1 Introduction and state of the art

1.1 Introductory words and definition

Following the first trials in the 1970s and more than four decades of R&D work on ballastless track, the level of development is such that it can be confirmed that ballastless track is suitable for use as an alternative to ballasted track. This book is based on the principles of *Eisenmann* and *Leykauf*, which were published in Beton-Kalender 2000, and makes a contribution to the state of the art of ballastless track by describing the basics for designing the slab.

A concrete ballastless track is a non-ballasted form of superstructure in which the loadbase function of the ballast is performed by a layer of concrete. Besides the aim of a longest possible service life and at the same time low maintenance requirements, the superstructure should be founded protected against the effects of frost and supported such that deformations are essentially ruled out.

1.2 Comparison between ballasted track and ballastless track

One of the advantages of a ballastless track compared with ballasted track is that maintenance requirements are minimized. With ballasted track, tamping and lining works at regular intervals are essential. The critical frequency range for increased wear of the ballast forming the track bed begins at about 30 Hz. This excitation frequency is reached at a speed of about 270 km/h with a bogie wheelbase of 2.50 m and an otherwise ideal wheel-rail contact. However, in addition to train speeds, there are other factors that have an influence on the frequency, e.g. wheel defects or defects in the rail running surface. As train speeds increase, so the ensuing frequencies, with increasing amplitudes and higher dynamic loads, result in the need for shorter intervals between ballast maintenance works [1–3].

Another factor affecting loads on the superstructure is the stiffness; as the stiffness of a track system increases, so do the loads on the ballast. In particular, bridges and tunnels, of which there are numerous examples on new and upgraded lines, lead to a higher system stiffness owing to the hard subsoil (bridge superstructure, tunnel invert) and so the loads on the ballast are very pronounced. The long-term behaviour of the ballast can be improved through suitable measures, e.g. the use of sleepers with enlarged bearing surfaces, elastic or highly elastic rail fastening systems, under-sleeper pads or under-ballast mats [3]. Experience shows that with train speeds exceeding 250 km/h, ballasted track already requires maintenance after about 100 million tonnes of load has passed over it. With 100 high-speed trains per day in each direction, that corresponds to a maintenance interval of only a few years. Therefore, Deutsche Bahn AG started specifying ballastless track as the standard form of superstructure for all new lines with train speeds >250 km/h as early as the mid-1990s.

Besides the wear to and redistribution of the ballast during its lifetime, the quality of the position of the track is an important criterion for ballasted track, as the track position steadily worsens over time. The need for tamping and lining work depends

Ballastless Tracks, First Edition. Stephan Freudenstein, Konstantin Geisler, Tristan Mölter, Michael Mißler and Christian Stolz.

on whether defined guide and limit values for track position parameters have been exceeded. Those guide and limit values should guarantee, primarily, stable wheelset running as well as good ride comfort. In contrast to ballasted track, a ballastless track guarantees that the track remains permanently correctly positioned with a defined track elasticity and eliminates the ballast maintenance measures necessary while ensuring a longer service life. A theoretical service life of 60 years for ballastless track is the aim [4].

The first ballastless track pilot project was carried out at Rheda station in 1972 and so Germany already has more than 40 years of experience with this form of construction. It is therefore clear that a service life of 60 years is certainly practical and, consequently, can be assumed.

Despite the long service life, however, it is necessary to guarantee that individual ballastless track components can be removed and renewed.

It can generally be assumed that the cost of a ballastless track installation on a plain track will be higher than that of the initial installation of a ballasted track with subgrade. However, the maintenance costs of the former lie well those of the latter. It is interesting to note that in tunnels on new lines, ballastless track can be laid more economically than ballasted track with an under-ballast mat.

When considering the economics of ballastless track, it is also necessary to take into account that a ballastless track can be laid with tighter alignment parameters. Better cant deficiency and cants can be achieved with a ballastless track than is the case with ballasted track.

Therefore, for high-speed rail lines, a ballastless track can be built with tighter radii and, if required, steeper gradients for the same design speeds. The outcome of that is a significant economic advantage because savings can be made when building large bridges or tunnels. The savings that can be made during the construction, operation and maintenance of just these complex and expensive engineering structures alone can quickly compensate for the extra cost of ballastless track compared with ballasted track. At the same time, it is possible to route lines alongside motorways and thus keep different modes of transport together.

Another advantage of ballastless track is that it avoids ballast being thrown about – a dangerous phenomenon that is caused by suction forces below a train or ice in winter, which can loosen particles. Loose particles can damage the running surface of the rail or other items in the immediate vicinity. Some countries, e.g. South Korea, are therefore starting to cover whole sections of track with elastomeric sheeting in order to overcome the dangers of flying ballast particles. Furthermore, unrestricted use of eddy current brakes on trains is only possible on ballastless track.

Yet another benefit is the lower construction depth while still maintaining the same cross-section. This is especially interesting for sections of track in tunnels. On the one hand, a smaller tunnel cross-section can be chosen for new lines, which in turn saves costs. On the other hand, on existing lines that, for example, are to be electrified, the installation of ballastless track can avoid having to enlarge a tunnel cross-section in some circumstances. This also means it is easily possible to refurbish old tunnels by installing a new lining.

In recent years there were a number of accidents in tunnels and so new and refurbished tunnels now include vehicular access. Vehicles can drive along a suitably modified ballastless track, so the superstructure can be used by emergency vehicles in order to rescue passengers or recover goods following an incident. As the superstructure is already very stable and firmly positioned, most ballastless track systems can be easily modified to incorporate a flat road surface. Providing access for vehicles across ballasted track is extremely awkward and costly, and it must be remembered that such means of access must be removed to enable the necessary tamping and lining work to be carried out and then reinstalled. Therefore, in future, laying ballasted track in tunnels where access is required for road vehicles as well cannot be justified on economic grounds.

A ballastless track has significant advantages when it comes to the environment as well. In contrast to ballasted track, controlling the growth of plants and weeds by chemical or physical means is unnecessary. That reduces the impact on the environment and, from the economics viewpoint, overcomes the need to apply herbicides and pesticides.

Owing to the reduced maintenance requirements, the distances between transfer points can be increased when building a ballastless track compared with ballasted track – even on busy routes. As that saves on switches and the associated signalling, that is another obvious economic advantage.

For trams and light rail systems in towns and cities, grass can be laid in a ballastless track, which besides the visual and ecological aspects, also improves noise control. In addition, the grass strips can be provided with a permeable base layer to avoid creating an impervious surface. For urban areas in particular, and taking into account the greater incidence of heavy rainfall likely in the future, this is a very significant advantage of ballastless track. When it comes to inter-city rail traffic, the benefits of laying grass between the rails are still being investigated in trials.

Despite all the aforementioned advantages of ballastless track, it should not be forgotten that, on the whole, laying a ballastless track involves a higher capital outlay, and the costs of potential renewal, modernization or modifications are much higher than those of ballasted track. Therefore, it is enormously important that a ballastless track installation be well thought out, properly engineered according to acknowledged codes of practice and always accompanied by scientific studies. In particular, the design of a ballastless track should not be carried out exclusively according to economic criteria. Instead, the design must always be backed up by a certain amount of experience.

1.3 Basic ballastless track types in Germany – the state of the art

There are essentially two types of ballastless track:

- With discrete rail seats,
- With continuous support.

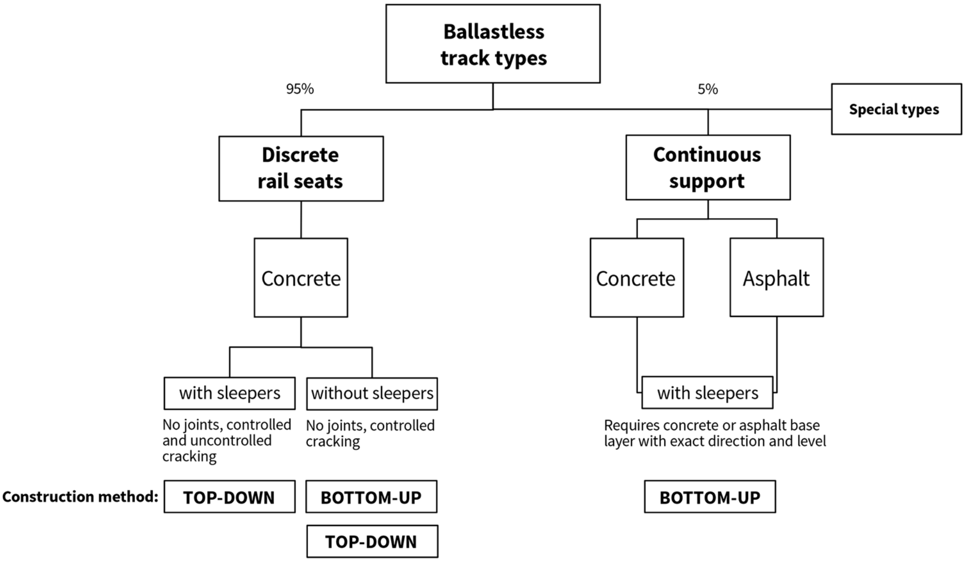


Fig. 1.1 Classification of ballastless track types (source: DB Netz AG)

There are also several special types of ballastless track, such as the continuously embedded rail, which, however, so far have been used almost exclusively for trams and light rail systems in towns and cities.

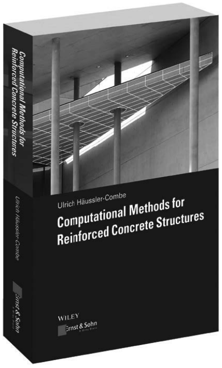
Figure 1.1 shows a detailed breakdown of these two types. We distinguish between discrete forms with or without sleepers and between continuous systems on asphalt or concrete basepavement, both with sleepers.

1.3.1 Developments in Germany

Wheelset loads and train speeds have been increasing constantly since Germany's first railway, the Ludwigsbahn between Fürth and Nuremberg, started operating in 1835. By 1900, speeds had already risen to 100 km/h and axle loads to 14 t. Now, in the twenty first century, the axle loads of freight trains are 22.5 t and passenger trains travel at speeds of 300 km/h, which means that the loads on the superstructure have increased substantially (see Figure 1.2). As increasing axle loads and, in particular, the high speeds lead to ballast having to be lined and tamped at ever shorter intervals [1,2,6], railway authorities had the idea of a non-ballasted superstructure, the ballastless track.

In the meantime, in Germany about 1300 km of ballastless track has already been laid or is currently being installed (approx. 320 km in the VDE 8 rail project as of June 2014). More than 95% of that is of the discrete rail seat type, and only about 5% the continuous support type on asphalt or concrete basepavement (see Figure 1.1).

A test ballastless track was laid at Hirschaid station on the Nuremberg–Bamberg line before 1970. However, it was removed not long after being laid and so relatively little



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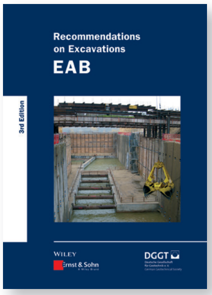

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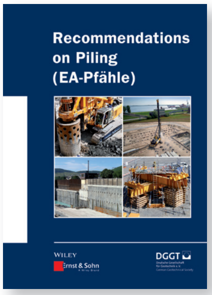

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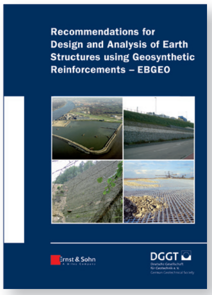

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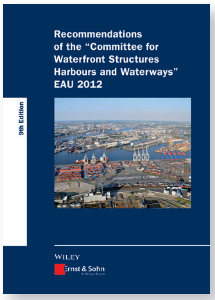

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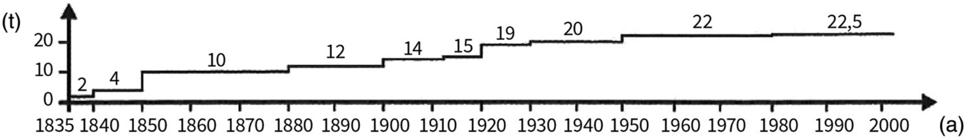
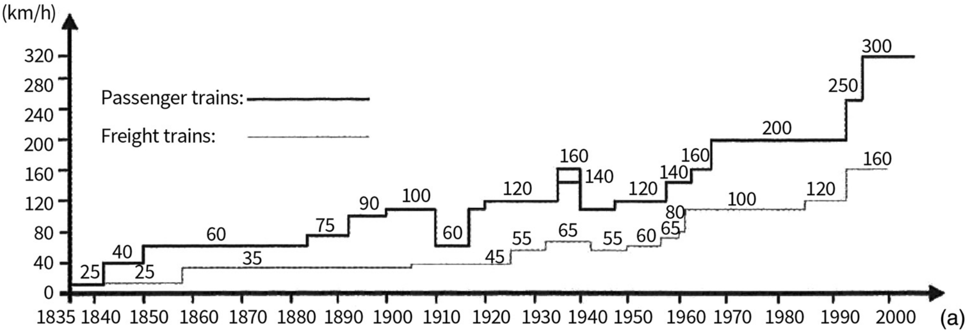


Development of wheelset loads for passenger and freight trains



Development of speed in km/h for passenger and freight trains

Fig. 1.2 Development of axle loads and train speeds over the years (source [5])

useful information is available about this stretch of line. Intensive research into ballastless track began in 1971 and led to the development of the ‘Rheda’ type, named after the place where it was installed, Rheda/Wiedenbrück station on the Bielefeld–Hamm line, in 1972 (see Figure 1.3). This ballastless track type was designed at the forerunner of today’s Institute of Road, Railway and Airfield Construction of Technical University of Munich and research and further development continued after the track was laid [7,8].

Based on that work, various companies started to develop a number of different ballastless track forms that were indeed installed. What that means is that the Federal Railway Authority has in the meantime approved more than 80 different types for use in the German railway network.

1.3.2 Sleeper framework on continuously reinforced slab

A distinction is made here between the version supporting prestressed concrete sleepers and the version with monolithically integrated sleepers.

The original system installed at Rheda station consists of a continuously reinforced concrete slab below a track panel that, following adjustment, is grouted in concrete. Using a preassembled track panel ensures good quality of rail alignment (gauge, level, etc.), which is very important for high-speed travel in terms of ride comfort and safety. To ensure a bond between the concrete sleepers of the track panel and the slab, holes were provided in the sleepers for reinforcing bars in the longitudinal direction. Stirrups were placed in the slab and encased in the concrete infill (see Figure 1.4).

Fig. 1.3 The Rheda system at Rheda station in 2010 (source: Institute of Road, Railway and Airfield Construction, Technical University of Munich)

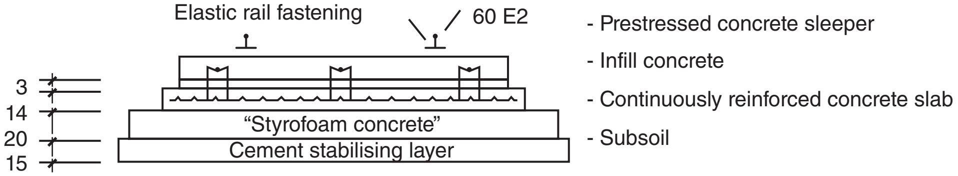


Fig. 1.4 Rheda 1972 superstructure (source: Institute of Road, Railway and Airfield Construction, Technical University of Munich)

The ballastless track at Rheda and those forms based on it were accompanied by the development of highly elastic rail fastening systems, initially by Vossloh, e.g. System 300 (Figure 1.5) or 336, in order to achieve an even, elastic deflection under the wheelset loads despite the stiff concrete superstructure.

This intended deflection of, on average, 1.5 mm under a 20 t axle load reduces the dynamic loading on the superstructure and also improves the load distribution over the slab.

Underneath the slab there is normally either a base layer with a hydraulic binder (BLHB) 30 cm deep or, occasionally, an bituminous base layer. Generally, the superstructure for a ballastless track should be founded frost-resisting below the

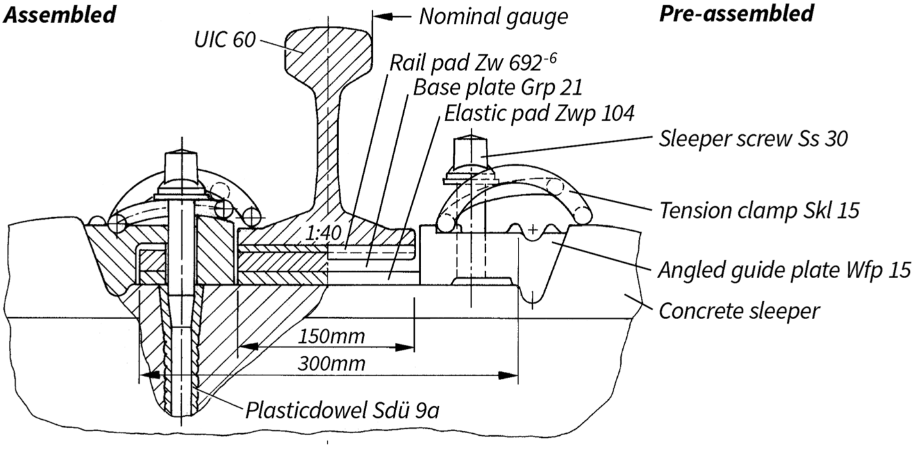


Fig. 1.5 Highly elastic rail fastening system 300, original version

frost penetration depth. Therefore, below the bonded base layers there should be a non-bonded frost protection layer on the prepared subgrade of the *in situ* or filled subsoil. The first superstructure systems with exclusively non-bonded base layers below the slab are still at the planning phase.

Taking the types described above as a starting point, many other ballastless track systems were investigated and designed at national and international level.

1.3.3 Continuously reinforced slab with discrete rail seats

Several ballastless track systems were installed for test purposes at Waghäusel on the Karlsruhe–Mannheim line in 1996. Five of the types installed had the rail seats placed directly on the continuously reinforced slab.

Besides systems for high-speed trains, a version with grass between the rails (see Figure 1.6) was also installed which underwent further development at the predecessor of today's Institute of Road, Railway and Airfield Construction at Technical University of Munich. The design consists of a permeable base layer of concrete with continuously reinforced longitudinal concrete beams above that. However, this system has not proved suitable for inter-city routes.

1.3.4 Precast concrete slabs

Among the few ballastless track systems that have become established in Germany, and also internationally, are those employing precast concrete slabs.

Here, the track panel, and possibly the concrete base layer (see Section 1.3.2), are replaced by precast concrete slabs). In the Bögl system (see Figure 1.7) these precast concrete slabs are prestressed in the lateral direction to limit the width of cracks. In the longitudinal direction, the precast concrete slabs of this system are joined by

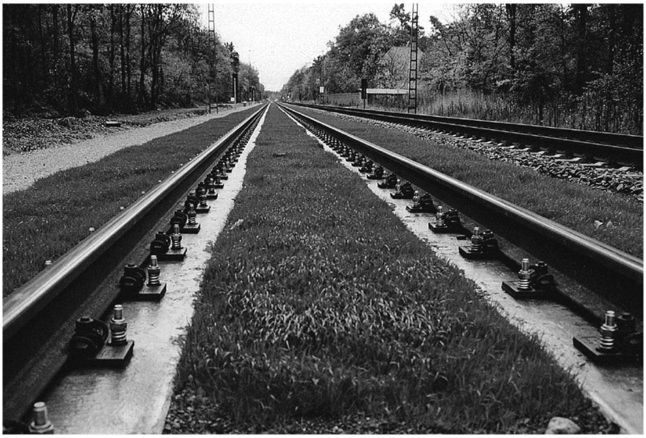


Fig. 1.6 Ballastless track with intermediate grass strip at Waghäusel near Karlsruhe (source: Institute of Road, Railway & Airfield Construction, Munich TU)

Fig. 1.7 Bögl ballastless track system (source: Institute of Road, Railway & Airfield Construction, Munich TU)

turnbuckles on the reinforcing bars. In addition, the aim is to control cracking by notched predetermined breaking points every 0.65 m between the rail seats. The slab is cast following final alignment of the rails (top-down method) using a grout and joined to the hydraulic bonded layer (or other base layer) such that it remains in position. The aim of this grout infill is to ensure the track remains in the right position and also to optimize the bond between the layers (hydraulic bonded layer – slab).

In order to avoid polygon line-type errors in the track positioning, the alignment elements (curves and, in particular, transition curves) must either be included in the

Fig. 1.8 NBU system in the New Kaiser Wilhelm Tunnel (source: Bilfinger)

precast concrete slabs by way of corresponding formwork at the rail seats on the slab or produced by milling the rail seats afterwards at the works.

1.3.5 Special systems for tunnels and bridges

Deutsche Bahn AG specifies ballastless track for tunnels that are more than 500 m long.

The advantages of installing ballastless track in tunnels are the construction depth, which is less than that of ballasted track, the stiff tunnel invert (no significant settlement is to be expected) and the chance of designing the superstructure to allow access for road vehicles.

The superstructure must satisfy special requirements on bridges and in tunnels. For example, it is a great advantage for inspection, maintenance and emergency personnel if the ballastless track also allows access by road vehicles. Owing to the lack of space, this is a very helpful solution. As an example, Figure 1.8 shows the NBU system (supplied by Naumburger Bau Union) in use in a tunnel. This system is currently being tested by Deutsche Bahn AG. Besides providing a road for vehicles, this system also has no longitudinal reinforcement in the tunnel and is divided into equal segments by contraction joints. Systems that require less reinforcement inside tunnels have already been used several times.

1.3.6 Further developments

Rheda 2000 is a further development of the Rheda system dating from 1972, which was described in Section 1.3.2. The objectives of Rheda 2000 were:

- Simplified system design due to the track panel being built directly off the hydraulic bonded layer
- Simplified installation of the ballastless track by reducing the number of layers

Fig. 1.9 Rheda 2000 system (source: Institute of Road, Railway & Airfield Construction, Munich TU)

- Lower construction depth
- Improved bond between sleeper and grout/infill concrete due to the development of the lattice truss grider sleeper
- Omitting the concrete trough and hence the need for longitudinal joints between trough and infill concrete
- Guaranteeing rail cant and gauge through prefabricated sleeper elements

Figure 1.9 shows a typical example of Rheda 2000 track.

The ballastless track system with twin-block lattice truss girder sleepers and no trough has proved its worth in the Deutsche Bahn AG network. Up until now, a 3.20 m wide and min. 24 cm thick *in situ* concrete slab with continuous reinforcement at mid-depth has been used on top of embankments for high-speed mixed passenger/freight traffic. As the alignment process for the track panel of the Rheda system is carried out directly together with the rails and the attached sleepers, it is important to make sure that changes in length of the rails as a result of temperature changes do not transfer any significant longitudinal forces to the sleepers during the concrete curing process. In the event of high outside temperatures, measures to reduce the increase in length of the rails must be considered. Besides modified alignment systems and methods, covering the rails and the use of shorter 'dummy' rails (instead of the actual running rails), carrying out the concreting works during the night has proved worthwhile.

A further development of the Rheda 2000 system is the Rheda 2000 ballastless track system without continuous reinforcement (see Figure 1.10). The difference between this and the classic Rheda 2000 system is that there is no reinforcement in the longitudinal direction. Transverse notches are formed in the slab with its cast-in sleepers while the concrete is still wet. A square or nearly square slab form is preferred and so the recommended maximum spacing of the notches for creating contraction joints is 3.25 m (slab width = 2.8 m). The slabs created by the controlled

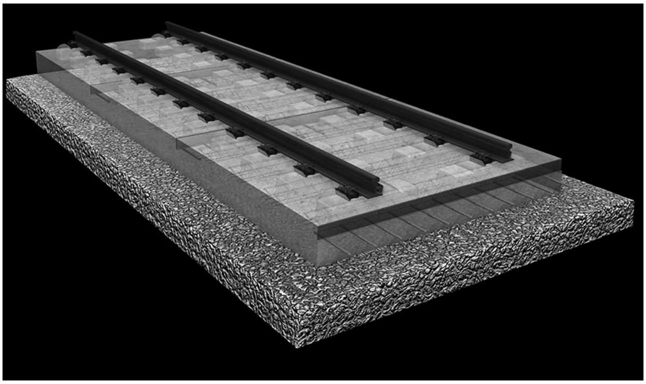


Fig. 1.10 Rheda 2000 system without continuous reinforcement on ballast base layer (source: RailOne)

cracking are joined by dowels across the transverse contraction joints in the longitudinal direction.

Experience with this system, which was developed by a German supplier, has been gained through tunnel sections in Hong Kong and Athens.

Apart from the longitudinal reinforcement, this system is similar to the classic Rheda 2000 system.

1.3.7 Conclusion

Ballastless track systems have been trialled in the Deutsche Bahn AG network and subjected to ongoing development for more than 40 years [9]. The Rheda types with their discrete rail seat concept and those systems with precast concrete slabs joined in the longitudinal direction have proved to be especially good for high-speed lines. It is the final top-of-rail level that governs their construction and therefore they achieve the construction accuracy necessary for high-speed trains without the need for any significant corrections to the track alignment during installation. Systematic further development of the individual components, and improvements to the design and construction processes have been critical for the technical success of ballastless track systems. Only through meticulous and persistent attention to detail was it possible to improve the handling of the individual components on the building site and, together with appropriate quality control measures, preclude construction errors.

In service, the ballastless track systems described have demonstrated stable, excellent track alignment. Assuming appropriate design, the systems meet the requirements for future rail traffic with its increasing loads and high speeds.

1.4 Ballastless track systems and developments in other countries (examples)

British Railways developed a ballastless track system in 1967 with a view to laying it in the tunnel between France and England. At that time British Railways was aiming at a

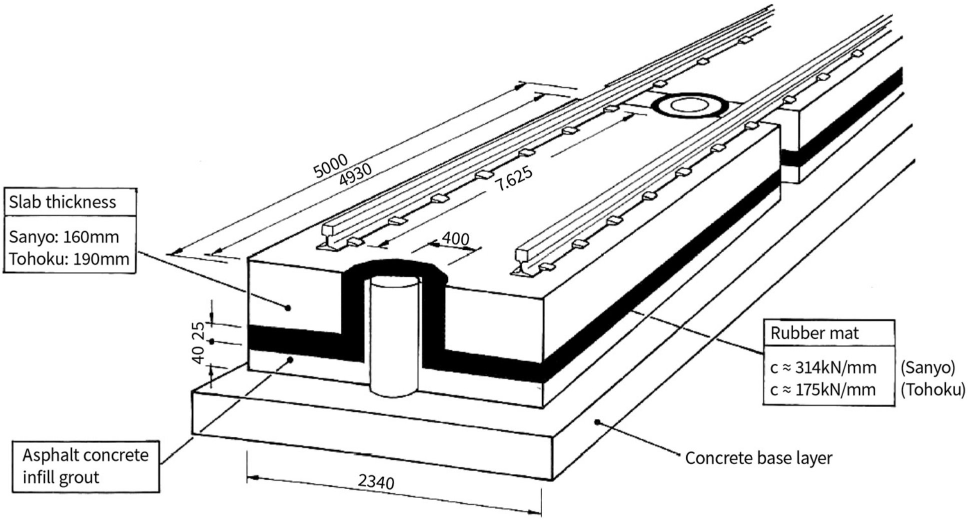


Fig. 1.11 Type VA ballastless track system [10]

deflection of 1.0 mm beneath a 25 t axle. The system, called PACT (Paved Concrete Track), had a continuous, elastic support on a continuously reinforced concrete slab and was finally installed for testing together with other ballastless track systems at Radcliffe-on-Trent in England (ORE test track). This system has been used worldwide (New Zealand, Australia, Canada, Spain), not only in tunnels, where it can be assumed that subsoil settlement is minimal, but also outside on terrain [10,11].

In Japan, the type VA ballastless track system was used from 1972 onwards for the Shinkansen high-speed lines (see Figure 1.11). Prior to that, research into this slab-type superstructure had been ongoing since about 1965, because trains (also train windows) had been damaged by ballast flying around caused by falling blocks of ice. The precast concrete slab superstructure type VA (slab length: 5000 mm; slab width: 2340 mm) had a rubber mat fitted between the reinforced concrete slab and the cement treated and bituminous grout to minimize structure-borne noise emissions, especially in residential areas. Figure 1.11 shows that the precast concrete slabs are held in position by round concrete dowels (ø = 40 cm) that are located along the centre-line of the track and firmly connected to the concrete. In the meantime, the grout, which was damaged by ‘pumping’ of the concrete slabs as trains pass and defective frost protection, has been refurbished and modified. Ballastless track in Japan is used on high-speed lines in tunnels, on bridges and on plain sections of elevated track. In Japan, type VA (or type A without rubber mat) is regarded as a standard form of superstructure for high-speed rail traffic.

The Gotthard Base Tunnel in Switzerland uses the LVT (low-vibration track) system throughout (Figure 1.12). The LVT system was developed from the ballastless track system with cast-in twin-block sleepers, which was installed as early as 1966 in the Bözberg Tunnel in Switzerland and became known under the name of STEDEF (the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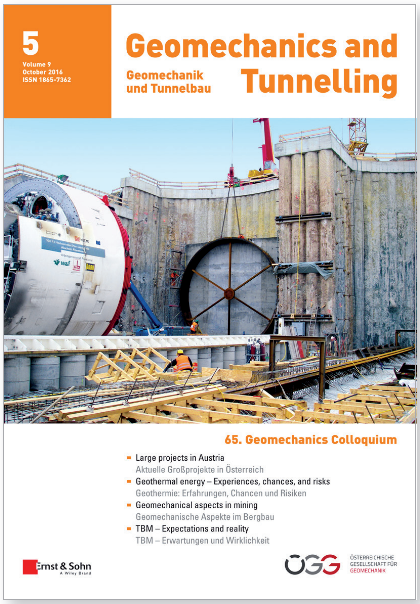
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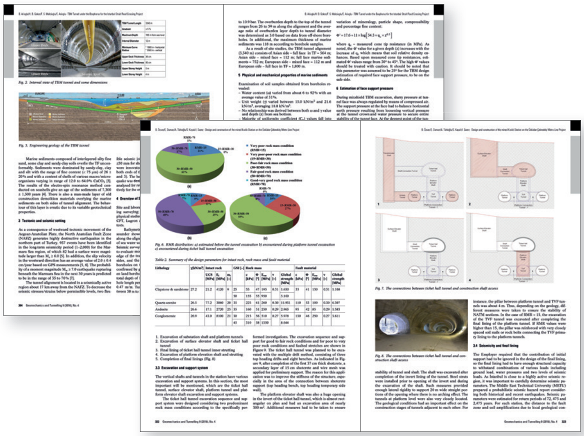

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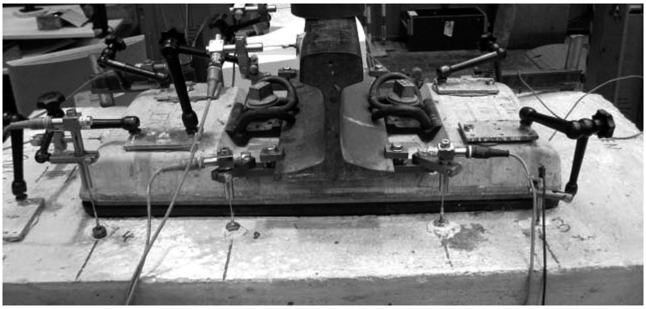

Fig. 1.12 Low-vibration track (LVT) system during tests to determine its characteristics at the Institute of Road, Railway and Airfield Construction, Technical University of Munich

name of a French company involved in the development together with *Roger Sonneville*). The twin-block sleeper was replaced by two separate concrete blocks acting as rail seats and it was this version that was used successfully in the Channel Tunnel in 1994. An LVT rail seat consists of the following components: rail fastening system with an elastic rail pad, reinforced concrete block, rubber boot and a resilient pad that fits inside the rubber boot and is mainly responsible for the elastic deflection. The individual rail seats are first aligned exactly before the unreinforced infill concrete is poured under and around them. In particular, the gauge and the rail cant must be set exactly at each rail support prior to concreting. This system was one of those tested at Radcliffe-on-Trent. In this system the resilient pad in the rubber boot minimizes vibrations but also ensures that the load is spread into the unreinforced concrete base layer. In order to guarantee optimum usage, this system with its rail pad and resilient pad in the boot is designed specifically for each project, approved in advance or tested in a laboratory according to a special specification (e.g. according to *Sonneville*). The LVT system is in the meantime being used worldwide, primarily in tunnels, e.g. in China, the USA, Turkey, Brazil and South Africa (source: Vigier Rail).

In Europe, however, other countries are still investigating the use of ballastless track as a superstructure system for high-speed rail traffic. For example, over the years 2002 to 2006, about 120 km of Rheda 2000 ballastless track was laid for the high-speed HSL Zuid line in the Netherlands, from Amsterdam Airport southwards to the border with Belgium. In the same period, the Spanish began using ballastless track for the first time for sections of their extensive high-speed rail network. Whereas the first high-speed track section from Seville to Madrid was built almost completely using ballasted track, on the continuation of the line from Madrid to Barcelona, short segments were built with ballastless track for the first time. From this time on, and particularly in the light of the higher maintenance requirements for these two initial high-speed lines, more and more ballastless track began to be used for new lines in Spain. For example, ballastless track was laid in many tunnel segments on the Madrid–Valladolid line running north-west from Madrid. One of those was the 27 km long Guadarrama Tunnel.

In Asian countries especially, ballastless track has scored many successes over the past decade. After the Chinese Railways Minister personally convinced himself of the high quality of ballastless track in Germany in the autumn of 2004, China began an intensive building programme for passenger-dedicated lines (PDL). Some 16 000 km of high-speed rail track has been built so far as part of that programme. The Chinese were very receptive to German technology, although Japanese and Chinese systems were also trialled in the initial test programme. It very quickly became clear, however, that the two German ballastless track systems, Bögl and Rheda 2000, are well suited to Chinese high-speed rail traffic projects. Since the first tests, thousands of kilometres of track have been designed and built based on these two German systems. Some further development work was carried out on these systems in China to meet special Chinese requirements. That gave Chinese engineers the opportunity to give their own names to the former German systems.

South Korea began introducing ballastless track for high-speed trains even earlier. For example, individual sections of track between Seoul and Daegu, the first high-speed rail line in South Korea, were built using ballastless track for test purposes (see Figure 1.13). After this first stretch of line went into operation and the disadvantages of ballasted track for high-speed rail traffic had been realised, it did not take long to decide on the use of ballastless track exclusively for further sections of track. A decision was made to use ballastless track for the entire line between Daegu and Busan. The interesting point here was that the Koreans adopted the Pandrol rail fastening system, which up until then had not been widely used for such high speeds.

The third section of high-speed track, which runs south-west towards Mokpo, is currently under construction. Again, only ballastless track is being used for this section.

Of course, many other countries have been building high-speed railways in recent years, but there is not space to mention all those here. Examples include Taiwan, Italy

Fig. 1.13 Stretch of high-speed track in South Korea (source: Institute of Road, Railway and Airfield Construction, Technical University of Munich)

and Russia. And we will certainly see many high-speed track sections being built in Arabic countries in the future. The interesting thing with the majority of high-speed lines is, however, that many sections of line were either developed and planned completely in Germany or at least make use of essentially German ballastless track technology.

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