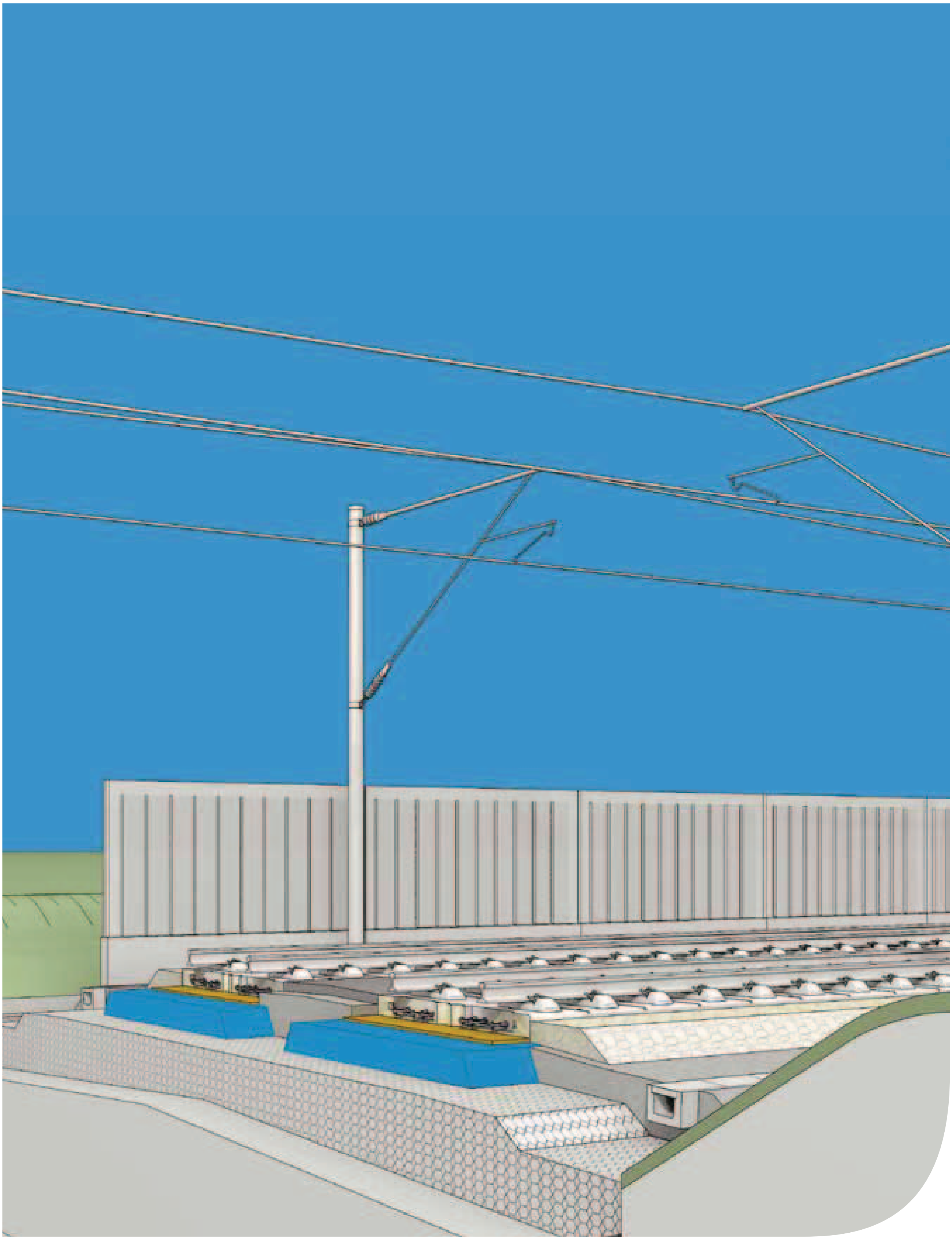
Slab track systems

on different substructures

SSF Ingenieure



A holistic design approach

For high speed railway lines with a velocity of up to 300 km/h, slab track systems provide good performance and durable riding quality. Intense teamwork and strong cooperation between civil engineers and geotechnical engineers is required in order to obtain a reliable design of the slab track systems. Designing ballastless tracks demands a holistic approach to optimize the vertical stiffness and longitudinal deformability of the whole track over its total length. An overview of different slab track designs with regard to geological and environmental conditions is provided. A special focus is set on soft soil and the transition between slab track sections with different vertical stiffness.

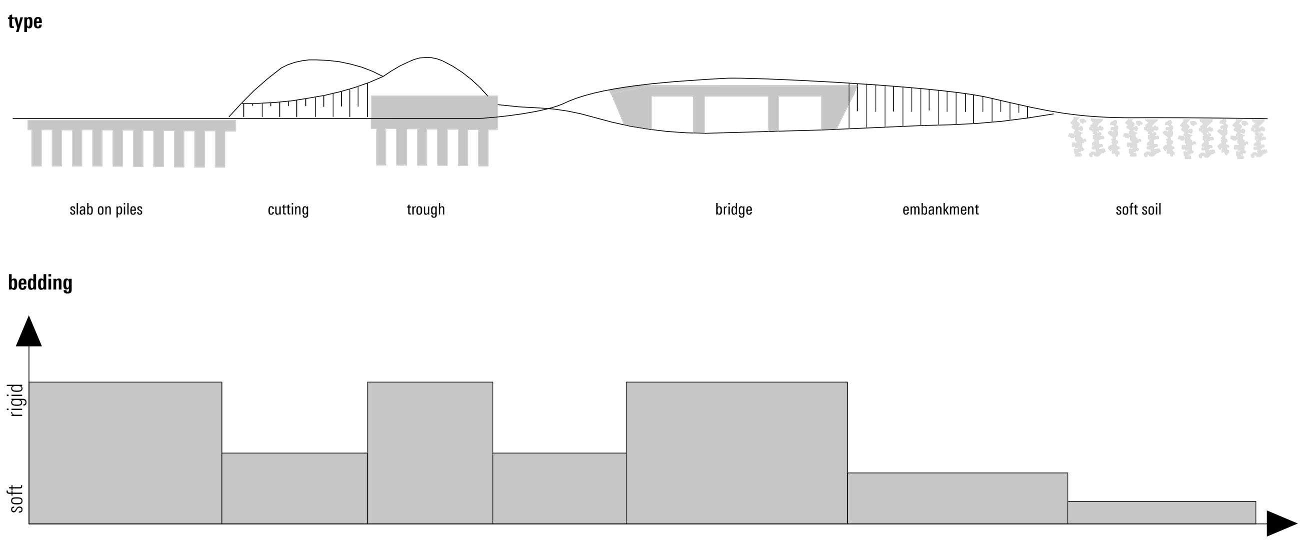
The Engineering Consultancy SSF Ingenieure has conducted several projects for high speed lines with slab track systems from the very beginning of the design phase till the end of construction including supervision.

Introduction

In slab track systems the ballast is replaced by concrete or asphalt, which provides a more stable position. In comparison to ballasted tracks these systems are much stiffer. Thus, the necessary elasticity has to be provided by inserting elastic elements below the rail or the sleeper.

The ballastless track requires subsoil, which is almost free of deformation or settlement. The substructure of the ballastless track has to be stabilised to a depth of at least 2.5 m below the bearing plate by appropriate earthwork constructions. Therefore, it is a challenge for the designer of ballastless track at grade to figure out the suitable and adequate system of the earthwork construction. The strict requirements lead to higher construction and material costs in earthworks construction. In return, slab tracks provide increased life time and decreased maintenance costs, when designed in an appropriate way.

Figure 1 Different slab track constructions with varying bedding modulus



right: Newly built railway line Nuremberg - Ingolstadt - Tunnel Göggelsbuch

Picture credits: SSF Ingenieure GmbH

Picture credits: Wolfgang Seitz

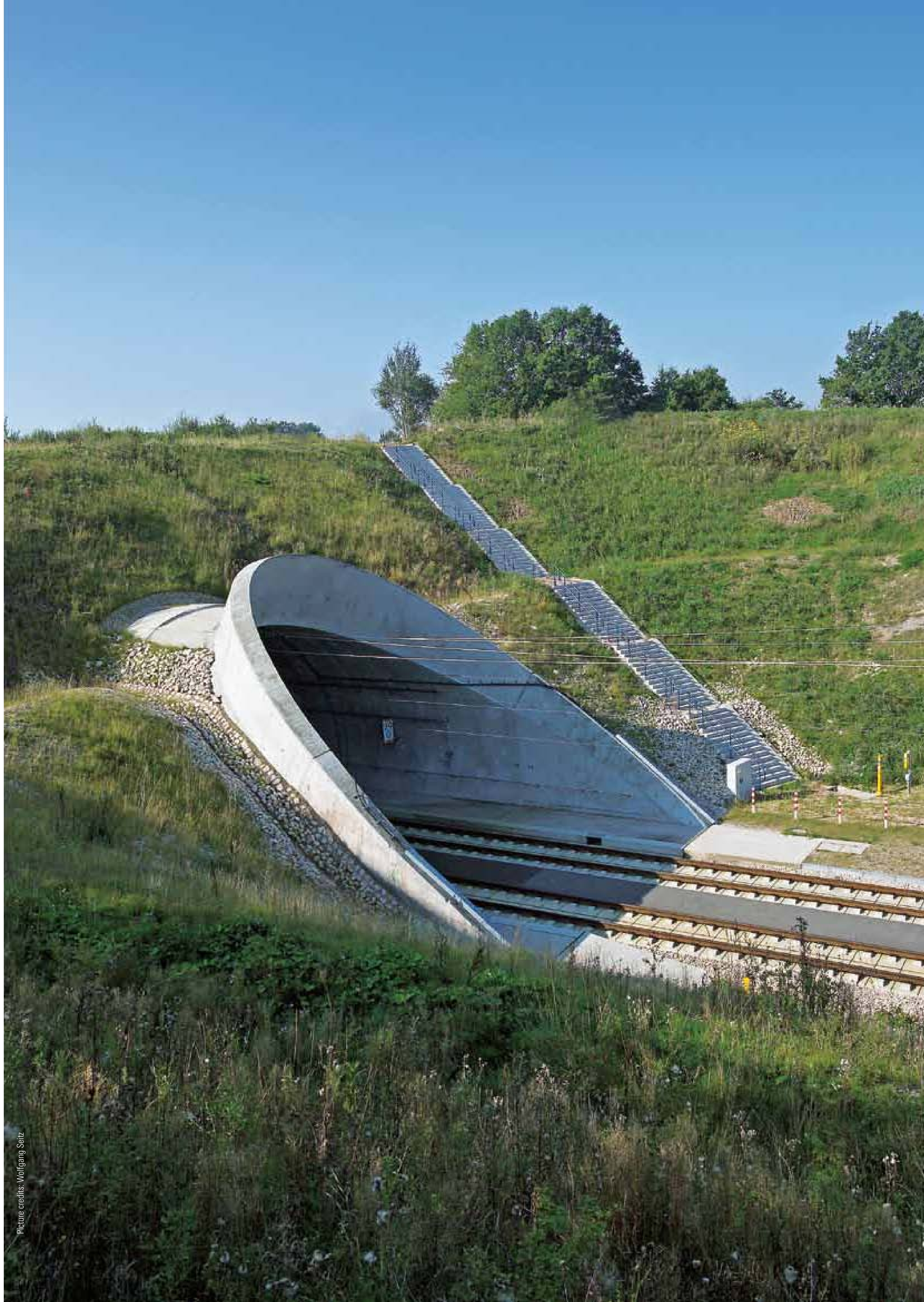
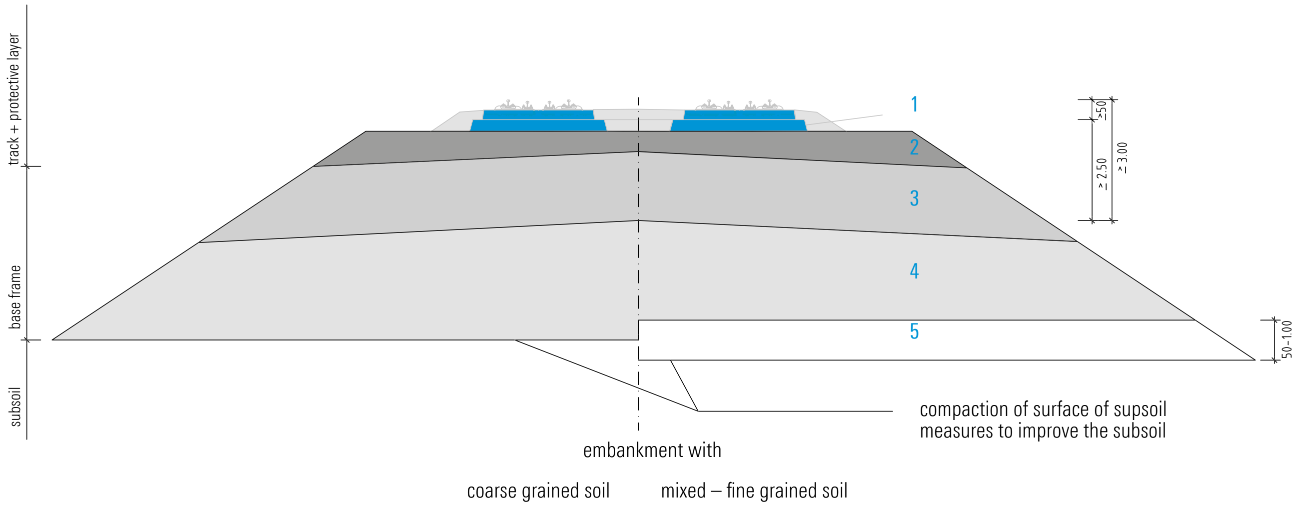


Figure 2 Cross section embankment



	Layer	KG	E_{v2}	E_{vd}	D_{Pr} coarse grained soil	D_{Pr} mixed-fine grained soil
1	hydraulic bonded layer: HBL	–	–	–		–
2	frost protection lager: FPL	2	120 MN/m²	50 MN/m²	1,00	1,00
3	subgrade material > 3,00 m	–	60 MN/m²	–	1,00 GW, GI, GE, SW, Si	1,00 GU, TG, SU, ST
4	subgrade material	–	45 MN/m²	–	0,98	1,00 GU, GT, SU, ST 0,97 and na < 0,12 GU, GT, SU, ST, UL, UM, TL
5	subgrade material if necessary improvement of surface of subsoil	–	–	–	–	0,98 GW, GI, GE, SW, SI, SE

Particularly important is the transition between slab track sections with different vertical bedding modulus – like stiff bridges to soft earthwork constructions. These transitions present a critical discontinuity of the ballastless track (figure 1).

Standardized track slab constructions

Codes provide only little information about slab track construction concepts. Standardized are only layouts for slab tracks on embankment and in cuttings. For all other localizations like slab tracks on bridges, in troughs or on soft soils as well as for transitions, engineering genius is demanded to develop adequate solutions.

Embankment

The most commonly used earthwork structure is the embankment. To reduce the possibility of self-settlement the layers and the slope of the embankment shall be arranged according to the scheme below.

This results in an earthwork construction with high stability and low settlement. Changing layers – one layer of cohesive and one layer of no-cohesive soil material (sandwich layers) – shall be avoided. Nevertheless, if alternating cohesive and non-cohesive soil material layers are used, every layer of cohesive soil should be built with a transversal gradient of 2.5 % (figure 2). The sub-

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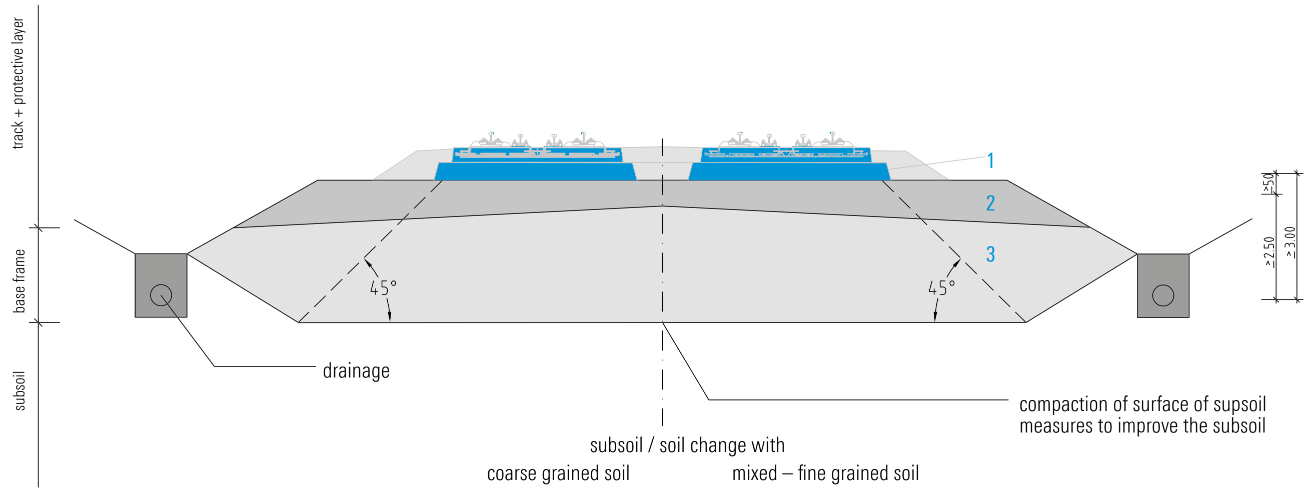
Figure 3 Cross section cutting



	Layer	KG	E_{v2}	E_{vd}	D_{Pr} coarse grained	D_{Pr} mixed-fine grained
1	hydraulic bonded layer: HBL	–	–	–		–
2	frost protection lager: FPL	2	120 MN/m²	50 MN/m²	1,00	1,00
3	subgrade material > 3,00 m	–	60 MN/m²	–	0,98	0,97 GU, GT, SU, ST 0,97 and na < 0,12 GU, GT, SU, ST, UL, UM, TL

soil has to be compacted, to avoid long-term settlement. If the requirements cannot be satisfied by standard compaction methods, or if no soil with the required parameters is available, subgrade treatment or methods for acceleration of settlement must be taken.

The soil has to be exchanged if the bearing capacity of the existing soil is insufficient. Soft, cohesive or organic soil in the subsoil should be exchanged to a depth of at least 4 m below top of rail. The influences of measures during construction, like lowering the groundwater level, have to be considered.

Cuttings

Also for cuttings the same strict regulations have to be applied. The arrangement of layers is shown in figure 3. Similar to the requirements for the embankment, the required arrangement of layers and compaction needs to be guaranteed for at least 3 m under the rail.

The subsoil needs to be durable and provide a suitable bearing capacity combined with small settlement behaviour in time. Soft, cohesive soil must be replaced or other sub-grade treatment has to be provided.

Ballastless track on enhanced sub-grade

In case of soft soil, appropriate measures are to be taken to improve the subsoil by different compaction methods. Soft subgrade can be enhanced by compacting the soil. A precise compaction program is to be established and accurately supervised on site. An alternative, very sophisticated solution is the use of CFG (cement, flue ash and gravel mixture) columns (figure 4).

CFG uses a type of auger to build cement columns by displacement of the surrounding soil. The soil laterally displaced leads to an improvement of the surrounding soil itself. The method can be used nearby sensitive structures like existing buildings or structures under construction. The load distributing layer on top of the CFG columns can be made out of well compacted soil. This avoids expensive pile caps or concrete slabs.

Ballastless track on piles

Very specific design approaches are necessary in geotechnical and hydrological difficult situations where other measures are not possible, to time consuming or too expensive to be executed. To avoid the problem of long term settlement and unknown consolidation behaviour ballastless track on piles can be designed. Here, the track superstructure is supported by a reinforced concrete slab which is founded directly on piles (figure 5). The loads are distributed by the slab track and then transferred by the concrete slab to the piles. There is no influence caused by problematic subsoil which finally acts just as filling material. This kind of construction is very stiff with almost no settlement. The chosen system is totally independent of soil quality used in the sub-grade. The construction is thus comparable to bridges regarding settlement and stiffness. A transition area to normal embankments or cuttings has to be installed.

Ballastless track in troughs

Troughs are applied in cutting situations with difficult geological and hydrological conditions or in proximity to steep slopes or buildings where retaining is necessary. In these situations slope angles are often very poor and groundwater or in the worst case constraint groundwater, tends to flood the construction. In case of soft soil, fast and uncontrolled settlement, depending on the water ratio and the capacity for dewatering, has to be expected.

Further, some soft soils like clay tend to swell when being unloaded by excavating superficial soil layers. High earth pressure – lateral and vertical –has to be supported by the structure. The Archimedes up-lift and the expansion pressure of the soil are often higher than the dead load and tend to cause instabilities.

Figure 6 Cross Section trough with open pit and free slopes

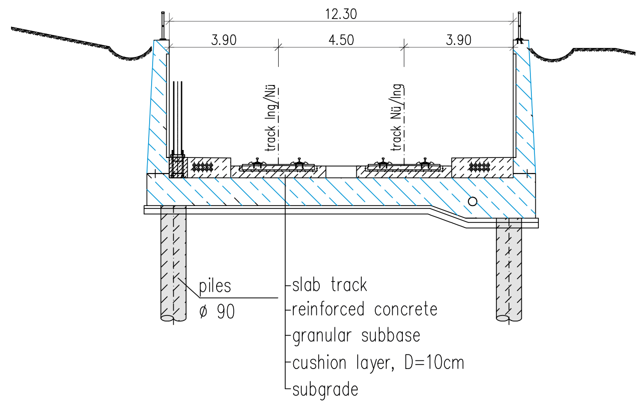


Figure 7 Cross section trough using piles as retaining walls

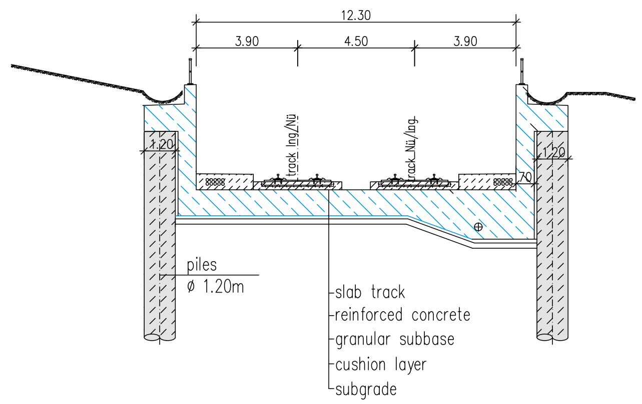
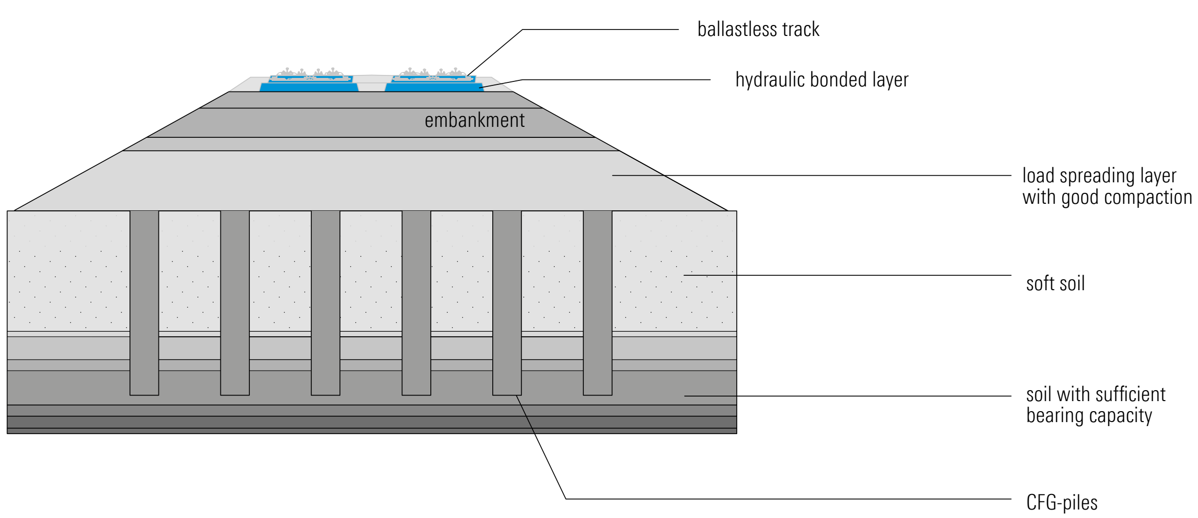
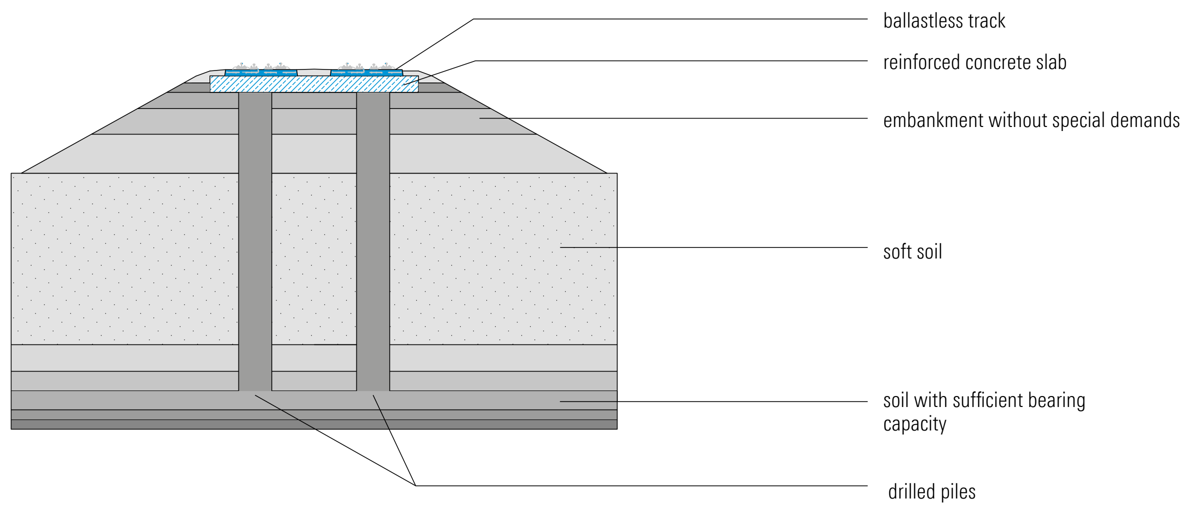


Figure 4 CFG Piles for subsoil improvement (Cement Fly-ash Gravel piles)



Picture credits: SSF Ingenieure GmbH

Figure 5 Cross section ballastless track on piles



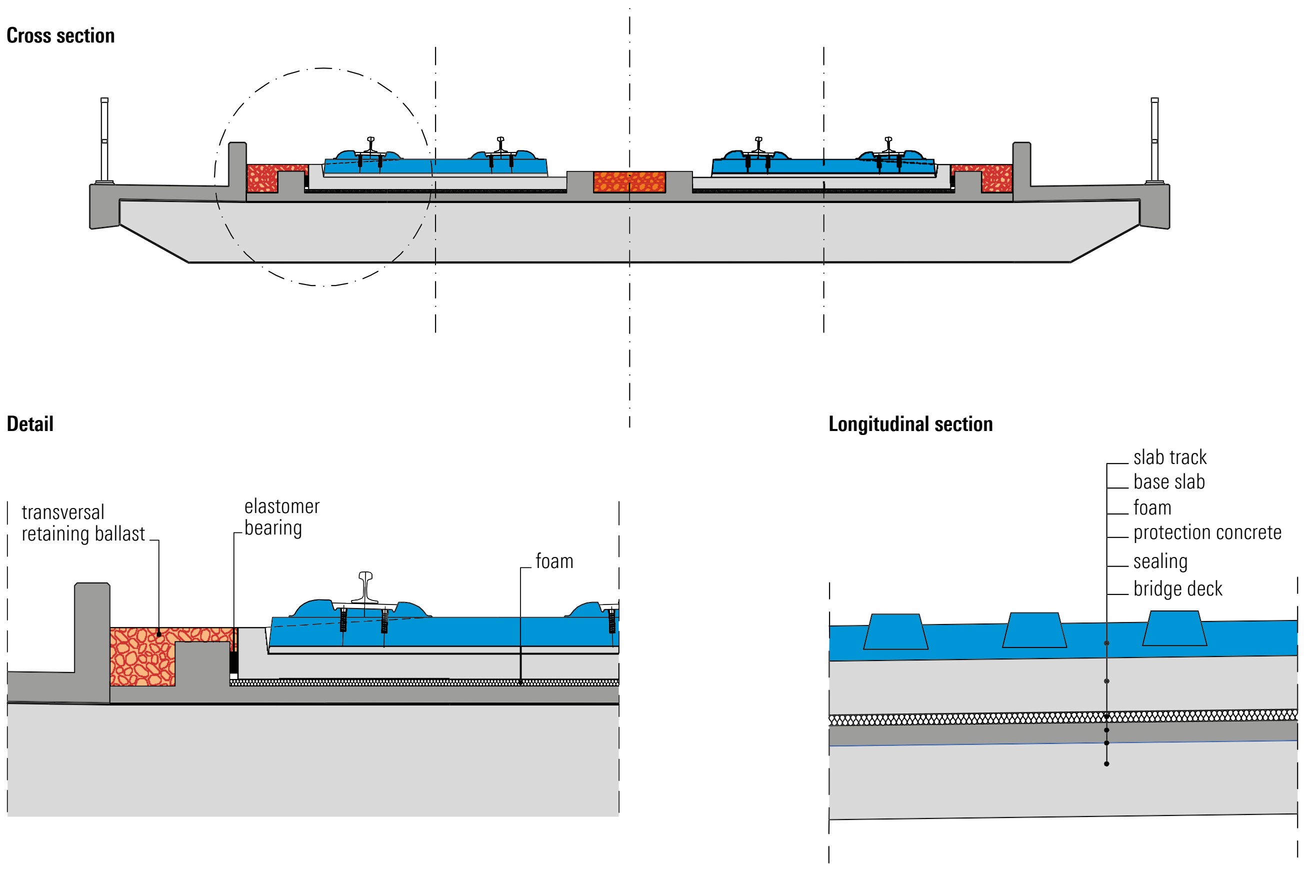


Figure 8 Typical layout of the slab track for a short bridge (<25 m)

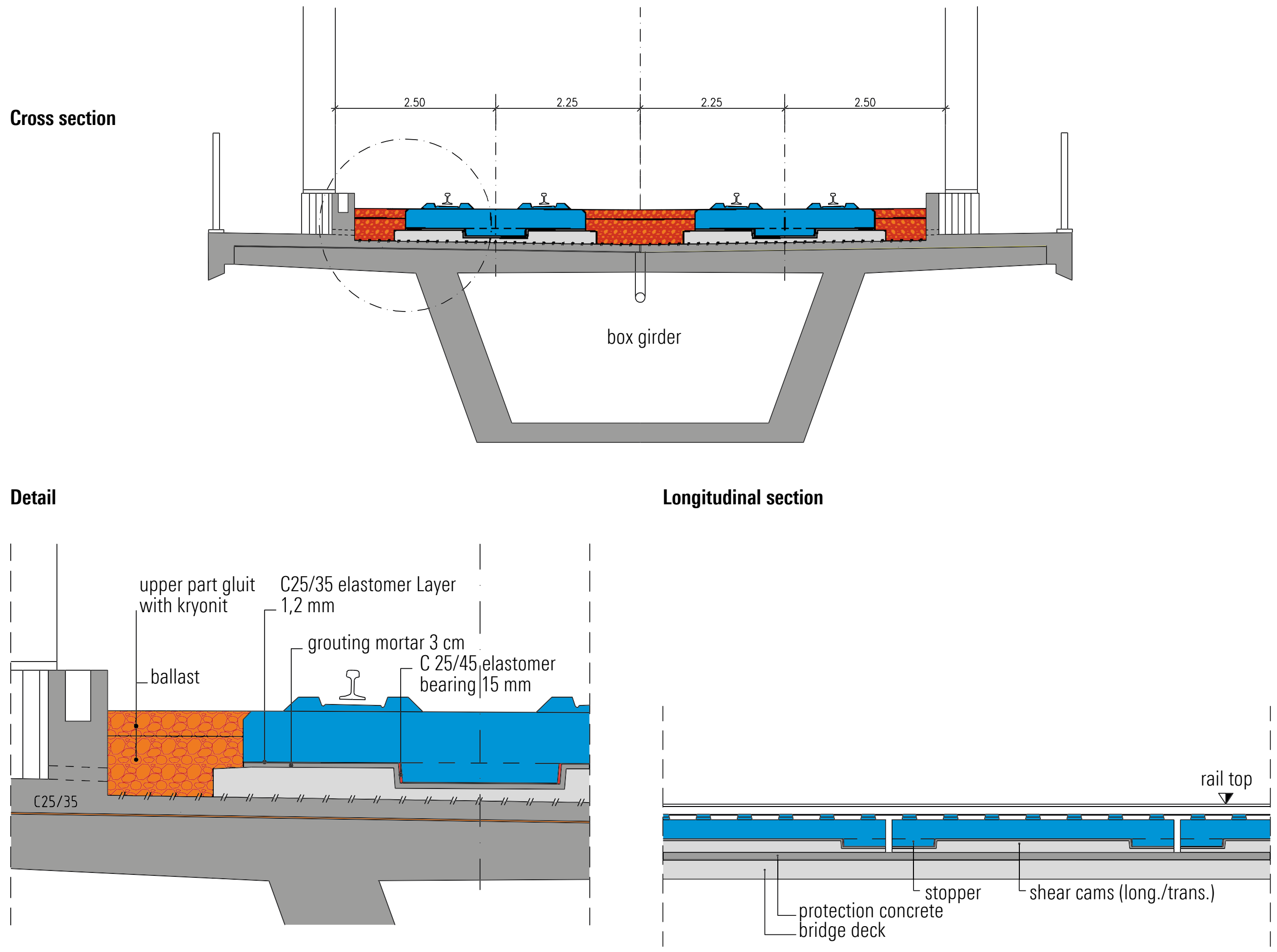


Figure 9 Typical layout of the slab track for a long bridge (>25 m)

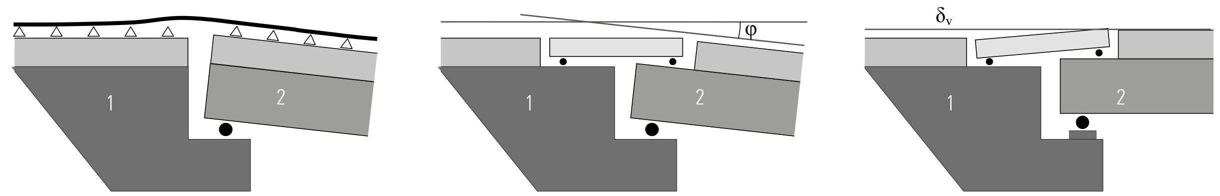
To control long time settlement in soft soil a trough on piles for slab track systems – similar to the track on a pile system presented above – has been developed. The design has been implemented for the new railway track Nuremberg – Ingolstadt near the village Offenbau. Two troughs 326 m each and one asymmetrical trough to retain a slope and a nearby highway with a total length of 488 m have been built.

Depending on geological conditions and nearby constructions there are different construction methods. In case of an open pit with free slopes the base slab in reinforced concrete is directly supported by piles and the retaining walls are back-filled (figure 6). When the piles initially serve as retaining wall for the pit, the trough in reinforced concrete is build in-between the walls and is supported on the upper ends of the side walls by small cantilevers (figure 7). The slab track system is applied on the base slab comparable to slab tracks on bridges.
In case of swelling soil, an often seen phenomenon in clay soils, a cushion layer has to be implemented under the trough to avoid unfavourable loading of the structure.

The construction of slab tracks in troughs on piles leads to a track rigidity comparable to slab track systems on bridges. There is quasi no time dependent settlement. To assure a smooth transition to neighbouring track sections with different stiffness or settlement behaviour, adequate transitions have to be designed.

Picture credits: SSF Ingenieure GmbH

Figure 10 a-c: a) high up-lift forces; b) compensation of girder end rotation; c) compensation of vertical offset



1 Abutment
2 Superstructure

Bridges

Besides the general aspects of slab tracks on earthwork constructions discussed above, specific requirements have to be considered for slab tracks on bridges.

Movement of the bridge

Bridge structures provide the required settlement-free base for slab track, but in return movements of the bridge demand detailed considerations. Longitudinal deformation of the bridge structure is caused by temperature variation. Traffic load causes deflection of the bridge girder and hence rotation of the section at the girders' ends. In case of concrete bridges, deformations of the structure due to creep and shrinkage have to be considered.

In consequence, slab track systems on bridges have to be adapted to the special technical conditions on bridges. Girder end rotation due to traffic load should be limited to 2 ‰. Up-lift forces due to bended rails close to the bridge joints have to be verified to avoid failure of the fastenings and excess of rail stress limits. Longitudinal dilatation has to be absorbed without provoking high longitudinal rail stresses. High up lift forces in the abutments can be reduced by adapted design of the transitions. This could be achieved by reducing the distance between the supports or by reducing the stiffness of the support. Further, structural elements like abutment cantilevers or transition girders can be adopted to smooth the transition (figure 10 a-c).

Newly built railway line Nuremberg – Ingolstadt – Viaduct Main – Danube – Canal

Picture credit: Wolfgang Seitz

Structural types

Concerning the structural design and detailing of slab tracks on bridges, bridges with a span up to 25 m and bridges with a span greater than 25 m have to be distinguished.

In case of short bridges (up to 25 m) –favourably designed without bearings or as frame structure, slab track can be built continuously over the bridge without any discontinuity. The slab track is separated from the structure by a sliding mat and rigid foam to prevent transmission of longitudinal forces (figure 8). In the case of long bridges (over 25 m), the track has to be fixed to the bridge structure. This is usually realized by retaining devices (figure 9). The design and detailing must conform to the requirements of temperature variation, and deflection of the structure in the joint; temperature gradients, creep and shrinkage are to be considered. Similar to bridges with ballasted track, for bridges exceeding a certain expansion length, expansion joints are to be designed to absorb the longitudinal dilatation in the abutments. These expansion joints include, depending on the expansion length and expected girder end rotation, a transition girder as well as a rail joint.

Longitudinal rail stresses

In continuous welded rail (CWR) tracks on bridges, considerable longitudinal rail forces and relative displacements may develop due to temperature variations, acceleration and breaking as well as creep and shrinkage. This stresses are caused by the

Bridge over the Rhine in Kehl

Picture credit: Fotostudio Köther / Max Bögl Bauunternehmung GmbH & Co. KG interaction between the bridge deck and the track system. They have to be limited as they are additional stresses adding up to the rail stresses that would appear on a normal track section.

Generally, this set of problems could be solved by installing rail expansion devices in the track. For high-speed track, however, this is not an attractive solution as these devices cause a local disturbance of the vertical track stiffness and track geometry which would require intensive maintenance. An alternative and very effective solution is the use of so-called zero longitudinal restraint (ZLR) fastenings over a certain length of the track. This method, currently in development, has already proven its performance in several projects but is not yet standardized.

Slab track in tunnel

The first application of ballastless tracks was the installation of slab tracks in tunnels. The already present solid tunnel bottom slab as well as the low construction height of the track provides best conditions for using slab tracks. In case of enlargements of the tunnel gauge in existing tunnels (for example during installation of an electrical catenary) the small construction height is a major advantage.

A pre-condition for a successful realization of a slab track in a tunnel are appropriate geological conditions. The rock/soil properties have to be appropriate for the installation of slab track. Tunnel in areas of rock fall or soil with the possibility of swelling and expansion could exclude the application of slab tracks.
All structural types of ballastless track used at grade can in general also be applied in tunnels. Building slab tracks in tunnels, normally a hydraulic bonded layers is rejected; concrete layers are applied with reduced thickness directly on the tunnel floor. Especially the concrete layer with a thickness of 30 cm at grade may be reduced to 15 cm for the use in tunnels.

Transitions

The superstructure of slab tracks has in comparison to traditional ballasted tracks a considerably higher vertical rigidity. Hence, changes in the rigidity of the sub-structure become more important for the vertical structural response of the whole track system. Adequate transitions from slab track on bridges to adjacent slab track at grade, cuttings and tunnels or even ballasted track sections have to be designed in order to assure good riding comfort and to avoid damages due to dynamic effects.

Usually the following transitions areas exist:
- At grade – bridge
- At grade – tunnel or trough
- At grade – culverts
- Different types of ballastless tracks
- Ballastless track – ballasted track

The standard solution for these transition areas is to apply transition wedges placed in-between subsoil and the track superstructure and additional elastic layers on the more rigid side. The shape of the transition wedge depends on the subsoil and the attributes of the subsoil for example the bearing capacity of subsoil. Transition areas have to be designed for each type of the above mentioned transitions.

Transition at grade – bridge

To obtain uniform settlement behaviour in the bridge structure and earthwork structure, both should have the same type of foundation. Behind the abutment a wedge of soil mixed with cement, content 3 – 5 %, should be arranged (figure 12). The length of the backfill depends on the subsoil. The minimum length is four times the height of the embankment or more than 20 m when the backfill and the embankment are built at the same time.

Transition at grade – tunnel or trough

In order to reduce the difference of stiffness between the rigid construction and the track founded on subsoil, an elastic layer (foam plate) is inserted under the ballastless track, situated at the end of the concrete bottom slab (figure 11). The minimum length of the foam plate is 3.50 m, positioned directly on the bottom slab of the tunnel or the trough. Depending on the subsoil situation and bearing capacity a wedge made of soil and cement can be applied. If the foundation of the tunnel or the trough is very stiff, e.g. founded on a pile construction a transition area made of concrete is useful.

Transition between ballastless track and ballast track

The transition between completely different track structures – ballasted track and ballastless track – with regard to the important rigidity difference of the track systems must be very smooth (figure 13). This transition area should be designed by using a calculation model for decaying settlements.

above: Newly built railway line Nuremberg - Ingolstadt
below: Section of a dutch railway line

Picture credits: RAIL.ONE GmbH

The functional requirements for the transition area are to be satisfied by the following measures:

- The transition to ballasted track has to be located on homogeneous subsoil conditions, with high bearing capacity and good settlement behaviour.
- The realization of the connection between the different bearing layers at the end of slab track merging into ballasted track is realized by anchors and dowels.
- An enlargement of the cement treated base at the end of slab track is necessary to rigidify the track structure beneath the ballasted track. Gluing of ballast shall be adopted. The distance of sleepers is limited to a maximum distance of 60 cm. Adding additional rails on a certain length on the ballasted track also increases the stiffness.

Additional measures:

- Adapting the elastic attributes of the fastenings on the slab track.
- Reduction of stiffness in fastening points on the slab track.
- An adoption of abutment constructions in the subsoil and a wedge of soil which is improved with cement, the typical backfill soil material mixed with 3 – 5 % cement.

Resume

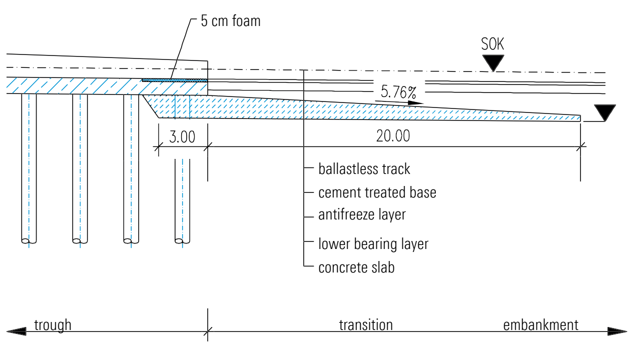
For the design of ballastless railway tracks, design approaches for slab tracks in different geological conditions and different track situation are required. In the regulations is included only basic information for the design of earthwork construction. In order to complete these regulations, SSF Engineering Consultancy has developed slab track designs adapted to difficult soil conditions – e.g. soft soil – as well as slab tracks on bridges and in troughs. In areas with soft soil, the poor soil normally has to be excavated. In case of large deposits the excavation of these soil layers could be very expensive. The excavation could be avoided by adopting a track on pile systems or enhancing the sub soil with CFG piles (Cement, Flue ash and Gravel). This measure stabilizes long-term settlements and prevents exploding construction costs and extensive mass transportation. Another application in soft soils are trough structures, applied were the track is slightly under natural surface level and standard open cuttings are not possible due to boundary conditions or groundwater. Here, retaining walls stabilise bordering terrain and piles avoid long-term settlements. If necessary the piles can also be used as retaining wall during construction.

On bridges the standard slab track systems have to be adapted to enable transfer of longitudinal forces from breaking and acceleration of the train. Also the bearing situation of the bridge has to be considered in order to avoid stress peaks in the rail which could cause breaking or buckling. A detailed verification of the longitudinal rail stresses is mandatory with consideration of all relevant load cases.

The vertical stiffness – the bedding modulus – of the above mentioned slab track constructions varies considerably. A slab track on a bridge or on piles is much more rigid than on earth work constructions. Also the long-term settlement behaviour diverges. Hence, transitions are to be designed to level these differences and to assure a smooth ride. The construction of these transition areas has the same complexity as every engineering structure.

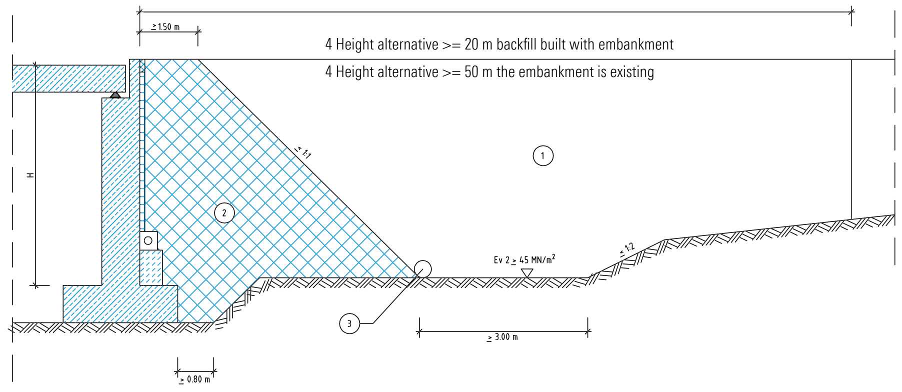
A holistic design approach is necessary in order to take into account longitudinal rail stresses as well as vertical stiffness of every single track slab section. The structural design of every section has to consider the characteristics of the next section in order to optimize the behaviour of the complete system. The analysis should be carried out considering not one section or construction separately but the whole track with all sections combined. Only this approach will lead to a statically efficient and economically reliable construction.

Figure 11 Transition at grade – tunnel or trough



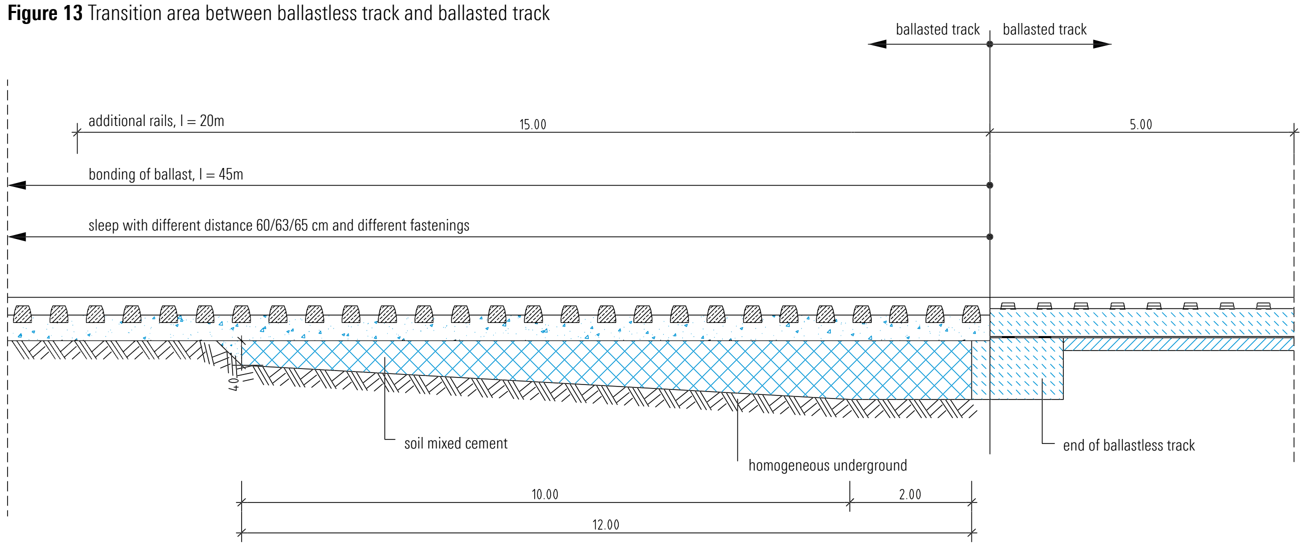
Picture credits: SSF Ingenieure GmbH

Figure 12 Transition bridge – embankment



1 see requirements for embankment
2 soil mixed with cement
3 full drain pipe

Figure 13 Transition area between ballastless track and ballasted track



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