Influence of the substructure and the track-bed system on the track position

The state of the substructure and the track bed are decisive for the quality of the track position and the availability of railway lines. This report presents an overview of track beds of the type “ballast superstructure on earthworks”, pinpoints the problems that may occur and describes the solutions to them.

1. Loads acting on the multi-layer system

Railway tracks are subject to time-dependent loads caused by the railway operation, which is comprised of the static loads of the wheelsets of the moving vehicles (quasi-static load) and the additional dynamic loads caused by deviations in the wheels’ contact surfaces from the ideal round shape and by unevenness in the track (Fig. 1).

The permanent way is exposed to changing weather influences. The influx of water into the track bed (Fig. 2) may lead to water retention, or an increase in the water content of the track bed and a reduction of the load-bearing capacity of the subsoil or to strong water currents, resulting in erosion, material being washed away and other material being deposited.

Frost may have the effects of adding capillary water, with the formation of ice lenses as well as frost and track heaving. A form of secondary frost damage may then occur during the thawing period with an accumulation of water causing a reduction in load-bearing capacity [1]. High temperatures and strong sunshine may lead to the soil drying out and a reduction in its water content, resulting in settlement and contraction cracks. What is typical for railway lines is that both the described effects and the resistance to them fluctuate sharply and, depending on the passing trains and their speeds, so do the state of the superstructure and the state in which the weather leaves the substructure.

Affected by this complex load, the track bed and its individual layers suffer stresses and deformations. Stresses must be assimilated by the superstructure, substructure and subsoil and dissipated without any damage being done. In this process, the vertical forces are transmitted to the multi-layer system comprised of the ballast, the substructure and the subsoil through the rails and sleepers in the form of a compressive load on the ballast, \( \sigma_{v,p,1} \), and distributed in it.

Temperature must be assimilated by the superstructure, substructure and subsoil and dissipated without any damage being done. In this process, the vertical forces are transmitted to the multi-layer system comprised of the ballast, the substructure and the subsoil through the rails and sleepers in the form of a compressive load on the ballast, \( \sigma_{v,p,1} \), and distributed in it.

Railway lines are linear works of engineering, which are subjected to static and dynamic loads caused by railway traffic and also to the various effects of the weather. The vertical, transverse and longitudinal forces between wheels and rails resulting from carrying, guiding and moving the railway vehicles and those resulting from the temperature must be assimilated by the superstructure, substructure and subsoil and dissipated without any damage being done. In this process, the vertical forces are transmitted to the multi-layer system comprised of the ballast, the substructure and the subsoil through the rails and sleepers in the form of a compressive load on the ballast, \( \sigma_{v,p,1} \), and distributed in it.

1 Loads acting on the multi-layer system

Railway tracks are subject to time-dependent loads caused by the railway operation, which is comprised of the static loads of the wheelsets of the moving vehicles (quasi-static load) and the additional dynamic loads caused by deviations in the wheels’ contact surfaces from the ideal round shape and by unevenness in the track (Fig. 1).

The permanent way is exposed to changing weather influences. The influx of water into the track bed (Fig. 2) may lead to water retention, or an increase in the water content of the track bed and a reduction of the load-bearing capacity of the subsoil or to strong water currents, resulting in erosion, material being washed away and other material being deposited.

Frost may have the effects of adding capillary water, with the formation of ice lenses as well as frost and track heaving. A form of secondary frost damage may then occur during the thawing period with an accumulation of water causing a reduction in load-bearing capacity [1]. High temperatures and strong sunshine may lead to the soil drying out and a reduction in its water content, resulting in settlement and contraction cracks. What is typical for railway lines is that both the described effects and the resistance to them fluctuate sharply and, depending on the passing trains and their speeds, so do the state of the superstructure and the state in which the weather leaves the substructure.

Affected by this complex load, the track bed and its individual layers suffer stresses and deformations. Stresses must be assimilated by the permanent way within its given mechanical properties, whereas deformations are not permitted to exceed certain limits.

The track and track bed suffer deformation, \( s \), when subjected to a load, \( P + P_{dyn} \). Assuming the railpad is not elastic, the deformation behaviour is described by the bending modulus, \( C = \alpha_{v,p,1}/s \) [N/mm²], which is a measure of the elasticity or stiffness of the track bed and includes the deformation behaviours of the ballast, the substructure (formation layer) and the subsoil. The elastic settlement (vertical deflection)
of the rails and the stress on the feet of the rails are not permitted to exceed certain authorised values. In order to comply with that, the elastic settlement at the upper edge of the track bed (corresponding to the height of the lower edge of the sleepers) must be limited. At the same time, the deflection must not be allowed to be less than a certain amount in order to guarantee the elastic transmission of the load with the longitudinal distribution of the wheel forces over the rail, thereby avoiding overloading the support points and the ballast.

The track bed and its individual elements must be dimensioned in such a way that the acting stresses, \( \sigma_{p,1} \) and \( \sigma_{p,2} \), can be assimilated without any destruction and without any harmful deformation s [mm]. According to Fig. 3, the minimum load-bearing capacities allowed are \( \sigma_{p,1} \) [N/mm²] for the ballast at the lower edge of the sleepers and \( \sigma_{p,2} \) at the top edge of the subsoil (corresponding to the height of the lower edge of the formation layer). The deformation s that occurs is dependent on the acting stresses, the inherent deformation moduli (E [N/mm²]) of the ballast, the formation layer and the subsoil as well as the thicknesses of the layers.

2 Requirements and quality of the track position

The permanent way must be created and maintained in such a way that:

- the track is available without any limitations for the traffic load envisaged and the ride comfort demanded (availability),
- fracture conditions in the earthworks are excluded (load-bearing capacity), and
- deformations that occur in or due to the permanent way are harmless for the railway operation and for third parties (suitability for use).

In an overall appraisal of the permanent way’s suitability for use, the track position, the state of the ballast, the quality and state of the substructure and the drainage installations as well as the outlay on maintenance ought all to be included.

For appraising the track’s suitability for use, it is above all the track position that is decisive. This is checked during inspections performed in connection with maintenance. According to DIN 31051, the term “maintenance” covers all measures that have the purpose of:

- establishing and evaluating the actual state (inspection),
- maintaining the target state (servicing), and
- re-creating the target state (repairs).

Like any technical installation that is used, the permanent way is subject to wear. A typical pattern over time is shown in Fig. 4.

At the time it is created or repaired, the permanent way possesses the target state and has a 100% reserve for wear and tear. As it is used over time, its state deteriorates and the residual amount of reserve for wear and tear declines. Notwithstanding, it remains entirely suitable for use for a while at least. If the actual state reaches the permissible limit value, the so-called intervention threshold, its suitability for use is impaired and measures are needed to re-establish its target state. The permissible limit values of the evaluation criteria (SR\(_{100}\)) which is known as SR\(_{100}\) at Deutsche Bahn) maintain an adequate margin compared with the threshold of damage, SR\(_{lim}\). Table 1 shows the fault parameters applied by Deutsche Bahn for deviations from the target track geometry for individual faults in the track position.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>SR(_{100})</th>
<th>SR(_{lim})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>km/h</td>
<td>( \leq 80 ) ( &gt;80 )</td>
<td>( \leq 120 ) ( &gt;120 )</td>
</tr>
<tr>
<td>Longitudinal elevation</td>
<td>mm</td>
<td>15 13 11 9 7</td>
<td>14 11 9</td>
</tr>
<tr>
<td>Elevation difference between the rails</td>
<td>mm</td>
<td>13 11 9 8 7</td>
<td>11 10 9</td>
</tr>
<tr>
<td>Vertical deflection</td>
<td>mm</td>
<td>15 13 11 9 7</td>
<td>14 11 9</td>
</tr>
<tr>
<td>Track gauge</td>
<td>mm</td>
<td>( +25 +20 +20 +15 +10 +5 +0 )</td>
<td>( +25 +20 +15 +15 +10 +5 +0 )</td>
</tr>
</tbody>
</table>

Table 1: Assessing the track position according to Deutsch Bahn’s rule 821.2001
3 Problematical locations for the quality of the track position

3.1 Problems at the interface between rails and sleepers (Fig. 5)
Discontinuities in the zone where loads are transferred between wheels and rails, such as rail joints, surface defects on rails and cavities under sleepers, are individual defects which lead to higher dynamic loads, which result in very considerably higher stresses in the track bed as train speeds become faster. To begin with, the ballast is subjected to excessive loading and this is followed by grain fragmentation, grain rearrangements and ballast settlement. The white patches that typically result from these processes migrate in the direction of train movement. If the cause of the damage is not rectified, the consequence may also be excessive loading of the substructure and the loss of load-bearing capacity.

3.2 Problems in the ballast (Fig. 6)
The consequences of the excessive loading and/or contamination of the ballast are changes in its deformation and elasticity behaviour and also in its shear strength and load distribution. Neither the ballast nor the subsoil is then any longer able to withstand the higher loads without undergoing harmful deformations.

3.3 Problems in the substructure (Fig. 7)
Higher elastic and plastic deformations and a reduction in the load-bearing capacity occur in the substructure as a result of the excessive loads it suffers on account of the overloads resulting from the inadequate load distribution in the ballast and the loss of load-bearing capacity of the soil beneath it due to its increased water content.

3.4 Problems in the subsoil (Fig. 8)
Readily deforming measures in the subsoil, such as fine soils with inadequate shear strength, soft strata and sands susceptible to disturbance may be compressed together or rearranged when subjected to loading and dynamic additional loading, leading to settlement and changes in the track position. Long-wave settlement is generally uncritical for the track, but if the value for SR100 is exceeded then both long-wave and short-wave settlement faults may, however, become critical.

Bedding moduli changing in quick succession along the length of the track lead in the overlapping zones to dynamic additional loads with excessive loads acting on the superstructure and substructure and post-compaction, grain rearrangements and settlement in the ballast and the substructure. Problems in these locations are crucial for deteriorations in the track position and...
must consequently be rectified – better still: they should not be allowed to occur in the first place through preventive action when constructing and maintaining the track.

4 Elements of track bed suitable for use and maintaining them

Considering the problem locations described in the preceding chapter, it can be concluded that the crucial requirements for the permanent way are:

- a bed of ballast with a high shear strength,
- a substructure with uniform elasticity and deformation behaviour thanks to the protective sublayer and properly functioning draining installations, and
- elastic elements acting as springs and shock absorbers in the superstructure.

The way of ensuring that a high degree of suitability for use and the corresponding quality of the track position will be maintained for a long period of time is to guarantee that there is a good quality level to begin with in the superstructure and substructure and that the performance of maintenance is assured as a function of the real state of the track. Making savings on these aspects pushes the life-cycle costs up very considerably and shortens the service life.

The purpose of maintenance activities is to ensure the availability of the track, and they will be economic if they guarantee a long service life and a high functional dependability of the elements making up the superstructure and substructure. In considering life-cycle costs, serious cost drivers have been found, in particular, in a poor substructure, a reduced ballast quality caused by overloading and discontinuities at transition to engineering features and in transitional zones to track points [2].

Ensuring optimum wheel/rail contact geometry and low additional dynamic loads in the vehicle/track system calls for continuous care to be taken of the rails (including preventive grinding) and the immediate correction of faults in the rails. Contamination of the track bed must be removed through ballast cleaning, thereby ensuring adequate shear strength of the ballast and a slope across top of the subsoil over the whole length of the track.

Drainage measures are a reliable means of preventing the retention of water from resulting in an accumulation of water and thus in a critical increase in the water content of the soil with a shift in its consistency and a reduction in its load-bearing capacity. The collection of surface water and its removal from the permanent way are handled by the slope across the top of the subsoil, the open ditches along the railway and the recipient waterways. Deep drainage installations are arranged underground for collecting and removing unbound water from the soil and subsoil water. Given their delayed effect, drainage installations ought to be installed before earthworks are created. They must always be kept in a functional state. Drainage systems based on gravity are only capable of taking free moving water out of the soil, in other words: only part of the interstitial water.

The protective sublayers constitute a system of layers on top of the subsoil which have both a load-bearing and a protective function and protect the subsoil from harmful deformations and the effects of frost. These layers are made out of mixtures of particles, and their effectiveness may be improved or complemented by geo plastics, transitional layers or soil stabilisation. The insertion of sublayers can be done with either road-based or track-based machines.

The effects of elastic elements in the track superstructure are:

- to act as a spring, producing greater deflection of the rails and a longer bending line, which reduces the force acting on the support points and the loads affecting the ballast; and
- to act as a shock-absorbing element, reducing vibration stressing. This leads to less serious deformations, stresses and vibration velocities not only in the superstructure but even down into the subsoil too.

It is possible for the elastic elements to be arranged under the rails (as pads in the rail supports, under the sleepers (as sleeper pads) or under the track bed (as under-sleeper matting).

Up until now, the deformation behaviour of the track bed has been expressed through the bedding modulus, C [N/mm²], as a ratio between the load acting on the sleeper and its elastic settlement. With the use of the elastic elements, the deformation behaviour at the sleeper-support system takes on a new interest. The elastic properties of the system as a whole are re-computed as the spring rate c [kN/mm] at the rail support point. This parameter is known as “track stiffness”.

Under a wheel load of 100 kN, the vertical rail deflection lies within a range of 0.8 to 1.2 mm, measured on the lower edge of the rail at the support point, assuming a superstructure with the characteristics of UIC 60 rails, B70 concrete sleepers (laid with a spacing of 600 mm) and a bedding modulus, C, of between 0.105 and 0.185 N/mm². This amount of vertical deflection can be regarded as optimum for ballasted track. The corresponding optimum “track stiffness”, c, then lies within the range of 30 – 53 kN/mm.

It is also possible to use elastic elements to compensate for stiffness differences in the track, for instance in the transitional zones shown in Fig. 8. That is particularly important where high speeds are involved.

5 Final remarks

The principles presented in this report are intended to draw attention to the interrelationships in the superstructure/substructure/subsoil system making up a single unified track bed. Excellent suitability for use combined with a high quality of track can only be assured by starting with a high quality to begin with when constructing or renewing the superstructure and substructure and when repairing them, so as to act to the problems arising quickly and by dealing with their causes. The key factors in all this are properly functioning drainage installations, load-bearing layers and protective sublayers, track beds with adequate shear strength and elastic elements incorporated in the superstructure.

References


Expert's Report and Preliminary work

Assessment of stability and dynamical stability in civil engineering
Finite Elements Modeling, Calculation of deformation, consolidation and settlement
Assessment of founding ground and foundation consulting service

Object and Structural planning

Traffic and civil engineering
Renewals and redevelopments in traffic engineering
Retaining constructions and constructive forms with geosynthetics

Construction Support

Signal monitoring and check tests
Supervision of waste permits
Construction supervision

GEPRO

GEPRO GmbH & Co. KG
Caspar-David-Friedrich-Strasse 8
D-01219 Dresden
Tel. +49 351 87775-0
Fax +49 351 87775-55
Internet: www.gepro-dresden.de
E-Mail: info@gepro-dresden.de

RTR 3/2011 29