer. The device can penetrate ballast and formation to obtain a 65mm diameter sample, typically to 1m depth, although a 0.6m sample depth can been used where it is only necessary to record the depth and condition of the ballast. If required a smaller 50mm diameter tube can be driven to greater depth through the hole formed in the ballast. The technique will even produce good quality samples below the water table. The samples are sealed in a plastic tube, enabling them to be returned to the laboratory for logging, photography and any appropriate materials testing.
A wide variety of materials testing can be undertaken on the recovered samples (or from supplementary bulk samples recovered from trial pits). The materials tests undertaken include:

- grading, and percentage fines in ballast;
- moisture content;
- assessment of shear strength using shear vane or cone penetrometer;
- Atterberg Limits of cohesive materials;
- Chemical analysis of trackbed materials for assessment of environmental contaminants.

Sampling cannot be carried out on the live railway because of the amount of equipment required. However all equipment is portable and can be quickly loaded onto a hand trolley. Productivity is very high; typically ten 1m samples can be taken per hour with a four man team. Depths of up to 5m have been achieved, but this takes about an hour.

The main advantage of the ABS is that the samples can be examined under controlled conditions in the laboratory by a trained geologist/engineer and the nature of the subgrade and trackbed layers can be accurately recorded. Photographs of the ABS core provide a permanent high quality record of the nature and thickness of each of the trackbed layers. In order to allow the information to be easily interpreted the logs are presented as legends. The legends are presented in sequence, to give an indicative longitudinal section. A standard legend key has been developed for this purpose to enable the nature and geotechnical properties of the various trackbed layers and the subgrade to be clearly presented. Figure 8 shows a typical ABS sample being logged, the associated materials description and trackbed materials legends.
When each sample is combined a longitudinal section of the trackbed for the site can be produced that shows that material types and horizons plotted at depths in relation to the top of rail level. Figure 9 shows an example ABS section from the site already used in previous examples in this paper.

The ABS logs are particularly valuable in understanding trackbed deterioration modes and calibrating the GPR profiles. The combined data set, when aligned with other data collated during the desk study process can provide an excellent picture of trackbed and formation make up. Using the ABS and GPR data from the site used in previous examples the combined data sets and site schematic are presented in Figure 10, to demonstrate the good correlation between the two data sources.
Trial Pitting, Structural trial pits and trial trenches

Although the ABS provides an excellent sampling technique for trackbed materials and is an efficient method of performing the trackbed investigation, the use of hand dug trial pits cannot be discounted. To fully understand the properties of the trackbed materials it is often necessary to carry out further laboratory analysis on bulk samples of material recovered from trial pits.

One such example would be the grading of ballast materials required to understand the effectiveness of ballast renewal using high output plant. [The high output plant effectively acts as a sieve removing undersize ballast particles and fines while returning good quality well graded ballast back into the trackbed. This returned material is then supplemented with new ballast]. It is therefore important that the existing ballast is sampled and graded before the high output renewals are undertaken to fully understand the requirements for volumes of new ballast to be delivered to site.

Hand dug trial pits are also important in assessing the possible conflicts of renewals plant with structures and other track ancillaries associated with the site (for example the concrete bases of signals and overhead line masts). A thorough trackbed investigation must provide the client and their renewals contractors with a clear indication of all of construction risks associated with the works that are to be proposed. Examples of possible obstructions that require investigations include, but are not limited to the following:

- Overbridge foundations;
- Tunnel Inverts or foundations;
- Underbridge decks and parapets;
- Under track culverts;
- Other under track crossings (conduits for cables for example);
- Overhead line and signal bases;
- Platform footings.

Figure 11 shows an example of a structural trial pit excavated on an underbridge with tight vertical and lateral clearances from the sleeper at the existing track level.

In addition to the reasons for trial pits to be excavated as above it is also beneficial to see the trackbed materials in-situ to understand the construction of the trackbed and observe it under different environmental conditions. It is not uncommon for water to infiltrate the trial pits during excavation and although this may limit their depth it does allow the trackbed engineer to observe the movement of water through the track system. Where the ingress of water or the level of the natural or perched water table does limit the depth of the trial pits that can be excavated a good sample of the materials below the water line can still be recovered by the ABS.

The open trial pit will also allow for additional in-situ materials testing to be undertaken. Two techniques often employed to undertake additional testing are:

- shear vane test - to provide an accurate indication of the shear strength of any underlying cohesive materials.
- Direct Cone Penetrometer (DCP) – to provide an indication of the bearing capacity of the underlying track foundation (CBR values).

Figure 11 - Example Structural Trial Pit
Detailed Investigation

Measurement of track support stiffness

The relationship between track support stiffness and track quality has been established through research undertaken over recent years [Sharpe 2000]. Previous studies have shown a direct correlation between measured trackbed stiffness and the best track quality that is achievable for a given section of track – this is known as the inherent track quality of the track. The measured support stiffness is therefore very important in understanding the potential track quality for a section of track or highlighting where the stiffness needs to be enhanced to provide a desired track quality. This would be particularly pertinent when carrying out route enhancements or line speed increases.

Ideally, as the trackbed and formation are subject to high impact loads, any stiffness assessment tool needs to recreate this loading regime (or approximate to it) to get a representative deflection response of the trackbed and subgrade. As such impact load assessment tools are typically more useful and relevant to the Trackbed Engineer.

The Falling Weight Deflectometer (FWD) is a tool that is widely used in highway applications for pavement evaluation and design. A rail mounted version has been developed that provides a convenient, relatively quick, method of applying a measured load to an unclipped sleeper, which then transmits the load to the trackbed (see Figure 12). The load applied is equivalent to a 25T axle load to allow a representative deflection response to be measured, although the technique does allow calibration for a range of axle loads and infrastructure. Deflections are measured to microns (thousandth of a millimetre), so precision is high.

By measuring the deflection response of the ballast, sub-ballast and subgrade using a series of geophones, the Sleeper Support Stiffness, along with the Critical Velocity (as described in the Network Rail Line Standards) can be determined. These are defined below:-

- **Sleeper Support Stiffness**: An important measure of overall structural adequacy and the variability of track support. It is essential for the track to have both adequate and uniform stiffness. Higher deflections represent lower stiffness (load spreading ability) and track quality deterioration is worse on trackbed exhibiting variable sleeper support stiffness (i.e. variable FWD deflections).
- **Critical Velocity**: Particularly important on high-speed lines built over soft subgrades where speeds may be limited due to “dynamic interaction”, characterised by increasing elastic displacement as the train speed increases.

The analysis of FWD data from existing track is not as advanced in comparison with international highways applications where it is embedded in pavement analysis and design tools; however the rail mounted version of the FWD is still a useful tool in any trackbed investigation. The FWD has a proven history of use at ‘problematic’ maintenance liability sites where other investigation methodologies have not been able to highlight and delineate failure mechanisms [Middleton et al 2005]. The FWD data presented in Figure 13 is again for the example site used earlier in this paper and shows a good correlation with the track quality data. It is apparent that the largest peak in the track quality data (i.e. where the track quality is poorest) is reflected in the FWD data as the location where the measured deflections suddenly change, indicating a location of marked variation in track support stiffness.

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*Figure 12 – Falling Weight Deflectometer (FWD)*
Internationally the FWD has been applied as part of route strategies to determine maximum line speeds on soft subgrades (e.g. peat) and to aid in the design of mitigation measures to avoid line speed restrictions.

The FWD can also be applied for the compliance assessment of compacted subgrade layers for new-build railways where access is not an issue and there is no existing infrastructure. The Light Weight Deflectometer (LWD) is another tool that can be used for this application, and allows rapid compliance testing of exposed compacted layers. The LWD incorporates a single load cell and geophone, similar to those used by the FWD, giving a history of time versus deflection along with an immediate output of peak deflection and surface stiffness. The equipment is portable and can be used to give an immediate assessment of the quality of construction and to identify potential problem areas quickly and effectively. The LWD is shown in Figure 14 along with an example stiffness profile. For this case study, stiffness values under each proposed rail line generally correlated with each other suggesting good quality control of compaction. Low stiffness values were observed at locations of visibly poor compaction and suspected cross track drains, as well as backfill areas at the ends of new underbridges.

Additional Geophysical Techniques

In addition to GPR other non-destructive techniques that rely upon geophysical principles are also available but are used more for specialist testing in the railway corridor, where more detail is required. These include resistivity and electromagnetic conductivity.
With resistivity systems, an array of metal electrodes are typically inserted into the ground to obtain a profile of electrical resistance with depth. These are presented as pseudo sections through the ground. Resistivity is generally better suited to the rail environment, though high contact resistances for electrodes in ballast make it quite a time consuming survey. Examples of applications of this technique include identification of badger setts; investigation of the loss of support to a rail sea wall, where bedrock levels, non conductive features such as voiding, and locations of saline incursion were assessed (see Figure 15); and location of mine workings.

![Figure 15 – Resistivity Profile of cess above suspected voiding behind sea wall](image)

Electromagnetic (EM) conductivity instruments have a comparable measurement response (conductivity is effectively the inverse of resistance), although are generally less sensitive, do not require direct contact with the ground and respond strongly to metal (a major disadvantage when, for example, rails are adjacent to the site). Little indication of variation with depth can be achieved with this technique, but a plan of conductive areas within a site can be completed with minimal survey time. Both techniques work on the same principle, highlighting features of higher or lower resistivity/conductivity than their surroundings. Electric current passes more easily through moist deposits (i.e. they are less resistive, more conductive) than through dry material, while organic deposits might conduct electricity more easily than surrounding soils.

All of the geophysical techniques mentioned above can add value in any site investigation scheme and can mitigate risks in subsequent designs. Often the techniques are simple to perform and are useful in ‘filling in the gaps’ between known ground conditions at intrusive sample locations. This can often lead to cost savings of the site investigation in general by reducing the requirement for more costly intrusive investigations. However it is important to recognise the limits of these techniques, else their benefits may be oversold; they should not be seen as panacea to all site investigation and a way of avoiding intrusive site investigation entirely.

**Detailed Drainage Investigation**

As noted previously it is also possible to carry out further drainage surveys as part of the detailed site investigation. This forms a key part of the investigation as it is essential that drainage paths out of the trackbed are understood and the conditions the route of water to outfalls is also established, before any trackbed design is produced.

The drainage survey would normally as a minimum include measurements of pipe invert levels and diameter relative to top of nearest rail level and a condition survey of each catchpit. When pipe invert levels are then plotted relative to the rail level (taking the known track gradient into account) an understanding of the intended flow of water through the system can be obtained. This, combined with the condition survey (notes of where the system is blocked etc.) can then be correlated with apparent sections of trackbed with poor trackbed condition. If it is intended that the drainage will be replaced as part of the trackbed renewal it would be necessary to undertake a full and accurate level survey of the drainage system, using traditional surveying techniques.

In addition to the above, an understanding of the permeability of the formation and subgrade materials is also of use in design as it is possible to design the trackbed to drain into a natural or man made soak away. A relatively simple infiltration test has been created using complimentary equipment to the ABS used for the trackbed investigation. This allows a stand pipe to be inserted into the hole left by a track window sampling
rig and the test performed, to give an infiltration rate. Figure 16 gives a simplified schematic section of the trackbed and typical test arrangement.

**Interpretation and Design**

Once the investigation has been undertaken (or in some cases as the initial data from the investigations is interpreted) the trackbed design process will begin. However before the data can be interpreted, more will need to be known about the criteria for design. As with any design, the overall design life, design parameters and client requirements need to be known otherwise ‘gold plating’ may occur resulting in an over-design.

For a typical plain line renewal the expected design life should be 20 to 30 years if designed to current line standards for the relevant line speed and annual tonnage. In the UK track renewals not achieving the bottom end of this range are surprisingly common. This can sometimes be attributed to the early onset of trackbed failure mechanisms. In the absence of a detailed trackbed investigation and design, or where the investigation and design has not been performed sufficiently in advance of renewal to book ‘fit for purpose’ possessions for any potential formation treatment required, tracked failure is common. Quick wins on site using geocomposites in place of sand blankets are sometimes seen as a solution in these instances, although whole life costs using this approach can be increased significantly due to early requirements for maintenance.

Whilst correct specification of geocomposites can lead to significant cost savings, getting it wrong can make a situation worst and this has been evidenced at several case study sites (see Figure 17). This was the subject of a recent paper discussing impermeable membranes and the problems with incorrect specification [Pope, 2007].

**Figure 17 –Incorrect Trackbed Design of Impermeable Geocomposites**

For some renewals, design life may be reduced if the works are only seen as temporary. Examples include major remodelling schemes involving staged temporary alignments to achieve the final Permanent Way design layout. There were a number of temporary alignments used during the staging process as part of the Trent Valley 4 Tracking project (a major scheme undertaken as part of the West Coast Route Modernisation in the UK). These stages would allow the railway corridor to remain operational while enabling works were undertaken to take all tracks to their final alignment. The temporary alignments used may have only been in place for a matter of months and with temporary speed restrictions applied the stages only required minimal
trackbed work to be undertaken. Although the design life was minimal an important consideration was the future impact of these temporary solutions on the final trackbed construction.

For trackbed design the most universally used parameter for assessing the performance of the track is the track quality as obtained from the NMT. The geometric characteristics of the line under vehicle load, and the 35m filtered vertical profile of the rails is of most relevance when judging the performance of the trackbed. Poor geometry will result in a rough ride, not only unpleasant for the passenger, but causing increased dynamic loading and more damage to track/trackbed/vehicle components, with consequent reduction in life.

Therefore as a starting point, track quality can be used to delineate problems throughout the site and give an indication of the possible cause(s) of trackbed failure. Designers do have to be wary of solely relying on track quality traces to locate problems and define the cause. Not only can track quality at a specific location be indicative of problems located further up or down the track (depending upon the direction of traffic) but deterioration can be a result of a myriad of problems not just related to trackbed failure.

The success of any trackbed remedial scheme can obviously be affected by the quality of the existing drainage. Alternatively poor drainage can, to some extent, be compensated by adopting a more robust trackbed treatment.

If no lineside drainage exists the capacity of the natural ground to drain water may need to be known. This is particularly pertinent with increased awareness of the impacts of climate change on flooding. Sustainable drainage solutions that rely less on existing or new ‘traditional’ drainage (i.e. lineside drainage) need to be considered wherever possible. This can normally be assessed from historical records and data sets, although the standpipe infiltration test previously described can aid in decision making.

Although not typically assessed from a technical standpoint in the UK the interdependency of the underlying trackbed, geology and hydrology on drainage of the Permanent Way will become of increasing importance. This is particularly pertinent in the urban area where attenuation rates from infrastructure need to be sufficient to prevent overloading the wider urban drainage system in times of high precipitation. In order to development appropriate trackbed designs which provide serviceable track support and are suited to the wider catchment area, the infiltration characteristics of the cess need to be taken into account.

Ballast

The ballast data sets obtained during the trackbed investigation will primarily depend upon whether the assessment is of in-situ trackbed material or is for a new-build scheme where development of a specification is required.

For projects where renewal of the track is required in some form (e.g. re-ballasting, formation renewal, ballast cleaning etc.) the designer needs to know the ballast depth, condition and the variation in these parameters (see Figure 18). By assessing material condition and depths against required excavation depths, the existing material can be assessed for its’ suitability to remain in service, its’ potential for re-use and the likely requirements for formation treatment if replacement is required.

![Figure 18 - Typical track cross section of ballast and sub-ballast](image)

When variation of depth is considered, deep ballast layers can suggest deeper seated problems and/or changes in support conditions. Deeper seated problems can often be temporarily resolved by the Permanent Way Engineer by ‘topping up’ with fresh ballast to maintain line and level. Over the years as this does not remediate the cause of the problem, ballast troughs can manifest that are indicative of historic or ongoing subgrade failure. An excellent example of the trackbed data obtained from a site where this action had been undertaken was presented in Figure 10 and other data sets used earlier in this paper.
Providing logging has been carried out to an agreed system the failure mechanism can easily be identified. In the UK, logging standards are typically to BS5930 but ultimately logging of material type, nature, consistency and moisture content will highlight failure due to ballast deterioration, pumping or fines ingress from other sources.

Additional sieve analysis data can also be obtained from the ballast layer that can determine a range of useful information for the designer (examples of where some of the following information has been used can be found in Armitage et al. [2003] and Lim et al. [2005]):

- Residual ballast life – a measure of the life in years of the ballast before it becomes life expired (i.e. the point at which tamping has no long lasting positive effect). This can be used for route upgrades where entire renewal is not possible (typically due to budget constraints) and utilization of existing materials is of paramount importance;
- Fouling index – a measure of the fines content of the ballast that can be used to assess permeability and drainage potential of the trackbed;
- Ballast Rate of Return – a measure of the likely rate of return of ballast if ballast cleaning is being considered. Ballast cleaning is a preferred method in the UK for ballast excavation as it can be more cost-effective than traxcavation and can result in savings associated with the import of clean ballast. This is particularly important for high output ballast cleaning systems where advance knowledge of this information is key to successful operations. This also goes hand in hand with ballast depth information particularly where physical limitations may impinge upon ballast cleaner cutter bars.

For new-build projects where bespoke material design is more relevant, the specification of the ballast is paramount. If not bound by current infrastructure specifications, a material can be designed to ensure that it meets the specific demands of the project in question. Whilst the choice may be limited by the availability of suitable aggregates (due to geographic location or budget), the designer must consider a range of aggregate properties including strength, durability, geology and freeze-thaw behaviour to name but a few (some are more related to extreme service and environmental conditions not typically anticipated on UK railways). The particle size distribution and shape properties of the material can also impact upon deterioration in service due to the inter-particle interaction and this must also be considered.

For renewal of existing Permanent Way and/or new-build projects, one of the most important design decisions for any renewal scheme is the required ballast depth. Ballast depth will need to be sufficient to allow maintenance and to reduce pressures from the sleeper bearing area to acceptable stress levels for the underlying material.

### Sub-ballast/Blanket

Often the condition of the existing interface between the ballast and the formation (consisting of the subgrade plus blanket and other protective layers) will point the designer in the direction of the likely over-riding trackbed failure mechanism. If the ballast sits on an adequate sub-ballast/blanketing layer, providing drainage of water is not impeded, failure mechanisms associated with underlying poor subgrade such as pumping will be mitigated. Furthermore a properly engineered sufficient depth of sub-ballast will also reduce the otherwise required greater thickness of more expensive ballast (often design charts specify a granular layer thickness that includes the ballast and the sub-ballast).

From a designer’s perspective, the question to ask will be whether the existing sub-ballast or blanket is adequate at the dig depth of any proposed excavation or as a prepared formation for any new-build scheme.

In the UK there are no material specifications for sub-ballast to assess site data against although in general terms sub-ballast needs to fulfil several primary functions:

- Keep subgrade and ballast separate and prevent upward subgrade fines migration;
- Reduce stress to the subgrade;
- Prevent subgrade attrition by ballast;
- Shed water from above and drain water from below.

From a materials’ perspective to cover these requirements, sub-ballast can be broadly-graded naturally occurring or processed sand-gravel mixtures, or broadly-graded crushed natural aggregates or slags. Provided these materials can act as a filter medium between ballast and subgrade determined from simple filter design principles founded in soil mechanics theory then they should be suitable as sub-ballast.

Although there is no material specification for sub-ballast, minimum depth of cover to poor subgrade materials are recommended in the UK that range from 50 to 100mm. In the absence of this cover depth
there will be a requirement for some form of formation treatment in the form of geocomposites or installed sand blankets (dependant upon existing cover and subgrade classification). International design guidelines however are more prescriptive regarding sub-ballast, opting for an increased sub-ballast depth with defined compaction and material specification criteria to avoid excessive ballast thickness. In general terms, UK renewal practice seems to favour minimum allowable depths of construction, partly due to budgetary, infrastructure and/or time limitations whereas greater depths may achieve reduced whole life costs (discussed further in the next section ‘Subgrade’).

Where newly constructed sand blankets are required, a material specification exists that ensures filter medium principles are satisfied with depth sufficient to ensure fines can be filtered effectively (research suggests fines ingress up to a maximum of 30mm through sand filters is typical). Even though 50mm sand blankets are allowed in the UK, typically where excavation depth needs to be limited (e.g. at platforms), 100mm depth is preferred to ensure that a sufficient depth of cross fall material can be practically installed on site.

**Subgrade**

Trackbed stiffness has a major influence on track quality deterioration. As such the understanding of this parameter and its importance to the designer is key. For construction of new railways, preparation of a formation with prescribed track stiffness does not attract a large premium on cost of construction, and as such optimization of stiffness in this application is justified.

For existing lines however, although track stiffness is a known problem in the UK, the main issue is justifying the cost of remedial works versus the cost savings made during the operational life. In the limited studies so far that have looked at whole life cost, remedial treatments have shown a large initial investment is required to achieve an overall whole life cost saving.

Ideally before design decisions can be made the influence of the remedial measures on stiffness and subsequent whole life costs needs to be understood to ensure the initial investment is justified. Typical case studies have shown that treatments to improve subgrade stiffness are only applied where there is no other option and the failure has been sudden or catastrophic either in terms of safety, capacity or speed.

For existing lines the subgrade is typically not a layer that can be readily enhanced or replaced on existing infrastructure and hence the large initial investment cannot be avoided. Therefore the Trackbed Designer tends to rely upon the application of shallow seated remedial techniques to ‘treat’ the problem not ‘cure’ it. Currently these rely upon increased granular layer thickness and/or installation of geocomposites in the layers above low stiffness subgrade.

Whilst the application of these techniques and their benefits are much better understood than other subgrade remedial techniques due to available in-service history, there is still a knowledge gap in the effects of these more traditional solutions on whole life costs. As a minimum an analysis of all renewals across the UK and the relative success of each treatment technique on track quality would give the designer information that would be invaluable.

**Future Developments**

In addition to the analysis of renewals performance to predict the effectiveness of trackbed designs going forward, current work is also underway to create better modelling techniques and predictive tools to manage the track asset.

Much of the data described in this paper can be collected on a route or site basis and is still valid once the track has been constructed or a renewal has been undertaken. This re-useable data can then be used in analytical models to predict with some accuracy how the track and trackbed will perform under traffic, throughout years of maintenance cycles and under different environmental conditions. The development of such models is however currently limited to academic studies rather than commercial applications, because of the time needed to construct the models arising from their complexity.

**Summary and Conclusions**

The importance and value of a detailed and well considered trackbed investigation meeting a client’s and project’s requirements has been well established in the UK. A variety of data sources are available to the trackbed engineer, who should be engaged as early as possible by the client to ensure that the appropriate level of investigation is undertaken using the most appropriate techniques from the range that have been developed and are available.
The combination of data that can be gathered as part of the desk study process together with information, data and samples recovered directly from site can build a robust picture of the way the track acts under loading and how and where failures have occurred. More detailed specialist techniques can be used on sites requiring further investigation to better understand how “non-standard” failures have occurred.

Ongoing development and research may lead to better forward predictions of trackbed failures and therefore allow for earlier intervention, instead of reactive renewals and provide an excellent asset management tool that could be used on any railway where suitable levels of data have been collected.

Scott Wilson’s website is http://www.scottwilson.com/sectors/transportation/railways.aspx

References


