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 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 three to five years, especially when drainage was poor. It was not until around 1865 that they were treated with substances such as creosote, 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 ballast 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 over time, experience gained by railway experts led to the development of rules and regulations governing material selection and construction methods for ballasted railway tracks. Normally, local railway managers 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 stones 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. In the ballast bed, the ballast is ballasted until the ballast reaches the top edge of the sleepers. There must also be sufficient drainage between them. A particular advantage of ballasted track is that it drains water safely and quickly [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 specific cross-slope, so that water can flow off the track. Water permeability of the ballast bed is essential to ensuring that the water can drain from the track. The water in the ballast bed 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. Once considered a "shock absorber", regardless of the type of soil – does not seem fitting. This is due to the relationship between the thickness of the ballast layer and the dimensions of the ballast stones. An additional factor is the location of the track – 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, which 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.

Schneider [7] investigated the dynamic elastic modulas of broken stone material. In this respect, he explored the phase shift in in-line 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 specifications, as well as the settings, which ensures that an optimum ballast compaction is achieved.

Extensive research conducted by ORE (later ERM) between 1965 and 1990 gave rise to various "ORR reports". ERM has 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 underneat concrete sleepers showed that this long-standing hypothesis does not stand up to scrutiny. Experimental work 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 force is transmitted to a significantly higher amount of pressure than previously thought.

Although scientists had discussed the option of using simulations to better understand ballast bed 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], Krouse [12], Desai [13], and Holtzendorff [14], as well as Auer, Omenovic and Philipp [15], is based on computer-generated ballast bed modelling (Fig. 2). It is now possible to depict the ballast bed "state by state" and for various contact situations. Fortunately, the research has confirmed what experience gained had already shown, such as the importance of using varying ballast stone sizes for instance.

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

Fig. 2: Simulation of ballast bed behaviour

Obligation: specific load P_interface, specific load-bearing capacity q_interface

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 area in that track, leads to a reduction in the localised pressure on the ballast stones. This mechanism manifests itself in a setting 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 plate show 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. Geoelectric analyses of this behaviour show that the track settles quickly under initial loading. After a few load cycles, the track settles at a much slower pace.

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.

Over time, 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 ballast bed must be less than its specific load-bearing capacity (Fig. 3).

Rail Engineering International Edition 2020 Number 4

4

5

Rail Engineering International Edition 2020 Number 4

5

5
Ballast fouling

The internal 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.

When there is too much fine grain in the ballast, it clogs up the drainage system of the track. 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 size for the limit and quantity of fines during several experiments. EARA 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 necessary. The first step is to remove the top ballast layer, which is 10 cm thick. A shovel or a ballast fork can easily accomplish 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 next substructure formation. Doing so provides a general overview of fouling distribution and the extent to which it fills the spaces between the stones.

Dumping zones are clear indicators of the degree of fouling and usually have a higher percentage of crushed ballast stones. This can be attributed to the forces caused by the loading being 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 endeavored to use standard track recording cur data as a way to assess whether ballast bed cleaning is necessary. Their discussions addressed the assessment time of the period between recurring track geometry faults, as well as the periodicity of maintenance in longitudinal track level. Permanent track bed deformations can be reflected in an asymptotic track geometry. Weak ballast beds (and substructures) may not be able to withstand the wave caused by the longitudinal track level. However, an assessment requires a great deal of experience and expertise, and may not still 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 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 bed and a track condition 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.

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

The RM 61 was the first fully hydraulic ballast cleaning machine – its hydraulics offered the advantage of greater operating reliability thanks to the automatic adjustment to the continuous changes in resistance acting on the ballast exac- tation. Furthermore, a new approach to the machine design permitted it to be stopped less because of wear. With the RM 61, a new 60 year-old period of ongoing machine development began, which has been entered in some of the highly complex machine systems that are in operation today.

FINAL REMARKS

From the beginning of railways, ballast bed cleaning has been a key component of track structure. Part 1 of this two-part article showed 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.

REFERENCES

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[13] Adopted in several countries in Europe, where it has delivered excellent and tangible results.

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