60 years of modern ballast cleaning machines: ballast bed behaviour and the importance of ballast bed cleaning, and introduction of first machines (Part 1 of 2)

The ballast bed is the load-bearing element of a railway track. Traffic loading subjects the ballast bed to static and dynamic stresses, causing ballast stone movement and wear that leads to fouling. Over time, this causes the ballast bed to significantly deviate from its original specifications – it can no longer adequately fulfil its load-bearing function, thus jeopardising track stability. It was recognised early on that, by cleaning the ballast, the load-bearing function of the ballast bed can be restored. Initially, ballast cleaning was carried out manually, but soon this arduous manual task was mechanised – the first machines built for this purpose appeared about one hundred years ago. Part 1 of this two-part article looks at ballast bed behaviour and the importance of ballast bed cleaning, as well as the introduction of the first ballast cleaning machines.

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BALLASTED TRACK – HISTORICAL DEVELOPMENT

When steel flat-bottomed rails and wooden cross sleepers, which retain the track gauge, were introduced around 1830, today's basic track type was born. Experiments with other types of track construction took place in later years, but the results were ultimately insignificant. Before 1870, wooden sleepers had a service life of only three to five years, especially when drainage was poor. It was not until around 1865 that they were treated with substances such as creosote and, as a consequence, their service life increased to 30 years or longer. Oak and beech wood continue to be ideal material for sleepers.

Granular material was added to the track to keep it level and ensure its functionality; it was shovelled or hammered into the space between the wooden beams and the substructure. This somewhat medieval measure led to a discovery: putting ballast – a readily available and, hence, affordable material – underneath the sleepers is a suitable and convenient method to create a track bed.

Over time, experience gained by railway experts led to the development of rules and regulations governing material selection and construction methods for ballasted track. Normally, local quarries are the source of the ballast used for railway track. Ballast stone dimension and shape are today governed by various regulations that all emphasise the importance of using stones with a compact, slightly cubic shape. Flat stones or ones with sharp edges are deemed unsuitable. Furthermore, the regulations define minimum requirements for stone density, as well as resistance to abrasion, freezing and thawing.

Ballast bed – importance of water permeability

A ballast bed should provide sufficient anchoring of the track against lateral forces, which requires the track to be ballasted until the ballast reaches the top edge of the sleepers. There must also be sufficient ballast around and between them. A particular advantage of ballasted track is that it drains water safely and surely [1].

A dry track bed and a track built layer-by-layer are two important prerequisites for ensuring an adequate and durable track geometry (Fig. 1). Additionally, the substructure must have a specified cross-fall, so that water can flow into the railway ditches. Water permeability of the ballast bed is essential to ensuring that the track structure remains dry – so that the track can reliably absorb static and dynamic forces in the long term without any deformation.

FUNDAMENTAL RESEARCH INTO BALLAST BED BEHAVIOUR

The ballast bed is a pile of coarse-grained material with limited dimensions. Describing it as "a homogeneous solid" – regardless of the type of solid – does not seem fitting. This is due to the

Fig. 1: Example of a modern, multi-layered ballast bed

relationship between the thickness of the ballast layer and the dimensions of the ballast stones. An additional factor is the location of the ballast – it is a relatively thin layer between the sleepers and the substructure. The development of powerful computer technology has made systematic investigations of this intermediate layer possible; these are still ongoing.

Fundamental research has been conducted over the years that has yielded a good insight into ballast bed behaviour, a selection of which is alluded to in the following.

Klugar [2], [3], [4] was the first scientist to use modern research methods to analyse the deformation behaviour of the ballast bed. The results of his research pertain to the long-term behaviour of ballast stones when subjected to repeated loading, as well as the "initial track settlement" phenomenon. The latter describes the immediate settlement of the track by 2-5 mm during initial traffic loading. It was shown that, due to the loading, the contact areas between the ballast stones change. Because of their small surface area, the edges and points of the ballast stones are subject to very high localised pressure, which causes abrasion. When the loading force being exerted gradually increases, the track settles again because of further pressure changes between the stones until, ultimately, the track achieves a state that changes very slowly and is proportionate to the forces exerted onto it. This behaviour is very much dependent on the respective type of stone used and the distribution of stone sizes. The types of stone locally available, as well as the deployment of stationary screening units, play an important role. Research conducted by Klugar, and also others, has shown that the density of the granular structure depends on the mixture of stone sizes and the normal force being exerted. When loading exceeds certain limits, irreversible plastic deformations occur. Research conducted by Profanter [5] and Povse [6] has also confirmed these findings.

Schneider [7] investigated the dynamic elastic modulus of broken stone material. In this respect, he explored the phase shift in ballast reaction in relation to induced high-frequency vibrations.

Fundamental research conducted by Fischer [8] has demonstrated how the parameters vibration frequency and amplitude influence the sustainability of the tamping result. His work still forms the basis of modern tamping unit design and settings, which ensures that an optimum ballast compaction is achieved.

Extensive research conducted by ORE (later ERRI) between 1965 and 1990 gave rise to various "ORE reports"; ERRI also conducted research in the same field and issued similar reports [9].

For many years, experts hypothesised that forces are directed via the ballast bed onto the formation at a diffusion angle of approx. 45 degrees and decrease in the process. Recent analyses of ballast underneath concrete sleepers showed that this long-standing hypothesis does not stand up to scrutiny. Experiments conducted during the last five years in Austria and other countries, using modern measurement equipment, drew the same conclusion – forces hit the formation in a more concentrated manner, with a diffusion angle of 17-20 degrees [10], which means that the formation is subjected to a significantly higher amount of pressure than previously thought.

Although scientists had discussed the option of using simulations to better understand ballast behaviour some 40 years ago, it was not until the rapid development of computer technology in recent years that this option became possible. Research by López-Pita and Estradé Panadés [11], Kruse [12], Desai [13], and Holtzendorff [14], as well as Auer, Omerovic and Philipp [15], is based on computer-generated ballast bed modelling (Fig. 2). It is now possible to depict the ballast bed "stone by stone" and for various contact situations. Fortunately, the modelling largely confirmed what experience gained had already shown, such as the importance of using varying ballast stone sizes for instance.

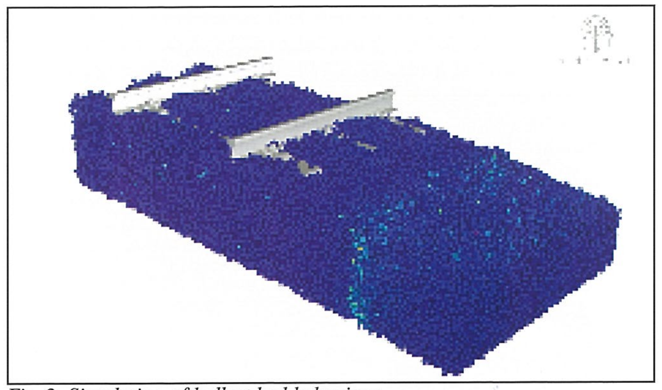


Fig. 2: Simulation of ballast bed behaviour

Being "caught between a rock and a hard place" is a term that well describes the contact of ballast with the underside of concrete sleepers. With the introduction of under-sleeper pads, around 1990, this particular problem was successfully solved. The application of this intermediate elasto-plastic layer between concrete sleeper and ballast leads to an enlargement of the ballast contact area and, thus, the locations at which forces are transmitted from the sleeper to the ballast bed, thereby transmitting them in a much smoother way. Their use also leads to a significant reduction in ballast attrition, resulting in longer ballast bed cleaning intervals.

Ballasted track – a proven structure

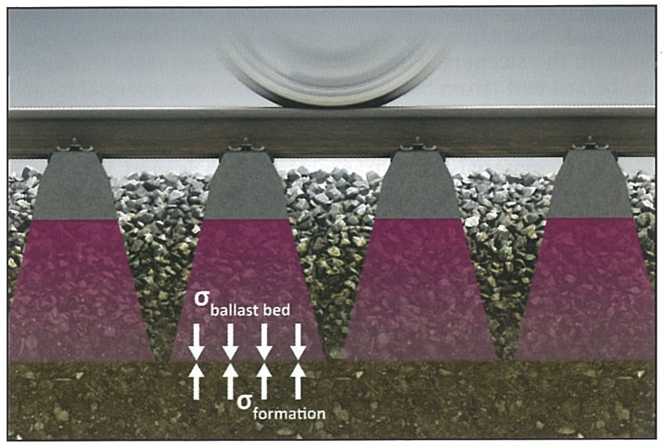
Over the past decades, railway technology has made a great deal of progress. High-speed railway lines clearly advertise this progress. The French railway operator SNCF achieved a "world speed record" of 574.8 km/h. Interestingly, this was on ballasted track – it demonstrates that this type of track is cost-effective and offers maximum precision. Widespread use of concrete sleepers may be an explanation for this – in their current form, they no longer feature components that deteriorate over time. Further, they do not shrink or stretch, which also offers certain advantages. In any event, the complete transition from manual to mechanised track construction and maintenance is largely responsible for ballasted track being able to meet the highest demands.

IMPACT OF TRAFFIC LOADING ON BALLAST

Modern ballasted track and ballast beds require constant care as, like any other technical structure, they are also subject to wear. A pile of ballast stones forms a structure with various contact points, which transfer the wheel forces exerted by the passage of trains to the substructure. In addition to "keeping the train on track", the rail positioned between the wheels and the ballast is also responsible for distributing the vertical forces, exerted as point forces, longitudinally and, thus, reduce the pressure exerted on the individual ballast stones.

Overall, the track is a force-distributing "load-bearing system". A certain amount of track elasticity is essential to safely distribute these forces. Experience gained has shown that, under a 20 t axle load, a track elasticity of 1.2-1.5 mm is recommended.

The height of the ballast bed distributes the forces further until, ideally, the substructure can accommodate them in the long term without continuously increasing deformations. Consequently, the forces acting on the substructure must be lower than its specific load-bearing capacity (Fig. 3).



Objective:
specific load $\sigma_{\text{ballast bed}}$ < specific load-bearing capacity $\sigma_{\text{formation}}$

Fig. 3: Vertical load distribution on substructure

The composition of the ballast bed determines how forces penetrate it. As noted earlier, the contact surface area of the edges and points of ballast stones is very small and, therefore, subject to very high localised pressure. Repeated pressure leads to ballast stone attrition, which increases the size of the contact surface areas that, in turn, leads to a reduction in the localised pressure on the ballast stones. This mechanism manifests itself in a settling of the track by a few millimetres, which corresponds to the adjustment of the contact surface areas to the localised pressure.

Experiments with observations of the ballast bed made through a transparent panel have shown that the edges of ballast stones break in a manner comparable to "rain" trickling through the ballast structure. With enough preload and a balanced ballast bed, the edges of the ballast stones will not break in that way, and there will be (almost) no "rain" trickling through. Geodetic analyses of this behaviour show that the track settles quickly when subjected to initial loading. After a few load cycles, the track settles at a much slower pace.

Ballast fouling

The splintered material trickles down through the cavities between the ballast stones, successively filling the spaces between them (Fig. 4). These filled spaces decrease water permeability, as well as friction between the ballast stones – this weakens the load-bearing capacity of the ballast bed, which negatively impacts track geometry durability and, thus, track stability. The water that remains in the ballast bed softens it, acting as a "lubricant" that lowers friction between the ballast stones.

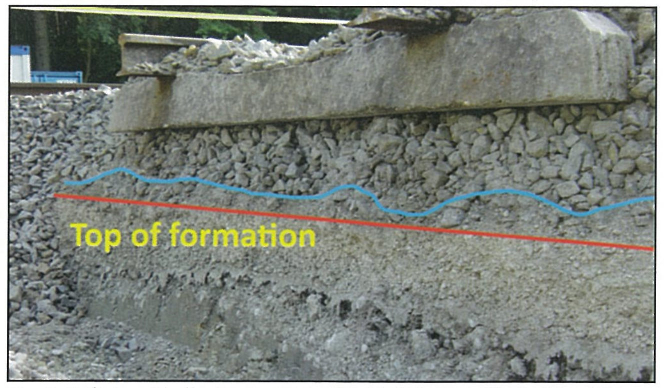


Fig. 4: Splintered ballast material has trickled down to the bottom (blue line) through the cavities between the ballast stones

Other types of ballast bed fouling entail similar consequences: when the substructure is not solid enough, for instance, because of poor compaction or the presence of water that was not drained properly, fine-grained material can mix with the water and turn into mud that rises and covers the ballast stones. During train passage, there is a constant alternation between the track being pushed down vertically and rising up again beneath the sleepers. This pumping action increases fouling of the ballast bed "from below". Further, wind can sweep dust and sand into the ballast bed, which may result in vegetation growth wherever there is an empty space in the ballast bed.

Finally, materials being transported, such as sand, limestone, grain, etc., can fall out of wagons, which also leads to ballast fouling. This usually happens when the wagons are not locked properly or are overloaded, which is frequently the case with mining and industrial railways.

ASSESSMENT OF BALLAST CONDITION

It is a good idea to examine the ballast and substructure of a track when it seems impossible to retain a good track geometry. The share of unwanted fine grain in old ballast, which is a form of fouling, determines the utility value of the entire ballast bed. In this case, the percentage of fines – expressed as a percentage by weight of the total sample – exceeds the limits defined in the technical terms of delivery. Screening the fines with a 22.4 mm square-meshed screen determines this percentage.

When there is too much fine grain in the ballast, it clogs up the drainage system of the track. Subsequently, the water in the track cannot drain as it is supposed to, which in turn increases fouling.

Scientists have often attempted to quantify a threshold limit for the size and quantity of fines during several experiments. ERRI developed a criterion that proved to be ideal: ballast bed cleaning is necessary when the share of fine grain is larger than or equal to 30% [16].

Visual inspections

In any event, visual inspections are the most common way of determining when ballast cleaning is needed. The first step is to remove the top ballast layer, which is approx. 10 cm thick. A shovel or a ballast fork easily accomplishes this. If the person inspecting the ballast sees fine or cohesive material in the spaces between the ballast stones, the next step is to excavate a section of ballast that extends down to the substructure formation. Doing so provides a general overview of fouling distribution and the extent to which it fills the spaces between the stones.

Tamping zones are clear indicators: they bear most of the traffic loading and usually have a higher percentage of crushed ballast stones. This can be attributed to how the stresses caused by the loading are distributed in the ballast bed. The part of the ballast bed with the largest shear stress is located just below the bottom of the sleeper.

For a long time, experts have endeavoured to use standard track recording car data as a way to assess whether ballast bed cleaning is necessary. Their discussions addressed the assessment of the time period between recurring track geometry faults, as well as the periodicity of differences in longitudinal track level. Permanent track bed deformations can be reflected in an asymmetrical track geometry. Weak ballast beds (and substructures) may manifest themselves as long-wave faults of the longitudinal track level. However, an assessment requires a great deal of experience and expertise, and may still not be completely reliable.

Fractal analysis – a revolutionary approach

Fractal analysis, however, offers a revolutionary approach to assessing track geometry quality, in that it allows scientists to assign vertical track geometry irregularities to a particular wavelength range and to associate specific fault characteristics with a corresponding image (Fig. 5). Irregularities in the medium wavelength range (3-25 m) provide information on ballast condition. Irregularities in the long wavelength range (>25 m) provide information on the condition of the transition area between the ballast bed and the substructure, i.e. the condition of the substructure, ergo its load-bearing capacity. Thus, fractal analysis allows a detailed analysis of recorded track geometry data to be made, which allows experts to assess the ballast and substructure condition of a track without having to rely on additional measurements [17]. It has already been adopted in several countries in Europe, where it has delivered excellent and tangible results.

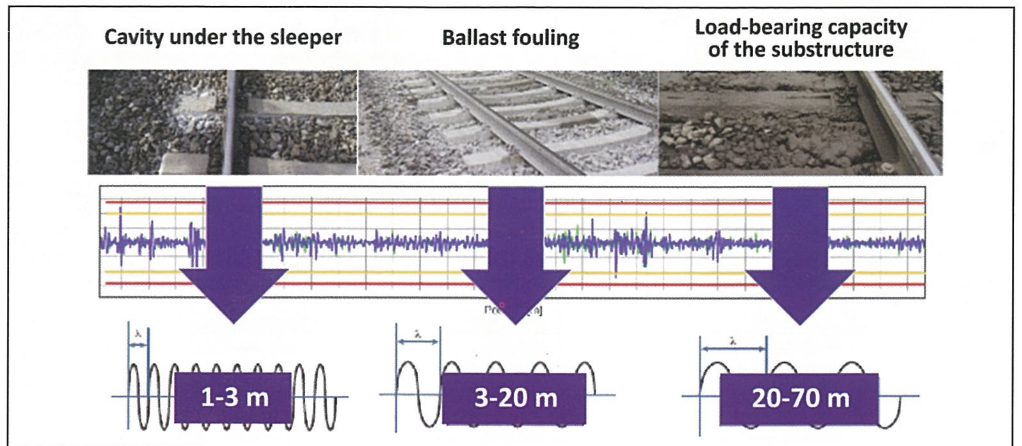


Fig. 5: Fractal analysis identifies the dominant wavelength ranges of a measured signal – a revolutionary approach

Geo-radar

About 30 years ago, the geo-radar method was introduced. This non-destructive diagnostics method can analyse the track bed up to a depth of 4 m [18]. A clear image of the ballast bed layers and the extent of fouling substantiates whether there is a need to carry out substructure formation rehabilitation and/or ballast bed cleaning [19].

BALLAST BED CLEANING MADE EASIER BY DEDICATED MACHINES

"Ballast bed cleaning" refers to the process in which the ballast is excavated, screened, and ballast stones with dimensions of less than 20 mm are discarded. Initially, ballast cleaning was carried out manually, but soon this arduous manual task was mechanised – the first machines built specifically for this purpose appeared one hundred years ago.

In the 1920s, the first machines for cleaning ballast, known as "shoulder cleaners", appeared in the USA. The assumption underlying this technology was that a track would only need to be drained from the side. Drainage of the entire track was not necessary. Collecting the shoulder ballast and removing the fine particles that cause fouling was deemed adequate. Shoulder cleaning is still a recognised method of work. However, for a ballast bed with a high degree of fouling, this method only offers a short-term improvement.

In the 1930s, Heinzelmann, Wieger, Neddermeyer, Knape, and Scheuchzer developed machines that were able to clean the entire ballast bed, including that of the track centre area [20]. These machines moved on chains, gauge rails, or on the track to be cleaned.

From 1945 onwards, MATISA took over a number of Scheuchzer's patents, and further developed the technology. Since then, using ballast excavation chains that work underneath the track panel has become state-of-the-art. They have shovels that transport the collected ballast to a screening unit located near the top of the machine. Once the fine particles have been removed, the clean ballast is reinserted underneath the sleepers below the rear part of the machine. After new ballast has been added, the track is tamped and aligned, in order to restore the track geometry. In most cases, the discarded fine ballast material used to be deposited next to the track and levelled, or it was used for agricultural road construction. In the case of modern machine technologies that automatically separate the spoil based on stone size, any spoil material is taken to depots, and may be used for landfills or other purposes.

The first fully hydraulic ballast cleaning machine

The first ballast cleaning machines were equipped with electromechanical drives and did not have their own drive unit. A small wagon for propelling was coupled to the machine, and a winch mechanism provided the required feed rate. In those days, however, electric drive systems were not as reliable as they are today, rendering these machines a modest work output.

In 1961, Plasser & Theurer developed its first prototype of a modern ballast cleaning machine, the RM 61 (Fig. 6), which had its own drive unit.

Fig. 6: The first fully hydraulic ballast cleaning machine – the RM 61 – a technological milestone

The RM 61 was the first fully hydraulic ballast cleaning machine – its hydraulics offered the advantage of greater operating reliability by allowing a better adjustment to the continuous changes in resistance acting on the ballast excavation chain. This led to an increase in work output, as the machine stopped less because of overstressing. With the RM 61, a now 60-year period of ongoing machine development began, which has culminated in the highly complex machine systems that are in operation today.

FINAL REMARKS

From the beginning of railways, ballasted track has been a trusted type of track structure. Part 1 of this two-part article has shown that ballast bed cleaning has gained in importance over the years. Part 2, which is scheduled for publication in Rail Engineering International No. 1/2021, will look at modern ballast cleaning technologies and the high quality of work that is achieved by their deployment.

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Part 2 of this article is scheduled to appear in Rail Engineering International Edition 2021 Number 1