Master's thesis

2019

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A framework for applying slab track on earthworks in Norway

May 2019

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Master in Road and Railway
Submission date: May 2019
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Preface

This master thesis is written from August 2018 to May 2019, as a part of a master's degree in Railway at Norwegian University of Science and Technology (NTNU). The master thesis is 30 credits, which equals 800 work hours. This work is done next to my job as a Coordinator for railway projects on the Vestfold Line in Bane NOR.

After learning about slab track in one of the mandatory subjects at NTNU, I found the topic very interesting and decided to do my master study about slab track. I quickly discovered that it is not permitted to build slab track on earthworks in Norway, and I wanted to investigate this topic closer.

This master thesis is a continuation of the project report *Fastspor i dagsone – bygging og vedlikehold* (Lien, 2018), which I finished last year. It is written in Norwegian, and the title translates to *Slab track on earthworks – construction and maintenance*. I chose to write my master thesis in English to be able to contribute my work on slab track to a wider audience and let the academic community outside of Norway learn about Norwegian development on this topic.

The goal of this thesis has been to provide a framework for applying slab track on earthworks in Norway and illustrate the consequences and possibilities of permitting this. In addition, the thesis aims to benchmark three known slab track systems against criteria for use on high-speed railway on earthworks in Norway.

I would like to thank my supervisor at NTNU, Elias Kassa, my colleagues in Bane NOR, especially Arne Svensøy, Frode Teigen and Morten Tangaard, Alexej von Glasenapp and Arnold Pieringer at RAIL.ONE, Peter Laborenz at Sonneville, Ivana Avramovic at PORR and Peter Veit at TU Graz. Your input and contributions have been very valuable to me. To my boss, Bjørn Ståle Varnes, thank you for believing in me and letting me do this study. Also, I direct a huge thank you to my better half, Anders, without your love and support the finish line would have still seemed miles away. To my lovely children; Filip, Kaja and Haakon, thank you for your patience and for cheering me on. I promise to be a better mom again.

To everyone who reads this, I hope you learn something new and find it an interesting read.

Hanna Agnethe Lien

Hanna Agnethe Lien

Drammen, May 15th, 2019

Picture on front page is from the VDE 8 project. Picture is borrowed from www.vde8.de.

Summary

Slab track is a track construction in which rails and sleepers are put on a slab of concrete or asphalt. Slab track normally provides lower construction height than ballasted track, and it often provides a more stable track geometry and demands less maintenance than ballasted track. The development of modern slab track started in the 1960s. The first pilot slab track built on earthworks was built in 1972 at Rheda station in Germany by Deutsche Bahn. Since then, many countries have built high-speed railway with slab track on earthworks and the countries with the most experience are Germany, China and Japan.

In Europe, the European Commission (EC) on behalf of the European Union (EU), established The European Union Agency for Railways (ERA) in 2004, as part of the process of securing interoperability of the railway infrastructure in Europe. EC has issued regulations and directives to secure interoperability. The European standards EN16432-1 and EN 16432-2 are standards for slab track. They are implemented in all EU countries and EEC countries as well, including Norway.

It is not permitted to apply slab track on earthworks in Norway today, only on solid substructure, such as bridges and tunnels. This thesis presents a framework for applying slab track on earthworks in Norway and illustrate the consequences and possibilities of this. There is an ongoing railway development in Norway where it can be relevant to consider building slab track for longer stretches than tunnel or bridge only.

For slab track the main principle is that there is a relatively flexible continuous or divided concrete slab which rests on a rigid substructure. This means that the substructure must be practically free of settlements. This is a considerable challenge when building in areas with poor soil conditions and this have previously required extensive and costly improvements to the substructure to satisfy the requirements for the required rigidity and carrying capacity. It also is important to secure enough drainage capacity when building slab track on earthworks, as well as securing the substructure against frost heaving when building through areas that are seasonally frozen. China has had experience with this over the last decade and has performed research on this topic that can have relevance for Norwegian conditions. Other important topics for slab track on earthworks are planning good transition zones and handling and reducing noise and vibrations.

There are three selected slab track systems that have been studied closer for this thesis. They are LVT - Low Vibration Track, ÖBB-PORR Slab Track Austria and Rheda 2000. The systems have been benchmarked against chosen criteria, and the system which received the highest score is the ÖBB-PORR system. This is mainly because the system has a good solution for adjustments, repairs and replacement.

A gradual approach for building slab track on earthworks in Norway is recommended, with applying slab track first in longer tunnels, secondly on shorter distances between tunnels and bridges and last on longer stretches on earthworks.

Recommendations for future work is to gather experience from operation and maintenance for the upcoming tunnels being built with slab track in Norway. More systems can be benchmarked with the chosen criteria and the selection of criteria can be extended further.

It is also recommended to gather more experience and research on frost protection and slab track performance in case of settlements and develop repair methods in case of damage caused by settlements.

Sammendrag

Fastspor er en sporkonstruksjon der skinner og sviller legges på en betong- eller asfaltplate. Fastspor gir normalt lavere byggehøyde enn spor med ballast, og gir ofte en mer stabil sporgeometri og krever mindre vedlikehold enn spor med ballast. Utviklingen av moderne fastspor startet på 1960-tallet. Deutsche Bahn bygget i 1972 en pilotstrekning med fastspor i dagsone på Rheda stasjon i Tyskland. Siden da har flere land bygget høyhastighetsjernbaner med fastspor i dagsone, og landene med mest erfaring er Tyskland, Kina og Japan.

I Europa etablerte EU-kommisjonen på vegne av Den europeiske union (EU) Den europeiske unions byrå for jernbane (ERA) i 2004 som et ledd i prosessen med å sikre interoperabilitet til jernbaneinfrastrukturen i Europa. Europa-kommisjonen har utstedt forskrifter og retningslinjer for å sikre interoperabilitet. De europeiske standardene EN16432-1 og EN 16432-2 er standarder for fastspor. De er implementert i alle EU-land og EØS-land også, inkludert Norge.

Det er ikke tillatt å bygge fastspor i dagsone i Norge i dag, bare på faste konstruksjoner, som broer og tunneler. Denne oppgaven presenterer et rammeverk for bygging av fastspor i dagsone i Norge og illustrerer konsekvensene og mulighetene ved å tillate dette. Norge har en pågående jernbaneutbygging der det kan være aktuelt å vurdere bygging av fastspor for lengre strekninger enn bare tunnel eller bro.

For fastspor er hovedprinsippet at det er en relativt fleksibel kontinuerlig eller delt betongplate som hviler på en stiv underbygning. Dette betyr at underbygningen må være praktisk talt fri for setninger. Dette er en betydelig utfordring når man bygger i områder med dårlige grunnforhold og dette har tidligere krevd omfattende og kostbare forbedringer av underbygningen for å tilfredsstille kravene til nødvendig stivhet og bæreevne. Det er også viktig å sikre tilstrekkelig dreneringskapasitet når man bygger fastspor i dagsone, samt å sikre underbygningen mot telehiv når man bygger gjennom områder som er utsatt for frost. Kina har fått erfaring med dette i løpet av det siste tiåret, og har utført forskning på dette emnet som kan ha relevans for norske forhold. Andre viktige temaer for fastspor i dagsone er å planlegge gode overgangssoner og håndtere og redusere støy og vibrasjoner der dette er nødvendig.

Det er tre utvalgte fastsporsystemer som har blitt studert nærmere for denne oppgaven. De er LVT - Low Vibration Track, ÖBB-PORR Slab Track Austria og Rheda 2000. Systemene har blitt evaluert mot utvalgte kriterier, og systemet som fikk høyest poengsum er ÖBB-PORR. Dette skyldes i hovedsak fordi systemet har en god løsning for justeringsmuligheter og reparasjon og utskiftning av plater.

Det anbefales en gradvis tilnærming til å bygge fastspor i dagsone i Norge, ved først å bygge fastspor i lengre tunneler, så på kortere strekninger mellom tunneler og broer og deretter på lengre strekninger i dagsone.

Anbefalinger for fremtidig arbeid er å samle erfaring fra drift og vedlikehold for de kommende tunnelene som bygges med fastspor i Norge. Flere fastsporsystemer kan evalueres med de valgte kriteriene, og valg av kriterier kan utvides videre.

Det anbefales også å samle mer erfaring og undersøkelser om frostbeskyttelse og fastsporets egenskaper i tilfelle setninger og utvikle reparasjonsmetoder i tilfelle skader forårsaket av setninger.

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Terms and definitions

At-grade: railway is level to surrounding land, mostly on earthworks

BANE NOR: a state-owned company responsible for the Norwegian national railway infrastructure

cDYN: dynamic stiffening ratio, describes dynamic vertical bedding modulus

Cuttings: where soil or rock from a relative rise along a line is removed, on earthworks or on bedrock

Earthworks: engineering works created through the processing of parts of the earth's surface involving quantities of soil or unformed rock. Shaped as embankment, cuttings or at-grade

Embankment: a raised structure of earth or gravel to carry a railway line, on earthworks

Elastic modulus: E-modulus or Youngs modulus. Is a quantity that measures an object or substance's resistance to being deformed elastically (i.e., non-permanently) when a stress is applied to it. High e-modulus means a stiffer material

Flexural stiffness: a measure of the resistance of bending deformation

Floating slab track: A system built to reduce vibration. The rails are fixed to a concrete slab foundation which is supported on a resilient mounting made up of an elastic layer, bearings or springs

Fastening: The fastening fixes the rail to the sleepers, secure correct rail gauge and prevent longitudinal movement of the rail

Gradient: the rise or fall of a railway line

Head checks: cracks on the head of the rail

InterCity: InterCity is an ongoing development of the railway infrastructure in Norrway, with 230 kilometres of new line from Oslo to Halden, Skien, Lillehammer and Hønefoss

LCA: Life Cycle Analysis

LCC: Life Cycle Cost

LCCA: Life Cycle Cost Analysis

MN/m^2: Meganewton per square meter

Night-time possession: Time at night which can be used for maintenance. Usually a few (2-5) continuous hours per night

Rail pad: elastic mats which are interposed between steel rails and sleepers to protect the sleeper top from wearing and impacting. Secures friction and increased resistance against moving of the rail

RAMS: Abbreviation for Reliability, Availability, Maintainability and Safety

Short and long pitch corrugation: regular depressions in the running surface, defect due to traffic load, common in high-speed railway lines

Substructure: earthworks, bridges or tunnel floor that lie below the slab track superstructure (below the formation level)

Superelevation (rail cant / track cant): is the rate of change in elevation (height) between the two rails or edges

Superstructure: the track elements above the formation level

Tamping: packing ballast under railway track to achieve correct alignment of track

TBM: Tunnel boring machine

TGV: Train à Grande Vitesse (high-speed train)

1 Introduction

This chapter describes the background for choice of topic for the master thesis and explains the aim and research questions of the study. Further on, the limitations of the study are listed, methodology is described, and the structure of the thesis is presented.

1.1 Background for choice of topic

The topic for this thesis, slab track on earthworks, was chosen after discussions with project supervisor. I was curious to learn more about this type of track system. After the research on slab track started, I discovered that in Norway it is only permitted to build slab track on solid construction, e.g. in tunnels and on bridges.

I wanted to investigate this topic closer. Many questions emerged. Why is it not permitted to build slab track on earthworks in Norway? What is needed of information and perhaps research to change these regulations? What are the consequences of permitted to build slab track on earthworks in Norway? What considerations must be taken when deciding on building slab track on earthworks? What are the challenges for building this type of track on earthworks? What kind of maintenance is required for slab track?

In spring of 2018 I did a literature study of slab track on earthworks to gain more knowledge on the topic. The project report was a preliminary study for the work with the master thesis. It presented a deeper understanding on the historical development of slab track, how technology has evolved and described the current status in the field. It also described plans for further development in railway infrastructure in Norway. The project report showed that slab track on earthworks is commonly used many places in the world and is gaining popularity on high-speed railway lines.

In the project report, the original plan for the master thesis was to perform an LCC-analysis for slab track on earthworks. This plan has later been changed due to insecurities connected to the demands for substructure, and hereby being able to set reliable values for costs for substructure works. It was established that there are not adequate demands for slab track substructure on earthworks in Norway to perform these calculations on this present time. To be able to establish these demands for substructure, the plan of this thesis has been changed to focus on presenting a framework for slab track on earthworks and a perform a study of consequences and possibilities of applying slab track on earthworks in Norway.

The Norwegian railway infrastructure owner Bane NOR is currently planning and building several projects with the aim of renewing and upgrading the railway. The railway infrastructure in Norway is being developed with several double track lines and for some of these, which mainly consists of tunnel, it has been decided to build with slab track. With higher speed and higher axle load on the railway system being built today, slab track is often a good choice for track construction due to its qualities with regards to track quality, availability and long lifetime.

The master thesis will also study three selected slab track systems and benchmark them against chosen criteria based on the findings in the thesis and what is highlighted as important requirements for slab track performance.

1.2 Aim of the study

The aim of this master study is to gain a better understanding of what is required when building slab track on earthworks, and to enlighten the reader on the consequences and possibilities of applying slab track on earthworks in Norway.

The aim is to learn from experience from other countries and see if they can be applied in Norway. The thesis will try to identify the demands to be set for slab track on earthworks.

When benchmarking the three slab track systems against criteria chosen for Norwegian conditions, the aim is to see if they are suited for application in Norway, and if some are better suited than other.

The aim is to recommend a process for applying slab track on earthworks in Norway, and which cases it will be relevant to consider applying build slab tracks on earthworks in Norway.

The thesis will try to answer the following research questions:

Which recommended requirements are relevant for building slab track on earthworks in Norway?

What is the recommended process for applying slab track on earthworks in Norway?

Which of the three selected slab track systems are best suited for application on earthworks in Norway?

1.3 Limitations

The following limitations has been made for this master thesis:

Countries for comparison:

There are many countries with experience with use of slab track on earthworks, but this thesis primarily focuses on experiences from Europe, and in addition some experiences from China and Japan.

Design speed:

As the InterCity project designs for speeds up to 250 km/t this is set as design speed for this thesis.

Elements in railway:

This master thesis only addresses the superstructure and substructure of the railway system. It does not include evaluation of switches and crossings, power supply and signalling system.

Fastenings and rails:

Fastenings and rails are not specifically described or evaluated, only mentioned when necessary.

Slab track systems:

In this thesis, slab track is defined as a track system consisting of a slab of concrete with rails attached to this, either with embedded sleepers or other fastening. For this work, only three slab track systems have been selected for further research and evaluation. They are LVT – Low Vibration Track by Sonneville, Rheda 2000 by RAIL.ONE and Slab track Austria by ÖBB (Austrian Federal Railways) and PORR.

Substructure:

All considerations in this thesis are made for double track line on earthworks. This includes cuttings, embankment and at-grade solutions. Solutions with pile supported slab track are left out, as this solution can be considered a bridge.

1.4 Methodology

This chapter describes the methodology used in the work with the master thesis.

Search for literature in databases, library and online has been performed. The searches for literature have been in Bane NOR's library Viten, NTNU's university library and online for relevant literature, books, articles, journals and government regulations. Several other master theses written about slab track have been studied. On account of the rapid development in technology and knowledge about slab track since first built, most of the searches have been limited to sources published after year 2000.

Communication with RAIL.ONE GmbH, Sonneville AG and PORR Bau GmbH via email and telephone has been used in gathering information about the three selected slab tack systems.

Meetings with project supervisor have been held in Oslo, Trondheim and on Skype. Meeting with colleagues in Bane NOR have been held in Oslo and Drammen. Meeting with Peter Veit has been held in Drammen.

A literature review of slab track development, slab track on earthworks and slab track requirements and European best practises has been performed.

A qualitative evaluation of three slab track systems has been performed. The qualitative criteria have been given values and weighted against each other, and a quantitative evaluation has been performed.

1.5 Structure of the thesis

This master thesis is built up of 10 chapters with the following content

1 Introduction

Describes background and aims of the study, limitations and structure of the thesis, and methodology used in the master study.

2 Slab track development

Gives a definition of slab track, gives a brief account of the history of slab track, describes the use of slab track on earthworks and describes slab track development in Norway.

3 System regulations

Describes the development and current status for slab track regulations in Europe and Norway. Bane NOR's Technical regulations is described and the Norwegian UPB-process, with LCC methods and RAMS are presented.

4 Slab track benchmarking

Describes the most important benchmarking factors for slab track on earthworks, with focus on topics that are relevant to Norwegian conditions. The topics in question are rigidity, substructure, poor soil conditions, settlements, drainage, frost, transition zone, noise and vibrations, installation, operation and maintenance and LCC.

5 European best practises

Description of three selected European slab track systems.

6 Systems evaluation

Contains an assessment and evaluation of the main topics related to applying slab track on earthworks. It sums up international best practises for slab track on earthworks with focus on topics especially relevant to Norwegian conditions. The three selected slab track systems are benchmarked and evaluated according to chosen criteria.

7 Discussion

Sums up and discuss the work in the master thesis and findings from the literature review and benchmarking. Highlights the most important consequences and possibilities of applying slab track on earthworks in Norway.

8 Conclusions and recommendations for future work

Concludes on the work in the master thesis and point to further work which is needed.

9 References

Alphabetical list of all sources referenced in the thesis.

10 Annex

Annexes referenced in the thesis.

2 Slab track development

This chapter gives a definition of slab track. A brief summary of the history and development of slab track is given. A brief description of slab track on earthworks follows. It accounts for present and future use of slab track in Norway, and present and future development in the Norwegian railway.

2.1 Definition

Ballastless track is a track construction in which rails and sleepers are not put on a layer of ballast. The layer of ballast has been replaced with a solid construction. Ballastless track normally provides lower construction height than ballasted track, and it often provides a more stable track geometry and demands less maintenance than ballasted track (Bane NOR, 2018b).

The term ballastless track also includes other types of track without ballast, e.g. tracks on bridges with special wooden sleepers. To avoid confusion of these terms, the term slab track is used in this master thesis, except for when "ballastless" is used in regulations that are valid for all types of track without ballast. This master study is limited to track constructions built up by a slab of concrete with rails attached to this, either with embedded sleepers or other type of fastening.

There is a large variety of designs of slab track systems. A way to distinguish between the different types is shown below in Figure 1. First, there is a distinction between two types of support; discrete or continuous rail support. These two can be further divided as shown below. Bottom row in orange lists some examples of slab track systems in the different categories.

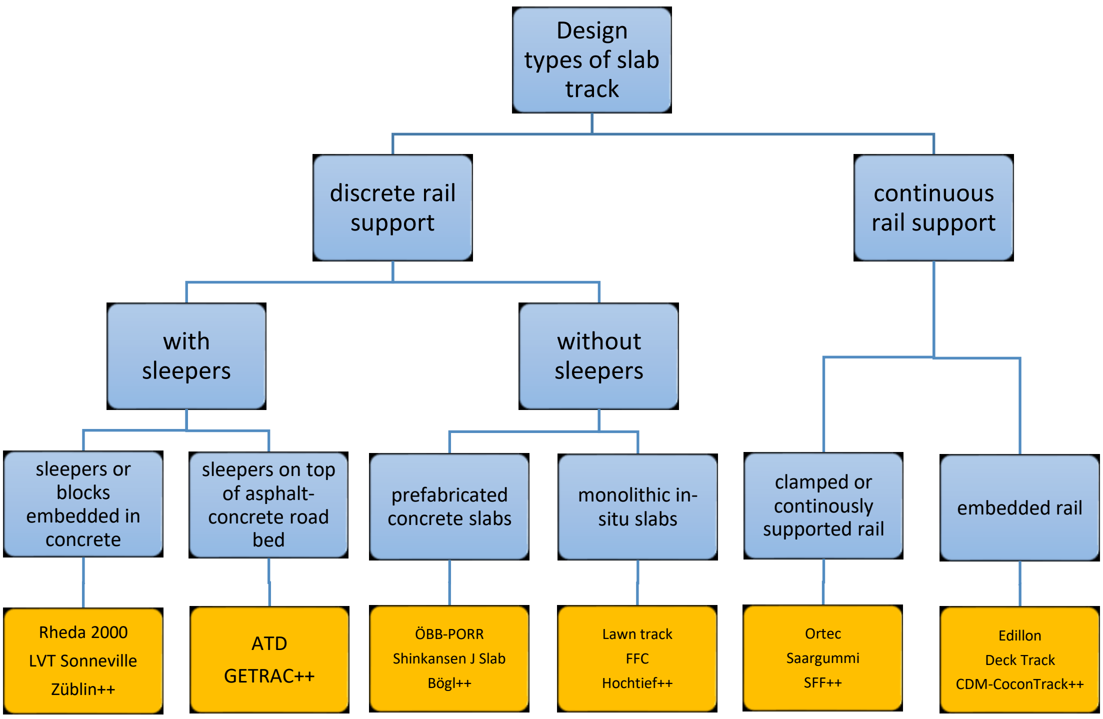


Figure 1 Design types of slab track

2.2 Historical development

The first slab track constructions were built in the early 1900s, but the development of modern slab track in Europe began in the 1960s. As a result of the construction of high-speed lines, the interest in slab track came. Due to stringent requirements for curvature, the new high-speed lines have a larger share of bridges and tunnels than before. It was observed that with ballasted tracks on solid substructure (e.g. bridges), the ballast had more rapid wear and tear than ballasted track on soil substructure. With ever-increasing train traffic in Europe, it became less available night-time possession out maintenance work. In addition, maintenance work in tunnels was more difficult for safety reasons.

The poor durability of tracks with ballast laid on solid substructure was also confirmed in Japan. The Tokaido line between Tokyo and Osaka (515 km) opened in 1964, and nearly 50% of the line is on fixed structures. After only 30 years, 75% of the distance had changed ballast twice. Similar experiences have also been made in France (TGV Paris - Lyon) and in Germany on their high-speed railways. In France, the ballast was changed after only 15 years, due to high speed and high traffic which resulted in high degradation (Leykauf, Lechner, & Stahl, 2006).

High speeds of 250 km/h or more and requirements for increased axle load mean that ballasted track in some areas has reached its technical limits. With high speed comes strict requirements for precise alignment horizontally and vertically, a minimum of settlements and constant vertical elasticity to maintain satisfactory ride comfort and minimize wear on tracks. For ballasted tracks, these requirements increase the need for maintenance. In addition to the weaknesses mentioned above, in the case of ballasted tracks and speeds above 250 km/h, one may experience the challenge with ballast flying and hitting the underside of the train or flying out to the side as a projectile. This is due to wind speeds and turbulence formed between the underside of the train and the ballast. In winter, at speeds above 160 km/h, blocks of ice which have fallen off the underside of the train, can be lifted and cause damage. Flying ballast and ice can damage the underside of the train, wheels and brakes and can get between wheels and rail and cause increased breakdown of the rails and damage to them. Ballasted tracks are also sensitive to fluctuations around 120 Hz that occur at high speeds (Eisenmann, 2006).

The conditions described above contributed to the resumption of slab track development in the 1960s. Slab track was built in Switzerland (Bötsberg Tunnel in 1966), and studies were made in England and France for the Channel Tunnel (first opened in 1994). High-speed railway studies were conducted in Germany, and in 1972 Deutsche Bahn built a pilot slab track at Rheda station (Münchschwander, 2006). This track is built on soil substructure. The basic structure of the track at Rheda station is shown in Figure 2.

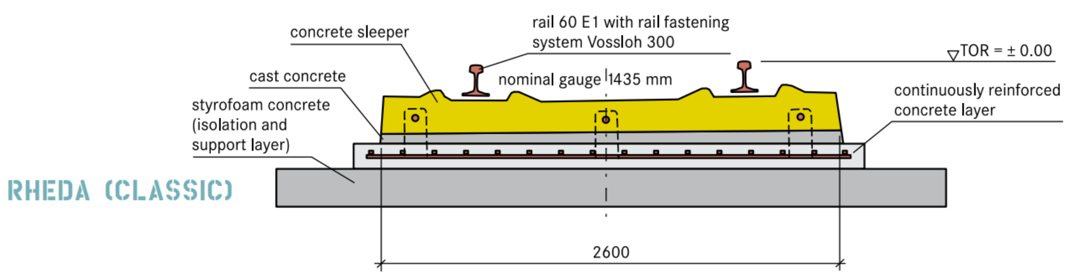


Figure 2 Classic Rheda slab track from 1972 (Rail. One, 2018)

Above the substructure there is a cement-stabilizing layer in the bottom, then a layer of styrofoam concrete as load distribution and frost insulation. On this layer, a reinforced concrete slab is cast, and the rail ladder with concrete sleepers is laid out and adjusted in permanent position before pouring in the concrete (Bane NOR, 2018b). Figure 3 shows pictures of the Rheda Classic system at Rheda station. It is 637 meters long, with radius 5700 m, superelevation 50 mm, fastening Ioarv 180, rails UIC 60, sleepers B 70 S. Speed for this line is 200 km/h.

Figure 3 Pictures of Rheda Classic, built 1972 (Fiebigs, 2019)

The slab track at Rheda station has not required any major maintenance work other than replacement of components in fastening and rail grinding. The rails have not yet been replaced. Adjacent ballasted tracks have been tamped several times in the meantime (Bane NOR, 2018b). One of the most important advantages of slab track is the low need for maintenance and consequently high availability.

Since the 1970s, the development of slab track has spread widely around the world. It is built in Germany, France, the Netherlands, Austria, Italy, Switzerland, USA, Japan, China and South Korea to name a few countries.

In Germany, after experiments with various types of track, it has been chosen to focus on solutions that have some form of sleepers in the construction, which makes it easier to achieve the desired accuracy in the track location (Bane NOR, 2018b). This is cast as a continuous slab.

As part of the further optimization of the construction process, the idea of prefabricated modular panels came as a replacement for slabs cast in-situ. The first prefabricated slab track panels were developed in Japan and were called J-Slab (also called Shinkansen) (Gautier, 2015). Today, there are several different prefabricated slab track systems, the most known are Shinkansen J-Slab, Bögl, ÖBB-PORR.

In Germany, the aim is to build continuously with the same track system for bridge, tunnel and earthworks, on new sections (Bane NOR, 2018b) Examples of lines where this is done are Cologne - Rhein/Main (2002), Nuremberg - Ingolstadt (2006) and the new VDE 8 project. Figure 4 on the next page shows a picture of the railway line between Nuremberg and Ingolstadt. Here, the railway line is in a cutting besides the motorway. Normally, high-speed railway lines have too strict curvature to be placed parallel to a motorway, but these two lines are constructed partly parallel to the motorway. This was made possible by the fact that slab track has a higher resistance to lateral loads than ballasted track, and a lower required minimum radius than ballasted track (CEMOSA et al., 2014).

Figure 4 Picture of railway line between Nuremberg and Ingolstadt (S. Terfloth, 2007) (Bahnbilder.de, 2019)

A new high-speed railway line in Germany, VDE 8 (German Unity Transport Project) from Nuremberg – Erfurt – Halle/Leipzig – Berlin is under construction. Section 8.2 between Erfurt and Leipzig/Halle is built with 90km x 2 with slab track. 67% of this section is on earthworks, as illustrated in Figure 5.

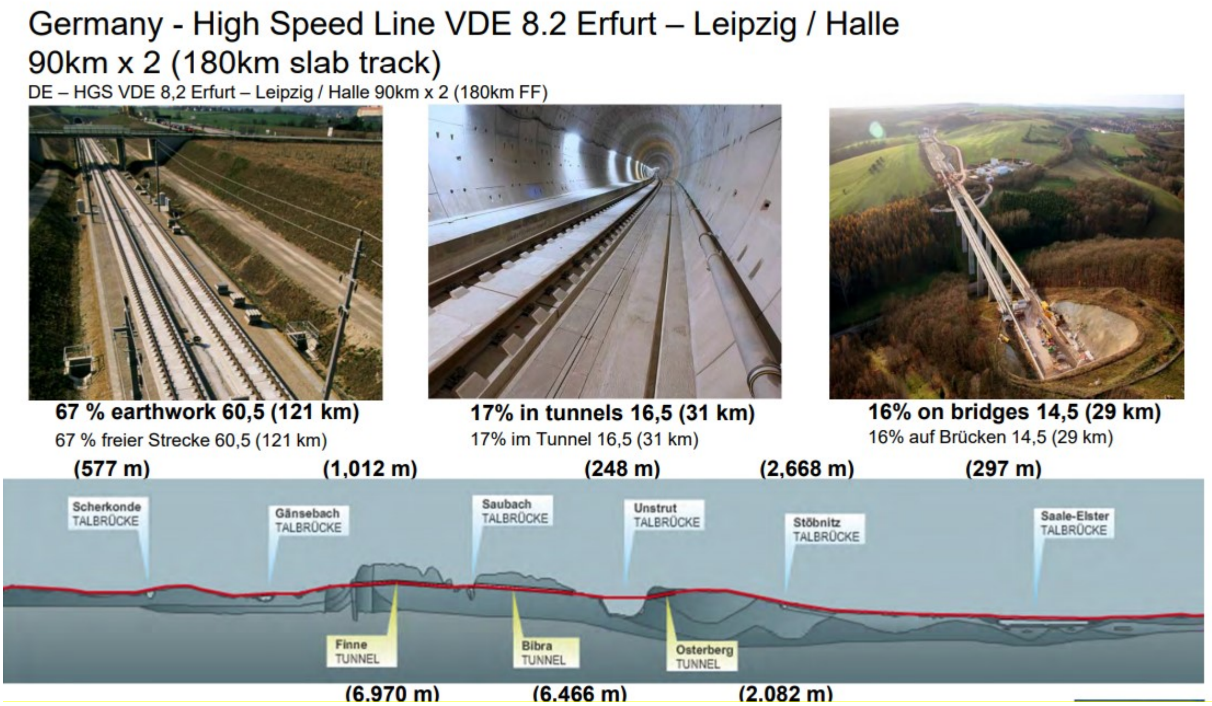


Figure 5 VDE 8.2 Erfurt - Halle/Leipzig (Zottl, 2012)

China are also building continuously slab track for new long railway projects. In China it has been built approximately 5000 km with slab track from 2008 to 2014. High-speed lines with slab track have covered most areas of China which have different climates and complex geological conditions, on earthworks, bridge and tunnel (Wang, 2011). In China they have encountered different technical difficulties, such as ensuring how different kind of slab track adapt to different climate and infrastructure and controlling settlement after work completion on soft soil, karst[1] and collapsed soil in order to lay slab track (Wang, 2011).

In Japan, over 55% of the total length of the five Shinkansen lines is built with slab track, originally only on bridges, viaducts and in tunnels (Yokoyama, 2010). Slab track for earthworks was developed in the early 1990s and in 1993 the newly developed reinforced concrete for slab track (RCRS) was applied for 10.8 km on the Hokuriku Shinkansen line, which accounts for 4% of its total length, and ¼ of all earthwork section (Ando, Sunaga, Aoki, & Haga, 2001).

In Switzerland and Austria slab track is primarily applied in tunnels and on bridges, according to reference lists for the slab track systems LVT and ÖBB-PORR. In Austria it is permitted to build on earthworks on shorter sections between for example tunnel and bridge, where it is deemed suitable for the specific project. The regulations in Austria RW 01-03 from 2014 Linienführung von Gleisen include comments on the use of slab track on earthworks, stating that this is permitted on sections with minimal settlements only. These rules are general and does not give any further details (Veit, 2019).

Another advantage of slab track compared to ballasted track is lifetime. In Germany, the new high-speed slab track are required to be built for 60 years lifetime (Bane NOR, 2018b). Estimated life time for high-speed ballasted track is 15-30 years, and the corresponding high-speed line with ballasted track will have to change the ballast up to several times within the same period as the total life time of slab track.

When building slab track in tunnel, a big advantage is that slab track has a lower total construction height than ballasted track. Slab track has been applied in several upgrades of older not yet electrified tunnels where the original tunnel height and profile are limited. Such tunnels which are planned for electrification, are frequently chosen for the conversion to slab track, as it often eliminates the need for extending the tunnel profile. It is also an advantage for new tunnels that are being driven with TBM, since the total tunnelling profile can be downsized if choosing slab track as superstructure. The lower need for maintenance is also relevant for building in tunnels, where access to track is restricted.

Ballasted tracks have traditionally been more popular than slab track. One of the main reasons for this is lower investment cost. The Japanese solution for slab track is said to be 30 to 50% more expensive to build than ballasted track, and experience from Germany indicate that it is about 40% more expensive to build slab track than ballasted track (N Bilow & M Randich, 2000). In Japan, there is a criteria that slab track should not be more than 30% more expensive to build than ballasted track (N Bilow & M Randich, 2000). In Japan, a prefabricated slab solution is used. Similar solutions with prefabricated slabs in Germany are the most expensive of all solutions and will hardly be used in Germany. Data from England indicate a cost increase of 30%, while data from France show a larger cost

[1] Karst is a topography formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum. It is characterized by underground drainage systems with sinkholes and caves.

difference (Bane NOR, 2018b). When it comes to the cost difference of 40% for Germany mentioned above, there is some disagreement about this, since there are others who believe slab track in Germany is 20% to 50% more expensive to build than ballasted track. Note that these comparisons are only for the superstructure of the track and does not include substructure works which are often higher for slab track than for ballasted track, especially on earthworks.

Common to all the articles and books about slab track is that almost all authors point out that there is a lack of experience with total lifetime costs. This is not so strange, since the "modern track" has only been in operation for just over 50 years, and the technological developments on the track solutions have been significant in this time and the newer improved solutions have only been around for 15-20 years.

The development of the various types of slab track has come a long way since this, and there are many types of slab track on the market, within the categories mentioned in chapter 2.1 Definition.

Table A below shows some of the most known slab track systems, that are in continued application today (2019). The systems in this table have all been applied on earthworks, and they are listed with the following properties:

- With or without sleepers
- casting method
- installation method
- approximate total length built around the world (track km, double track equals double length)
- All the listed systems are applicable for high speed > 250 km/h

System	**High-speed > 250 km/h**	**Sleepers?**	**Casting method**	**Installation method**	**Total length built around the world**
Bögl	Yes	No	Precast	Bottom-up/ Intermediate	>6000 km
LVT	Yes	Yes	In-situ	Top-down	~1400 km
Rheda 2000	Yes	Yes	In-situ	Top-down	~ 3500 km
Shinkansen J-Slab	Yes	No	Precast	Bottom-up/ Intermediate	>3000 km
Züblin	Yes	Yes	In-situ	Bottom-up	> 600 km
ÖBB-PORR	Yes	No	Precast	Top-down/ intermediate	780 km

Table A Known slab-track systems, casting method, installation method and length (Tarmac & Max Bögl, 2015), (Sonneville AG, 2018), (RAIL.ONE GmbH, 2019), (Ando et al., 2001), (Michas, 2012) and (PORR Bau GmbH, 2019a)

In chapter 5 European best practises, there is performed a selection of three slab track systems based on different criteria and thereafter the systems are described in detail.

2.3 Slab track on earthworks

The different countries of the world have had a separate approach to design and development of slab track. Regulations and design theories for slab track varies around the world because of the differences in development in the current countries.

In Germany, slab track was first built on earthworks, and thereafter on solid substructure as bridges and tunnels. In Germany, the continuous slab construction pay attention to difference in temperature (Liu, Zhao, & Dai, 2011). Germany developed design for slab track by borrowing from the design concept for road construction. Synergies between road and railway the last four decades have been used to implement and improve slab track technology, especially when it comes to high-speed railway (Lechner, 2009).

Figure 6 shows the basic structure of the system Rheda 2000 on earthworks. Rheda 2000 is a further development of the Rheda Classic system which was added at Rheda station in 1972. It is mainly intended for use on high-speed lines and has been used on the stretch between Nuremberg and Ingolstadt, where it is designed for a speed of 300 km/h and 225 kN/axle (Gautier, 2015).

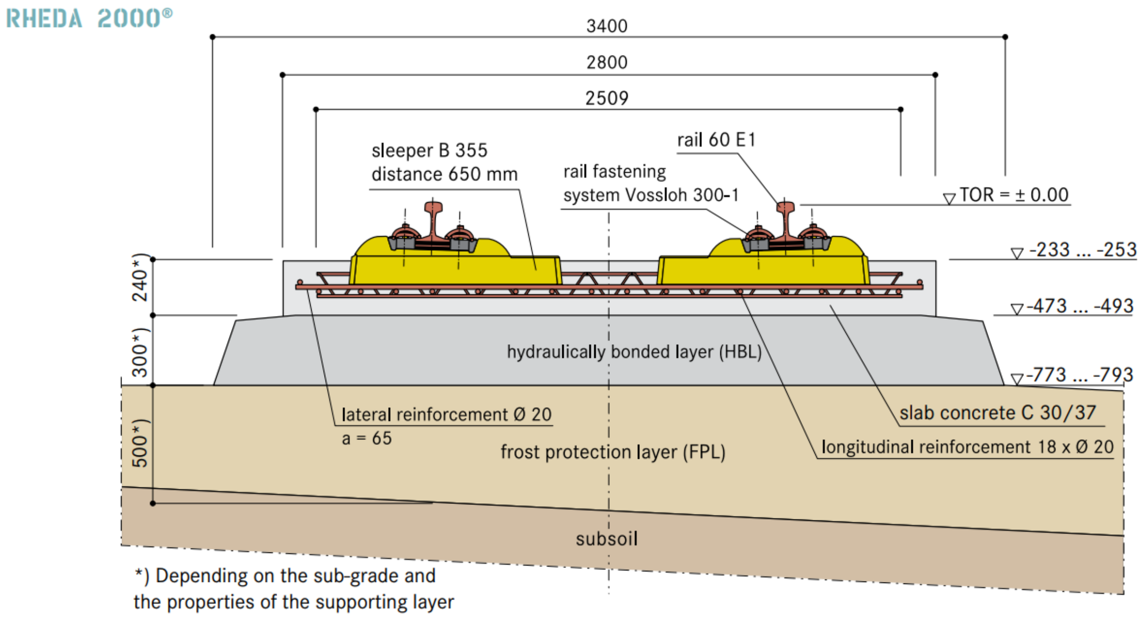


Figure 6 Rheda 2000, principal construction on earthworks (RAIL.ONE GmbH 2018)

In Japan, slab track was first constructed on solid substructure as bridges and tunnels. In the 1970s and gradually further developed for use on earthworks. Because Japan primarily uses prefabricated slabs in 5 metre lengths, the main design criteria is train load. Variation in temperature has little impact on this type slab track. In the slab track base design, the maximum settlements occur at the mid-point and at the ends of the baseplate. Based on deformation, the stiffness is calculated for de different locations for settlements over 5 metres. This is to secure that the slabs can withstand the established limitations for settlements below the superstructure (Liu et al., 2011). Figure 7 on the next page shows the construction principle of the 5-metre-long slabs used in Japan. The concrete slabs are built on top of cement asphalt mortar. Figure 8 on the next page shows a picture of J-Slab built in Taiwan.

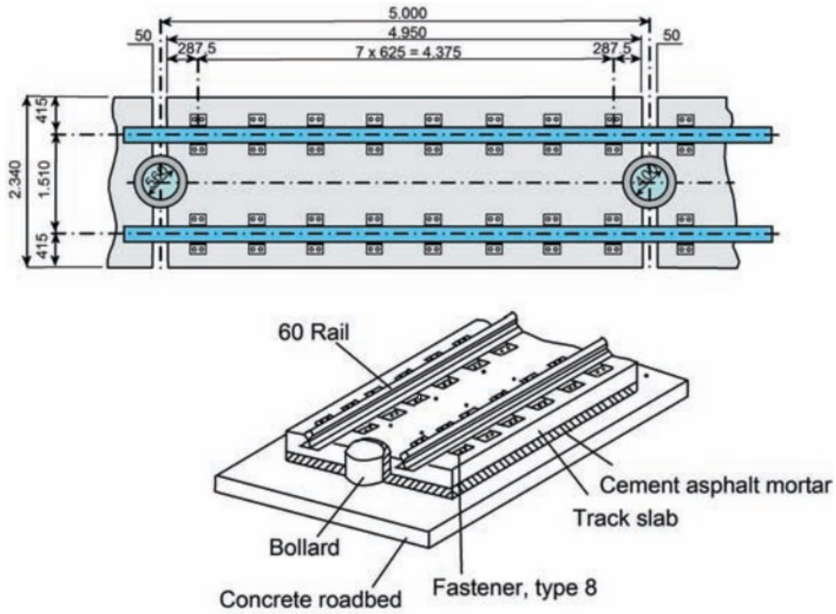


Figure 7 J-Slab(Esveld, 2003)

Figure 8 J-Slab in Taiwan (Gautier, 2015)

As for Japan, the first slab track lines in China were built in tunnel, regarding train load as the primary design criteria. With the increasing use of slab track a general design theory and regulations have gradually been developed as research on high-speed railway with slab track has evolved (Liu et al., 2011). As the Rheda 2000 system has been applied for very long railway lines in China, they have had to take into consideration difference in temperature.

Chapter 4 Slab track benchmarking describe in detail the requirements for slab track on earthworks, including rigidity, substructure, poor soil conditions, settlements, frost, transition zone and noise and vibrations.

2.4 Norwegian development

In Norway there are very few railway lines with slab track. Bane NOR’s technical regulations only permit slab track to be built on bridges and in tunnels, not on earthworks (Bane NOR, 2019f).

As mentioned above, there are only a few metres of slab track in Norway (as of May 2019). There is an embedded slab track (Edilon system) on a railway bridge in Drammen, and there is a variation of discrete supported rail slab track on a side-track on a railway bridge near Porsgrunn (opened 2016). The experience with operation and maintenance of these are limited. The Edilon system in Drammen has been in maintenance free operation for over 20 years but is being renewed in the summer of 2019 due to wear and tear.

There are two ongoing railway projects in which it has been decided to build slab track in tunnels. They are:

- The Follo line, a new 20 km long double track railway line between Oslo S and Ski in the Blix tunnel (plus new Ski station and various reconstruction of Oslo S, total length 22 km). The distance is mainly designed for a speed of 250 km/h. Based on, among other things, the length of the tunnel and the requirement for low downtime, it was decided to build the main tunnel as two single-tracked tunnels and they are driven by 4 tunnel boring machines (TBM). As consequence of these choices, analyses were made for the recommendation of the type of track construction for the line. The choice fell on slab track and it will be built with the system Rheda 2000. The section will open in 2021. The line is designed for a speed of 250 km/h, but will open with 200 km/h (Bane NOR, 2019b).
- Arna – Bergen, a railway line with tunnel, under expansion/development to double track. The new tunnel, beside an existing tunnel, is under construction and the main part is driven by a TBM. In this section, it is decided to build slab track, also the Rheda 2000 system. The newly built tunnel with slab track will open in 2020, and it will be Norway's first line with this type slab track, and the total rehabilitated double track line will open in 2024 (Bane NOR, 2019a).

In the last 15 years there has been an increased railway development in Norway. Several double track projects have opened after 2005, including Sandvika - Asker (2005), Sandnes - Stavanger (2009), Lysaker - Sandvika (2011), Barkåker - Tønsberg (2011), Langset - Kleverud (2015) and Holm - Nykirke (2016). For the next 15 years, a further development is planned for InterCity with double track from Lillehammer, Halden, Hønefoss and Skien to Oslo. A total of 270 km of double track will be built and completed by 2034 (it is currently unclear when completion of Sandvika - Hønefoss and Porsgrunn - Skien will be, but work is being done on planning this section). Figure 9 on the next page shows an overview map of the total area called InterCity.

For the InterCity lines there have been developed a Technical Design Basis, to secure standardisation and suitable solutions for the railway lines in the InterCity area. The Technical Design Basis should specify preferred technological choices for the systems that form the railway where ever possible (Bane NOR, 2017c).

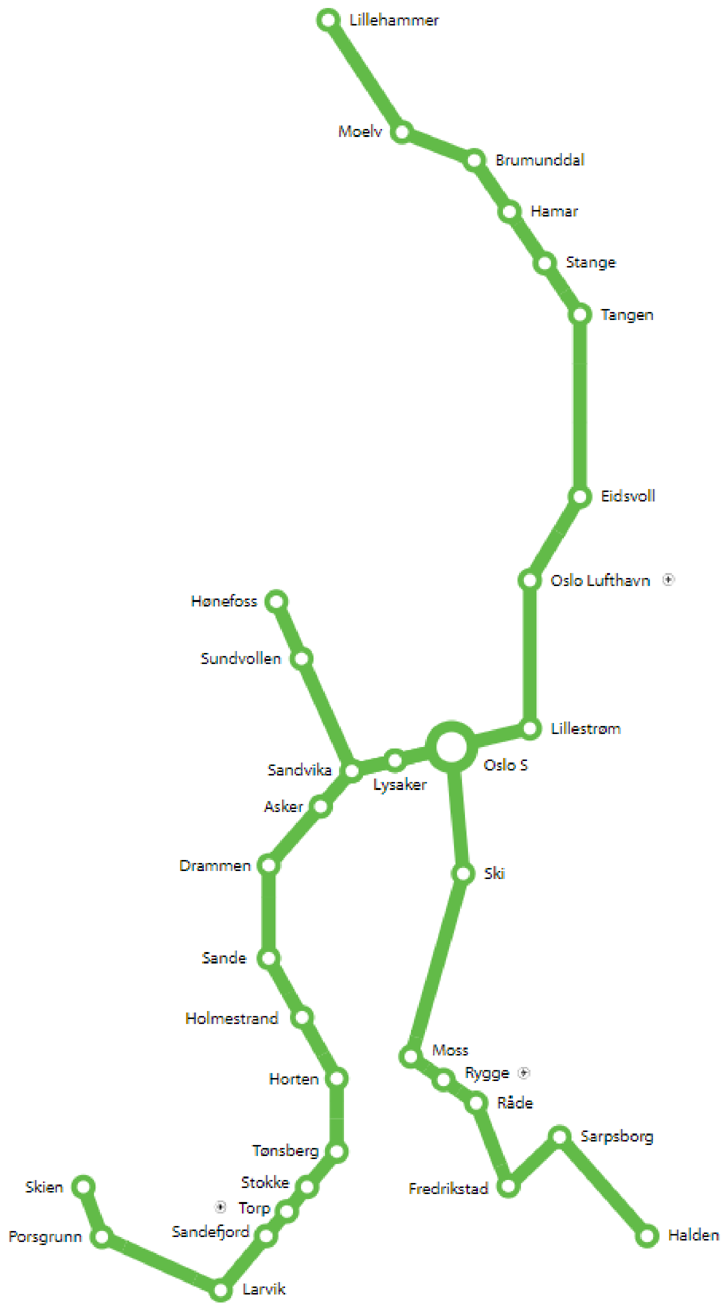


Figure 9 Map of InterCity (Bane NOR, 2019c)

The line (horizontal and vertical curvature) shall be designed for 250 km/h where this does not entail significant cost increases compared to a speed of 200 km/h (Bane NOR, 2017c). Norway is a country with varied topography with many mountains, valleys and fjords. 250 km/h gives normal requirements for horizontal radius from 3400 m and vertical radius from 24050 m. These stringent requirements mean that new railway sections that are planned are often on large proportion on bridges and in tunnels because of the terrain conditions of the various lines.

An example of this is the new double track section that has been built on the Vestfold Line, from Farriseidet to Porsgrunn. The route was opened September 2018 and is designed for a speed of 250 km/h (opening speed 200 km/h because of restrictions in signalling system). This line, which runs across several valleys, is 22.5 km long and is built with seven tunnels and ten bridges. The seven tunnels on the line make up total approximately

15 km. The ten bridges total approximately 1.5 km. That means it is approximately 6 km of track on earthworks on the line, of which much of this goes on high embankments. See Figure 10 which shows the length profile of the section Farriseidet - Porsgrunn. The dotted lines are tunnels, the orange are bridges and the white are earthworks. Farriseidet - Porsgrunn is built in its entirety with conventional ballasted track, with exception of 40 meters on the bridge to Norcem (side track) which is built with slab track.

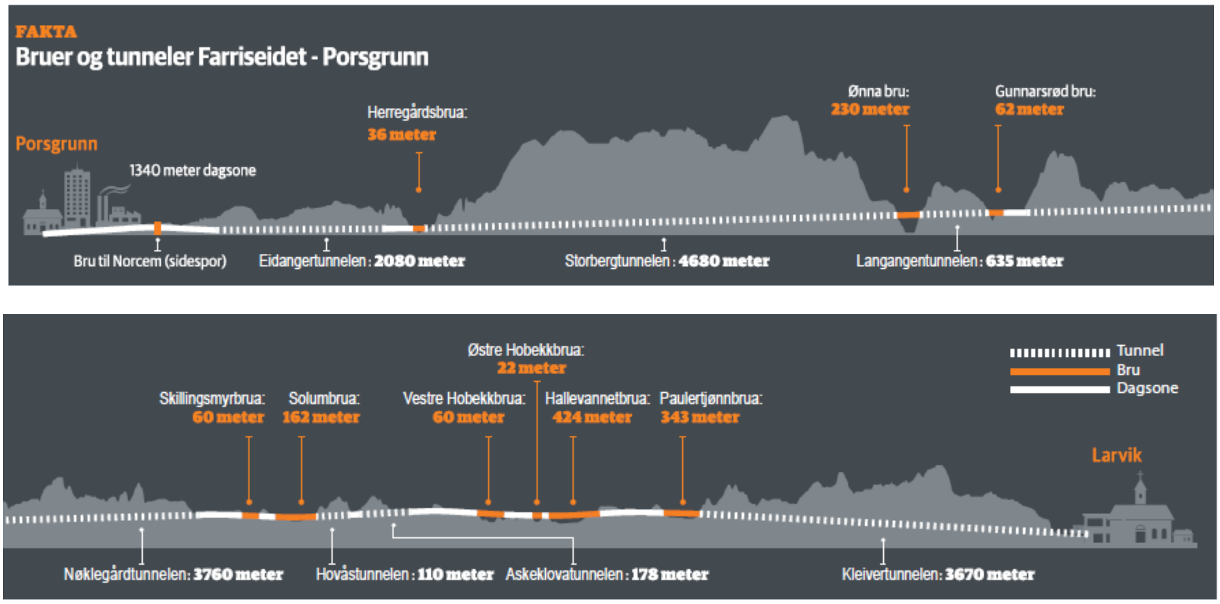


Figure 10 Length profile Farriseidet - Porsgrunn with tunnels, bridges and earthworks

For the upcoming project Ringeriksbanen, a 250 km/h double track line between Sandvika and Hønefoss, 40 km of double track is planned. On this line, there is a 23 km long railway tunnel from Jong (in Bærum) to Sundvollen (in Ringerike) and a 3 km long railway tunnel northwest of Sundvollen. There will be several long bridges on the line. The railway tunnel between Jong and Sundvollen is planned as a double-track railway tunnel with parallel escape and service tunnel. The driving method of the long tunnel was decided in July 2018, a traditional method with drilling and blasting has been chosen. Track construction for the tunnel is not yet selected (May 2019).

Another upcoming project is Tønsberg – Larvik with a 40 km long 250 km/h double track line. The corridor for this line has not been decided yet, but it is expected that the line will include multiple tunnels and bridges/viaducts (Bane NOR, 2019h).

There are several similarities for these projects under construction and upcoming projects. All projects have long tunnels, several have bridges close to the tunnels and the share of tunnel and bridge on the sections is high. As mentioned above, it is decided to build slab track in two of these tunnels, the Blix tunnel between Ski and Oslo, and the new Ulriken tunnel between Arna and Bergen. The choice here has fallen on slab track partly because of the fact tunnel boring machines (TBM) have been used to drive the tunnels. Slab track is well suited for TBM tunnels by saving profile size on account of lower construction height of slab track.

As this chapter shows, applying slab track in Norway first started on bridges. In the next few years, the first slab track is applied in tunnels.

3 System regulations

This chapter describes the development and current status for slab track regulations in Europe and Norway. Bane NOR's Technical regulations is described and the UPB-process, with LCC methods and RAMS are presented.

3.1 International regulations

Over 20 years ago, the European Commission (EC) initiated work to ensure the interoperability of the trans-European rail system. In 1996, The Trans-European Rail network was established (European Commission, 1996). In 2002 EC presented a proposal for a regulation establishing a European railway agency for interoperability and safety. This was adopted in 2004 and The European Union Agency for Railways (ERA) was created shortly afterwards.

EC is responsible for proposing legislation on behalf of the European Union (EU) and publish regulations[2] and directives[3]. The main current directive and regulation regarding railway infrastructure are

- Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union (Text with EEA relevance) (European Commission, 2016a)
- Regulation (EU) 2016/796 of the European Parliament and of the Council of 11 May 2016 on the European Union Agency for Railways and repealing Regulation (EC) No 881/2004 (Text with EEA relevance) (European Commission, 2016b)

Figure 11 shows top-down correlation between the different types of directives, specifications etc. The directive for interoperability of the rail system published by EC defines the subsystems, either structural or functional, forming part of the railway system of the EU. The Technical Specifications for Interoperability (TSIs) developed by ERA define the technical and operational standards which must be met by each subsystem or part of subsystem in order to meet the essential requirements and ensure the interoperability of the railway system of the EU (European Union Agency for Railways, 2019).

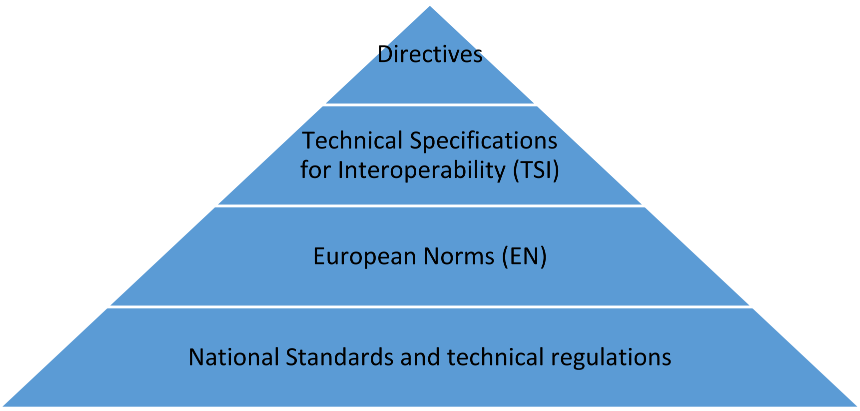


Figure 11 Hierarchy for technical regulations for interoperability for railway within the EU and EEA

[2] A "regulation" is a binding legislative act. It must be applied in its entirety across the EU (European Union, 2019).
[3] A "directive" is a legislative act that sets out a goal that all EU countries must achieve. However, it is up to the individual countries to devise their own laws on how to reach these goals (European Union, 2019).

ERA has compiled the TSIs for each subsystem. The TSI for Infrastructure (European Commission, 2014) covers:

- the infrastructure structural subsystem (line layout, track parameters, switches and crossings, platforms, track resistance to applied loads, structures resistance to traffic loads, immediate action limits on track geometry defects etc.)
- the part of the maintenance functional subsystem relating to the infrastructure subsystem (i.e. washing plants for external cleaning of trains, water restocking, refuelling, fixed installations for toilet discharge and electrical shore supplies).

For Norway, as the country is not part of the European Union, every new TSI or changes in TSIs are evaluated by the Norwegian Ministry of Transport and Communications and the TSI is added as an appendix to the EEA (European Economic Area) agreement.

There are no specific demands for slab track in the EU directives or the TSIs, slab track is required to meet the same demands for interoperability as is set for a conventional ballasted track.

European Standards are a key component of enabling interoperability in all industries, including railway. Each European Standard is identified by a unique reference code which contains the letters 'EN'. A European Standard is a standard that has been adopted by one of the three recognized European Standardization Organizations (ESOs): CEN, CENELEC or ETSI.

There are two main European Standards for slab track. They are developed by the Technical Committee CEN/TC 256 "Railway applications". They were approved by CEN on May 11th, 2017. They are listed below:

- EN 16432-1:2017 Railway applications - Ballastless track systems - Part 1: General requirements
- EN 16432-2:2017 Railway applications - Ballastless track systems - Part 2: System design, subsystems and components

EN 16432-1 defines the general requirements concerning the design of ballastless track systems. It does not include any requirements for inspecting, maintaining, repairing and replacing ballastless track systems during operation. This European Standard is applicable to all railway applications up to 250 kN axle load. The requirements of this standard apply to: - plain line track, switches and crossings and rail expansion joints; - various substructures like embankments and cuttings, tunnels, bridges or similar, with or without floating slabs; - transitions between different substructures; - transitions between different ballastless track systems; - transitions between ballasted and ballastless track systems. Requirements for characterization of the substructures listed above are included in this standard. Design of the substructures is covered by other European Standards, e.g. EN 1992–2[4], EN 1997–1[5], etc. (CEN, 2017a)

EN 16432-2 specifies system and subsystem design and component configuration for ballastless track system. The system and subsystem design requirements are assigned from the general requirements of EN 16432-1. Where applicable, existing subsystem or component requirements from other standards are to be referenced (CEN, 2017b).

Part 3 of the standard, EN 16432:3 Acceptance, is under preparation.

[4] EN 1992-2 Eurocode 2: Design of concrete structures - Concrete bridges - Design and detailing rules
[5] EN 1997-1 Eurocode 7: Geotechnical design - Part 1: General rules

The English language version of European standards EN 16432-1 and EN 16432-2 has been adopted as Norwegian standards NS-EN 16432-1 and NS EN-16432-2 in October 2017.

The content and relationship between part 1, 2 and 3 are shown in Figure 12.

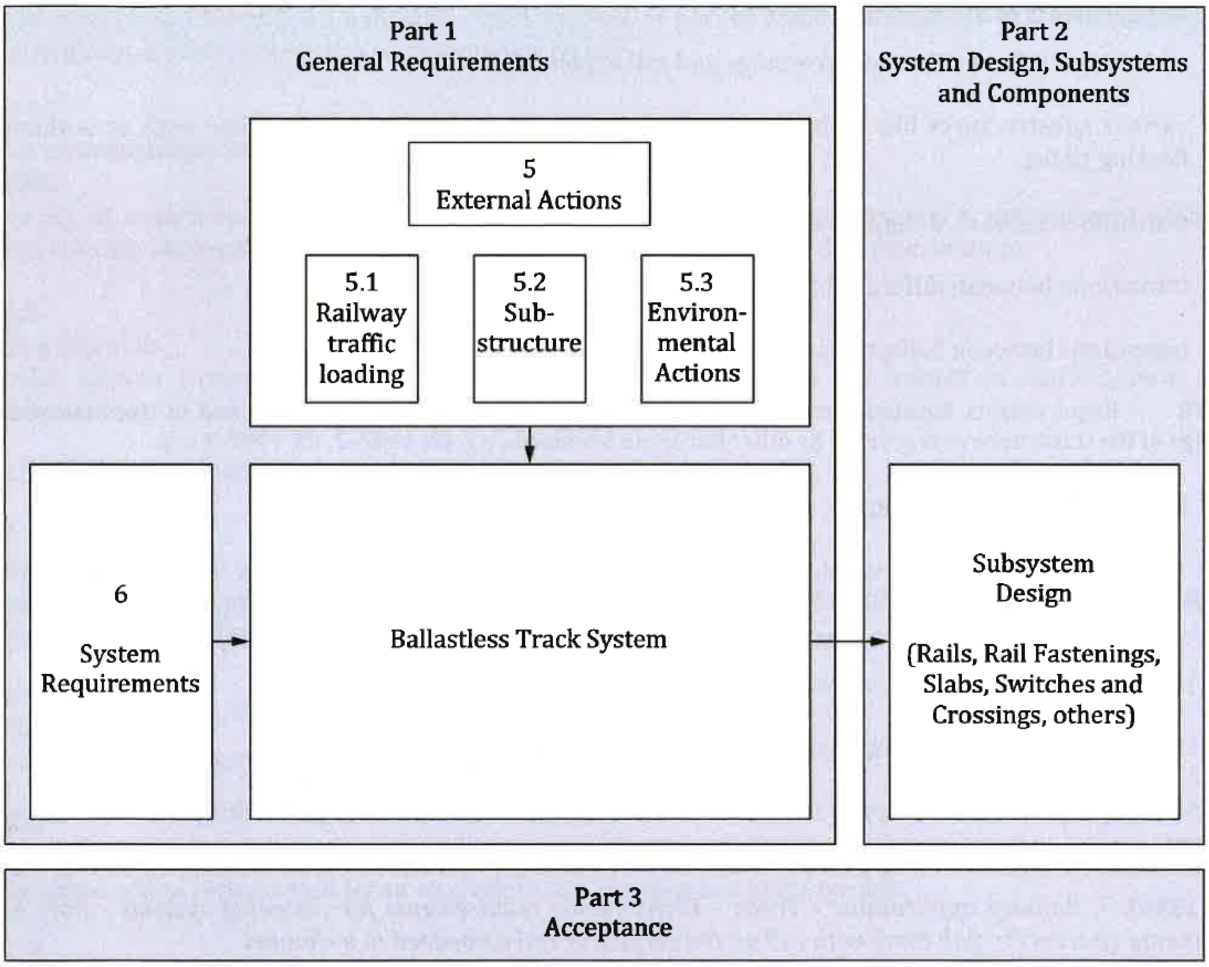


Figure 12 Structure of EN 16432-1, EN16432-2 and EN 16432-3 (CEN, 2017a).

Both Germany, Switzerland and Austria (and other European countries with slab track, including Norway) has implemented these rules from EN 16432-1 and EN 16432-2, in their different technical regulations in the countries.

This thesis will not explore the regulations for each country further in this chapter, as the requirements and best practises will be described in chapters 4 Slab track benchmarking and 5 European best practises.

3.2 Bane NOR’s Technical Regulations

In Norway, Bane NOR’s Technical Regulations are an important management tool and an important aid in the design, construction and dimensioning of railway installations. Bane NOR’s Technical Regulations meet requirements for interoperability given in the Norwegian regulations on interoperability on the railway system (Ministry of Transport and Communications, 2010) and technical requirements for the infrastructure provided in regulations for railway infrastructure (Ministry of Transport and Communications, 2011). Bane NOR’s Technical Regulations also comply with applicable TSI requirements from regulations that have been implemented in Norwegian legislation. Bane NOR’s Technical Regulations are published 2 times a year, normally in January and July. The latest version was published February 5th 2019 (Bane NOR, 2019e).

Regulations for slab track can be found under the discipline Superstructure – chapter 530 Design – under 6 Track constructions – subchapter 6 Ballastless track (Bane NOR, 2019f). As mentioned in chapter 1.1 Background for choice of topic, these regulations set the limitations for application of slab track. Currently (May 2019) it is only permitted to build slab track in tunnels and on bridges.

It is not permitted to build slab track on earthworks in Norway (Bane NOR, 2019f), as shown in Figure 13, section 6.1 from Bane NOR’s Technical Regulations.

6.1 Application of ballastless track

a) Ballastless track constructions may be applied in tunnels and on bridges.

b) Ballastless track constructions may not be applied on earthworks.

c) Geological surveys shall be carried out to assess the suitability of the ballastless track. Ballastless track should not be applied in places with unstable formations that may cause deformation.

d) Ballastless track can only be used in conjunction with switches if the switches are in the tunnel with ballastless track construction.

e) In case of tunnelling with traditional methods, additional work must be carried out for the preparation of smooth sole at the bottom. In the lower layer of the tunnel sole under the constructive layer, bonded material must be used.

Figure 13 From Bane NOR's technical regulations, about ballastless track, translated from Norwegian (Bane NOR, 2019f).

Design loads and construction requirements are given in Bane NOR’s Technical Specifications for ballastless track. This specification sets out objective requirements to enable suppliers to deliver ballastless track construction systems that meet the expectations of Bane NOR. This specification applies to delivery of a complete track system comprising bearing elements, elastic elements and rail fastenings. This specification is applicable for railway applications up to 250 kN axle load and a nominal track gauge of 1435 mm (Bane NOR, 2019g).

These are the rules for slab track in Norway as of today. There is a process going on in Bane NOR to revise Technical Regulations for slab track. Bane NOR’s Technical Department is working on updating and changing the rules in spring of 2019. The sanctioned changes will be adapted from August 2019.

The goal of this process is to move all demands for slab track from Technical Specifications to Technical Regulations. In addition, the Technical Regulations will to a greater extent refer to the standards EN 16432-1 and EN-16432-2 (Teigen, 2019).

Another important change which is being evaluated is the possibility of permitting to build slab track on shorter distances on earthworks between solid substructures, such as tunnels and/or bridges. There is a suggestion of adding an exception from the rule:

Ballastless track may not be applied on earthworks.

- Exception: When applying ballastless track through multiple tunnels and/or bridges, ballastless track is permitted on the intermediate embankments with length up to 1000 metres.

As of May 2019, it is not yet decided what is the outcome of this suggestion.

Another topic which is not yet clarified, are the exact demands to set for the substructure. More about substructure and other demands for slab track already built on earthworks in Europe and Asia are described in chapter 4 Slab track benchmarking.

3.3 UPB-process

Bane NOR has developed a process called the UPB-process. UPB is Norwegian, and the letters stands for Inquiry (Utredning in Norwegian), Planning and Building. According to Bane NOR's STY-604571 Project Execution – Corporate Standard, projects with an estimated cost over 750 million NOK are obliged to follow the UPB-process. For projects with estimated cost between 50 and 750 million NOK, the UPB-process should be followed, with necessary adjustments according to the project scope and complexity. The most recently finished large railway infrastructure projects in Norway had total costs of respectively 5,3 billion NOK (Langset – Kleverud opened 2016), 5,5 billion NOK (Holm – Nykirke opened 2016) and 7,2 billion NOK (Farriseidet – Porsgrunn opened 2018) (Bane NOR, 2019c). All these projects were built with conventional ballasted track as superstructure, but it would make no difference on the demands for following the UPB-process if they were built with slab track. This means that almost all railway infrastructure projects of a certain size need to follow the UPB-process.

The UPB-process is shown below in Figure 14.

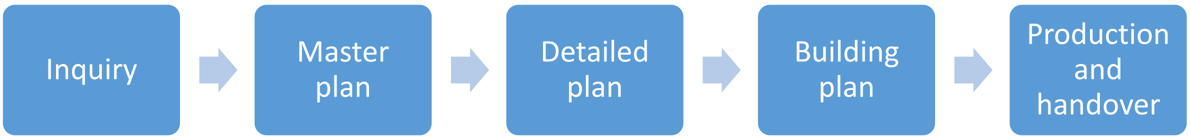


Figure 14 Stages of the UPB-process

The UPB-process is divided into five phases (Bane NOR, 2019d). They are:

1. <u>Inquiry</u>
   This phase is under evaluation in Bane NOR, and as of May 2019 it is not yet clarified with the Corporate management if "Inquiry" should be part of this model and within Bane NOR. Most large inquiries are performed by The Norwegian Railway Directorate (established January 2017).
   In this phase it is obligatory to follow the Regulation for Inquiry of Government Measures (Ministry of Finance, 2016). There are six minimum demands that are required to be answered in all inquiries:

- What is the problem, and what do we want to achieve?
- Which measures are relevant?
- What principal issues do the measures raise?
- What are the positive and negative effects of the measures, how lasting are they and who are afflicted?
- Which measure is recommended, and why?
- What are the prerequisites for successful completion?

From this stage it is possible to select a single concept, and there is a cost estimate of +/- 40% relative to standard deviation in the level of uncertainty.

2. Master plan
   To establish this phase Bane NOR receives and enters into a K03-agreement[6] from The Norwegian Railway Directorate. The purpose of the master plan is to establish the projects and select the preferred railway line. The technical plan must have technical detailing to meet a cost estimate of +/- 20%, and secure that the predefined functionality is met. The public plan needs to secure area for railway.

3. Detailed plan
   The purpose of this phase is to detail the selected solution, based on evaluation of:
- continued feasibility
- technical detailing to meet a cost estimate of +/- 10%
- establish minimum basis to gather zoning plan and secure investment decision

4. Building plan
   The purpose of this phase is:
- Design that is necessary to be able to produce documentation for building (answer the demand specification from the detailed plan)
- Quality follow-up of the supplier
- By execution contract: create the contract basis to be able to contract the entrepreneur

5. Production and handover
   The purpose of this phase is to secure compliance with technical and contractual requirements and secure and follow up implementation of time, cost, quality and SHA. The main delivery of this phase is completed new railway infrastructure, handed over to the Infrastructure division.

In the first phase costs are calculated for the different concepts. These cost analyses are repeated through the following phases. To differentiate between concepts, it is important to follow a method for analysis. A way of analysing costs for railway projects is to calculate the total life cycle costs (LCC). More about LCC and a breakdown of LCC-categories follows in subchapter 3.3.1 LCC method.

Another topic which is repeated throughout the phases is a high focus on RAMS. When planning and building new railway infrastructure in Norway, according to the Railway Infrastructure Regulations (Ministry of Transport and Communications, 2011), the Process Standard EN 50126 (RAMS standard) (CENELEC, 2017) must be followed. RAMS is short for Reliability, Availability, Maintainability and Safety, and the purpose is to ensure that the facilities being built become reliable, accessible, maintainable and secure. More about RAMS follows in subchapter 3.3.2 RAMS.

In addition to following the RAMS process, it is required to perform various socio-economic analyses in the different phases of the UPB-process (Bane NOR, 2018a). The analyses should be done as a forecast of the project's lifetime. In such an analysis, one will use input data from RAMS analyses and lifetime cost analyses (LCCA) to be able to assess between alternative technical solutions or alternative routes for a railway line.

[6] K03-agreement: Agreement between the Norwegian Railway Directorate and Bane NOR about planning and design of a railway project.

3.3.1 LCC method

Life cycle costs (LCC) are all costs for a system or construction from purchase and installation to use and maintenance through the entire lifecycle (Hokstad, 1998).

According to Guideline for LCC and RAMS Analysis a life cycle cost analysis (LCCA) found the basis of making strategic decisions, choose between different types, to pick suitable solutions for products and processes or to optimize existing systems. Life cycle cost analysis is a methods to calculate the total costs for a system or product over the entire life time (INNOTRACK, 2006). LCCA is therefore an instrument of cost control for a project related to different project alternatives or for producing a facility with the lowest overall cost according to its quality and function (Ren, Lechner, & Liu, 2008).

Both Hokstad and Innotrack use the same definitions for the LCC-phases, deriving from IEC (International Electrotechnical Commission):

- Concept and definition
- Design and development
- Manufacturing
- Installation
- Operation and maintenance
- Disposal

A life cycle analysis (LCA) for an entire railway line will also include costs for environmental effects caused by the railway to the society nearby. It is generally complicated to estimate environmental effects in money and they are often left out of LCA when analysing choice of track systems etc. It is necessary to point out that slab track with a concrete slab demands more resources in the form of processing of material and emissions in production than a ballasted track but setting the value of this impact is quite extensive work.

The total life cycle costs can be described as:

$LCC = Cost_{Investment} + Cost_{Maintenance} + Cost_{Delay} + Cost_{Hazard}$

Figure 15 shows a breakdown of LCC categories.

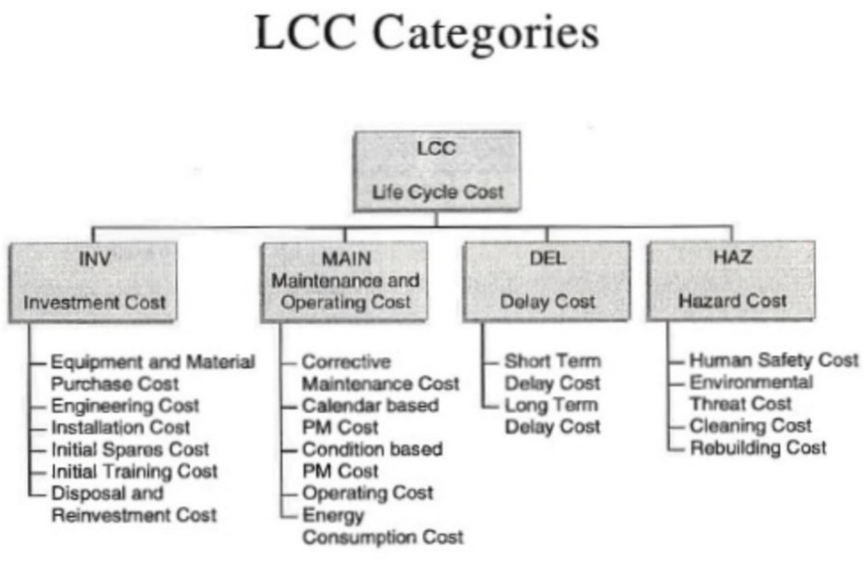


Figure 15 LCC categories (Hokstad, 1998)

Life cycle costs for a railway construction consists of all costs related to investment, operation and maintenance, delays and hazards throughout the life of the construction, as well as costs related to dismantling and disposal at the end of life.

The following formula can be used to calculate life cycle costs, shown in Figure 16:

LCC = Investment cost
+ Present Net Value (Maintenance and operating cost + Delay cost + Hazard cost)
- Present Net Value (residual value Investment cost + residual value Maintenance and operating cost)

$$LCC = IC_0 + \sum_{i=1}^{N} [(MC_i + DC_i + HC_i)*(1+d)^{-i}] - ((RV_{IC} + RV_{MC})*(1+d)^{-N})$$

D = discount rate
N = length of analysis period (years)

Figure 16 Formula for calculating LCC, translated from Norwegian (Hoff, 2016)

The input values are investment costs + present net value of (maintenance and operating costs + delay costs + hazard costs) − present net value of (residual value investment costs + residual value maintenance and operating costs).

Seeing as the value of money today is different from the value of money tomorrow, it is normal to use the present net value principle to calculate all costs and revenues that come at different times during the lifetime of a railway line. Figure 17 shows the formula for calculating net present value.

$$NPV = \sum_{all} B_i * (1+p)^{-T_i}$$

NPV = Net present value
B = amount (cost or revenue)
p = interest rate
T = Time from net present value time (years)
i = year number
$(1+p)^{-Ti}$ = discount rate

Figure 17 Formula for net present value (Hoff, 2016)

By using this formula, one can calculate all future costs and revenues on a planned railway line to the present net value. This gives a good basis for comparing costs between different options.

In calculating present net value, there is a discount rate. "The discount rate represents the socio-economic alternative cost by binding capital in a given measure. The discount rate reflects the return on capital in the best alternative application and thus sets requirements for the return on the measures that are analysed. A low discount sets a low requirement and gives more profitable projects" (Norwegian Railway Directorate, 2018). The discount rate is set by the Ministry of Finance, and cannot be changed in the individual project and for the first 40 years this is normally set to 4%, from 40-75 years to 3% and after 75 years to 2% (Norwegian Railway Directorate, 2018). These figures are adjusted for risk, which is applied to the real risk-free interest rate.

The Norwegian Railway Directorate has developed a guidebook for socio-economic analyses for railway (Norwegian Railway Directorate, 2018). This manual also describes technical lifetime for different systems of railway infrastructure. For substructures, a lifetime of 100 years and for superstructure 40 years is stated. As mentioned in 3.2 Bane NOR's Technical Regulations; slab track in Norway must have a lifetime of at least 50 years. Usually, an analysis period of 40 years is used for transport projects (Norwegian Railway Directorate, 2018), but since slab track has a longer expected lifetime than this, it will be natural to set a longer analysis period to calculate the lifetime costs for slab track.

3.3.2 RAMS

As mentioned in chapter 3.3 UPB-process, when planning and building new railway infrastructure in Norway, one must follow the process standard EN 50126 (RAMS standard) (CENELEC, 2017).

To fulfil requirements of the standard EN 50126, Bane NOR has developed a RAMS manual that must be followed to document that the technical solutions chosen are the most optimal for the entire lifetime of the construction. Bane NOR's work on RAMS is based on an overarching principle of distributing relevant RAMS activities over the lifecycle phases in the investigation, planning and construction phase and the operation and maintenance process.

This process standard should be followed in all phases of a project, from early evaluation, through planning, construction, operation and maintenance and until disposal of the construction, see illustration in Figure 18. The activities in RAMS-phase 1-10 and 13 will be carried out in investment projects where new railway infrastructure is being built and in the case of significant changes in the railway infrastructure. The activities in RAMS-phases 11 and 12 relate to the operation and maintenance of the railway infrastructure and the activities in RAMS-phase 14 come into use when rail infrastructure is to be disposed of.

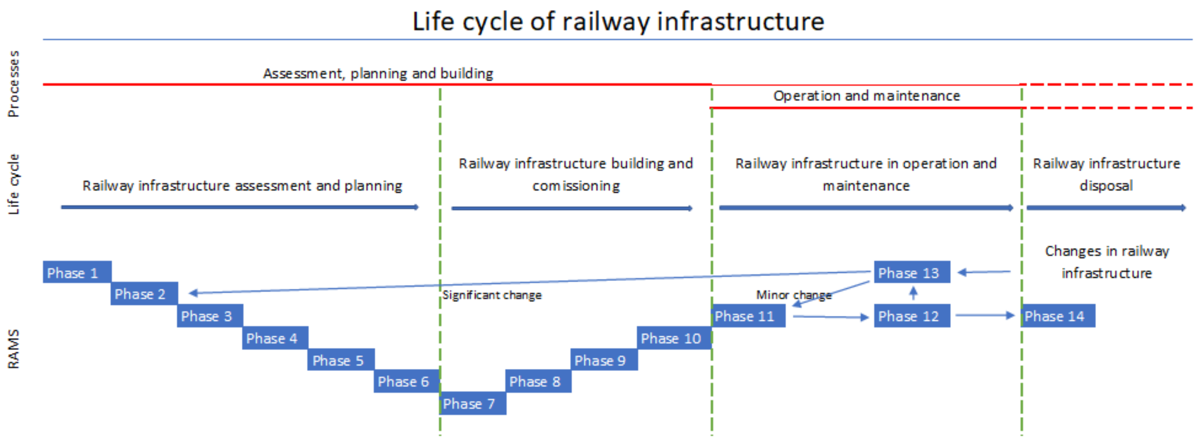


Figure 18 Lice cycle of railway infrastructure, translated from Norwegian (Bane NOR, 2017a)

The different phases are described in detail on the next page in Figure 19. EN 50126 often illustrates these phases through a V-model which indicates a Top-Down and Bottom-Up distribution of the phases, where phase 1-6 constitutes the development phases of planning a railway system, while phase 7-10 constitutes the actual production and approval for commissioning. Phase 11-13 focuses on the actual operation and maintenance period, while phase 14 constitutes the dismantling and disposal of the system after the lifetime has expired (Bane NOR, 2017b).

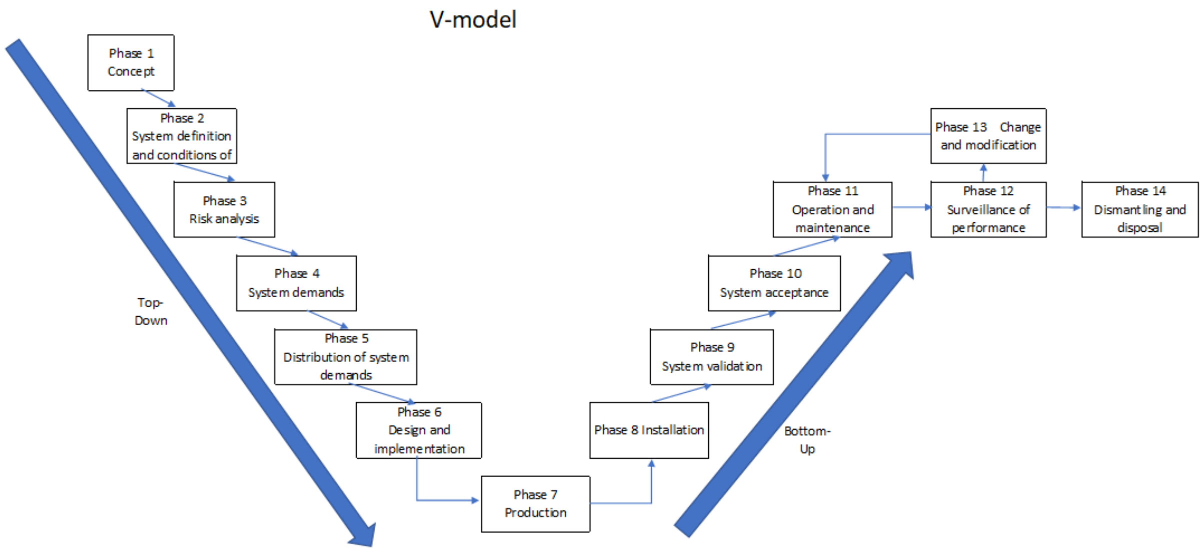


Figure 19 V-model showing a Top-Down and Bottom-Up distribution af the 14 phases in the RAMS lifecycle, translated from Norwegian(Bane NOR, 2017b)

Important outputs of the RAMS process from phase 7-10 to phase 11 are:

- Plan for operation and maintenance
- Operation and maintenance instructions
- Documented training for operation and maintenance

The project is required to prepare a Plan for operation and maintenance for the railway line that is built, provide instructions for operation and maintenance and conduct training of the personnel which are going to perform operation and maintenance on the newly built track.

This is especially important when building new systems that have never been in operation in Norway before. It is often necessary to perform FMEA[7] or FMECA[8]-analyses to establish controls routines and maintenance tasks for the new system. These routines will have to be described and planned before commissioning of the new track.

Although building slab track on earthworks should possibly be permitted in the future in Norway, it is still obligatory to follow the RAMS process in order to be able to make all the necessary assessments of the chosen system, since this process applies regardless of all cases when planning and building new railway infrastructure.

[7] FMEA - Failure mode and effects analysis
[8] FMECA - Failure mode, effects, and criticality analysis

4 Slab track benchmarking

This chapter gives an account of the most important benchmarking factors for slab track on earthworks, with focus on topics that are relevant to Norwegian conditions. The topics in question are rigidity, substructure, poor soil conditions, settlements, drainage, frost, transition zone, noise and vibrations, installation, operation and maintenance and LCC.

4.1 General requirements

Quite a few studies on slab track has been conducted over the years resulting in project reports, two of them are *Feasibility Study "ballastless track"* by UIC Infrastructure Commission Civil Engineering Support Group (Fumey et al., 2002) and Capacity for Rail; *Design requirements and improved guidelines for design* (CEMOSA et al., 2014). These reports both highlight these important topics for slab track; track geometry, rigidity, slab track on earthworks, substructure, drainage, noise and vibrations, transition zones, installation and LCC. This chapter will also focus on these topics.

EN 16432-1 (CEN, 2017a) specifies general requirements for the slab track system.

Superstructure: The track shall provide accurate and durable geometry. The track shall be designed to provide resistance to buckling as a result of longitudinal forces in the track structure particularly due to thermal actions. Design for the surface profile shall comply with EN 15273-3[9]. The TSI for Infrastructure states that for high speed railway, maximum superelevation is set to 180 mm (European Commission, 2014).

Vertical loads: If no specific information is available regarding the vertical loading then load model 71 shall be applied as static vertical load, it represents all type of vehicles and European standard railway traffic up to 250 kN axle load.

EN 16432-1 specifies general requirements for the slab track system according to the substructure characteristics. They are:

- Earthworks
- Bridge structures
- Tunnels
- Transition zones between different substructures

For this thesis the main interest is on earthworks and transition zones.

Earthworks: The earthwork formation which supports the ballastless track shall be able to transfer the vertical and horizontal loads from the ballastless track system into the subsoil, without failure of the ground support or excessive deformation. The design of the ballastless track shall be compatible with the characteristics and performance of an earthwork as specified in EN 1997-1, Eurocode 7: Geotechnical design – Part 1: General rules.

Transition zones: Transitions between earthworks, bridges and tunnels shall ensure a gradual transition with respect to track geometry and track stiffness.

Lifetime: Slab track systems should have a design life of at least 50 years unless otherwise specified.

[9] EN 15273-3, Railway applications – Gauges – Part 3: Structure gauges

4.2 Rigidity

There are, as previously described, several different types of slab track and they have different properties. The different slab track systems have different flexural stiffness, from low to high. Slab track systems with low flexural stiffness depend on the load characteristics and stiffness of the substructure. The superstructure must not be subjected to bending forces. In cases where there is poor and unstable substructure, a flexural stiff, reinforced track construction will have extra strength and act as a bridge over weaker areas and local settlements in the substructure (Esveld, 2001). Table B below lists different types of fixed and their possible flexural stiffness.

SLAB TRACK SYSTEM	Flexural stiffness	
	Low	High
Sleepers or blocks embedded in concrete	<---------------->	
Sleepers on top of asphalt-concrete roadbed	<---->	
Prefabricated concrete slabs	<--------->	
Monolithic in-situ slabs	<----------------->	
Embedded rail	<---------------------->	
Clamped and continuously supported rail	<----------------->	

Table B Slab track systems with possible flexural stiffness (Esveld, 2001)

In slab track the ballast is replaced by concrete (or asphalt) as load distributing material. Concrete is less elastic than ballast. To achieve the desired elasticity of the track, elastic rail pads between rail and sleeper and/or elastic under sleeper pads beneath the sleepers are used.

Normal thickness of concrete slab is 200 mm. To achieve sufficient flexural stiffness, (Lichtberger, 2011) recommends a minimum thickness of 180 mm for the concrete slab.

For concrete slab track the concrete quality is recommended to be C30/37 (previously B35). The required accuracy on top of the layer is ± 2 mm. The recommended proportion of reinforcement of the cross section of concrete is 0.8 – 0.9 %. This is to ensure the cracks on the surface remains below 0.5 mm (Lichtberger, 2011).

4.3 Substructure

Almost all slab track structures used today are based on the principle of a relatively flexible continuous or divided concrete slab which rests on a rigid substructure. Many high-speed railway lines have been built in several countries (Germany, the Netherlands, Japan, China etc.) through flat areas in river valleys where there are poor soil conditions with weak ground. Here, extensive and costly improvements to the ground have been necessary to satisfy the requirements for necessary rigidity and carrying capacity (Steenbergen, Metrikine, & Esveld, 2007).

The requirements for the substructure are demanding because of the design principle described above. The ability to adjust the track geometry after construction is limited. According to the possibilities offered by adjustable fastening systems, only simple corrections up to 26mm in vertical position and 5mm in horizontal position are possible to counteract small deformations (CEMOSA et al., 2014). Settlements must be avoided. The requirement is a substructure that is practically free from deformation and settlements.

The substructure under the track must be secured at least 2.5 meters below the formation level (Frühauf, Stoiberer, Scholz, & Schmitt, 2006). It may be challenging to find suitable stabilizing means or methods to secure substructure to satisfy these requirements. This also leads to higher building cost for substructure than for ballasted tracks. The quality of the existing ground is crucial for building costs.

Slab track is built up of layers. Figure 20 shows the system from top to bottom consisting of the slab track itself, hydraulically bound support layer, frost protection layer, reinforced substructure and the subsoil (Frühauf et al., 2006).

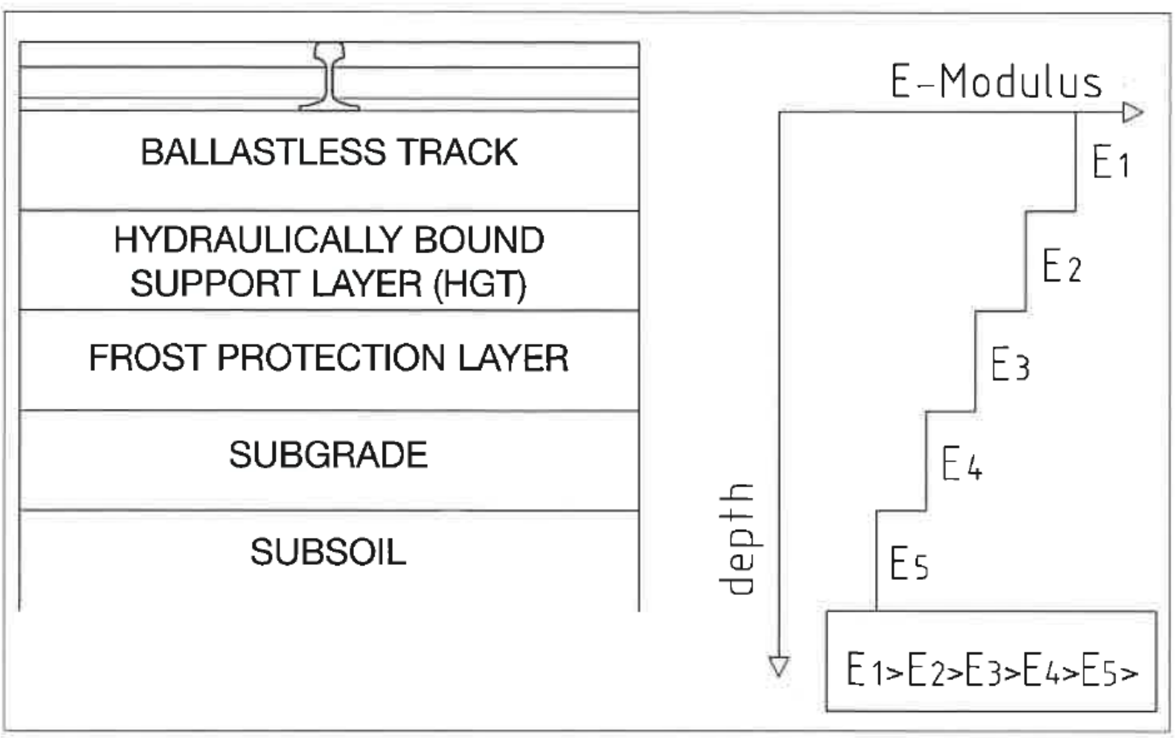


Figure 20 Layered construction and stiffness for slab track (Frühauf et al., 2006)

This layered construction implies that the required rigidity increases upwards for each layer closer to the rails. Here, greater forces are handled over smaller areas than further down, and higher resistance to elastic deformation is needed higher up.

In Germany, a settlement-free foundation is assumed. In order to achieve this several demands are set for substructure and the layers under the track. The railway operator Deutsche Bahn AG (DB AG) and its subsidiary infrastructure manager DB Netz AG have drafted special rules and guidelines for slab track:

- Catalogue with basic demands for the construction of a ballastless track
- Guideline 804: Planning, construction and maintenance of bridges (and other technical constructions)
- Guideline 836: Planning, construction and maintenance of substructure and earthworks

The hydraulically bound support layer is a mix of mineral aggregate of graded particle size (maximum particle size 32 mm) compacted by a hydraulic bonding agent. The typical thickness of this layer is 300 mm (Lichtberger, 2011). The required accuracy on top of the layer is ± 10 mm.

The requirement for the support layer/frost protection layer which has a thickness of approximately 30 cm is that it should have a considerable stiffness, an elastic modulus of minimum 120 MN/m^2. The substructure should have an elastic modulus of at least 60 MN/m^2 (Steenbergen et al., 2007). To achieve these values, thorough preparation is performed, by means of dynamic compression and, if necessary, by improving the ground on the site, for example, with lime cement stabilization or by replacing masses.

This is especially important where there is embankment or cutting, and in transition areas between bridges and earthwork constructions, as there is a discontinuity in the stiffness for substructure. Prior to processing the substructure, detailed geotechnical investigations are planned and performed. These investigations will give an accurate description of the type and condition of existing ground conditions and a description of groundwater table (Frühauf et al., 2006). It is required that groundwater level should be more than 1.5 meters below the rail top level (Svensøy, 2018).

According to guideline 836, the ground should be examined at least 5 meters below planned embankment, especially for planned high-speed railway, depending on the homogeneity of the soil. The distance between boring points should be less than 50 meters, on each side of the track (Frühauf et al., 2006).

As explained above, Germany has a concept where no settlement must not occur. In China, where high-speed railway have developed rapidly, uneven settlement has been inevitable at the subgrade-bridge transitional sections and high embankment. (Liu et al., 2011) suggested that in order to ensure the proper operation of slab track, the influence of uneven settlement of foundation should be considered in the design of slab track in China.

The behaviour of the substructure is significantly controlled by environmental conditions which are associated to thermo-hydro-mechanical processes occurring between the atmosphere and railway track bed layers. According to local hydro-geological and climatic characteristics, the design of the substructure must account for instability problems due to rainfall events and snow melting processes with particular focus on extreme scenarios where the duration, intensity and frequency of these phenomena must be adequately considered (CEMOSA et al., 2014).

Based on what is described above, slab track is a conservative construction which, due to stringent quality requirements of substructure, is more expensive to build than traditional ballasted track.

4.4 Poor soil conditions

In chapter 4.3 Substructure, a traditional structure of track is described, with a rigid substructure and relatively flexible track construction. Requirements for stiffness in the support layer/frost protection layer are given to 120 MN/m^2.

In addition to improving the substructure, it is also possible to increase the flexural stiffness of the slab track superstructure, in order to make it less sensitive to differential settlements. Increasing the bending stiffness increases the elastic stiffness of the slab and it must be ensured that the reinforcements made in the concrete slab can withstand creep forces and dynamic deflection forces due to traffic loads. An important factor here is the reinforced concrete slabs' resistance to fatigue, vertical deflection of the slab, and the level of soil stress (Esveld, 2001). Figure 21 shows an example of a modified slab track design for soft soil.

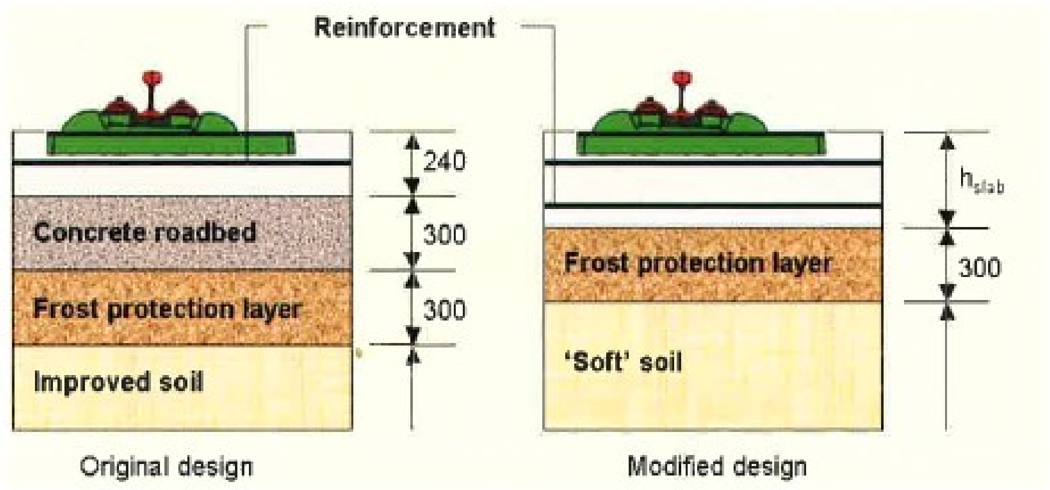


Figure 21 Example of original and modified slab track design

Track slab with higher bending stiffness is capable of withstanding bending moments and spreading traffic loads over a longer track length, thereby reducing the stress on the substructure. The track plate is thus able to act as a bridge over weak zones and local subsidence without changing the track geometry. This can present an economical way to meet the rigidity requirements for high-speed railway (Esveld, 2001).

As mentioned in chapter 4.2 Rigidity, there is different flexural stiffness for the various slab track systems. An example of a system that has very high bending stiffness is "Deck track". This system was specifically designed to be used on soft soil and consists of a continuous concrete structure that is built into the ground. On the concrete slab, the rails can be fastened with embedded rails or with direct mounting. The concrete structure is designed as a hollow concrete beam that weighs about the same as the masses that have been removed. Thus, there will be no settlements due to the weight of the construction. The high flexural rigidity of the construction allows one to avoid differential settlements and reduce vibration. There is also high torsional stiffness due to the hollow construction.

Deck track acts as a bridge over weak zones, and as a result of the stiffness/mass ratio it will generate less vibration into the ground (Esveld, 2001). In 1999, 200 meters of test track was built in Rotterdam, and preliminary experiences were then good and the constructability of the track had been demonstrated (Tayabji & Bilow, 2001). The track is used by heavy freight trains every day.

4.5 Settlements

As explained in chapter 4.3 Substructure, the slab track system has limited possibilities for adjustment in case of settlements. It is therefore imperative that the settlement of embankments newly constructed is nearly finished at the time of the construction of the track (CEMOSA et al., 2014). In Germany, the permitted settlements after commissioning of the track is limited to 15 mm (Frühauf et al., 2006).

Settlements, or deformations, in substructures can be elastic (reversible) and plastic (irreversible) (Frühauf et al., 2006). Elastic settlements are most often caused by traffic loads. These settlements disappear as soon as the load is removed. Elastic deformation is primarily a strain on the superstructure due to the design and joining of rails, sleepers and ballast. It is important that all layers in the substructure are thoroughly dimensioned and designed to absorb traffic loads and thus protect the superstructure against elastic settlements (Frühauf et al., 2006).

Plastic or irreversible deformations are defined as swellings and settlements. The swelling comes from the fact that the soil expands. This applies, for example by frost heaving as presented in chapter 4.7 Frost, or in places with deep cuttings in soil that have great expansion capacity, and high swellings will occur. Irreversible settlements can occur where the soil is loaded with weight over time, in which the soil is continuously compressed. This can give permanent settlements. If these long-term settlements become too large, they will adversely affect the superstructure (Frühauf et al., 2006).

EN 16432-1 specifies that for a slab track system it is necessary to limit permanent deformations (settlement or heave) as well as elastic deformations due to variable loading.

One must therefore try to prepare the substructure in such a way that one reduces settlements to a minimum. There are different types of settlements; settlements of the subsoil, settlements of the embankment, settlements due to traffic loads and swelling. The majority of these settlements come from; settlements in the substructure and embankment, settlements due to traffic loads are almost negligible compared to the other two (Frühauf et al., 2006).

The quality of an earth work is highly dependent on the compaction process defining the initial conditions after construction. When subjected to traffic loading and environmental actions, the deformational behaviour of substructure soils depends on its previously loading history, particularly on the maximum preconsolidation stress ever applied to the soil. An adequate compaction process must ensure that the compaction stress is higher than the expected maximum stress that will ever be applied to the soil (CEMOSA et al., 2014).

There is a general agreement among experts on this topic that it will be impossible to prevent settlements of substructure for slab track altogether, but they can be reduced to a minimum by means of thorough research and pre-construction calculations.

4.6 Drainage

Ensuring adequate drainage of slab track is critical. In Norway, it is decided to use 200-year flood as dimension criteria for calculating drainage (Bane NOR, 2019e). In ballasted tracks, the use of separated sleepers, unbound bearing layers (ballast and sub-ballast) and transversal slope ensures that water leaves out the track and goes to parallel culverts.

EN 16432-1 state that slab track systems shall have a drainage system with enough capacity, strength and stability to resist ground water pressure, which permits rapid removal of surplus water and which is easy to maintain. This system shall be compatible with the drainage system for ballasted track (important for transition between slab track and ballasted track).

Because of this, in case of slab track, the evacuation of water between the sleepers and between parallel lines may require additional drainage channels (CEMOSA et al., 2014).

Figure 22 shows a comparison between typical cross section on ballasted track and slab track (Rheda) design. It can be observed that water between parallel slabs require an additional central drainage tube. There are different solutions for drainage for the different slab track systems, this is further described in chapter 5 European best practises.

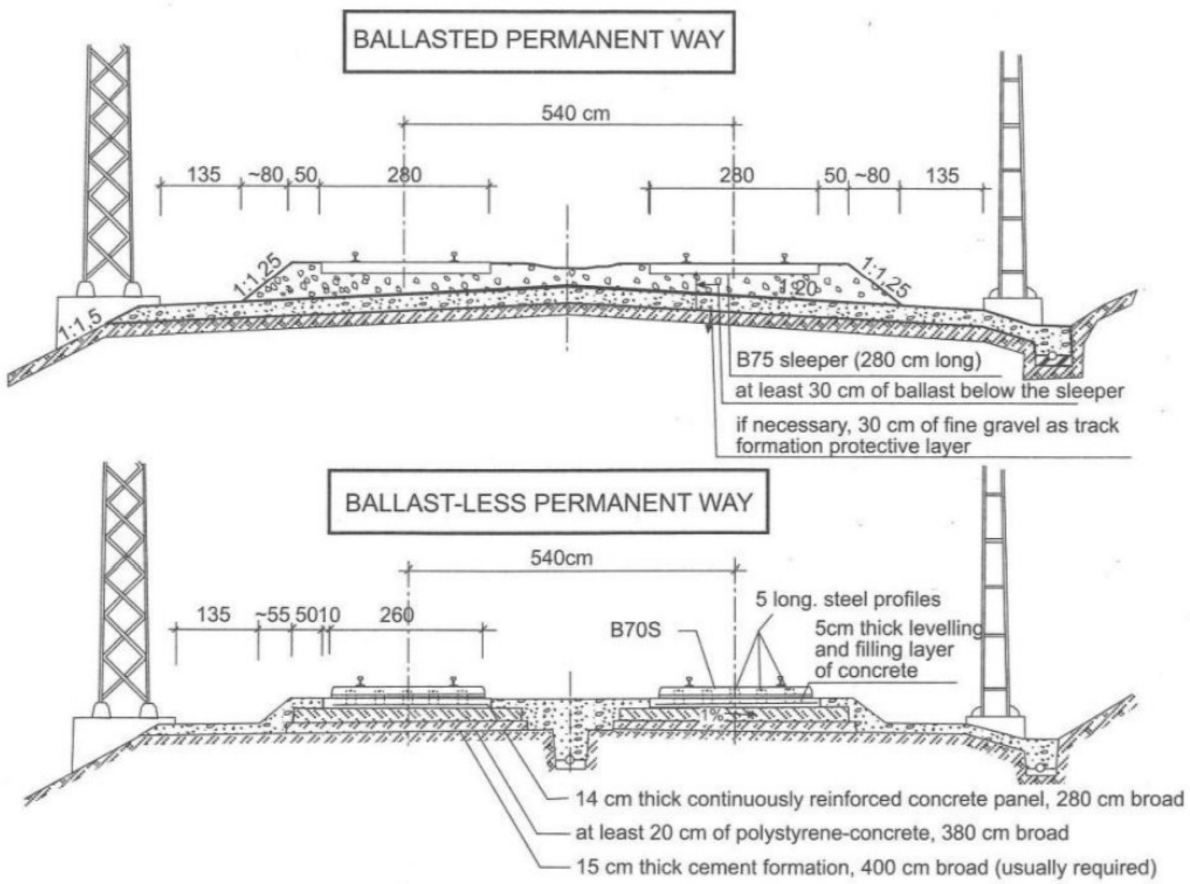


Figure 22 Comparison between standard cross section of ballasted track and slab track design (Lichtberger, 2011)

4.7 Frost

EN 16432-1 (CEN, 2017a) specifies that the performance of the substructure due to ground freeze / thaw cycle shall not adversely impact the performance of the slab track system, the design speed and the ride quality of railway traffic.

Frost heaving is a basic problem for high-speed railway regardless of superstructure, but it is especially critical for slab track. Slab track needs a rigid substructure, and frost heaving creates undesirable swelling in the substructure caused by water in the soil freezing to ice and growing in volume. Ice growth requires water supply that delivers water to the freezing front. The soil needs to be "frost susceptible", it is porous enough to allow capillary action, but not so porous as to break capillary continuity. In many countries high-speed railway lines are in areas with seasonally frozen ground[10]. Figure 23 shows distribution of maximum extent of seasonally frozen ground in the Northern hemisphere.

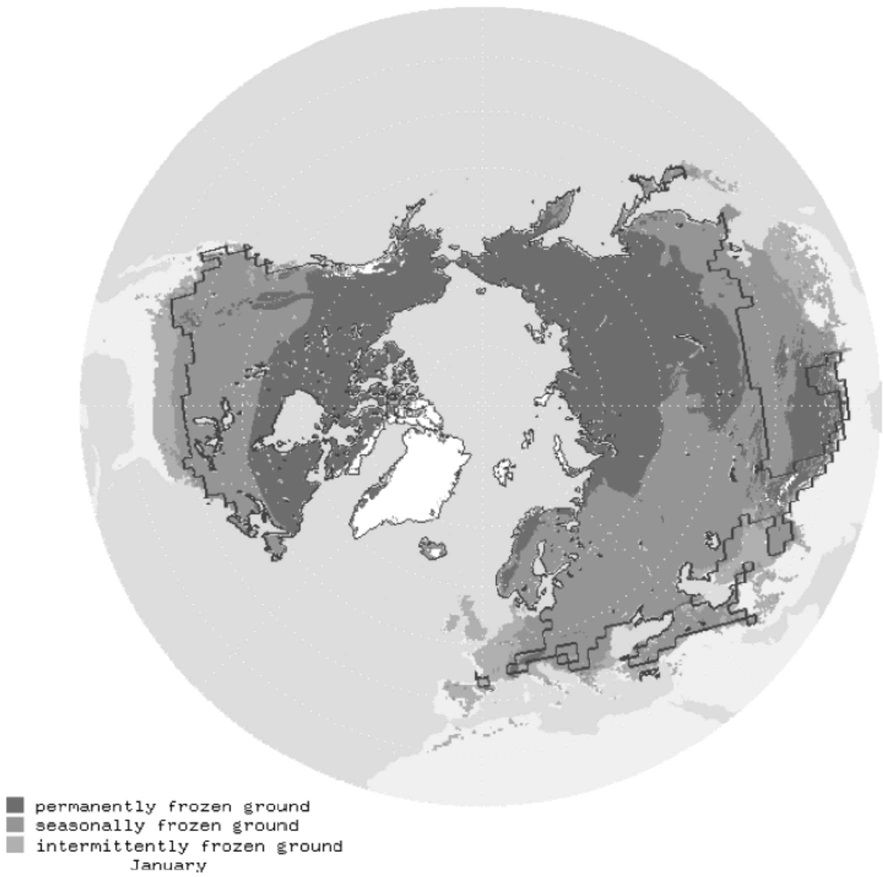


Figure 23 Distribution of permafrost, average maximum extent of seasonally and intermittently frozen ground (1950–1996), and average maximum snow extent (Solid line 1972–1995) in the Northern Hemisphere (T. Zhang, Barry, Knowles, Ling, & Armstrong, 2003)

Norway is a country with an area of permafrost and seasonally frozen ground throughout rest of the country. In comparison, Germany seems to have approximately ½ of its area with only intermittently frozen ground and the other ½ with seasonally frozen ground. Austria and Switzerland both have permafrost and seasonally frozen ground, as Norway. Another country worth mentioning that have both permafrost and seasonally frozen ground is China. Japan also has seasonally frozen ground.

[10] Ground that freezes and thaws annually.

There are some measures to avoid frost heaving. It is important to secure that the groundwater level is located at least 1.5 meters under rail top level as mentioned in chapter 4.3 Substructure. There are demands for use of coarse filling material in the frost protection layer to create a "frost-protected" substructure and controlling the number of fine particles. The layer's capillary-breaking property must prevent water from rising from the subsoil. The layer has to lead surface water away rapidly, and permeability between $1*10^{-5}$ m/s and $1*10^{-4}$ m/s is required (Lichtberger, 2011). The frost protection layer is typically between 500 and 700 mm thick but can be thicker if necessary. Required accuracy on top of this layer in ± 20 mm (CEMOSA et al., 2014).

China has built two high-speed lines through very cold regions with large temperature differences. They are the Harbin – Dalian HSL (904 km, opened 2012) and the Lanzhou – Urumchi second line (1775 km, opened 2014). These lines go through regions with temperatures down to between -20°C and -40°C. On the Harbin – Dalian line, wide-spread frost heave was observed during the first winter of its operation and the heave occurred mainly in coarse fills that were considered not susceptible to frost heave. The frost heaves varied from 5 to 30 mm, creating geometric fail in the track and reducing the speed on the line from design speed 350 km/h to 200 km/h in winter and 300 km/h in summer (S. Zhang, Sheng, Zhao, Niu, & He, 2016). 20% of the Harbin – Dalian line had to be rebuilt on viaducts because of the frost-induced heave of the subsoil (Powrie, 2017).

The same frost heaving has been observed on the Lanzhou – Urumchi line (X. Y. Wu et al., 2018). It was difficult to explain the observed heave using existing theories. On theory is that cyclic train loads cause the development of excess pore water pressure in the underlying subgrade soil, and hence 'pump' up the water table to the frost front, which in turn feeds the formation of ice and results in continuous frost heave. The mechanism is called pumping-enhanced frost heave (Sheng, Zhang, Niu, & Cheng, 2014). Another issue detected in this research is that frost depth in the subgrade reaches 220–400 cm, deeper than that in surrounding natural ground (~185 cm). The suggested solution is that the replacement depth of A/B group fill should be equal or greater than twice natural freezing depth (Lin et al., 2018). Another study also suggests P0.25 content should be less than 11.3% for the A/B group soil and the initial water content should be less than 14%, and the underground water supplement should be cut off (X. Y. Wu et al., 2018).

4.8 Transition zone

When planning and building slab track over a long distance, the railway line typically shifts between earthworks with cuttings and embankments, tunnels and bridges. Figure 24 shows an illustration of the varying bedding modulus for slab track along a typical railway line. The bedding modulus varies from soft to rigid as the line goes through piles, cuttings, trough, bridge, embankment and soft soil.

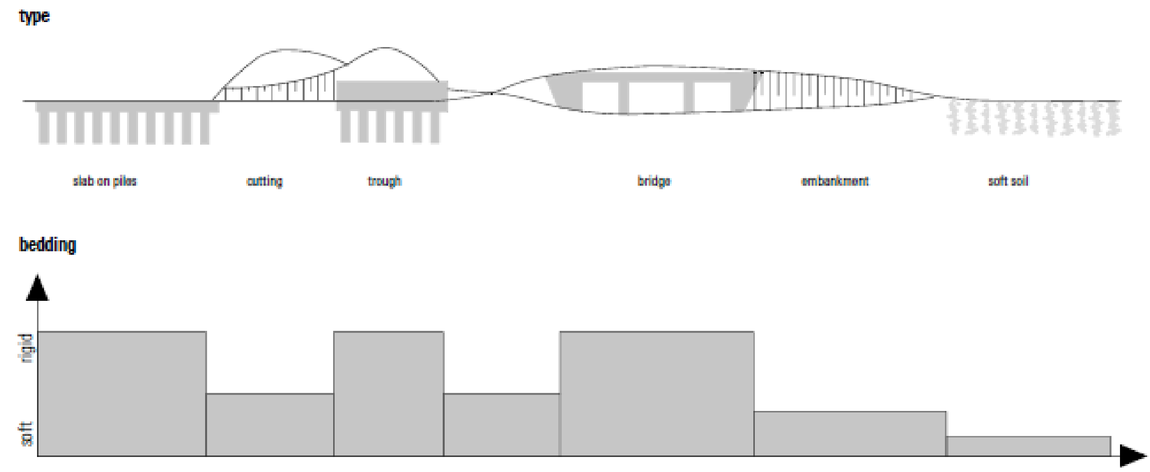


Figure 24 Slab track construction with varying bedding modulus (SSF Ingenieure GmbH, 2011)

Transitions zones between earthworks constructions and rigid structures such as bridges and viaducts present high variations of the vertical stiffness which leads to divergent long-term deformational behaviour. In the long run, this divergence results in differential settlements of the slab track eventually leading to concrete cracking and track geometry deterioration which is worsened at each train passage and aggravated by the exposure to atmospheric actions (CEMOSA et al., 2014).

Hence, transition zones from slab track on bridges to adjacent slab track at embankments, cuttings and tunnels or even ballasted track sections have to be designed in order to assure good smooth transition of the vertical stiffness avoiding damages due to dynamic effects and future unwanted maintenance needs (CEMOSA et al., 2014). For transition between earthworks and bridges, it is important to keep in mind the longitudinal movement of the bridge structure caused by temperature variation in addition to the different stiffness in substructures.

EN 16432-1 does not set specific design rules for transition zones, but state that transition zone shall be designed to take account of long-term variation in track geometry due to settlement and the variation in stiffness of the substructure. The length of the transition zone will depend on the design speed for the line and the differences in the settlement and stiffness characteristics of the adjacent structure and substructure (CEN, 2017a).

In addition to these transition zones between different bedding modulus, there is a need for especially designed transition zones between slab track and ballasted track.

In Norway, there is a requirement for this type of transition zone: «There shall be constructive solutions that equalize the differences in the elastic properties of the track structures. Investigations shall be made for assessing whether the transition zone is to be located entirely in the tunnel or on earthworks, or if the transition zone can be partly in tunnel and partly on earthworks. Length (m) of transition zone must be minimum v (m / s) x 0.5 (s). 3/4 of the transition zone's length should lie in the ballasted track" (Bane NOR, 2019f). A speed of 250 km/h (≈ 70 m/s) equals minimal length of the transition zone of 35 meters.

Several solutions have been proposed to construct such transition zones. It is normal to gradually increase the stiffness of the ballasted track before the change to slab track. It is possible to increase the length of the sleepers, use auxiliary rails and improve the substructure (Shahraki, Warnakulasooriya, & Witt, 2015). It is also a possibility to install an approach slab of reinforced concrete coming from the side of the slab track and gradually decreases under the ballasted track (Jenks, 2006).

By gradually increasing sleeper length in the ballasted track, the stiffness of the track increases without changing the sleeper distance or the shape of the embankment. The length can be increased in three levels, as shown in Figure 25.

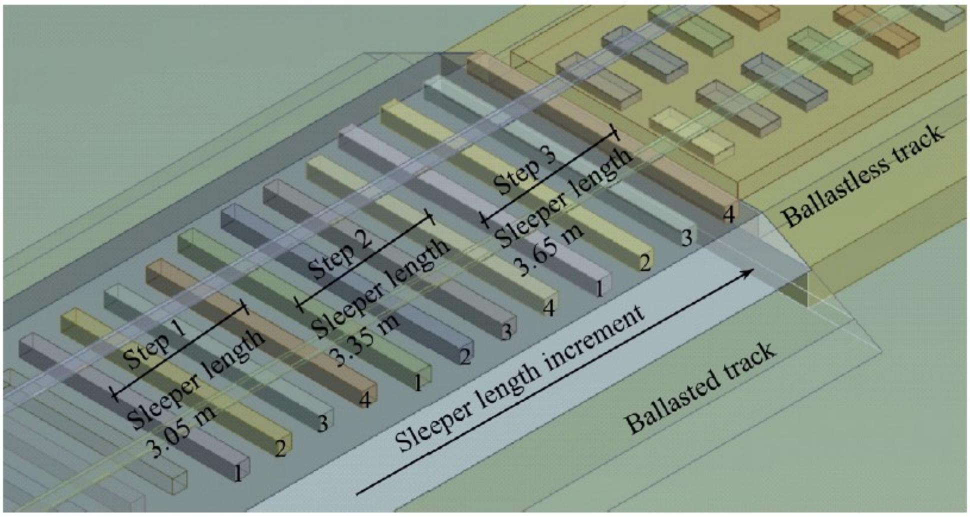


Figure 25 Transition zone with gradually longer sleepers (Shahraki et al., 2015)

The method of using auxiliary rails to increase the stiffness of the ballasted track was first developed in Germany (Shahraki et al., 2015). This entails that attaching two extra rails to the sleepers between the main rails. Experience with this solution is good and it is still used around the world. The auxiliary rails increase the bending stiffness of the track structure and allow an increased load distribution and reduces load on the ballast.

Another method mentioned above is to improve the substructure. This can be solved, for example, as shown in Figure 26 on the next page. The transition zone here consists of two different layers, at a depth of 4 meters, with sloping transitions towards each other. The material properties of these new layers have been developed from study of transition zones between ballasted track and track on bridges (Shan, Albers, & Savidis, 2013).

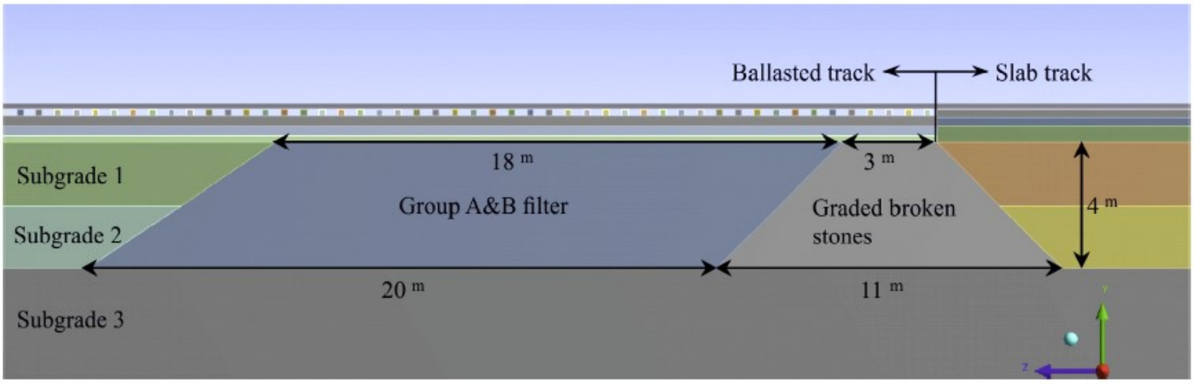


Figure 26 Model showing improved substructure in transition zone (Shahraki et al., 2015)

An approach slab is a reinforced concrete slab installed as a structural element in the track substructure to increase the stiffness of the track. Most slabs are reinforced concrete and are designed either with a taper to gradually increase the stiffness over an approach distance of about 6 metres, or are uniform in thickness but placed at an angle with tapering of the ballast depth to achieve the same ramping effect (Jenks, 2006).

As described, Bane NOR's Technical Regulations state that one must find a constructive device for solving the transition zone, but it does not recommend type of solution. (Shahraki et al., 2015) does not conclude which solution is best suited but points out that the use of auxiliary rails provides good dynamic improvement in the track. Nevertheless, there is a sensitive zone generated when the load is moved from lower stiffness to higher stiffness, and this applies to the first 5 meters of the track. In this area one should search for opportunities to increase the dynamic properties of the track.

(Frühauf et al., 2006) points out that it is desirable that the transition zone between ballasted track and slab track is in an area with homogeneous substructure with a high bearing capacity. A proposed method here is that for the first part of the track with ballast, the sleepers must be anchored down into the underlying layers to ensure a smooth transition between the support layers for slab track and the support layers for ballasted track. It may be necessary to extend the HBL layer beyond the end of the slab track to increase the rigidity below the ballasted track. There is also a practice for gluing ballast to stabilizing it.

The methods described above are general. The various manufacturers and slab track systems have developed their own way of building transition zones (Profillidis, 2014). This is described in detail for the three selected slab track systems in chapter 5 European best practises.

Experience with transition zones is that they require more maintenance than continuous slab track or continuous ballasted track. As consequence of this, in Austria transition zones between slab track in tunnels and ballasted track are always placed outside of tunnels (Veit, 2019). This to ensure easier access to this area demanding higher maintenance. Maintenance of the transition zone is described further in chapter 4.11 Operation and maintenance.

4.9 Noise and vibrations

For both surface and underground railway lines, there are several ways that railway noise and vibration can be transmitted to receptors in close proximity to the railway (Arup, 2016), illustrated in Figure 27. Noise and vibration can lead to annoyance and sleep disturbance. Exposure to railway noise may also be associated with stress related illness and cognitive impairment.

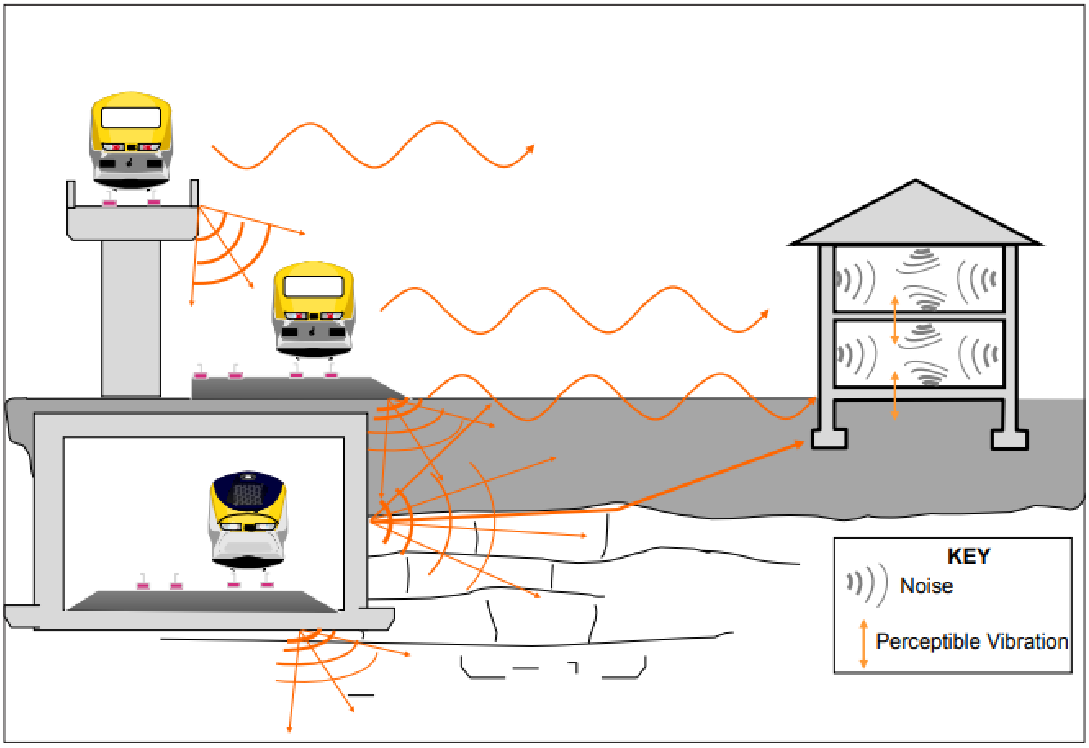


Figure 27 Noise and vibration from railway to surroundings (Arup, 2016)

<u>Airborne noise</u>

The dominant sound sources are the propelling forces of the vehicles up to a speed of about 40km/h, the rolling noise between 40 and 250km/h and the aerodynamic noise over 250km/h. So the rolling noise is the most important for the greatest proportion of traffic (CEMOSA et al., 2014).

Railway noise is a highly relevant topic when it comes to high-speed railway. Slab track differ from ballasted track. For slab track, the fastening has lower rigidity, which results in increased vibrations in the rail, which in turn results in increased rolling noise. This is called airborne noise (Bane NOR, 2018d). Ballast is a good sound-absorbent, unlike an untreated concrete slab in slab track that will act as a reflector for noise generated from wheels/rail. Slab track has an average increase in noise of approximately 3 dB (A) compared to ballasted track (Gautier, 2015).

Some different measures have been applied to reduce airborne noise from slab track. Regular rail maintenance grinding is necessary to control noise emissions. Screening with conventional noise barriers are frequently used. Another measure is to have ballast on the side of the track to absorb noise or to have sound absorbing panels near the track. In order to maximize their effectiveness, these panels should be placed as close to the rail as possible. Figure 28 illustrates noise absorbing elements mounted on the Bögl slab track system.

Figure 28 Noise absorbing elements, Bögl slab track system (Bögl, 2006)

<u>Vibrations</u>

In Norway, there is often soft clay as substructure in the densely populated areas. Vibrations come when traffic on the railway creates changes in tensions and deformations in the substructure. These will be propagated to surrounding areas and can be transferred to neighbouring buildings in the form of vibrations where buildings have foundations in soil. The vibrations can be amplified by transfer to floors, walls and ceilings and in some cases they can cause inconveniences (Bane NOR, 2018d). This is illustrated in Figure 29, situation b.

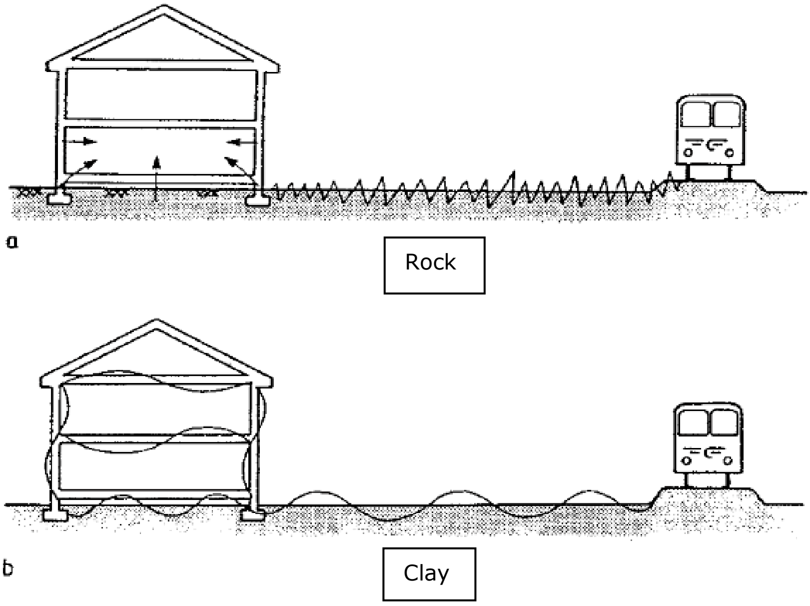


Figure 29 Situation a can produce structure born noise from railway, situation b can produce vibrations from railway (Bane NOR, 2018d)

For slab track, the concrete slab in the track construction can provide increased vibrations that propagate in the ground below the slab track and to adjacent buildings and structures. Various solutions of using elastic fastenings, elastic rubber boot around and below sleepers or applying floating slab track (mass-spring systems) prove to have a good effect on reducing vibrations in the ground (T. X. Wu, 2008).

Floating slab track or mass-spring systems is a way to achieve improved vibration attenuation by the interposition of elastomeric layers within the rigid track structures (CEMOSA et al., 2014). Mass-springs systems can be implemented in light, medium-heavy and heavy models. Light mass-spring systems are mounted on either strip supports or entire-surface supports made of elastomer matting. For heavy mass-spring systems, individual supports in the form of elastomer blocks or steel springs are employed. The deeper the frequency of the vibration to be reduced, the higher the required mass of the mass track concrete layer (RAIL.ONE GmbH 2018). An example of a floating slab track is illustrated in Figure 30.

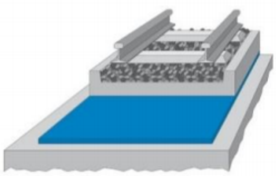
MASS-SPRING SYSTEM	DESCRIPTION
Full-surface support for floating slab 	Depending on the specific application, a full-surface elastic support achieves natural frequencies in the range of 14-25Hz. This corresponds to an achievable structure-borne noise damping of up to 30dB in the supercritical frequency range.

Figure 30 Example of floating slab track system (CEMOSA et al., 2014)

<u>Structure-born noise</u>

Another issue is structure-born noise. Rail traffic use metal wheels that roll against metal rails. Rails and/or wheels cause vibrations through the ground with frequency that is so high that it causes audible sound, structure-born noise, when vibrations move building surfaces. Such noise may occur, for example, in a building over a railway tunnel where you do not see the trains but hear rumbling when they pass. Structure-born sound creates particular problems where both track and buildings are on mountain or hard substructure (Bane NOR, 2018d). This is illustrated in Figure 29, situation a.

There is also a claim that the construction techniques can have effect on rail roughness and longer wavelengths, which affects both ground-borne noise and vibration. 'Top down' construction techniques – where the line and the level of the rail is fixed to a high tolerance before the sleepers and/or baseplates are hung from the rails and the second stage concrete is poured – are likely to deliver alignments with the lowest levels of roughness at long wavelengths. As opposed to 'bottom-up' construction – where the rail is the last track component to be installed and the vertical rail alignment is set once the sleepers and other components are in place – which has greater potential to introduce long wavelength variation in the alignment (Arup, 2016). Measurements of long wavelength roughness indicate that slab track constructed to a high level of accuracy can deliver roughness levels which are three times smoother than ballast track (Marshall et al., 2015).

4.10 Installation

Special installation techniques have been developed for slab track installation. One can distinguish between two main installation methods.

- Top-down installation
    - Uses the rail at the datum, connecting the fastenings and slab system to it
- Bottom-up installation
    - Incremental adjustment under the rail to achieve alignment and level

Top-down installation is used for systems such as Rheda 2000 and LVT Low Vibration Track et al., bottom-up installation is used for systems such as Züblin, GETRAC and ATD et al.

A typical procedure for top-down installation is:

1: Preparation of the substructure, placing frost protection layer and hydraulically bonded layer
2: Assembly of the track panel, placing reinforcement and sleepers if not prefabricated
3: Rough alignment of the track panel
4: Installation of the track formwork
5: Final alignment of the track panel and rail, horizontal and vertical alignment
6: Pouring concrete for slab

Figure 31 shows installation of the Rheda 2000 system at high-speed line between Nuremberg and Ingolstad. It shows the workers adjusting the rail with manually with special equipment with spindles.

Figure 31 Installation of Rheda 2000 system at high-speed line Nuremberg-Ingolstadt. Top-down construction (Lechner, 2007).

A typical procedure for bottom-up installation is:

1: Preparation of the substructure, placing frost protection layer and hydraulically bonded layer
2: Assembly and rough adjustment of track panel or placing prefabricated slab
3: Final adjustment of sleepers or prefabricated slab
4: Pouring concrete for monolithic slab or to secure prefabricated slab
5: Mounting and welding of rails

It might be challenging to obtain the required geometrical precision for high speed with bottom-up installation and prefabricated slabs, as the bearing layers must be produced very precisely to reduce the need for vertical adjustment (CEMOSA et al., 2014).

A possible intermediate approach is to preassemble plates without anchors, on rails, to get the desired rail geometry, to drill holes through the plates, to put in place the anchors with chemical sealing and to adjust the plate vertically with a mortar. This method is used by FF Bögl, ÖBB-PORR and Shinkansen J-Slab.

When constructing a new double track railway with slab track, on earthworks, most companies have developed efficient methods for installation, with automated or semi-automated methods. Seeing as earthworks are not in a tunnel or on a bridge, access is often easier and makes logistic planning simpler. Is it normal to construct both tracks up to formation level, and use the track not being laid as access, either with temporary tracks or for use with large trucks. After installing one side with slab track, this track can be used for access to build the remaining track.

The construction performance of a slab track system depends on the number of in-situ works, including the assembly of precast elements and the track alignment. There is always a critical step which determines the overall construction performance. For example, the construction of the base layer at the HSL Zuid had a construction performance of 600m/day, but the backbone was the positioning and concreting of the track frame, which was 300m/day (CEMOSA et al., 2014).

The manufacturing of precast elements can also limit the construction performance. This can be avoided if the slabs can be stacked and stored in advance (CEMOSA et al., 2014).

Figure 32 shows the construction performance of some of the most common slab track systems. The most efficient systems achieve more than 300 m/day.

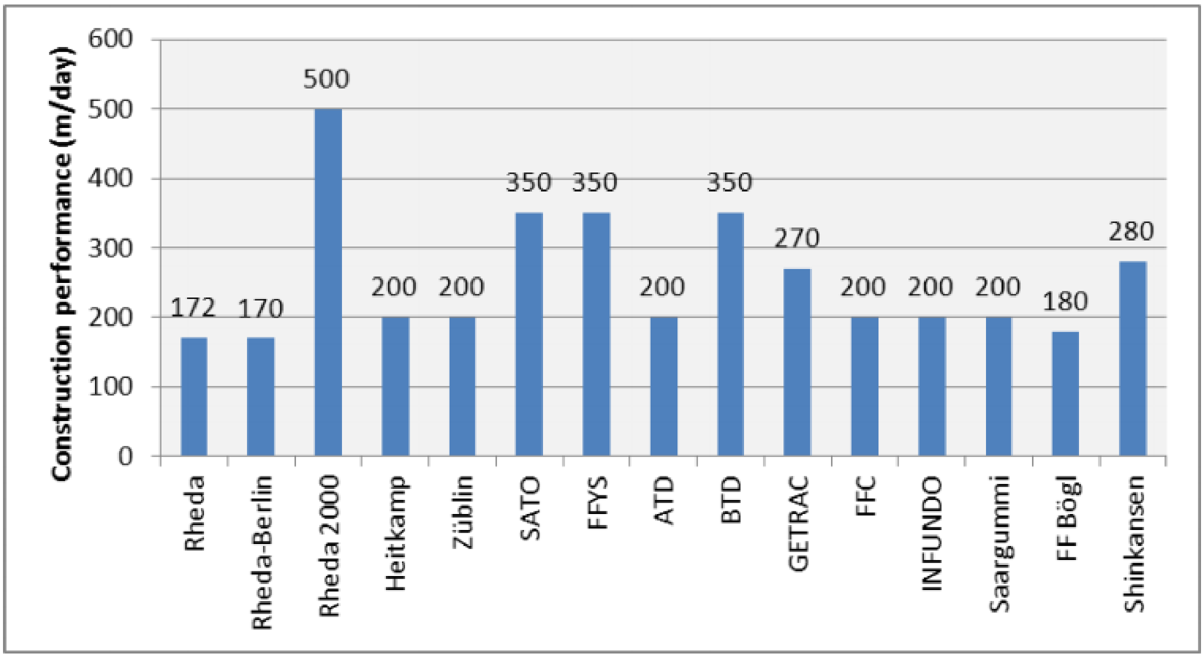


Figure 32 Construction performance on different slab track systems (CEMOSA et al., 2014)

In case of prefabricated slab track, the size and weight of the slabs are an important issue for transport and installation in the construction phase. There are limitations on European roads for transportation of large heavy loads. Normal trailers usually have a 12 m long and 2,6 m wide area for placing cargo. Most prefabricated slab track systems can be moved by road, but no more than 3 to 6 slabs at once, as shown in Figure 33 (CEMOSA et al., 2014). With an estimated production of about 200 m/day, there is a need for over 13 truckloads with slabs per day (3 slabs per truck with length ca. 5 m).

Figure 33 Transportation and rough placing of precast slabs, FFB Slab track Bögl (CEMOSA et al., 2014)

There are strict demands for the finished quality of a newly built slab track. EN 16432-1 does not specify these limits, other than state that the track shall provide accurate and durable geometry (CEN, 2017a). The requirements for quality of track geometry during operation are set out in EN 13848-6[11] (CEN, 2014). The different slab track systems provide different finished track geometry quality, this is described in chapter 5 European best practises, for the three selected slab track systems.

[11] EN 13848-6 Railway applications - Track - Track geometry quality - Part 6: Characterisation of track geometry quality

4.11 Operation and maintenance

EN 16432-1 states that the requirements for maintenance shall be considered during the design phase. This shall include inspection, repair and replacement of components, subsystems or the entire system as well as most common maintenance activities (CEN, 2017a)

One of the biggest advantages with slab track is the need for very little maintenance. Slab track systems require little routine maintenance. An inspection regime is necessary, but as the track is fixed in position there is no requirement for regular realignment of the rails, as is common for ballasted track. The very low maintenance requirement also means that track workers spend less time trackside, improving worker safety.

Experience from slab track lines in Germany shows that they meet the expectations of low maintenance requirements. A consequence of this good, durable track quality is high availability for the track (Esveld, 2001).

For slab track, track geometry is maintained by rigid concrete slabs. To ensure driving comfort and maintain the quality of the rails, preventive rail grinding is performed. This further prevent the development of grooves, headchecks and other injuries/recesses in the rails. Grooves and other irregularities will also develop much slower than for rails on ballasted track, since the dynamic forces are smaller. It has been found that the cost of maintenance of the track at Rheda is only 10% of the cost of ballast tracks (Profillidis, 2014). In Japan, experience has shown that the maintenance cost of slab track is about 20-30% of the cost of ballasted track (Esveld, 2001). This is confirmed in figures collected from the tracks on Sanyo Shinkansen, see Figure 34.

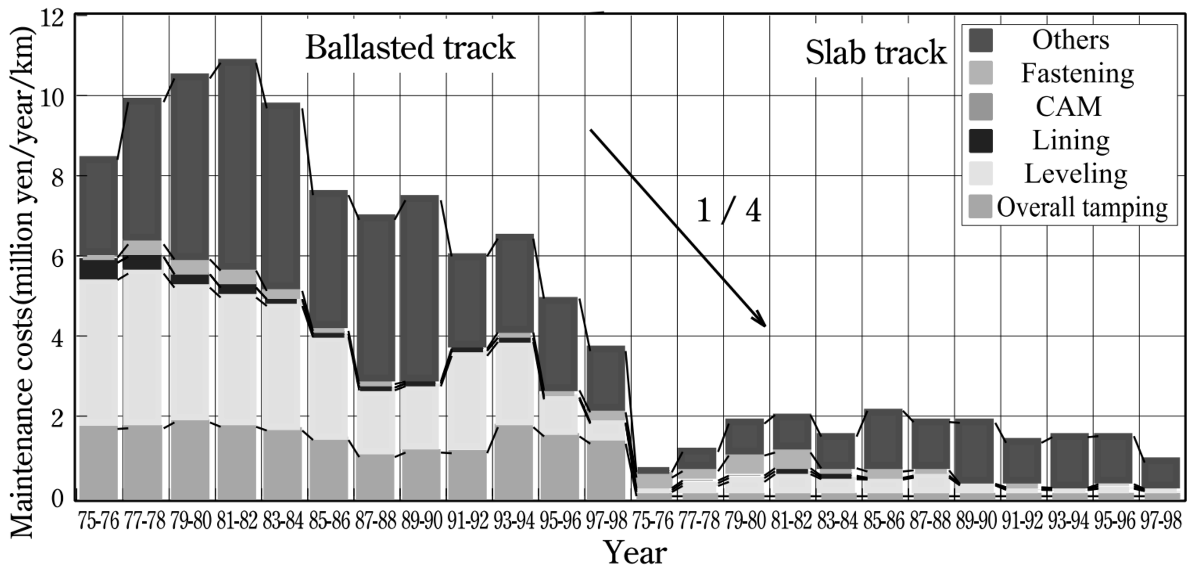


Figure 34 Maintenance costs of tracks on Sanyo Shinkansen (Ando et al., 2001)

It is pointed out in the literature and experience about slab track that one still does not have long enough experience with the operation and maintenance of slab track to be able to draw safe conclusions, but the experience so far is very promising. Experience shows that slab track has a substantially lower maintenance need than corresponding ballasted track.

Although slab track represents a low need for maintenance, it is important to point out that in case of an accident that cause damage to the slab track, it is in most cases more time consuming and expensive to perform repairs on this type of track compared to ballasted track. Both large residual settlements, derailments and fire in trains have caused extensive damage to slab track in the past. For example, a settlement defect of 20mm occurred at the high-speed line Berlin-Hannover (Germany) made necessary to temporarily restrict speed to 70km/h. The repair works were carried out during expensive night shifts (Lichtberger, 2011). The system in question at this line was the Rheda 2000 system.

In general, systems with either rubber booted sleepers or prefabricated slabs are easier and faster to repair or replace than monolithic systems where sleepers are used for alignment purposes and are embedded in-situ concrete, unable to be separated from the slab.

In chapter 5 European best practises; repair methods are described for the three selected slab track systems.

In the following subchapters the different maintenance tasks for superstructure and substructure are described.

Superstructure

The following control activities and maintenance tasks will be relevant for superstructure for slab track on earthworks.

Control activities:

- Periodic measurement with track recording car
- Ultrasound control of rails
- Ordinary track visitation (walking or by vehicle)
- Visual inspection of fastenings, rail pads and insulators
- Visual inspection of rails

When it comes to control activities, it may be appropriate to look at increasing the interval for controls on track in relation to what is set for ballasted track. In Germany in 2010 they still used the inspection intervals set for ballasted track (Nyquist, 2010).

Periodic measurement with track recording car to check the track geometry is performed every 2 months for lines with speed >200 km/h. Measurement to control track quality must be performed every 3 months, vertical geometry and horizontal geometry is checked. This control requires track access and is performed from track recording car that runs in line speed. That is, for railway line with speed of 250 km/h, the track recording car will run 6 times a year.

Ultrasound control of rails is performed with a dedicated ultrasonic measuring car. It runs at 40 km/h when measuring. Ultrasound control is performed all over Norway once a year and twice a year at Ofotbanen (Grimsrud, 2018).

In ordinary track visitation, one performs a visual inspection of the infrastructure to detect errors or beginnings of errors. This inspection is carried out monthly either by walking along the track or by running track vehicle. This control activity requires track access.

Visual control of fastenings, rail pads and insulators is performed either every 5 years or every 3 years, depending on the type of fastening. It is natural to assume that a newly built track will have high quality fastening and thus have a control interval of every 5 years. The control is carried out only after a given number of years after commissioning, the time varies depending on the type of fastening and curve radius on the track but is from 10-20 years when concrete sleepers are applied. What this figure will be for slab track must be investigated more closely, as it is important that especially rail pads are in good condition for a slab track to maintain the elastic properties. This control activity requires track access.

Visual inspection of rails on sections with speeds above 160 km/h is performed annually. The foot and web on the rail are checked for corrosion, the running surface is inspected for corrosion coating and the rail head is checked for drip damage. This control activity requires track access.

Corrective Maintenance:

- Track adjustment laterally and vertically for track geometric errors
- Sealing of cracks that may occur in the concrete slab
- Replacement of elastic rail pads
- Rail grinding
- Rail Replacement
- Replacement of fastening

Track adjustment for track will be performed in case of track geometric deviations over limit values. It is restricted how much adjustment is possible, this varies with different types of slab track and fastenings.

Cracks can occur in the concrete slab due to temperature changes and freezing. These can be repaired with special material mixes that become very resistant to temperature changes. This has happened in Japan, but they have changed the way the concrete slabs are constructed and have less fracture problems now. In Germany, they have had some problems with fracturing between the sleepers and the place-cast concrete slab on the older systems like Rheda Classic, but this does not occur in the new systems such as Rheda 2000 and FF Bögl (Nyquist, 2010). In Germany, they have measured these cracks with high-speed cameras and the results are good, there are fewer cracks than expected on the railway lines that have been controlled.

Rail grinding on the German high-speed railway is performed at regular intervals, but it also depends on the condition of the rails. Roughly twice a year the rails are grinded with rail grinding machines running at 80 km/h (Nyquist, 2010). In Norway, it is performed both preventive and corrective grinding. Preventive grinding is done to prevent the development of waves and other wear damage to the rails. This preventive grinding is based partly on traffic load and not just on visual/measurable criteria. Corrective grinding is performed where short and long pitch corrugation or defects occur. Multiple grinding passages are often required to grind away short and long pitch corrugation (Bane NOR, 2018c).

Elastic rail pads can lose their desired properties over time, and these elastic properties are particularly important to maintain in a slab track. The rail pads who appear to be too poor in quality after control are replaced. The type of rail pads depend on which track system is chosen.

Rail replacement is performed when the rails have reached their lifetime and are in poor condition, both in terms of safety and in terms of quality limits. The lifespan of the rails is affected by wear and fatigue. Rails of type UIC60/S64 with steel quality 90 have an estimated lifetime of 45 years (Bane NOR, 2018e).

There are several types of fastenings, but the main point is that due to the relatively rigid construction of slab track, the rail fastening must be highly elastic. The different types of fastenings developed, have advantages and disadvantages, and some types are more prone to fatigue than others. Fastenings are replaced after checks if they do not maintain the desired quality. The type of fastening depends on which track system is chosen.

Substructure

The following control activities and maintenance tasks are relevant for substructure of slab track on earthworks.

Control activities:

- Control of smallest cross-section and structure gauge with recordings of laser scanning or other measurements every 3 years, requires track access
- Control of culverts, every year, does not usually require track access
- Control of track drainage (either open or closed), every 5 years, does not usually require track access
- Control of terrain ditches, every 5 years, usually does not require track access
- Control of surface water pipeline, every 5 years, does not usually require track access
- Checking the drains, every 5 years, usually does not require track access
- Control of cable routings, every 10 years, requires track access
- Control of side terrain, earthworks, every year, usually does not require track access
- Geotechnical control of side terrain, earthworks, every 10 years, requires track access

These control activities for substructure are the same for slab track and ballasted track, and this thesis will not elaborate them further.

Transition zone

The transition zone between slab track and ballasted track is a problematic area. As described in chapter 4.8 Transition zone, it is important that the substructure is designed in such a way that no settlements occur. However, it is impossible to avoid settlements altogether, so they still occur. Small vertical settlements of less than 26 mm can be adjusted using adjustment possibilities in the fastenings (CEMOSA et al., 2014).

When the Øresund connection was built, it was decided to apply slab track superstructure. Initially, no special transition zone was built between the slab track and ballasted track, and this quickly led to problems in this zone, with the need for frequent tamping and already after 2 years it was decided to build proper transition zones. This was done and after the rebuild there have not been problems in the transitions between slab track and ballasted track (Nyquist, 2010).

Depending on the solution chosen for a transition zone, different types of control tasks, maintenance needs and special types of challenges will be generated. An example of this is if the ballast is glued the last meters before the slab track, and it will be difficult to perform tamping and adjustment of the track if settlements occur in this area.

In all cases, it is important to take account of the increased need for tamping of ballast in the transition zone, because it is very difficult to avoid settlements entirely.

4.12 LCC

As mentioned in chapter 3.3.1 LCC method, LCC are the total costs for a system or construction from purchase and installation to use and maintenance through the entire lifecycle. EN 16432-1 state that slab track systems should have a design life of at least 50 years unless otherwise specified. Subsystems and components which are subject to shorter design life due to wear or fatigue, e.g. rails, shall include provision for replacement.

The initial cost of slab track is higher than that of ballasted track. Agencies in Europe and Japan have developed criteria to properly evaluate the cost-effectiveness of slab track. The Japanese consider the slab track to be cost-effective if the initial cost is less than 1.3 times that of ballasted track. The Europeans also use similar criteria. For high speed lines, some claim it is expected that the higher initial cost of the slab track would be recovered within 8 years of revenue service due to reduced maintenance costs and reduced downtime for the slab tracks (Tayabji & Bilow, 2001).

In Japan, on the Hokuriko Shinkansen line, the initial construction cost of slab track on earthworks, including typical subgrade, was higher than that of ballasted track by 18% for cuttings and by 24% for embankments. Figure 35 shows an example of comparison of the total costs between the two tracks. These costs include personal expenses, maintenance costs, municipal property tax and depreciation costs. In this case, the extra investment might be redeemed in about 12 years of commercial operation.

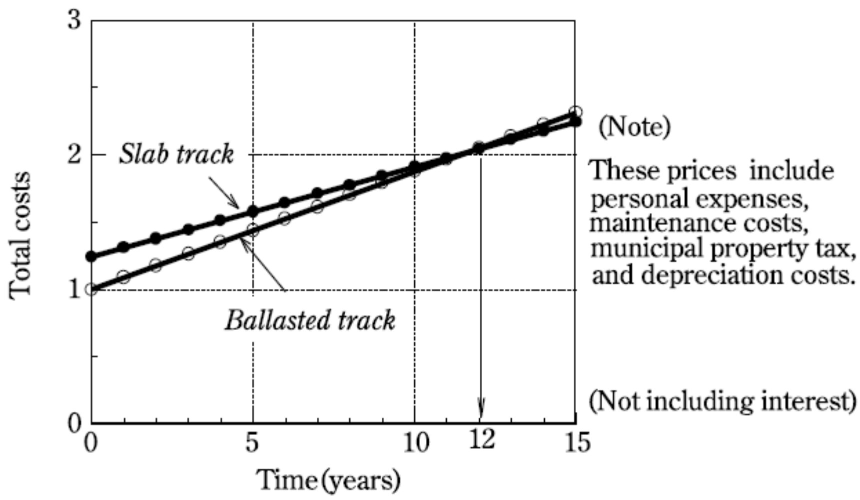


Figure 35 Comparison of total costs between slab track and ballasted track (Ando et al., 2001)

In Europe it has been claimed that normally, in the open and on earth structures, slab track is not economically efficient when compared to the conventional ballasted track. The additional cost that requires for the use of slab track on earthworks to limit long-term settlement in the substructure is higher than for conventional ballasted track by the factor 2-2.5 (Lichtberger, 2011). Other research claim that the factor varies from 1.3 to 3 (Ren et al., 2008). The initial cost is a key factor to estimating economic efficiency for slab track.

It is the previously mentioned considerably low need for maintenance which is slab track's most important advantage. This, together with high operational safety level and high initial track geometrical quality, contribute to make slab track economically advantageous in an LCC-perspective.

As shown in Figure 34 in the previous chapter, maintenance costs are considerably lower for slab track than for ballasted track. Figure 36 shows an example of annual costs in euro/m based on LCC-categories Construction, Maintenance and Risks. When comparing a Rheda system against ballasted system, it is clear the construction costs are higher for Rheda, but maintenance costs and risk costs are significantly lower for Rheda.

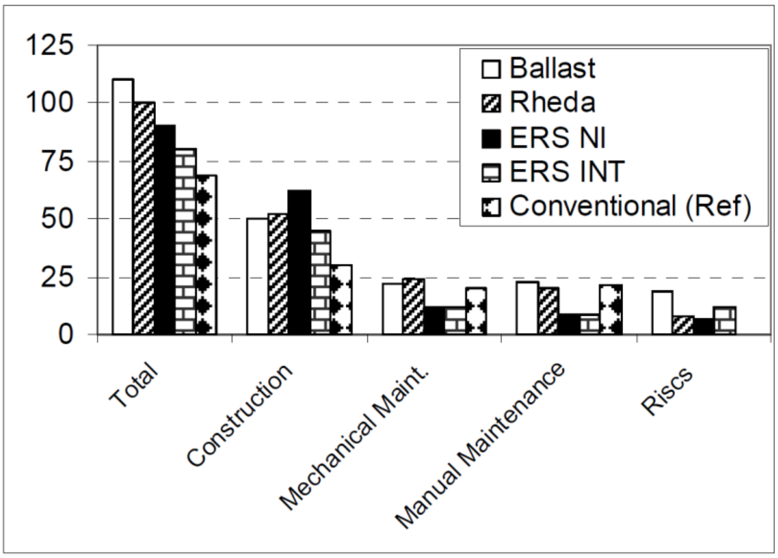


Figure 36 Annual costs in EUR/m based on LCC (Ren et al., 2008)

There have been performed several LCC calculations of various slab track systems. An LCC analysis from Austria used discount cash flow methods. Figure 37 shows that the initial costs at year 0 was higher for slab track that ballasted track by a factor of 1.4. The calculations predict that costs between slab track and ballasted track will balance each other within 15 to 20 years.

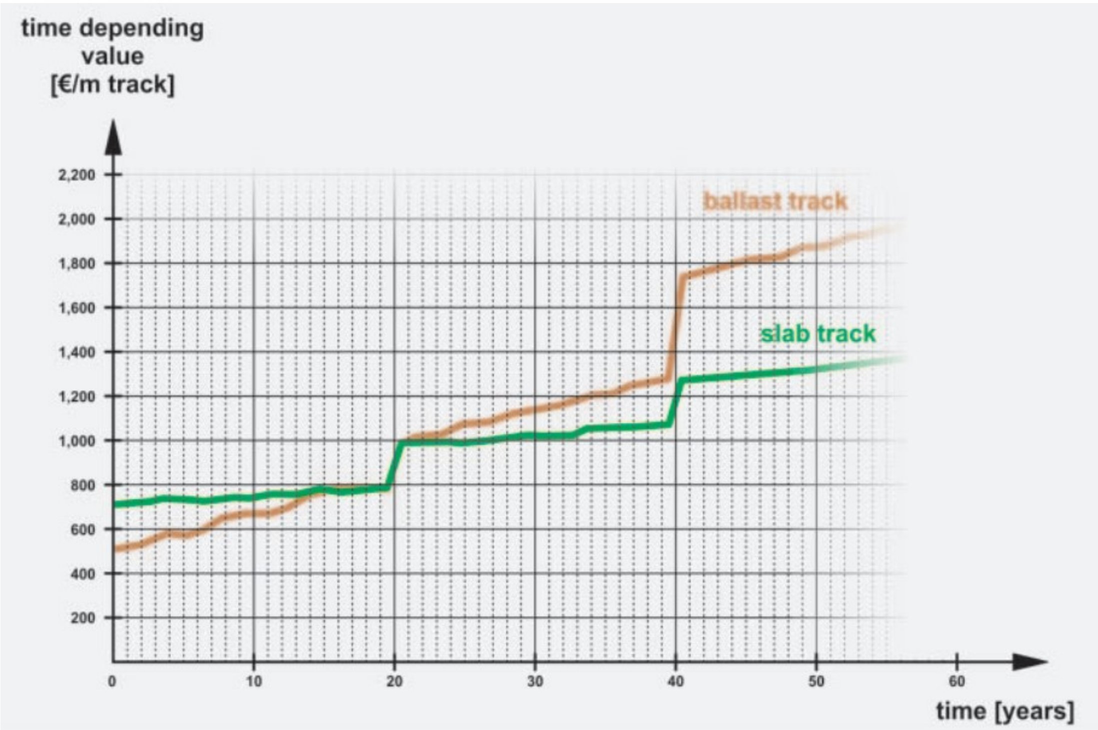


Figure 37 Time depending value, ballasted track and slab track (Rudolf Schilder & Diederich, 2007)

5 European best practises

5.1 Selected slab track systems

In this chapter, three selected slab track systems are described. To select systems relevant to Norwegian conditions with enough experience in operation, the following criteria were set for selection of systems to analyse:

- Total length built with system in the world > 500 km
- Both in-situ systems and precast systems are selected
- Only top-down installed systems are selected
- Only European systems are selected
- The systems must be applied on earthworks to be selected
- It is desirable with different maintenance possibilities for the different systems

After discussions with project supervisor, it was recommended to study these three different slab track systems; Low Vibration Track from Sonneville AG in Switzerland, ÖBB-PORR Slab Track Austria from Austria and Rheda 2000 from RAIL.ONE in Germany. The three systems are built up somewhat differently and in the following chapters the systems are more thoroughly described and illustrated.

5.2 LVT – Low Vibration Track

5.2.1 System development

This system was developed by Roger Sonneville more than 50 years ago, as one of the first slab track systems in the world. It was developed from bi-block sleepers, to a mono-block sleeper system without connecting bars between. This was defined as the Low Vibration Track (LVT). The system was developed in cooperation with SSB (Schweizerische Bundesbahnen). Sonneville AG holds the licence for the LVT system, and offers project specific design, technical advice and quality control through all project phases.

The system has proven to be successful in tunnels, and today 3 out of 4 of the world's longest railway tunnels are equipped with LVT. It has been built a total of 1398,7 km of track (as of June 2018) with this system around the world (Sonneville AG, 2018). Figure 38 show a picture of the LVT system installed in the Gotthard Base tunnel. This track has a design speed of 250 km/h (Sonneville AG, 2018).

Figure 38 The LVT System in Gotthard Base tunnel (SBB, 2019)

The LVT system is approved in Germany by EBA (Eisenbahn-Bundesamt) and in Switzerland by BAV (Bundesamtes für Verkehr) and has been tested according to the standards EN 13481-5[12], EN 13481-6[13] and EN 13230-3[14] (Sonneville AG, 2019b).

5.2.2 Reference projects and future projects

The LVT system is in use in many railway tunnels, including the Gotthard Base tunnel in Switzerland between Erstfeld and Bodio. It was opened in June 2016 (full service began on 11 December 2016) and it is the world's longest railway tunnel.

Sonneville AG presents a list of reference projects from June 2018 and this shows that the LVT system is mainly used in tunnels, but there are also projects that are built on viaduct or earthworks, 17 projects in total on earthworks.

The LVT system as we know it today (2019) has been in use in Switzerland for more than 15 years without need of maintenance. The predecessor which was installed in the Bözberg tunnel in Switzerland can show to more than 50 years of maintenance free use.

5.2.3 Track superstructure

Construction:

The LVT system is constructed with reinforced concrete blocks (supports) separated from the rest of the concrete slab by a rubber boot specially designed for this purpose. Under the concrete blocks inside the rubber boots there are resilient block pads. These pads are specially designed for each project and help improve load distribution. Figure 39 shows the three key components in the LVT system.

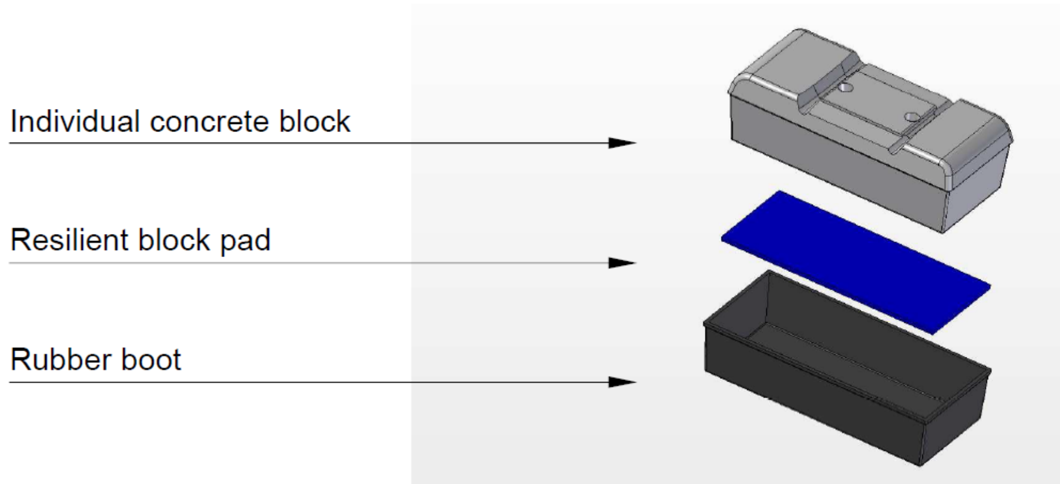


Figure 39 Principle structure of LVT mono block system (Sonneville AG, 2011)

Regardless of the type of fastening system mounted, an elastic rail pad with cDYN = 150 kN/mm is used as this is decisive for one of the characteristics of this system – the dual-level elasticity (Sonneville AG, 2011).

[12] European standard: Railway applications - Track - Performance requirements for fastening systems - Part 5: Fastening systems for slab track with rail on the surface or rail embedded in a channel

[13] European standard: Railway applications - Track - Performance requirements for fastening systems - Part 6: Special fastening systems for attenuation of vibration

[14] European standard: Railway applications - Track - Concrete sleepers and bearers - Part 3: Twin-block reinforced sleepers

Inclination and superelevation:

In terms of the rail inclination the LVT system can create any rail inclination using two methods (Laborenz, 2019a):

1. Using blocks without inclination. During track installations the blocks are fixed to the rails and then the complete LVT support including rails get inclined using temporary adjustment jigs before pouring in concrete.

2. Using blocks with an inclined rail seat. In this case the base of the support is horizontal after installation, whereas the base of the support in option 1) is inclined like the rail. Option 2) is more beneficial for rail inclinations of 1:20, whereas option 1) is usually used for tracks with a rail inclination of 1:40.

The limitations in terms of superelevation are resulting out of the alignment, usually a maximum superelevation of 180 mm on high speed lines. The construction of a track with this superelevation is difficult as it is a challenge to handle in-situ concrete in a quite steep slope. Sonneville informs it has been carried out in the past, hence it is manageable.

Gradient:

Sonneville informs that there is no limit in terms of gradient (Laborenz, 2019a), and there has been built a very steep ramp in Zurich out of a tunnel on a viaduct (Durchmesserlinie project in Zurich), the slope of the steepest ramp being approximately 8%. For the LVT system it is not an issue during service. It is more a challenge during installation, when you need to keep the in-situ concrete where it should be. This requires a good concrete quality and special formwork.

Minimum radius:

In terms of the minimum radius LVT supports are used in very tight radius, currently in Metro Copenhagen (50 m radius) but also in Metro Glasgow with tracks in the range below 50m. This is not a limit, according to Sonneville. The supports are independent, which gives flexibility in terms of the arrangement in curves. LVT supports are also installed in small turnouts with tight radius below 100 m (Laborenz, 2019a).

Drainage:

Sonneville claims that the system allows for a flexible arrangement of track drainage, also in the track axis (Sonneville AG, 2019b).

Versions:

Sonneville AG has developed several versions of the LVT system, both for use in railway and on metro. The following versions are in use on railway lines.

LVT Standard – This is the most widely used version. It can be customized after project specifications, especially with regards to support rigidity and choice of rail fastening. LVT Standard can be applied both heavy haul and high-speed lines. Figure 40 illustrates the concrete block for LVT Standard. LVT Standard has been in use for over 25 years, on both bridges, viaducts, earthworks and in tunnels.

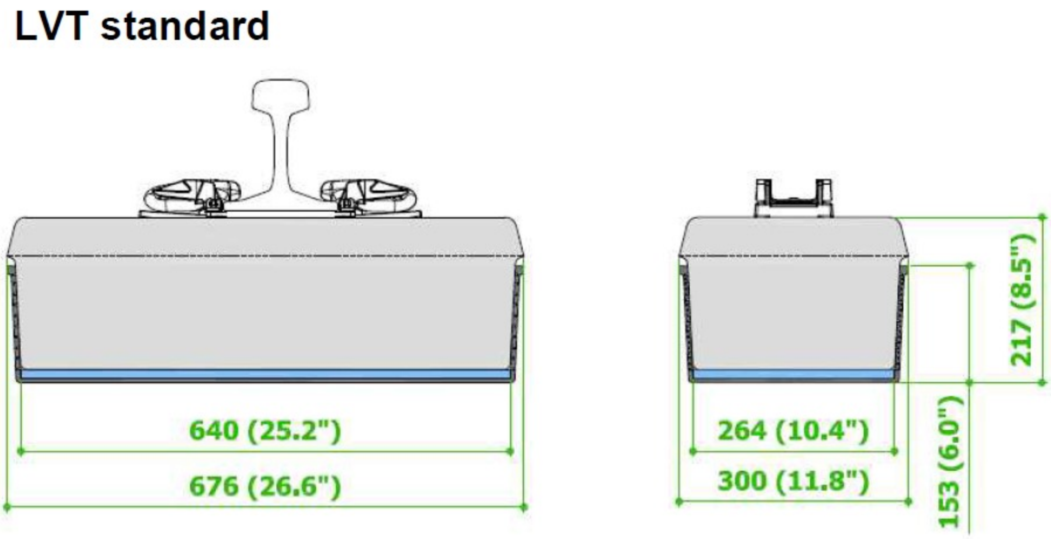


Figure 40 Illustration of LVT Standard concrete block (Sonneville AG, 2011)

LVT HA (high attenuation) – This version is a further development from the LVT Standard system. It was installed for the first time in 2009 on the Los Angeles Metro, and is also used in the world known Gotthard Base tunnel. Compared to LVT Standard, LVT HA has larger dimensions and lower rigidity. This combination provides a slab track system like a light mass spring system or floating slab track and can replace the need for these more expensive systems in many cases. Figure 41 illustrates the slightly larger dimensions for the LVT HA system.

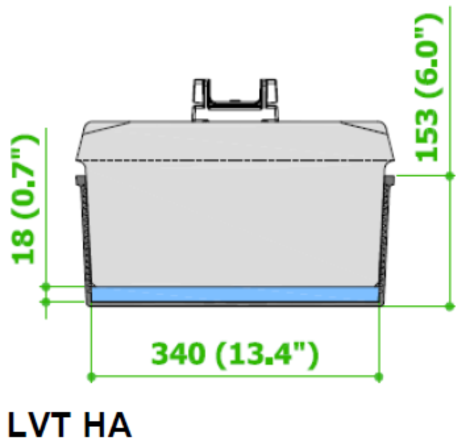


Figure 41 Illustration of LVT HA system (Sonneville AG, 2011)

Low profile – Depending on the conditions on the site, both LVT Standard and LVT HA supports with a lower profile can be used. This can reduce total height for the cross-section by 40 mm.

LVT S & C (for switches and crossings) – this version is especially designed for use in switches and crossings. It consists of five different sleepers with different length and rigidity, as depicted in Figure 42. They can be adapted to be used with conventional switches. This version is otherwise like the LVT Standard regarding vibration damping and reduction of structural sound.

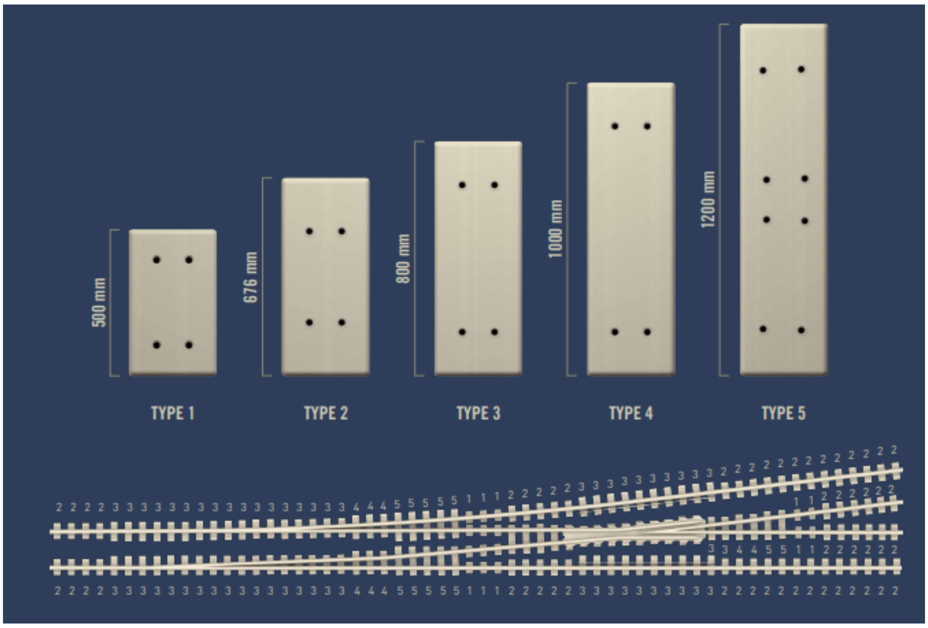


Figure 42 Illustration of LVT S & C system (Sonneville AG, 2019b)

LVT Traffic – this version is designed to meet the demands of modern rescue concepts for railway tunnels by enabling the track to be run with regular air-filled tires. As shown in Figure 43, there is an extra layer of concrete that creates a roadway with a minimal gap to the rails.

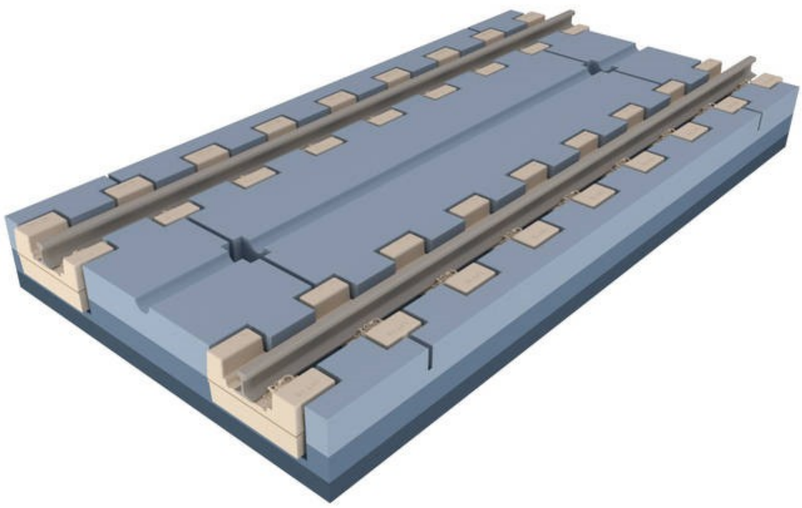


Figure 43 Illustration of LVT Traffic system (Sonneville AG, 2019b)

LVT Panel – in this version four LVT concrete supports are integrated into a precast slab which can be used for renewal of track during short maintenance breaks. Figure 44 shows the principle of this system.

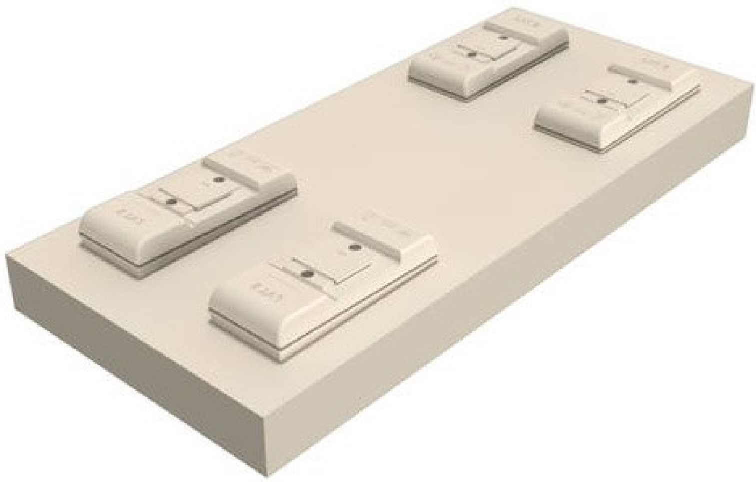


Figure 44 Illustration of LVT Panel system (Sonneville AG, 2019b)

LVT SE (for severe environment) – this version is equipped with a rubber gasket which fixes the rubber boot to the concrete block. The rubber gasket also prevents the penetration of fine particles and liquids into the rubber boot. Figure 45 shows the system installed in a washing depot in England.

Figure 45 Picture of LVT SE system (Sonneville AG, 2019b)

5.2.4 Production and installation

Sonneville AG is a system provider, and the patented blocks are produced locally in factories in the actual countries where the track is being laid.

The LVT system is mounted "top-down". This ensures correct track geometry by temporarily positioning and adjusting the track before pouring in the concrete. The pictures below show that this can be done in different ways. Figure 46 shows Rhomberg Bahntechnik AG's installation method. The installation speed depends on many parameters, such as man power, equipment, accessibility, experience of contractor, track section dimensions and more. In Europe, Sonneville claims that the installation speed of the superstructure is in the range of 80 – 220 metres per day (Laborenz, 2019a). Installation quality is good. Sonneville claims to achieve a gauge accuracy of ± 0.5 mm (Sonneville AG, 2019b).

Figure 46 Installation of LVT by Rhomberg Bahntechnik AG (Sonneville AG, 2011)

Figure 47 shows installation procedure using installation bars.

Figure 47 Installation of LVT system (Sonneville AG, 2011)

5.2.5 Transition zone between slab track and ballasted track

For the LVT system, the transition zone between slab track and ballasted track are designed especially for every project. The transition zone can be designed in several ways, e.g. with varying distance between sleepers, adjustments in stiffness for the elastic under sleeper pads, with ballast mats, using ballast binder, using auxiliary rails etc. Sonneville AG informs that there are examples of transition zones for the LVT system available, see example in Annex 1.

Sonneville AG informs that different transition designs are available as clients have slightly different ideas and requests. For Swiss Federal Railways the favourite solution is with additional rails in the centre of track. Others prefer gluing of ballast in the transition zone, installation of under ballast mats, under sleeper pads etc. The design depends on the project conditions (Laborenz, 2019b).

5.2.6 Maintenance aspects

An important advantage with the LVT system is that you can easily replace concrete blocks and rubber boots seeing as they separated from the concrete slab by the rubber boots.

If an LVT component requires replacement or if vertical adjustment becomes necessary, the following procedure applies (Sonneville AG, 2019a):

1. The rail fastenings are released over a length of approximately 10 m (30 ft) on both sides of the work area.

2. The rail is lifted with two or more (depending on the length of the work area) standard rail jacks as shown or equivalent equipment, the affected concrete blocks remaining fastened to the rail (Figure 48).

Figure 48 Lifting of rail LVT system (Sonneville AG, 2019a)

3. Once the base of the concrete blocks clears the track concrete by a maximum height of 200 mm (8 in), the rail is secured in place (Figure 49).

Figure 49 Lifted LVT supports (Sonneville AG, 2019a)

4.

- If a block pad or rubber boot needs to be replaced, that component is removed and substituted by a new one
- If a concrete block needs to be replaced, the corresponding cavity in the track concrete is covered with plywood, the rail fastenings are dismantled, the block is lowered onto the plywood and slid away, a new block is slid under the rail and the rail fastenings are re-assembled and tightened
- If vertical adjustment is required, shims of appropriate thickness are inserted under the concrete blocks (over the block pads) up to a maximum adjustment height of 25 mm (1 in).

5. The rubber boots are pulled up onto the concrete blocks and secured in place.

6. The rail is lowered back into its original position.

In case of greater damage to concrete slab, there is a challenge on doing a repair as quick as possible, seeing as the entire slab will have to be replaced. LVT has developed LVT Panel as presented earlier, for replacing damaged slab faster than by concreting the entire slab, but one still must demolish the broken slab before installing LVT Panel slabs.

5.3 ÖBB-PORR Slab Track Austria

5.3.1 System development

This system, also referred to as Slab Track Austria, was developed through a cooperation between Österreichische Bundesbahnen and Allgemeine Baugesellschaft – A. Porr AG. This system has been the standard slab track construction in Austria since 1995, and since 2001 it has been built in Germany as well. The oldest section, a 264 meter long test-track in Langenlebarn, has been in operation since 1989 without ever requiring panel replacement due to failure of the slab track system (PORR Bau GmbH, 2016), see picture in Figure 50.

Figure 50 Langenlebarn – First Installation PORR Slab Track System in 1989 (Pichler & Floh, 2016)

Slab Track Austria is in use in tunnels, on bridges and on earthworks.

The system is tested and in use in Germany and Austria for operating speed over 300 km/h. Test results indicate that the system is suitable for speed for at least 350 km/h. In Germany, the system is authorized for use on high-speed lines, with no speed limitation. The system was also licensed for use in Switzerland from 2007 (Rudolph Schilder, 2007), and other European countries after this.

5.4.2 Reference projects and future projects

The ÖBB-PORR system have been applied for over 781 km of railway lines around the world, from 1989 to 2018 (PORR Bau GmbH, 2019a). Up until 2010, it was only built in Austria and Germany. From 2010 it has also been built in Slovenia, The Czech Republic, Slovakia, UK and Qatar.

The first long railway project built partly on earthworks, was By-Pass Melk in Austria (8.6 km long). It is a high-speed line consisting of Wachberg tunnel, Melker tunnel, bridge and earthworks, with a light mass spring system. It was opened in 2000 with a speed of 200 km/h. Figure 51 shows pictures of this line under construction.

Figure 51 Westbahn By-pass Melk, Austria (Pichler & Floh, 2016)

The ÖBB-PORR system is used in the build of the currently longest railway project undergoing construction now (as of May 2019). It is called VDE 8 (German Unity Transport Project 8), and it connects Berlin and Munich. The system is built in tunnels, on bridges and on earthworks. Figure 52 shows a typical cross-section with the ÖBB-PORR system built on VDE 8 on earthworks.

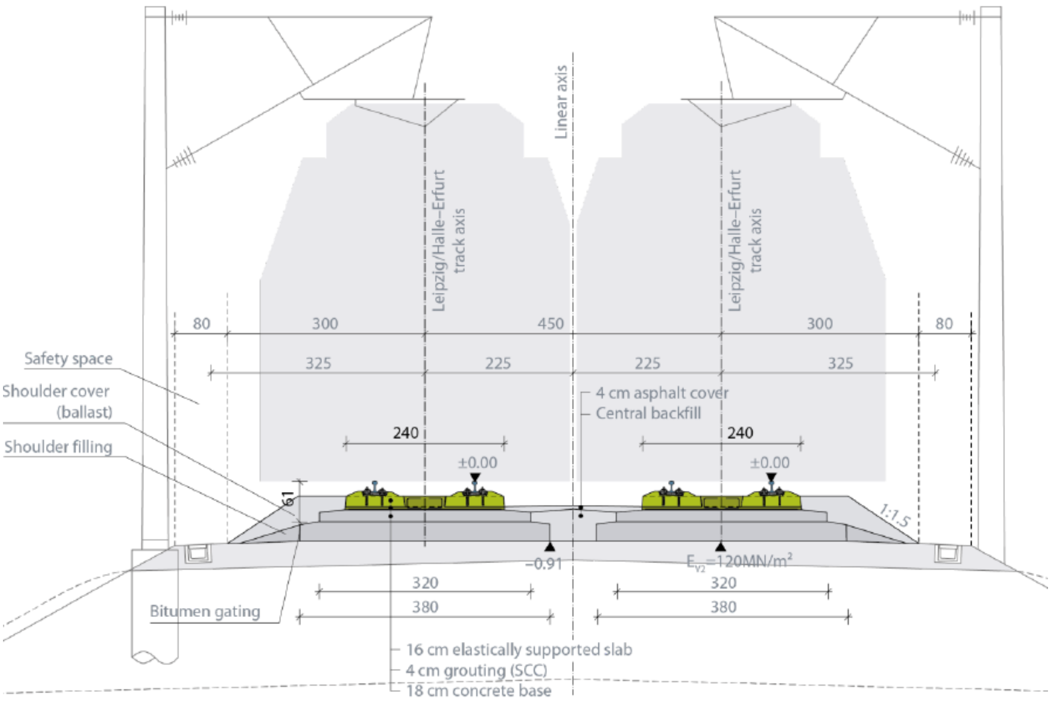


Figure 52 Cross-section and picture ÖBB-PORR on earthworks, high-speed line VDE 8 (Pichler & Floh, 2016)

5.3.3 Track superstructure

Construction:

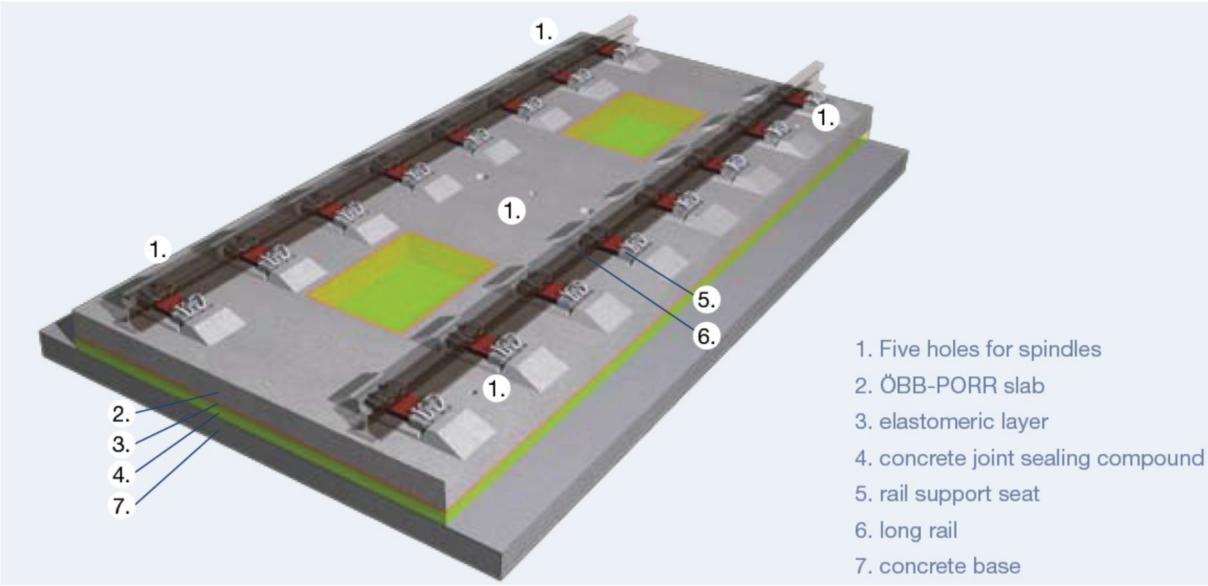


Figure 53 ÖBB-PORR Slab (PORR Bau GmbH, 2016)

The principle of the system is elastically supported prefabricated concrete slabs. The slabs are untensioned reinforced precast slabs with integrated rail support seats. Under the bottom of the slabs, as well as in the tapered openings, sits an elastomeric layer (as seen in Figure 53 with red colour). The result is double-layered elasticity, reduction in vibrations or structural-borne noise, and decoupling from its structural supports. A joint width of 40 mm separates the slabs from each other and compensate any deformations caused by creeping, shrinking or temperature changes. The joints serve also as surface water drainage or spaces for cable-crossing. The slabs are supported and fixed on a thin base layer of self-compacting concrete (SCC), shown with green colour in Figure 53. This allows homogeneous setting, and without the need to vibrate the concrete reduces disturbances of final track alignment to a minimum (PORR Bau GmbH, 2016).

The slabs measure 5200 mm in length and 2400 mm in width. Figure 54 and Figure 55 shows the slab in cross-section and plane. The system is tested and approved for Vossloh and Schwihag fastenings, and it is possible to adjust for other fastenings such as Pandrol.

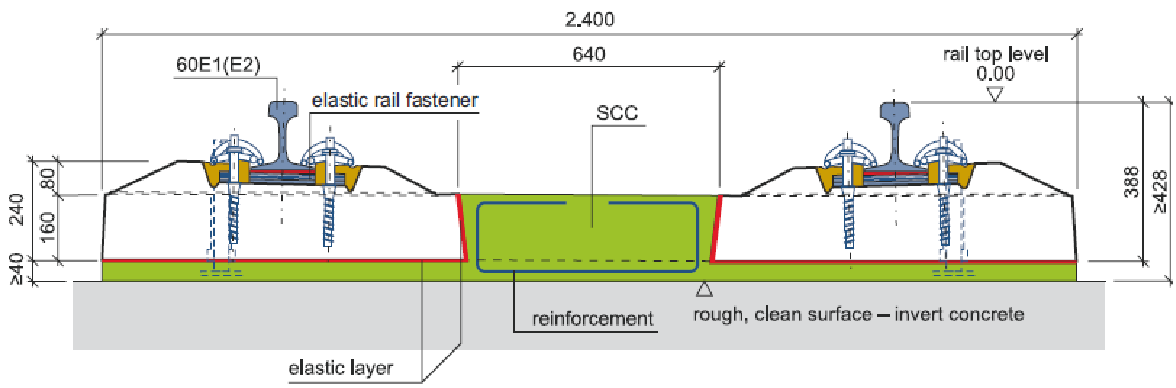


Figure 54 Cross-section of the ÖBB-PORR system

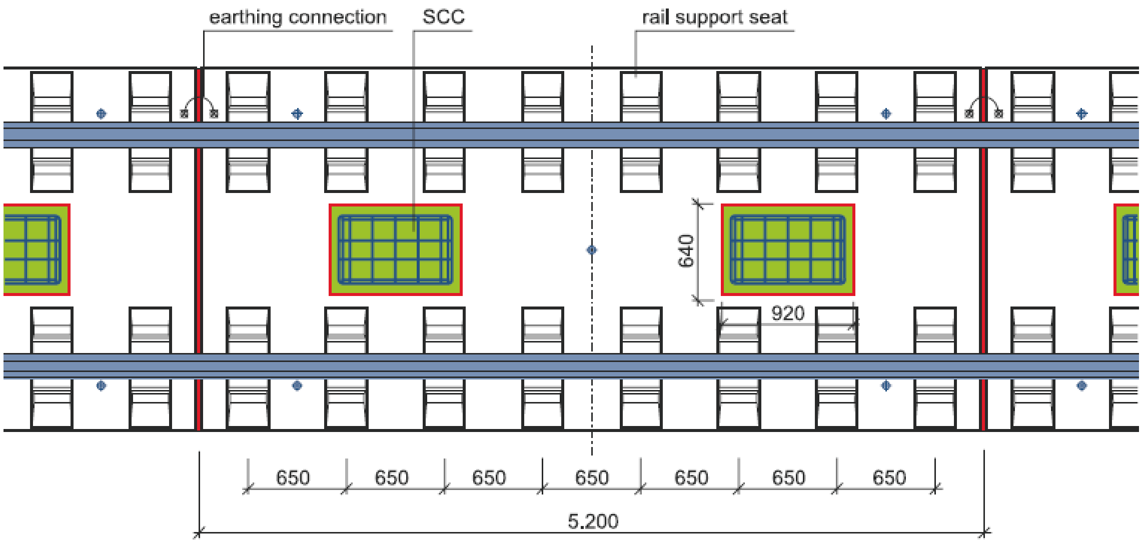


Figure 55 Plane of the ÖBB-PORR system (PORR Bau GmbH, 2016)

<u>Inclination and superelevation:</u>

The ÖBB-PORR system has been built on high-speed railway lines with 300 km/h which demands superelevation of up to 180 mm. There are no limitations in the system for building different inclination and superelevation, only in regulations (Avramovic, 2019).

<u>Gradient:</u>

There are no limitations in the system for maximum gradient, it depends on the project in question. One of the projects with a steep gradient where the system has been installed is the Queen Street Tunnel in Glasgow, Great Britain, with 2,5% gradient (Avramovic, 2019).

<u>Minimum radius:</u>

Slab track panels can be constructed down to very small radii. The system has been applied on projects with radii of 180 m, but smaller radii is possible (Avramovic, 2019).

<u>Drainage:</u>

The joints between the panels serve as surface drainage. Further drainage is supplied by the substructure.

<u>Versions:</u>

The ÖBB-PORR panels can be reduced to 2.1 m width and 43 cm track height from top of the rail.

The ÖBB-PORR system has designed special slabs for switches and crossings, including openings for switch boxes, and the system has many additional equipment which can easily be fitted, such as noise absorbing plates, accessibility plates, buffer stops, track magnets and guard rails (PORR Bau GmbH, 2016).

The ÖBB-PORR system can be combined with mass spring system (floating slab track), which further increases attenuation and reduces vibration. The design can be varied from lightweight to heavyweight mass spring systems through installing elastomeric sheeting layer, elastomeric strips or point-loaded bearings (PORR Bau GmbH, 2016)

5.3.4 Production and installation

The slabs are manufactured in a prefabrication factory or at a project-specific factory. Production is therefore independent of weather conditions.

The steel moulds used to produce the slabs are adjustable to cover all radii required. It is also possible to reduce the length of the panels, add extra openings, coatings and plugs, all with millimetre precision.

Each produced slab is labelled with bar code and can be identified throughout the process until installation. Figure 56 and Figure 57 shows production in factory, with steel moulds and finished slabs in storage.

Figure 56 Production facility with steel moulds (PORR Bau GmbH, 2016)

Figure 57 Finished slabs in storage (PORR Bau GmbH, 2016)

Correct and secure installation of the slabs are secured by following these steps (PORR Bau GmbH, 2016):

- Surveying of setting out points
- Placement of reinforcement and cross drainage pipes on the track foundation
- Transportation of slabs to installation site to intermediate placement to accuracy of ± 1 cm (Figure 58 nr 1 and 2). Laying of the track base plates is normally done with portal cranes, but in case of missing track connection the laying of the track base plates is performed by a truck with a loader arm
- Placement of long rails and track adjustment (Figure 58 nr 3), the final track calibration is performed by using spindles
- Installation of side formwork
- Concreting with self-compacting concrete (Figure 58 nr 4)
- Final track adjustment

Figure 58 nr 5 shows finished track on earthworks.

Figure 58 Installation of the ÖBB-PORR system (Pichler & Floh, 2016)

Installation speed varies depending on access points to site, access roads and logistics. PORR informs that the peak installation rate was 500 m/day per team when installing the ÖBB-PORR system on earthworks on the high-speed project VDE 8 in Germany. The average construction rate in single track tunnels on that project was about 250 m/day (Avramovic, 2019).

After measuring installed track, it is shown that 99% of installed track is within accuracy of ± 1 mm for planned position, 95% of the track is within ± 1mm for planned superelevation (Pichler & Floh, 2016).

5.3.5 Transition zone between slab track and ballasted track

The ÖBB-PORR system has solutions available for building transition zones. Transition areas from ballast to slab track are carried out according to the Catalogue of Specifications for Slab Track or in accordance with the ÖBB regulation RZ no.17220. The ballast area is strengthened in sections by using synthetic resin (PORR Bau GmbH, 2016).

Figure 59 shows an example of a transition zone with the system. From left it shows the ordinary elastically supported slab, then 4 pieces of a special transition slab (10.4 m), then ballasted track with 25 pieces of prestressed concrete sleepers (15.0 m), then 20 pieces of turnout concrete sleepers (12.0m). In addition, auxiliary rails are added, and ballast is fully glued for 7.2 m and partially glued for 22.8 m. Total length of the illustrated transition length is 37.4 m.

A more detailed version of this transition zone can be found in Annex 2.

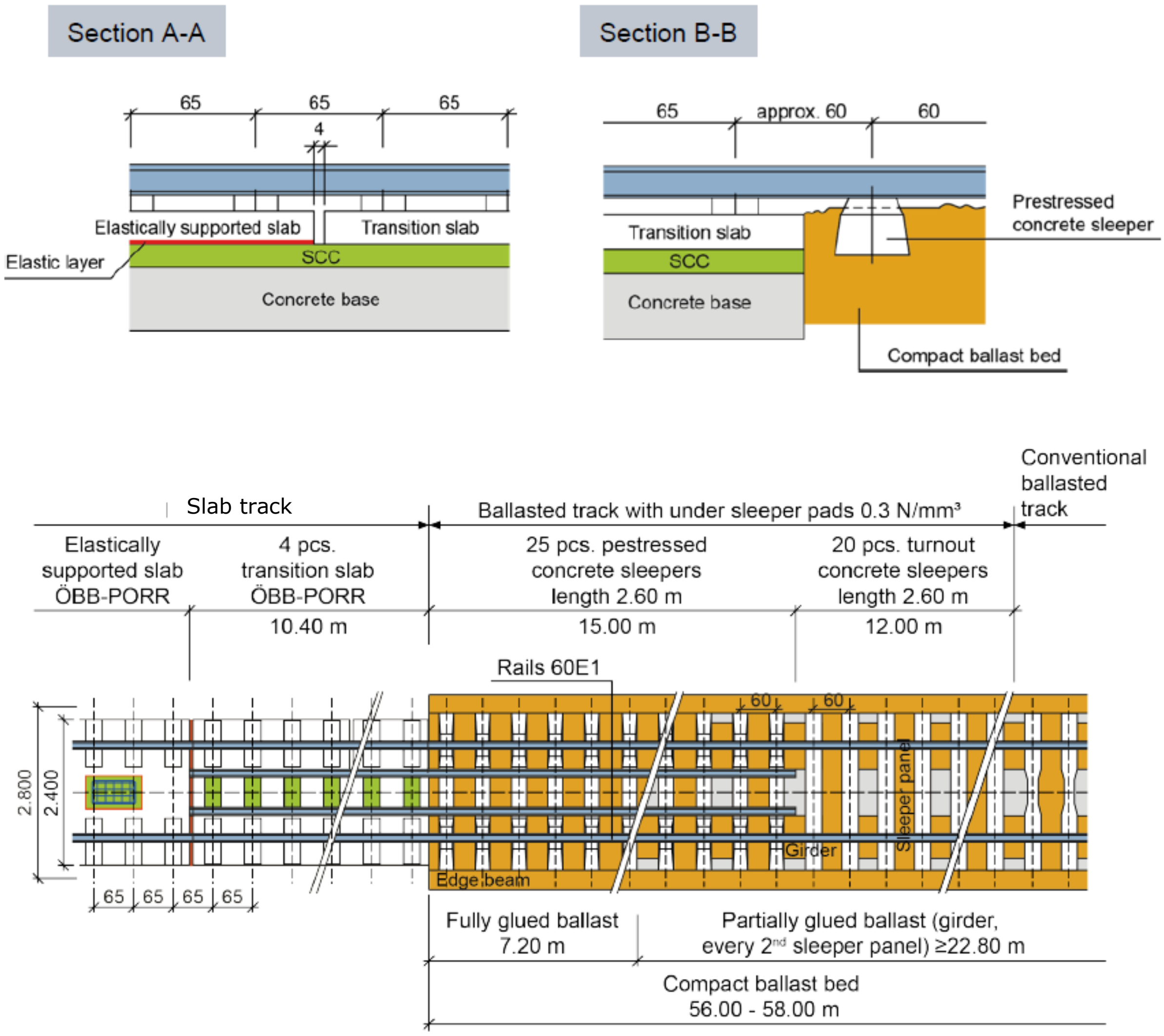


Figure 59 Example of transition zone with the ÖBB-PORR system (Pichler & Floh, 2016)

5.3.6 Maintenance aspects

In case of differential track settlement, track adjustment can be performed. There is a limited possibility of adjustment of the fastening system. If the required adjustments exceed the maximum adjustments of the fastening system, can be made by manipulating the track base plates themselves. There is no upper limit for adjustment of settlements (PORR Bau GmbH, 2013).

This is performed by the following method (PORR Bau GmbH, 2019b):

- The concrete locking the slabs in place is removed from the tapered slab openings in order to allow the decoupling of the panels
- Track base plates level is adjusted by using the spindles to lift the plates to the correct new position
- Side formwork is placed
- Concrete is poured to fill up the gap between the plate and the settled base and to lock the plates back in place
- Adequate strength is achieved within 24 hours

In case of derailment, repair or replacement of panel can be performed. In cases where damage is limited to rail support concrete shoulder and the fastening system, this is easy to repair. To repair such damage the rail, fastenings and rail pads are removed. Special formwork is placed over supports and grouting concrete is poured to cast new rail supports, as shown in Figure 60. It is possible to use a special grouting concrete which hardens only in a few hours, to reduce repair time and get the track operational quickly.

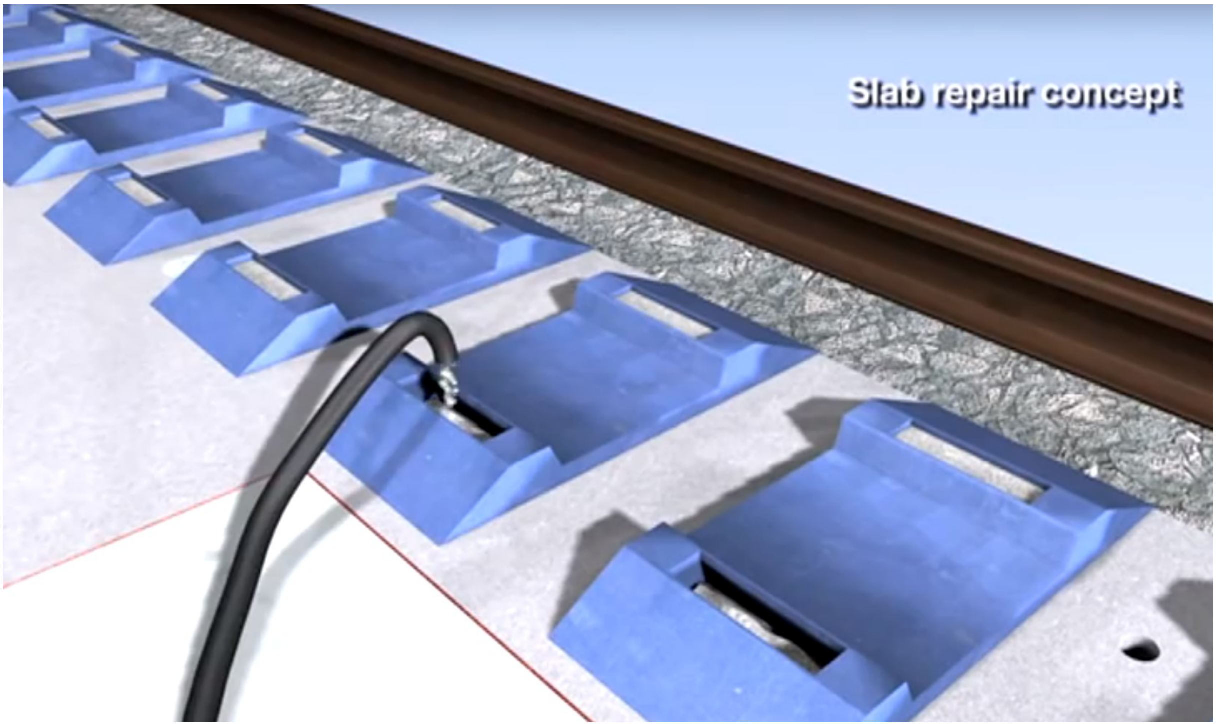


Figure 60 Repair of support shoulder with special formwork (PORR Bau GmbH, 2013)

In case of damage to the track base plates, these can be replaced. The elastic layer separates the slab from the self-compacting concrete. Concrete locking the track base plates in place can be removed from the openings, therefore allowing the plates to be easily lifted and replaced within three to four hours. There is a record of replacing 50 metres of track base plates in as little as 10 hours (PORR Bau GmbH, 2013).

5.4 Rheda 2000

5.4.1 System development

The predecessor of Rheda 2000 is a track design first implemented in 1972 on the line from Bielefeld to Hamm, Germany, at a station named Rheda. The track at Rheda station is the first slab track to be built on earthworks. The principal structure of the Rheda Classic system is shown in Figure 61. Above the substructure is styrofoam concrete, functioning as isolation and support layer. Then a layer of reinforced concrete, before the sleepers are laid and adjusted in to permanent position, then cast in with concrete. The track at Rheda station has had a practical function as a pilot project which has been further developed and optimized, without a change in basic principles.

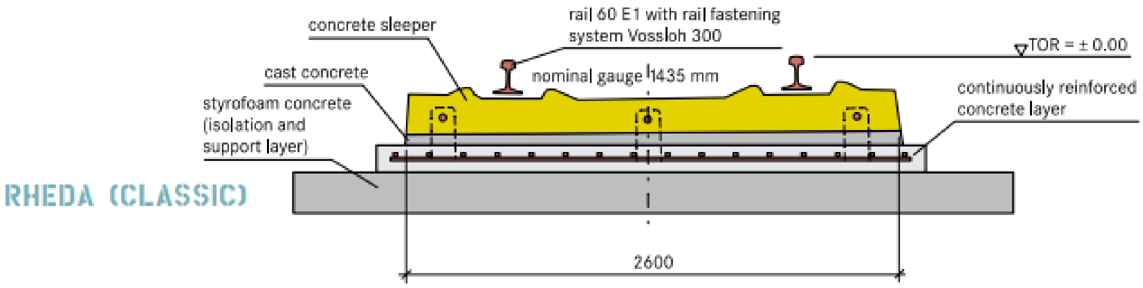


Figure 61 Cross section of original Rheda track system (RAIL.ONE GmbH 2018)

In the following years after 1972, the Rheda system underwent a development and gained modifications, most importantly introducing an integrated bi-block lattice-truss sleeper.

The Rheda 2000 system was first built in Germany in 2000, as a pilot project with a length of approx. 1,000 m., on a new rail line between Erfurt and Halle-Leipzig. Thereafter it was installed on a 3 km long section.

5.4.2 Reference projects and future projects

On account of promising experiences with planning, building, operation and maintenance of these pilot projects, Deutsche Bahn decided to use the Rheda 2000 system on the high-speed line between Köln and Frankfurt Am Main (finished 2002). In addition to this, 75 km of Rheda 2000 system was built on the new line between Nuremberg and Ingolstadt (finished 2006) (RAIL.ONE GmbH 2018).

One of the largest railway projects so far in Europe, is the high-speed line HSL-ZUID (opened 2009). It is an over 100 km long double track railway from Amsterdam, via Rotterdam, to the Dutch-Belgian border. With the exception of a short section, the entire line is constructed with Rheda 2000 (RAIL.ONE GmbH 2018).

Rheda 2000 was launched in Asia in 2004, with application of the system in new construction of the high-speed line from Taipei to Kaohsiung, in Taiwan. 80 km track and 115 turnouts were built with Rheda 2000. The double track passenger-dedicated line (PDL) from Wuhan to Guangzhou in southeast China was built almost entirely with Rheda 2000. It has a length of nearly 1,000 km and opened December of 2009 at a speed of 350 km/h (RAIL.ONE GmbH 2018).

As of 2019, more than 3500 km of track has been built with the Rheda 2000 system (RAIL.ONE GmbH, 2019).

5.4.3 Track superstructure

Construction:

According to the producer, Rheda 2000 is a flexible system that can be individually adapted to the specific requirements and the individual limitations of each project. The basic system structure, however, always consists of modified bi-block sleepers which are embedded in a monolithic concrete slab with longitudinal reinforcement. Elastic rail fastenings achieve the vertical rail deflection required for load distribution and smooth train travel. Figure 62 shows Rheda 2000 on earthworks.

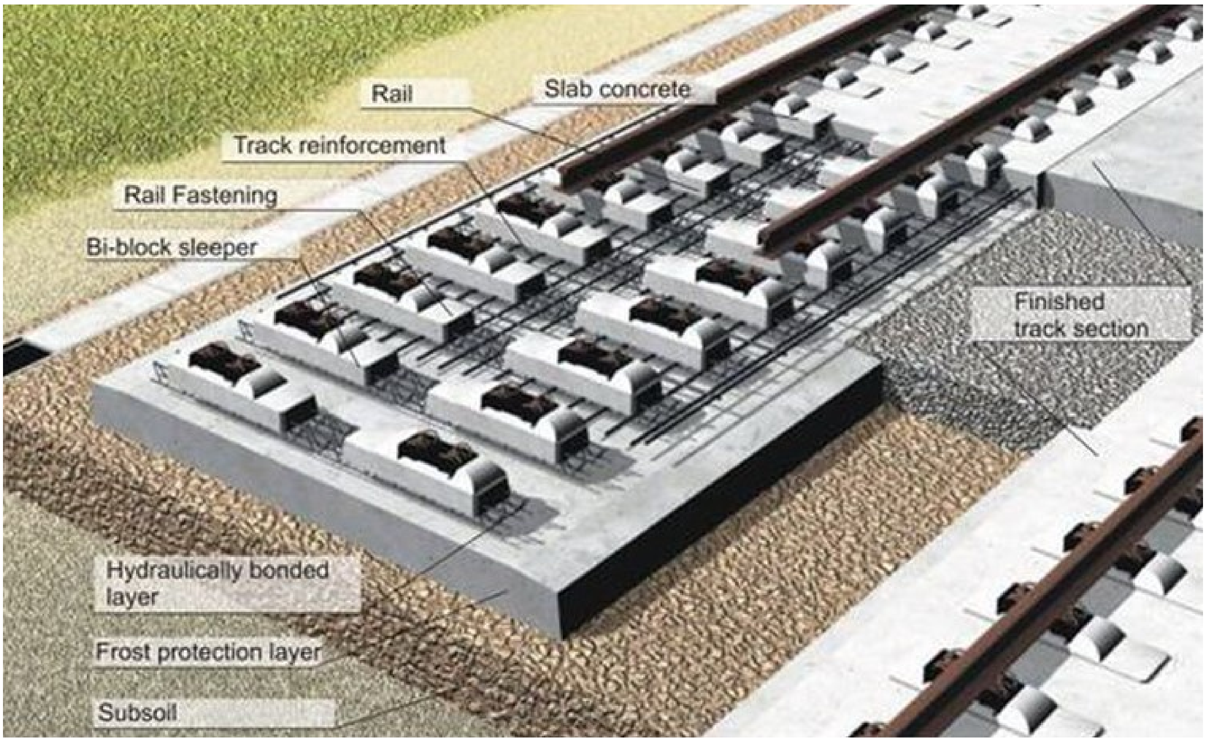


Figure 62 Rheda 2000 on earthworks (von Glasenapp, 2019)

The B 355-M sleeper represents the core of the Rheda 2000 system. These precast sleepers are mass produced. The most commonly used fastenings for the Rheda 2000 system are Vossloh and Pandrol, but the concrete blocks can be individually designed to enable use of all conventional elastic fastening systems and anchor fittings. The lattice truss track reinforcement is needed to limit the cracks in the monolithic concrete slabs due to shrinkage (RAIL.ONE GmbH 2018).

The concrete slab is the primary load-distributing element of the system. Since it is cast-in-place, it can be individually adapted to any type of substructure and other conditions. For earthworks, it is designed as a continuous slab with free crack formation. For highly compacted soil – which is strongly advised for slab track to prevent settlement – the slab can be constructed in unit dimensions of 2.8 m x 0.24 m. To assure the required durability, the minimum strength of the concrete layer must be 30/37 MPa (cube/cylinder) (RAIL.ONE GmbH 2018).

The Rheda 2000 system has a degree of flexibility. The basic structure is as mentioned bi-block sleepers in a concrete slab cast-in-situ. The system can be changed to adapt to different types of sub-grade, structural-engineering requirements, rail-support conditions, as well as improved installation processes.

On earthworks, an additional bonded support layer – often a hydraulically bonded layer – is installed in order to conform to the permitted levels of stress in the supporting layers and on the substructure (RAIL.ONE GmbH 2018).

Tunnels have a much higher rigidity of the tunnel flooring. Therefore, no additional track supporting layers are required. The concrete track-supporting layer is installed directly onto the track substructure. Further optimisation measures are possible both in the concrete layer-thickness as well as in the content of reinforcement (RAIL.ONE GmbH 2018).

Inclination and superelevation:

The limitations in terms of inclination and superelevation are resulting out of the alignment, usually a maximum superelevation of 180 mm on high speed lines. The construction of a track with this superelevation is difficult as it is a challenge to handle in-situ concrete in a quite steep slope. RAIL.ONE informs it has been built in the past, hence it is manageable (Pieringer, 2019).

Gradient:

RAIL.ONE informs that there is no limit in terms of gradient (Pieringer, 2019). It can propose a challenge during installation, when you need to keep the in-situ concrete where it should be. This requires a good concrete quality and special formwork.

Minimum radius:

In terms of the minimum radius there are no limitations in the system. The limitations lie in the regulations.

Drainage:

The system allows for flexible arrangement of track drainage, an example of drainage system with a Rheda system is shown in Figure 22 in chapter 4.6 Drainage.

Versions:

Turnouts are possible with special turnout sleepers.

The system offers different solutions to prevent derailment, see Figure 63 and Figure 64.

Figure 63 Derailment equipment Rheda 2000 (von Glasenapp, 2019)

Figure 64 Derailment equipment Rheda 2000 on the HSL Zuid line (von Glasenapp, 2019)

The system offers a road-vehicle access system, primarily for use in tunnels (since European safety regulations stipulate that access for vehicles must be ensured in railway tunnels for all types of road vehicles). This can be installed directly onto the track and can be used for up to 10-tonne axle loads. These are shown in Figure 65.

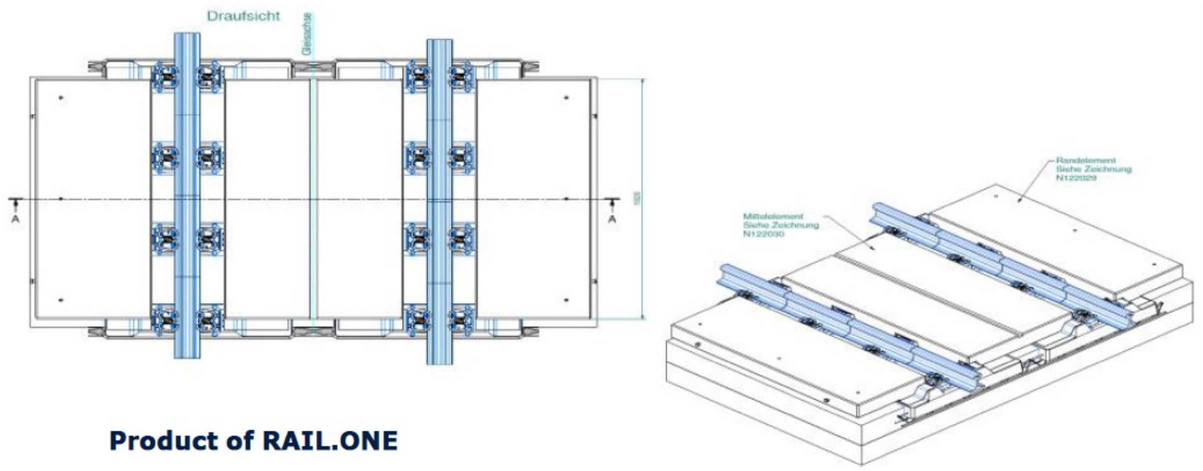


Figure 65 Vehicle access system (von Glasenapp, 2019)

Special prefabricated noise absorber elements are available, see Figure 66. These can cover half or entire track, as illustrated.

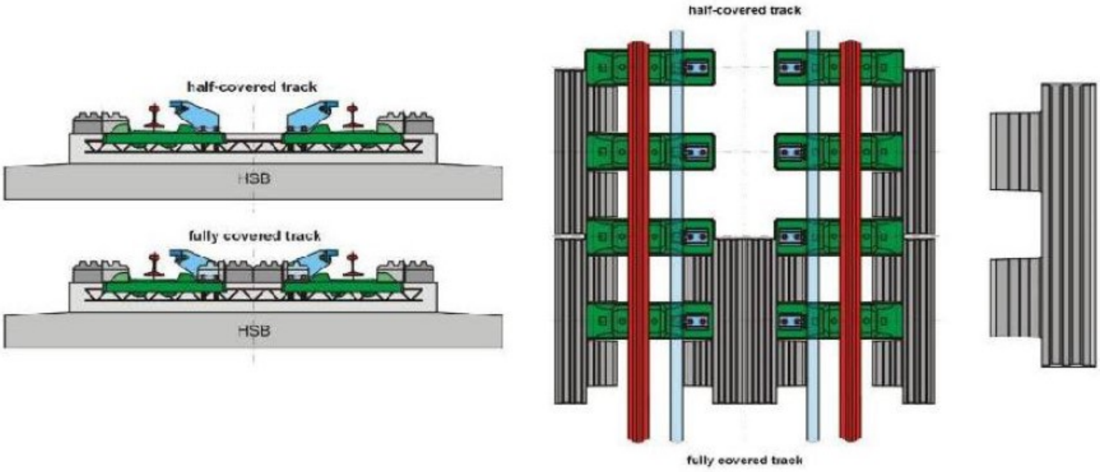


Figure 66 Prefabricated noise absorbing elements for Rheda 2000 (von Glasenapp, 2019)

The most recent development stage of Rheda 2000 consists of a non-reinforced concrete supporting layer with controlled formation of cracks. This system was approved in Germany in 2006. This track system features provision of lateral dummy joints that enable controlled formation of cracks in the concrete track-supporting layer. These joints are sealed to prevent the intrusion of water. The transfer of lateral forces, previously enabled by aggregate interlock, is now provided by bolt anchors. Furthermore, the higher concrete quality C35/45 can be used, instead of concrete quality C30/37 usually employed. This achieves greater resistance to frost, which in turn leads to longer life cycles. Ballastless track without continuous reinforcement can be executed either with or without a hydraulically bonded layer. Without the extensive lateral reinforcement, the installation process is shortened and the costs are reduced (Kleeberg, 2009). See Figure 67 and Figure 68 for illustration. The system has been applied in Guadarrama Tunnel in Spain (opened 2007).

Figure 67 Rheda 2000 as installed, with controlled crack formation

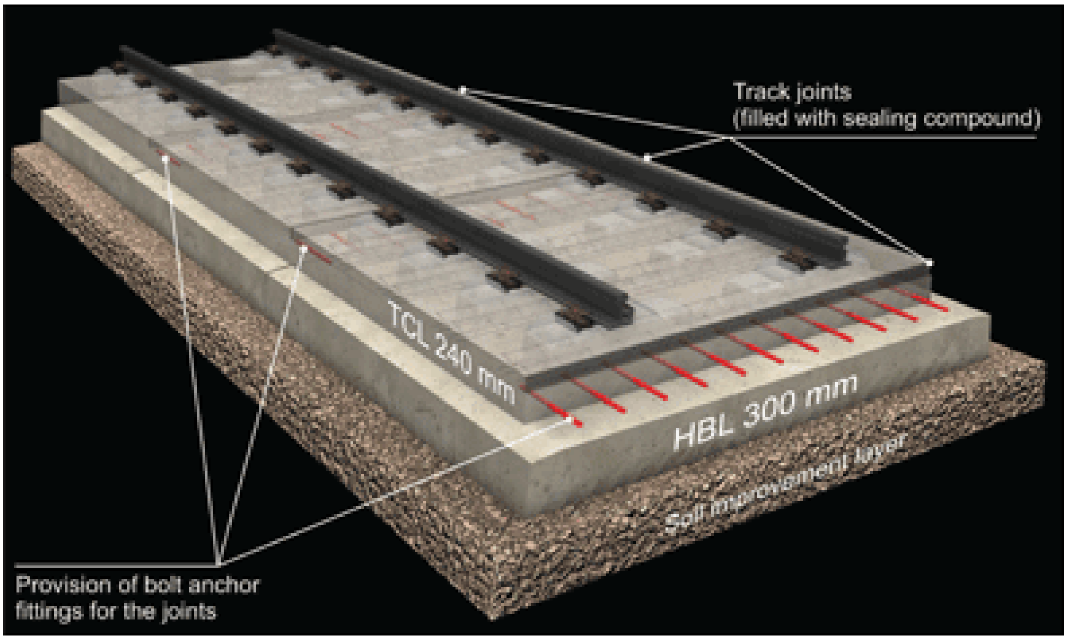


Figure 68 Rheda 2000 with controlled crack formation, on HBL-layer

5.4.4 Production and installation

The precast bi-block sleepers for the Rheda 2000 system are produced locally near project facility or in especially constructed production plants on site. This means that transport costs to site are reduced. Gauge accuracy is secured by high quality prefabricated bi-block sleepers, produced according to EN 13230-3[15].

The Rheda 2000 system is installed top-down. The installation follows these steps (RAIL.ONE GmbH 2018):

- Preparation of the substructure, including placing of the frost protection layer and the hydraulically bonded layer
- Assembly of the track panel, either on site or pre-assembled, including placing reinforcement, placing single sleepers and installation of track reinforcement and installation of rail
- Lifting and rough alignment of the track panel, either manual or automatic
- Installation of the track formwork, either manually manufactured formwork (timber), pre-fabricated formwork elements (steel) or pre-fabricated formwork system elements with rails for construction vehicles
- Final alignment of the rail, vertical, for superelevation and horizontal using the spindle brackets
- Placing of the track concrete, either manual or automatic
- Supplementary working steps, including watering concrete etc. and loosening rail fastenings to avoid stress in unset concrete

Seeing as the Rheda 2000 system is installed both on earthworks, in tunnels and on bridges, there has been developed different installation strategies to adapt to the different conditions. Inside a tunnel or on a long bridge, it may be complicated to plan the logistics of building the slab track most efficient, seeing as there is only two points of entry to the building site.

[15] EN 13230-3 Railway applications - Track - Concrete sleepers and bearers - Part 3: Twin-block reinforced sleepers

On earthworks out in the open it might be more space and easier access to the building site. When building double track, it is possible to access the track currently being built via the neighbouring track which is not yet built. This may rationalize the installation of the track so you may build up to 250-300 meter of track per day, depending on work shifts. If it is possible to build during night time with 24-hour production, it is possible to build up to 500-600 meter of track per day. This all depends on the location of the track, access points for concrete trucks and other material which is needed on site (Pieringer, 2019).

5.4.5 Transition zone between slab track and ballasted track

According to RAIL.ONE, the transition zones are planned especially for each project but there are some details which apply for most projects. Figure 69 shows a picture of transition zone built with the Rheda 2000 system.

Figure 69 Picture of transition zone for the Rheda 2000 system (RAIL.ONE GmbH 2018)

The transition zone for Rheda 2000 consists of several measures to adjust the stiffness of the fastening and the ballast. As a rule, it includes gluing the ballast and extending the hydraulically bound layer. In addition, one uses pre-stressed sleepers with elastic fastenings in the ballasted track. These measures increase the rigidity of the ballasted track. As shown on Figure 69, it is also possible to use auxiliary rails on the ballasted track to help equalize the differences between track systems (RAIL.ONE GmbH 2018).

Annex 3 illustrates a typical transition zone of the Rheda system. The transition zone illustrated is about 20 meters long, and will not satisfy the requirement of length set in Bane NOR's Technical Regulations for transition zones for railway line with speed of 250 km/h (Bane NOR, 2019f), but as mentioned above, the transition zones are planned especially for each project, and adapted to the national requirements.

5.4.6 Maintenance aspects

This system is developed in Germany, where the principle is that the substructure is settlement free. There are no other adjustment possibilities for this system than what is possible to adjust in the fastenings.

Until now, no derailment on the Rheda 2000 system has required full replacement of the track slab. There have been fires in trains causing damage to slab track, and it is challenging to evaluate the amount of damage and decide on the correct amount of repairs needed (Pieringer, 2019).

Derailment which result in damages that are limited to the fastenings or sleeper shoulder can be easily repaired. To repair damage to the sleeper shoulder, the same procedure as for the ÖBB-PORR system is performed. The rail, fastenings and rail pads are removed. Special formwork is placed over supports and grouting concrete is poured to cast new rail supports. It is possible to use a special grouting concrete which hardens only in a few hours, to reduce repair time and get the track operational quickly.

In case of greater damage to concrete slab because of derailment or settlement causing damage, there is a challenge doing a repair as quick as possible, seeing as the entire slab will have to be replaced. There is no quick solution available for this.

6 Systems evaluation

This chapter contains an assessment and evaluation of the main topics related to applying slab track on earthworks. It sums up international best practises for slab track on earthworks with focus on topics especially relevant to Norwegian conditions. The three selected slab track systems described in chapter 5 are benchmarked and evaluated according to chosen criteria for applying slab track on earthworks in Norway.

6.1 International best practises to building slab track on earthworks

<u>Development</u>

The need for a more solid track construction in tunnels and bridges and the need for a track with high availability, initiated the development of slab track as we know it today.

Slab track is defined as track constructions built up by a slab of concrete with rails attached to this, either with embedded sleepers or other type of fastening. There are several different types of slab track, and important factors to differentiate the systems are;

- Type of rail support
- With or without sleepers
- Cast in-situ or prefabricated
- Installed top-down or bottom-up

The slab track systems that have been applied on high-speed lines on earthworks, and have the highest total length applied in the world (listed in Table A in chapter 2.2 Historical development) are Bögl, LVT, Rheda 2000, Shinkansen J-Slab, Züblin and ÖBB-PORR. All these systems have discrete rail support. Bögl, Shinkansen J-Slab and ÖBB-PORR are precast systems without sleepers and Rheda 2000, LVT and Züblin are systems cast in-situ with sleepers.

Advantages with slab track are:

- Low maintenance need
- High availability
- Long lifetime
- Reduced structure height and weight
- High accuracy in track geometry
- Increased transverse resistance
- No problems with ballast flight

There have been two types of approaches to applying slab track on earthworks around the world. As explained in chapter 2.3 Slab track on earthworks, In Germany, slab track was first built on earthworks (from test-section in 1972), and thereafter on solid substructure as bridges and tunnels. In Austria, a test-section on earthworks with the ÖBB-PORR system was built in 1989, and in 1992 it was built in Tauern tunnel and thereafter on bridges and in more tunnels (PORR Bau GmbH, 2019a). In other countries, such as Japan and China, slab track was first built in tunnels and on bridges, and thereafter on earthworks. In Switzerland, slab track has mainly been built in tunnels and on bridges.

In Germany, the aim is to build consequently with the same track system throughout the planned projects. In China and Japan, slab track is used consequently on many new railway lines, and this seems to be a strategy also in these countries.

Many of these railway lines built with slab track can show to practically maintenance free lifetime so far. This is of course only possible with settlement-free subgrade.

In Norway, the first railway lines with slab track are being built in tunnels, on the Follo line and Arna – Bergen line. As of 2019, we are following the same approach as in Switzerland, Japan and China. As mentioned in chapter 3.2 Bane NOR's Technical Regulations, it is as of May 2019 only permitted to build slab track in tunnels and on bridges in Norway. In 2020, the newly built tunnel with slab track on the Arna – Bergen line will open, and in 2021, 20 km of double track slab track will be opened in Norway on the Follo line. Both projects are applying the Rheda 2000 system.

Technical Regulations in Norway does not currently permit to build slab track on earthworks, but there is a process going on in Bane NOR to revise the Technical Regulations for slab track, and the sanctioned changes are planned to be adapted from August 2019. The goal of this process is to move all demands for slab track from Technical Specifications to Technical Regulations. In addition, the Technical Regulations will to a greater extent refer to the standards EN 16432-1 and EN-16432-2. A big change that is being discussed is the possibility to permit to build slab track on earthworks between fixed structures, as tunnel and bridge, up to a distance of 1000 metres. Permitting this will give planners the opportunity to calculate and plan with one coherent system throughout new railway lines, in the UPB-process. This makes it easier to compare different slab track and ballasted track, when recommending track system. Both performing LCC-analyses and following the RAMS-process will be less complicated if the superstructure is continuous over a longer section.

<u>Benchmarking factors</u>

The benchmarking factors explained in chapter 4 Slab track benchmarking are rigidity, substructure, including poor soil conditions and settlements, drainage, frost, transition zone, noise and vibrations, construction, operation and maintenance and LCC.

Different slab track systems have different rigidity. In general slab track has lower elasticity than ballasted track, and to achieve the desired elasticity of the track, elastic rail pads and/or elastic under sleeper pads are applied.

Substructure for slab track must be free of settlements and heaving. To achieve this, there is a need for extensive examinations in advance of building, to be able to plan the required measures to obtain a satisfactory substructure. Chapter 4.3 Substructure describes different procedures necessary to secure enough information about the substructure. For extremely poor soil conditions, it is a possibility to reinforce the slab track construction as to act like a bridge over weak zones. This might be more cost efficient than reinforcing the substructure. Chapter 4.5 Settlements focuses on eliminating settlements, and especially the long-term settlements, which are challenging to calculate and predict. It is recommended to perform extensive preconsolidation measures to avoid long term settlements after commissioning of the track.

Another important factor in a country like Norway, is drainage. It is critical to ensure enough drainage of slab track systems. This will most likely require additional drainage compared to ballasted track.

Frost heaving is an especially critical problem for slab track. Slab track needs a rigid substructure, and frost heaving creates undesirable swelling in the substructure caused by water in the soil freezing to ice and growing in volume. The normal measures to avoid frost heaving are controlling the ground water level and controlling the number of fine particles in the substructure. These measures are sometimes not enough, and the frost goes deeper in the substructure than calculated or occur in embankments built up of coarse materials that are not theoretically frost susceptible. China has done and is undergoing research on this topic as the country has recently built new high-speed railway lines with slab track in very cold regions. They suggest different measure to control frost heaving, and one of them is that the replacement depth of A/B group fill should be equal or greater than twice natural freezing depth.

Use of transition zones is very important to ensure a stabile track construction and a smooth ride. This applies for both transitions between different substructures and for transitions between slab track and ballasted track. For transition zone between different substructures, there are no specific rules for designing this zone, there is a general rule that it shall be designed in a way to ensure gradual transition with respect to track geometry and track stiffness. For transition zone between slab track and ballasted track, the different slab track systems have different solutions, and the different countries have different preferences on what is applied. It is normal to gradually increase the stiffness of the ballasted track before the change to slab track. It is possible to increase the length of the sleepers, use auxiliary rails, glue the ballast, use an approach slab and/or improve the substructure.

Slab track has an average increase in noise of approximately 3 dB (A) compared to ballasted track. To mitigate this noise, frequent rail grinding is required and possibly further measures like sound absorbing panels in the slab track construction or conventional sound barriers along the railway line. In addition, slab track can generate increased vibrations that propagate in the ground below the slab track and to adjacent buildings and structures which can also give structure-born noise. Various solutions of using elastic fastenings, elastic rubber boot around and below sleepers or applying floating slab track (mass-spring systems) prove to have a good effect on reducing vibrations in the ground.

Method of installation will affect two parameters in particular; quality and speed (and indirectly cost) of build. Required quality of slab track is decided by the different countries regulations or specific for each project, and most slab track systems fulfil these demands. There have been developed new more efficient building methods for the different slab track systems over the latest decades, and average building speed vary, but can be up to 250 m/day.

Operation and maintenance for slab track includes all control activities, preventive and corrective maintenance during the track lifetime. For slab track, it is necessary to perform the same control activities to register the condition of the track as is necessary for ballasted track. There is a question of how often to control the track, and that the interval may be increased for slab track, but it is indicated that the same intervals are being used for both slab track and ballasted track as of today. In case of damage to track, there are different possibilities for repairs and replacement, depending on the slab track system in question. This is one of the benchmarking factors in the evaluation in chapter 6.3 Benchmarking of the selected systems.

Life cycle costs are an important factor in the UPB-process when selecting track system and when calculating total costs of a planned project. LCC include investment cost, cost for operation and maintenance, delay cost and hazard cost for the entire project. For slab track the investment cost is higher than that of ballasted track, and some claim this initial difference is so big that LCC for slab track throughout the lifetime will be higher than LCC for ballasted track. Others claim that for high speed railway, costs for slab track will after between 8 and 20 years be lower than costs for ballasted track. This is very much dependent on the size of the initial investment, as shown in chapter 4.12 LCC.

Based on this the previous findings, the most important factors with high influence on slab track performance on earthworks in Norway are substructure, drainage, frost, transition zone, installation and operation and maintenance. These factors will contribute substantially to the total LCC costs and overall performance of slab track on earthworks.

Analysed systems

To select systems relevant to Norwegian conditions with enough experience around the world, the following criteria were set for selection of systems to analyse:

- Total length built with system in the world > 500 km
- Both in-situ systems and precast systems are selected
- Only top-down systems are selected
- Only European systems are selected
- The systems must be previously applied on earthworks to be selected
- It is desirable with different maintenance possibilities for the different systems

After discussions with project supervisor, it was recommended to study these three different slab track systems; Low Vibration Track (LVT) from Sonneville AG in Switzerland, ÖBB-PORR Slab Track Austria (ÖBB-PORR) from Austria and Rheda 2000 from RAIL.ONE in Germany.

Total length built for the systems are:

- LVT: ~1400 km
- ÖBB-PORR: 780 km
- Rheda 2000: ~3500 km

The LVT system and the Rheda system are cast in-situ, and the ÖBB-PORR system is precast. The three systems are all installed top-down (or the intermediate solution for ÖBB-PORR). All three systems are of European origin, and previously applied on earthworks.

6.2 Evaluation methodology

This chapter describes the evaluation methodology for benchmarking of the three selected systems. This evaluation will be split in two parts. First, a qualitative evaluation will be performed, where the characteristics and qualities of the three selected systems are listed. Secondly, a quantitative evaluation will be performed to be able to rank the systems against each other.

The evaluation will follow these steps:

1. Define the purpose of the evaluation
2. Set criteria for the evaluation
3. Qualitative evaluation of the three systems based on set criteria for benchmarking
4. Quantifying and weighting of criteria against each other subject to relevance for Norwegian conditions
5. Quantitative evaluation of the properties listed from the qualitative evaluation

6.3 Benchmarking of the selected systems

This subchapter presents a qualitative and quantitative evaluation of the selected slab track systems.

6.3.1 Purpose of evaluation

The purpose of the evaluation is to benchmark the three selected slab track systems against the chosen criteria important for slab track on earthworks in Norway.

The goal is to identify how well adapted the selected systems are to Norwegian conditions, and if there is a difference between the systems and if one is better than the others.

6.3.2 Criteria for benchmarking

Criteria for benchmarking the three systems are selected based on the findings in chapters 2 Slab track development and 5 European best practises and what is highlighted as important requirements for slab track performance.

When selecting criteria for benchmarking of the three slab track systems, it is assumed that factors regarding substructure, soil conditions, settlements and frost are equal for all systems seeing as these factors are primarily connected to the substructure and not the superstructure of slab track.

The following criteria has been selected for benchmarking the three systems:

- Experience on earthworks
- Possible superelevation
- Gradient limitations
- Radii limitations
- Maximum design speed
- Adjustment possibilities
- Design change possibilities
- Installation speed
- Installation quality
- Noise and vibration
- Drainage solution
- Transition solution for the transition between slab track and ballasted track
- Maintenance aspects, including regular maintenance and repair concepts in case of accidents which cause damage to the slab track

These criteria have been chosen because the findings in chapter 5 indicate that there are some differences between the three selected slab track systems. The evaluation in the next subchapters is a way to systemize and illuminate the differences.

6.3.3 Qualitative evaluation

This chapter performs a qualitative evaluation of the selected slab track system against the selected criteria.

Below is Table C, which offers a qualitative evaluation of the three selected slab track systems based on the selected criteria from chapter 6.3.2 Criteria for benchmarking.

Name of system Criteria	LVT – Low vibration track	ÖBB-PORR Slab track Austria	Rheda 2000
Experience on earthworks	17 projects on earthworks, no high-speed lines	7 projects on earthworks, including high-speed lines	>10 projects on earthworks, including high-speed lines
Possible superelevation	180 mm has been built, is complicated because of handling in-situ concrete in slope	180 mm has been built, prefab makes it less complicated to cast on site	180 mm has been built, is complicated because of handling in-situ concrete in slope
Gradient limitations	None, depends on what is possible to install, steepest gradient built 8%	None, depends on what is possible to install, is within normal demands	None, depends on what is possible to install, is within normal demands
Minimum radii limitations	No limitation in system, only in regulations, smallest radii built under 50 m	No limitation in system, only in regulation	No limitation in system, only in regulation
Maximum speed in use all projects	250 km/h	300 km/h	350 km/h
Adjustment possibilities in addition to fastenings	Can be adjusted vertically up to 25 mm with inserting shims under concrete blocks	Can be adjusted by manipulating the track base plates	Not offered
Design change possibilities in addition to standard version	High attenuation version, switches and crossings, road vehicle access version, severe environment, guard rail	Switches and crossings, road vehicle access version, guard rail	Switches and crossings, rail expansion joints, derailment equipment, road vehicle access version, version without reinforcement
Installation speed	80 – 220 m/day in Europe, likely to be higher on earthworks because of better accessibility	250 m/day or 500 m/day depending on shifts per day	250 m/day or 500 m/day depending on shifts per day

Installation quality	Gauge accuracy of ± 0.5 mm, produced according to EN 13230-1	99% of installed track is within accuracy of ± 1 mm in position, and 95% of installed track is within accuracy of ± 1 mm in superelevation, gauge accuracy produced according to EN 13230-1	Gauge accuracy secured by high quality prefabricated bi-block sleepers, produced according to EN 13230-1
Noise and vibrations	Dual-level elasticity system is standard to reduce vibration, high attenuation system available No specially made noise reduction panels	Dual-level elasticity system to reduce vibration is standard to reduce vibration. Specially made noise reduction panels can be fitted, can be fitted with mass spring system	Single-level elasticity system standard. Noise absorber elements can be applied. Possible to fit with mass spring systems.
Drainage solution	The system allows for a flexible arrangement of track drainage, also in the track axis, built in-situ	Surface drainage in joints between panels, but less flexible than in-situ built systems	The system allows for flexible arrangement of track drainage, built in-situ
Transition solution	No standard solution, depends on project and country	Standard solution proposed, but also designed to each project and country	No standard solution, depends on project and country
Maintenance aspects	Easy to replace damaged supports, but substantial amount of work if slab itself is damaged, possible use of LVT Panel slab	Easy to repair limited damage on shoulders, also fairly easy to replace damaged slab panels	Easy to replace damaged supports, but substantial amount of work if slab itself is damaged

Table C Qualitative benchmarking of LVT, ÖBB-PORR and Rheda 2000 slab track systems

6.3.4 Quantification and weighting of criteria

This chapter presents a possible quantification of the selected criteria including weighting them against each other. Possible top score for all criteria is maximum 3 points:

- Experience on earthworks
  This is quantified by how many projects the system has built on earthworks, and divided into the following with points:
  0 – 10 projects = 1 point
  10 – 20 projects = 2 points
  Use on high speed lines gives 1 extra point

- Possible superelevation
  This is quantified by which superelevation has been built, how complicated the build is and divided into the following with points:
  Cast in-situ, possible with < 180 mm = 1 point
  Cast in-situ, possible with = 180 mm = 2 points
  Prefabricated, built with 180 mm = 3 points

- Gradient limitations
  This is quantified by whether a limitation exists, and if it is compliable with normal requirements and divided into the following with points:
  Limitation exists, within normal requirements for high-speed railway = 2 points
  No limitation, cast in-situ = 2 points
  No limitation, prefabricated = 3 points

- Minimum radius
  This is quantified by the lowest radius possible to build, and divided into the following with points:
  Limitation in system, <200 m is not acceptable = 1 point
  Limitation in system, 0 – 200 m is acceptable = 2 point
  No limitation in system, only in regulation = 3 points

- Maximum design speed built so far
  This is quantified by speed in km/h, and divided into the following with points:
  ≤ 250 km/h = 1 point
  > 250 km/h ≥ 300 km/h = 2 points
  > 300 km/h = 3 points

- Adjustment possibilities
  This is quantified by how many adjustment possibilities exist and divided into the following with points:
  Only in fastening = 1 point
  Fastening + blocks = 2 points
  Possible to elevate entire slab panel = 3 points

- Design change possibilities
  This is quantified by how many design change possibilities exist and divided into the following with points (no points for low profile version as this is not considered relevant for earthworks):
  0.5 point per possible ad-on, maximum 3 points

- Installation speed
  This is quantified by metres built per day and divided into the following with points:
  < 200 m/day = 1 point
  200 – 250 m/day = 2 points
  > 250 m/day = 3 points

- Installation quality
  This is quantified by demands in European standards, all systems are within limits = 3 points

- Noise and vibration
  This is quantified by how many levels of elasticity is possible with the system and divided into the following with points:
  Single elasticity, not possible to build as mass spring system =1 point
  Single elasticity, but possible to build as mass spring system = 2 points
  Dual elasticity, possible to build as mass spring system = 3 points

- Drainage solution
  This is quantified by how flexible the system is, divided into the following with points:
  System offers drainage on top of construction, prefabricated = 2 points
  System allows for a flexible arrangement of track drainage = 3 points

- Transition solution for the transition between slab track and ballasted track
  Transition zone designed per project, limited amount of solutions in use = 1 point
  Transition zone solutions are available for system, or designed per project = 2 points
  Transition zone designed per project, multiple solutions available = 3 points

- Maintenance aspects, including regular maintenance and repair concepts in case of accidents which cause damage to the slab track
  This is quantified by what is possible to repair and divided into the following with points:
  Possible to repair shoulder/supports within short time = 1 point
  Possible to replace shoulder/supports within short time = 2 points
  Possible to replace both track plates and repair shoulders/supports within short time = 3 points

All these chosen criteria are not equally important to provide a slab track of good performance. Below, in Table D, the chosen criteria have been weighted and given importance relevant to each other.

The following criteria are considered the most important: *adjustment possibilities* and *maintenance aspects*. They are considered the most important criteria for slab track on earthworks because of the probability of settlements and damage to track during operation.

The second most important criteria are *experience on earthworks*, *drainage solution* and *transition solution*. This is because slab track on earthworks is, relative to slab track in tunnels and on bridges, much less applied. Experience with application on earthworks in considered to be of high value. *Drainage solution* and *transition solution* are also important criteria and areas in the track that have shown to provide challenges during operation and maintenance.

The third most important criteria are design change possibilities, installation quality and noise and vibrations. This is because the quantitative evaluation shows these criteria are quite similar for the systems.

The least important criteria are *possible superelevation*, *gradient limitations*, *radii limitations*, *maximum speed in use* and *installation speed*. This does not mean they are not important at all. It is because the qualitative evaluation shows that *possible superelevation*, *gradient limitations*, *radii limitations* are quite similar for the three slab track systems, because demands for these are given in standards and regulations and not in the specific system. The difference between the systems lie in the construction method, and prefabricated slab track is here considered less complicated to build with high superelevation and high gradient than the in-situ cast systems.

Maximum speed in use is not the most important criteria for Norwegian conditions as the planned top speed for Norway is currently 250 km/h.

Installation speed differs for the three systems, but has some insecurity attached to it as none of these slab track systems has yet been built in Norway.

Criteria	**Weighting**	**Possible top score**	**Weighted points**
Experience on earthworks	10%	3	3.90
Possible superelevation	5%	3	1.95
Gradient limitations	5%	3	1.95
Radii limitations	5%	3	1.95
Maximum speed in use	5%	3	1.95
Adjustment possibilities	12%	3	4.68
Design change possibilities	7%	3	2.73
Installation speed	5%	3	1.95
Installation quality	7%	3	2.73
Noise and vibrations	7%	3	2.73
Drainage solution	10%	3	3.90
Transition solution	10%	3	3.90
Maintenance aspects	12%	3	4.68
Total	**100%**	**39**	**39**

Table D Weighting of criteria

As shown in this table, the highest possible score is 39 points.

6.3.5 Quantitative evaluation

This subchapter presents a qualitative evaluation of the selected slab track system against the chosen criteria.

Below is Table E, which presents a qualitative evaluation of the three selected slab track systems LVT, ÖBB-PORR and Rheda 2000, based on the selected criteria from chapter 6.3.2 Criteria for benchmarking.

Name of system / **Criteria**	**Importance of criteria**	**LVT – Low vibration track**	**Weighted points LVT**	**ÖBB-PORR Slab track Austria**	**Weighted points ÖBB-PORR**	**Rheda 2000**	**Weighted points Rheda 2000**
Experience on earthworks	10%	2	2.60	2	2.60	3	3.90
Possible superelevation	5%	2	1.30	3	1.95	2	1.30
Gradient limitations	5%	2	1.30	3	1.95	2	1.30
Radii limitations	5%	3	1.95	3	1.95	3	1.95
Maximum speed in use all projects	5%	1	0.65	2	1.30	3	1.95
Adjustment possibilities in addition to fastenings	12%	2	3.12	3	4.68	1	1.56
Design change possibilities in addition to standard version	7%	2.50	2.28	1.50	1.37	2.50	2.28
Installation speed	5%	1	0.65	3	1.95	3	1.95
Installation quality	7%	3	2.73	3	2.73	3	2.73
Noise and vibrations	7%	3	2.73	3	2.73	2	1.82
Drainage solution	10%	3	3.90	2	2.60	3	3.90
Transition solution	10%	3	3.90	2	2.60	3	3.90
Maintenance aspects	12%	2	3.12	3	4.68	1	1.56
Score	**100%**	**29.50**	**30.225**	**33.50**	**33.085**	**31.50**	**30.095**

Table E Quantitative evaluation of LVT, ÖBB-PORR and Rheda 2000 slab track systems

This evaluation shows that according to these criteria, the system ÖBB-PORR is ranked number 1. It has achieved 33.5 points before weighting, and 33.085 points after weighting. The systems Rheda 2000 achieve 31.5 points and LVT achieve 29.5 points before weighting, but after weighting Rheda 2000 get 30.095 points and LVT get 30.225 points. This shows that the weighting of the criteria makes a difference for the result. The high priority of the criteria adjustment possibilities and maintenance aspects work in favour of the ÖBB-PORR and LVT systems.

All systems show high performance and good qualities, as the final scores differ little. Table F below shows the rank of the three systems.

Rank	Name of system	Score before weighting	Final score
1	ÖBB-PORR Slab Track Austria	33.5	33.085
2	LVT Low Vibration Track	29.5	30.225
3	Rheda 2000	31.5	30.095

Table F Rank of systems after evaluation

Alternative weighting of criteria

If the criteria are weighted differently against each other, the result will be different. If the criteria *adjustment possibilities* and *maintenance aspects* are given a slightly lower importance, and the criteria *maximum speed* and *installation speed* are given a slightly higher importance, the score changes. Table G below illustrates this. With the changed priority, the rank of the three systems change.

Name of system Criteria	Importance of criteria	LVT – Low vibration track	Weighted points LVT	ÖBB-PORR Slab track Austria	Weighted points ÖBB-PORR	Rheda 2000	Weighted points Rheda 2000
Experience on earthworks	10%	2	2.60	2	2.60	3	3.90
Possible superelevation	5%	2	1.30	3	1.95	2	1.30
Gradient limitations	5%	2	1.30	3	1.95	2	1.30
Radii limitations	5%	3	1.95	3	1.95	3	1.95
Maximum speed in use all projects	7%	1	0.91	2	1.82	3	2.73
Adjustment possibilities in addition to fastenings	10%	2	2.60	3	3.90	1	1.30
Design change possibilities in addition to standard version	7%	2.50	2.28	1.50	1.37	2.50	2.28
Installation speed	7%	1	0.91	3	2.73	3	2.73
Installation quality	7%	3	2.73	3	2.73	3	2.73
Noise and vibrations	7%	3	2.73	3	2.73	2	1.82
Drainage solution	10%	3	3.90	2	2.60	3	3.90
Transition solution	10%	3	3.90	2	2.60	3	3.90
Maintenance aspects	10%	2	2.60	3	3.90	1	1.30
Score	**100%**	**29.50**	**29.705**	**33.50**	**32.825**	**31.50**	**31.135**

Table G Quantitative evaluation, change of importance of criteria

Now, the ÖBB-PORR system is still ranked as number 1, with 32.825 points. Rheda 2000 is now number 2, with 31.135 points and LVT is number 3 with 29.705 points.

The new rank is shown below in Table H.

Rank	Name of system	Score before weighting	Final score
1	ÖBB-PORR Slab Track Austria	33.5	32.825
2	Rheda 2000	31.5	31.135
3	LVT Low Vibration Track	29.5	29.705

Table H Rank of systems after change of importance of criteria

This change of criteria importance shows that by simply changing the priority between the criteria, one can change the result all over.

This can be useful when benchmarking systems for use in tunnel and bridge, where other criteria will be of higher importance seeing as tunnels and bridges can be considered free of settlements.

7 Discussion

General considerations

With increasingly higher speeds and axle loads on the existing railway system in the last century, the need for a stable and durable track with high availability came. Slab track has been developed over the last 50 years in Europe and Asia. Slab track has shown that when properly planned and built, it provides a high-quality track with good quality geometry and high availability.

As shown in this thesis, high-speed railway with slab track on earthworks is widespread around the world, especially in Europe and Asia. Different countries have had different approaches to applying slab track on earthworks in their country. Germany started building slab track on earthworks, and thereafter in tunnel and on bridges, China and Japan started building slab track on bridges and tunnels, and thereafter on earthworks. China has built slab track on very long stretches through cold areas and have encountered several difficulties related to frost. It is natural to assume that some of these issues will be relevant for Norwegian conditions and that Norway can learn from experience in China.

In Norway, slab track has been built on a couple of bridges and is planned for two railway tunnels currently under construction. The experience with operation and maintenance for slab track in Norway is limited. When the two tunnels with slab track open in 2020 and 2021 and operation begins, it will be interesting to learn if the chosen track solution delivers the high quality and low maintenance need that is predicted. The projects will deliver Plan for operation and maintenance for the newly build lines, in accordance with the RAMS process in Bane NOR, and after a few years of operation it is assumed that one can start to evaluate the overall track performance based on experience with operation, fails and measured track quality.

The next natural step for applying slab track in Norway is on shorter distances on earthworks between fixed structures. This is also what is considered permitted in Bane NOR's Technical Regulations from august 2019; to build slab track on earthworks between fixed structures for distances shorter than 1000 metres (where slab track is established in for example the adjacent tunnel).

There are some challenges when building slab track on earthworks, such as fulfilling the high demands for a stable substructure, handle areas with poor soil conditions, prevent settlements and frost heaving, secure enough drainage and reduce noise and vibrations.

Consequences

A consequence of permitting to apply slab track on earthworks in Norway, is that Bane NOR's Technical Regulations will have to be changed.

It will be challenging to set demands for the substructure in terms of strength and frost protection, which are two key points for achieving success with slab track on earthworks in Norway.

The European norms EN 16432-1 and EN 16432-2 applies for Norway with general requirements. Based on these requirements, along with findings in this thesis, the following specific requirements are recommended for slab track on high-speed railway on earthworks in Norway, see Table I on the next page.

Sub system	Demands
Superstructure	- Maximum superelevation 180 mm - Concrete quality C30/37 - Thickness normally 200 mm - Installation accuracy ± 2 mm
Hydraulically bonded layer	- Mix of mineral aggregate of graded particle size (≤32 mm) and hydraulic bonding agent - Thickness normally 300 mm - Installation accuracy ± 10 mm
Frost protection layer	- Thickness normally 500-700 mm or more - Elastic modulus ≥ 120 MN/m^2 - Granular materials (not frost susceptible) - Permeability between $1*10^{-5}$ m/s and $1*10^{-4}$ m/s - Installation accuracy ± 20 mm
Substructure	- Elastic modulus ≥ 60 MN/m^2 - Preferably homogeneous, if not transitions are required - Substructure secured at least 2.5 metres below formation level - Groundwater level at least 1.5 metres below rail top level - Ground should be examined at least 5 metres below planned embankment - Minimizing long-term settlements with planned preconsolidation - Drainage designed for 200 year flood
Transition zone between slab track and ballasted track	- Minimum length of transition zone = v (m / s) x 0.5 (s) - Recommended placed outside of tunnels because of higher maintenance need - Possible measures: gluing of ballast, auxiliary rails, longer sleepers, improving substructure, using approach slab
Noise and vibrations	- Chosen system must be able to provide extra noise and/or vibration reduction if needed - Possible measures: noise absorbing elements attached to track, ballast near track, traditional screening, mass-spring systems

Table I Recommended requirements for slab track on earthworks in Norway

These requirements are found from experience and regulations in the countries that have built slab track on earthworks. Since this thesis mainly has focused on experience from Germany, China and Japan, it is a possibility that the research on the best practices is inadequate and that there is more relevant information available to complete this recommendation.

The requirements for frost protection layer and substructure are only suggestions based on experience and regulations already in use, and the latest research on frost heaving from China mentioned in chapter 4.7 Frost has not been included in them. It is recommended that this research is studied further to be able to conclude if the recommendations in the studies are relevant for implementation in Norway, seeing as there are some differences between China and Norway and that the operational speed in China is much higher than what is planned for in Norway.

Possibilities

If slab track is permitted on earthworks on shorter distance than 1000 metres, it will be possible to apply on new railway projects for longer stretches.

Norway has some upcoming railway projects consisting of a relatively large portion bridges and tunnels, e.g. Ringeriksbanen and Tønsberg – Larvik. Ringeriksbanen has a 23 km long tunnel from Jong in Bærum to Sundvollen. When entering Sundvollen the line goes on to a bridge over Kroksund. If analyses performed according to the UPB-process shows that the recommended choice of track system for the tunnel is slab track, it can be natural to continue the slab track system out of the tunnel, on the short distance of earthworks and over the bridge as well. In addition, it is possible to perform these analyses for longer stretches of railway with the same superstructure. This will simplify the analyses.

This way, with a continuous slab track superstructure over different substructures, it is possible to gather experience first with building and thereafter with operation and maintenance of slab track on earthworks in Norway. First, on a smaller scale (up to 1000 metres on earthworks between fixed structures), and if this is found successful, later in a larger scale on longer railway lines with slab track built for longer stretches over 1000 metres on earthworks. This will allow for adjusting requirements after some time of experience with operation and maintenance of slab track on earthworks in Norway.

Seeing as slab track has not yet been built on earthworks in Norway it will be challenging to plan and calculate both for building and operation and maintenance. It is a requirement in the UPB-process that the technical plan in phase 2 must have technical detailing to meet a cost estimate of +/- 20%. This is challenging to fulfil when building a new track structure on earthworks, as has never been done in Norway before. When limiting the permitted distance of slab track on earthworks between fixed structures to maximum 1000 metres, it can be easier to estimate costs, and it is a gradual approach with less risk than permitting to build slab track on earthworks with unlimited length immediately.

System benchmarking

The qualitative and quantitative evaluation shows that all three slab track systems offer high performance and good qualities, as there are only small differences in the final scores. All systems are more or less equal and difficult to differentiate within the criteria possible *superelevation*, *gradient limitations*, *radii limitations*, *installation quality*, *drainage solution* and *transition solution*.

Both with and without the weighting of the criteria, the ÖBB-PORR system ranks number 1 in the quantitative evaluation according to the result in Table E and Table F. The ÖBB-PORR system excels in the criteria *adjustment possibilities*, *installation speed*, *noise and vibrations* and *maintenance aspects*. It is also quite good in the criteria *experience on earthworks* and *maximum speed in use*.

The LVT system is ranked number 2 after the quantitative evaluation. The system excels in the criteria *design change possibilities* and *noise and vibrations*. It is not as good as the other systems in the criteria *maximum speed in use* and *installation speed*.

The Rheda 2000 system is ranked number 3 after the quantitative evaluation. The system excels in the criteria *experience on earthworks*, *maximum speed in use* and *installation speed*. It is not quite as good as the other systems when it comes to *adjustment possibilities*, *noise and vibrations* and *maintenance aspects*.

This qualitative and quantitative evaluation has been performed on criteria chosen by the author of this thesis in cooperation with project supervisor. There are insecurities connected to the choice of criteria and the evaluation itself. The quantification of the criteria is complex and small differences between the systems give an entire point in difference on the total score. The weighting of criteria is a topic for discussion, as the two different results in chapter 6.3.5 Quantitative evaluation illustrate. The criteria *adjustment possibilities* and *maintenance aspects* are given a high importance because of the insecurities connected to building slab track on earthworks in Norway, with possible settlements after commissioning. There is of course a possibility that these criteria are given to high importance.

The research for input to the evaluation has been performed carefully, but there is of course a possibility of errors in the evaluation. With the small margins in the final rank between the systems, a single wrong appraisal in the quantitative evaluation can change the order of the three systems entirely.

One could argue that installation costs is an obvious criterion that has been left out for the evaluation. This has been done with intention, as installation costs for these systems on earthworks in Norway are related to high insecurity and a will give this criterion insufficient credibility for the evaluation. When performing LCC analyses for a project, this is one of the most important input values and have to be carefully calculated, especially for slab track on earthworks which has not yet been built in Norway, and consequently there are no historical figures to use for calculation.

Both the findings in chapter 5 European best practises and chapter 6.3 Benchmarking of the selected systems show that all the three selected systems are of good quality, cleverly designed and thoroughly tested. The systems have been applied in many projects of different size and character around the world. Findings indicate that the systems are suitable for different purposes. The LVT system seems to be specialized for application in tunnels and for speed up to 250 km/h. The ÖBB-PORR system har been developed for faster installation, with possibility for considerable adjustment after installation and for higher speed than 250 km/h. The Rheda 2000 system is the system with much more experience on application on high-speed railway (up to 350 km/h) than the other systems and continuous application over multiple bedding modulus and long distances.

8 Conclusions and recommendations for future work

Slab track on earthworks for high-speed railway has been built in many countries around the world. The countries with most experience in building slab track on earthworks are Germany, China and Japan. Many of these experiences are valuable for Norway when considering applying slab track on earthworks.

Critical topics to handle when planning and building slab track on earthworks are setting the correct requirements for substructure, avoiding settlements, coping with frost and drainage and building good transition zones between different substructures and between slab track and ballasted track. Operation and maintenance are also very important topics to consider when planning railway, and slab track has several advantages over ballasted track in operation and maintenance. It has higher availability than ballasted track, require less maintenance and as this thesis shows, there have been developed different repair concepts in case of damage to the track. It is the need for less maintenance and higher availability that makes slab track compatible with ballasted track over the entire lifetime.

In Norway it is not currently permitted to build slab track on earthworks, but it is suggested that it shall be permitted from August 2019 to build slab track on shorter distances than 1000 metres between fixed structures (e.g. between tunnel and bridge).

The recommended process for gradually building slab track on earthworks in Norway and getting experience is:

1. Building slab track in tunnels, Follobanen and Arna-Bergen
2. Building slab track outside of tunnels on distance ≤ 1000 metres, between fixed structures, as tunnel and bridge
3. Building slab track continuous on longer railway lines

The benchmarking of the three selected slab track systems shows that with the chosen criteria and weighting of these, the ÖBB-PORR system is ranked number 1. The system has been applied for several high-speed railway lines on earthworks in Europe, although not as many as the Rheda 2000 system. This system has a higher degree of flexibility for adjustment and repairs than the other two systems, and this is the reason for the higher score.

Recommendations for further work is divided into gaining experience with operation and maintenance and expanding the research on selected topics. It is recommended to gather experience from operation and maintenance in the upcoming tunnels Blixtunnelen and Ulriken tunnel and perform updated LCC analysis with figures from experience.

More slab track systems can be benchmarked with the chosen criteria and the selection of criteria can be extended further, to be able to compare the systems characteristics against each other.

It is recommended to perform more research on frost protection as this is an important and relevant issue for Norwegian conditions, and because it is a critical problem for slab track superstructure.

It is recommended to perform more research on slab track performance in case of settlements and repair methods in case of damages caused by settlements.

9 References

Ando, K., Sunaga, M., Aoki, H., & Haga, O. (2001). Development of Slab Tracks for Hokuriku Shinkansen Line. *QR of RTRI, 42*(1).

Arup. (2016). General Guidance for Low Noise and Low Vibration Slab Track. In Britpave (Ed.). Britpave: Britpave.

Avramovic, I. (2019, 2019-04-17). [Question about the ÖBB-PORR system].

Bahnbilder.de. (2019). Bahnbilder. Retrieved from www.bahnbilder.de

Bane NOR. (2017a). *STY-603097 RAMS-styring i Bane NOR*.

Bane NOR. (2017b). *STY-603102 RAMS - introduksjon og oversikt EN 50126, med RAMS-begrepsordbok*.

Bane NOR. (2017c). *TEKNISK DESIGNBASIS FOR INTERCITY*. In. Retrieved from http://www.banenor.no/globalassets/documents/inter-city/teknisk-designbasis.pdf

Bane NOR. (2018a). Bane NOR Prosjekteringsveileder. Retrieved from https://proing.opm.jbv.no/wiki/

Bane NOR. (2018b). Fastspor. Retrieved from http://www.jernbanekompetanse.no/wiki/Fast_spor

Bane NOR. (2018c). Skinnesliping. Retrieved from http://www.jernbanekompetanse.no/wiki/Skinnesliping

Bane NOR. (2018d). Støy og vibrasjoner. Retrieved from http://jernbanekompetanse.no/wiki/St%C3%B8y_og_vibrasjoner#Vibrasjoner

Bane NOR. (2018e). Vedlikeholdsmetodikk. Retrieved from http://www.jernbanekompetanse.no/wiki/Vedlikeholdsmetodikk

Bane NOR. (2019a). Arna - Bergen Retrieved from https://www.banenor.no/Prosjekter/prosjekter/Arna-Bergen/

Bane NOR. (2019b). Follobanen. Retrieved from https://www.banenor.no/Prosjekter/prosjekter/follobanen/

Bane NOR. (2019c). InterCity. Retrieved from http://www.banenor.no/Prosjekter/prosjekter/intercity/

Bane NOR. (2019d). Prosjektportalen.

Teknisk regelverk, (2019e).

Teknisk regelverk/Overbygning/Ballastfri sporkonstruksjon, (2019f).

Bane NOR. (2019g). Tekniske spesifikasjoner - Overbygning/Ballastfri sporkonstruksjon - General design rules. Retrieved from https://trv.jbv.no/ts/Overbygning/Ballastfri_sporkonstruksjon#General_design_rules

Bane NOR. (2019h). Tønsberg - Larvik. Retrieved from https://www.banenor.no/Prosjekter/prosjekter/vestfoldbanen/tonsberg-skien/

Bögl, S. (2006). Slab track system - FF Bögl. *RTR Special State-of-the-Art, Slab Track*(September 2006).

CEMOSA, Administrador de Infraestructuras Ferroviarias, A., Ingenieria y Economia del Transporte S.A., I., Instituto Superior Tecnico, I., Réseau Ferré de France, R., SYSTRA S.A., S., . . . Trafikverket, T. (2014). *Capacity for Rail. Design requirements and improved guidelines for design (track loading, resilience & RAMS)* Retrieved from www.capacity4rail.eu

CEN. (2014). EN 13848-6 Railway applications - Track - Track geometry quality - Part 6: Characterisation of track geometry quality. In.

CEN. (2017a). EN 16432-1:2017 Railway applications - Ballastless track systems - Part 1: General requirements. In: CEN.

CEN. (2017b). EN 16432-2:2017 Railway applications - Ballastless track systems - Part 2: System design, subsystems and components. In.

CENELEC. (2017). EN 50126-1 Railway applications - The specification and demonstration of reliability, availability, maintainability and safety (RAMS) - Part 1: Generic RAMS process. In: European Committee for Electrotechnical Standardization.

Eisenmann, J. (2006). Introduction: Ballasted tracks and the goals of slab track development. *RTR Special State-of-the-Art, Slab Track*(September 2006), 8-9.

Esveld, C. (2001). *Modern railway track*. Duisburg: MRT-Productions.

Esveld, C. (2003). Recent developments in slab track. *European Railway Review*(2).

Decision No 1692/96/EC of the European Parliament and of the Council of 23 July 1996 on Community guidelines for the development of the trans-European transport network (1996).

Commission Regulation (EU) No 1299/2014 of 18 November 2014 on the technical specifications for interoperability relating to the 'infrastructure' subsystem of the rail system in the European Union Text with EEA relevance, (2014).

Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union (Text with EEA relevance), (2016a).

Regulation (EU) 2016/796 of the European Parliament and of the Council of 11 May 2016 on the European Union Agency for Railways and repealing Regulation (EC) No 881/2004 (Text with EEA relevance), (2016b).

European Union. (2019). Regulations, Directives and other acts. Retrieved from https://europa.eu/european-union/eu-law/legal-acts_en

European Union Agency for Railways. (2019). Technical Specifications for Interoperability. Retrieved from https://www.era.europa.eu/activities/technical-specifications-interoperability_en

Fiebigs. (2019). Die Feste Fahrbahn. Retrieved from http://fiebigs.de/rheda-spezial.html

Frühauf, W., Stoiberer, H., Scholz, M., & Schmitt, C. (2006). SSF engineering: earthwork construction for ballastless track on HSLs. *RTR Special State-of-the-Art, Slab track*(September 2006), 69-76.

Fumey, M., Hofmann, C., Schilder, R., Godart, P., Trevin, J. M., Simovic, T., . . . Zuber, P. (2002). Feasibility study "ballastless track". In U. I. C.-C. E. S. Group (Ed.).

Gautier, P.-E. (2015). Slab track: Review of existing systems and optimization potentials including very high speed. *Construction and Building Materials, 92*, 9-15. doi:10.1016/j.conbuildmat.2015.03.102

Grimsrud, G. W. (2018). [Spørsmål om ultralydkontroll].

Hoff, I. (2016). *Levetidskostnader*. Paper presented at the NTNU EVU Kurs Kostnader og nytte av samferdselsanlegg, Trondheim.

Hokstad, P. (1998). *Life cycle cost analysis in railway systems* (Vol. STF38 A98424). Trondheim: SINTEF, Industrial Management, Safety and Reliability.

INNOTRACK. (2006). Guideline for LCC and RAMS analysis. In.

Jenks, C. W. (2006). *Design of track transitions*. In.

Kleeberg, J. (2009). New development stage of RHEDA 2000®(3). Retrieved from Global Railway Review website: https://www.globalrailwayreview.com/article/124/new-development-stage-of-rheda-2000/

Laborenz, P. (2019a, 2019-04-17). [Questions about the LVT system].

Laborenz, P. (2019b, 2019-02-20). [Request for information about building costs LVT system].

Lechner, B. (2007). *Design and layout of ballastless track systems using unbound base course layers* (Vol. 131).

Lechner, B. (2009). Developments in Road Pavement Construction and Railway Track Technology for a Sustainable Surface Transportation Infrastructure. In (pp. 2656-2665).

Leykauf, G., Lechner, B., & Stahl, W. (2006). Trends in the use of slab track / ballastless tracks. *RTR Special State-of-the-Art, Slab Track*(September 2006), 10-17.

Lichtberger, B. (2011). *Track Compendium*: Eurailpress.

Lien, H. A. (2018). *Fastspor i dagsone - bygging og vedlikehold. Forprosjektrapport.* NTNU.

Lin, Z., Niu, F., Li, X., Li, A., Liu, M., Luo, J., & Shao, Z. (2018). Characteristics and controlling factors of frost heave in high-speed railway subgrade, Northwest China. *Cold Regions Science and Technology, 153*, 33-44. doi:10.1016/j.coldregions.2018.05.001

Liu, X., Zhao, P., & Dai, F. (2011). Advances in design theories of high-speed railway ballastless tracks. *Journal of Modern Transportation, 19*(3), 154-162. doi:10.1007/BF03325753

Marshall, T., Sica, G., Fagan, N., Perez, D., Bewes, O., & Thornely-Taylor, R. (2015). *The predicted vibration and ground-borne noise performance of modern high speed railway tracks* Paper presented at the Inter.Noise, San Fransisco, Caifornia, USA.

Michas, G. (2012). *Slab track systems for high-speed railways.* (Master), KTH Royal Institute of Technology, DiVA Portal.

Instruks om utredning av statlige tiltak (utredningsinstruksen), FOR-2016-02-19-184 C.F.R. (2016).

Forskrift om samtrafikkevnen i jernbanesystemet (samtrafikkforskriften), (2010).

Forskrift om nasjonale tekniske krav m.m. for jernbaneinfrastruktur på det nasjonale jernbanenettet (jernbaneinfrastrukturforskriften), (2011).

Münchschwander, P. (2006). Foreword: The development of slab track systems in Germany. *RTR Special State-of-the-Art, Slab Track*(September 2006), 6-7.

N Bilow, D., & M Randich, G. (2000). *SLAB TRACK FOR THE NEXT 100 YEARS*.

Norwegian Railway Directorate. (2018). Veileder i samfunnsøkonomiske analyser i jernbanesektoren. In.

Nyquist, D. (2010). *Underhåll av fixerat spår : erfarenheter från europeiska och japanska system.* (Bachelor), Lund university, http://www.tft.lth.se/.

Pichler, D., & Floh, J. (2016). *Ballastless track on earthworks. Fixed Track Forms for High Speed Lines* Paper presented at the PWI/UEEIV 2016 Techinal Conference, Manchester, UK.

Pieringer, A. (2019, 2019-05-06). [Questions about Rheda 2000].

PORR Bau GmbH. (2013). Slab Track Austria - System ÖBB-PORR elastically supported slab - information film.

PORR Bau GmbH. (2016). Slab track Austria - System ÖBB-PORR elastically supported slab. In.

PORR Bau GmbH. (2019a). References Slab Track Austria (ÖBB-PORR). Retrieved from http://www.slabtrackaustria.com/fileadmin/content/39_slabtrackaustria/04_download/reference_list_-_slab_track_austria_by_porr.pdf

PORR Bau GmbH. (2019b). Repair concept. Retrieved from http://www.slabtrackaustria.com/index.php?id=5110&L=1&L=1

Powrie, W. (2017). Ballast or slab? *, Aug/Sep 2017*.

Profillidis, V. (2014). *Railway management and engineering* (4th ed. ed.). Farnham: Ashgate.

RAIL.ONE GmbH (2018). *Rheda 2000® ballastless track system*. In (pp. 20). Retrieved from https://www.railone.com/fileadmin/daten/05-presse-medien/downloads/broschueren/en/Rheda2000_EN_2011_ebook.pdf

RAIL.ONE GmbH. (2019). References. Retrieved from https://www.railone.com/fileadmin/daten/05-presse-medien/downloads/referenzen/20190226_RAILONE-references_EN_1903.pdf

Ren, J., Lechner, B., & Liu, X. (2008). Economical evaluating the ballastless railway track with consideration of LCC viewpoint. In (pp. 4665-4671).

SBB. (2019). The Gotthard Base Tunnel. Retrieved from https://company.sbb.ch/en/media/background-information/gotthard-base-tunnel.html

Schilder, R. (2007). The ÖBB/Porr ballastless track system. Retrieved from https://www.globalrailwayreview.com/article/1145/the-obbporr-ballastless-track-system/

Schilder, R., & Diederich, D. (2007). Installation Quality of Slab Track - A Decisive Factor for Maintenance. *RTR Special (2007)*, 3.

Shahraki, M., Warnakulasooriya, C., & Witt, K. J. (2015). Numerical study of transition zone between ballasted and ballastless railway track. *Transportation Geotechnics, 3*, 58-67. doi:10.1016/j.trgeo.2015.05.001

Shan, Y., Albers, B., & Savidis, S. A. (2013). Influence of different transition zones on the dynamic response of track–subgrade systems. *Computers and Geotechnics, 48*, 21-28. doi:https://doi.org/10.1016/j.compgeo.2012.09.006

Sheng, D., Zhang, S., Niu, F., & Cheng, G. (2014). A potential new frost heave mechanism in high-speed railway embankments. *Géotechnique, 64*(2), 144-154. doi:10.1680/geot.13.P.042

Sonneville AG (2011). [System description].

Sonneville AG. (2018). LVT reference list. Retrieved from http://www.sonneville.com/fileadmin/media/sonneville/downloads/LVT_Reference_list_worldwide_english_km_June_2018.pdf

Sonneville AG. (2019a). Low vibration track system (LVT) Track adjustment and component substitution. In S. AG (Ed.).

Sonneville AG. (2019b). sonneville low vibration track system. In. http://www.sonneville.com/fileadmin/media/sonneville/downloads/LVT_English_08.2018.pdf.

SSF Ingenieure GmbH. (2011). Slab track systems on different substructures. In.

Steenbergen, M. J. M. M., Metrikine, A. V., & Esveld, C. (2007). Assessment of design parameters of a slab track railway system from a dynamic viewpoint. *Journal of Sound and Vibration, 306*(1), 361-371. doi:10.1016/j.jsv.2007.05.034

Svensøy, A. (2018). [Om ballastfritt spor i dagsone].

Tarmac, & Max Bögl. (2015). Delivering innovation. Slab track solutions for UK high speed rail. In: Tarmac Trading Limited.

Tayabji, S., & Bilow, D. (2001). *Concrete Slab Track State of the Practice* (Vol. 1742).

Teigen, F. (2019). [Krav til Ballastfri sporkonstruksjon - utkast til ny tekst i Teknisk regelverk].

Veit, P. (2019, 2019-02-13). [About slab track in Austria].

von Glasenapp, A. (2019, 2019-03-22). [Rheda 2000 Introduction].

Wang, J. (2011, May 4th 2011). *The Ballastless Track Technology For China High-Speed Line.* Paper presented at the 2011 High-Speed Rail Practicum, Baltimore, Maryland, USA.

Wu, T. X. (2008). On effectiveness of vibration isolation using super-elastic rail support combined with booted sleeper or floating slab. *The Journal of the Acoustical Society of America, 123*(5), 3258-3258. doi:10.1121/1.2933553

Wu, X. Y., Niu, F. J., Lin, Z. J., Luo, J., Zheng, H., & Shao, Z. J. (2018). Delamination frost heave in embankment of high speed railway in high altitude and seasonal frozen region. *Cold Regions Science and Technology, 153*, 25-32. doi:10.1016/j.coldregions.2018.04.017

Yokoyama, A. (2010). *Infrastructure for high speed lines in Japan.* Paper presented at the International Practicum on Implementing High-Speed Rail in the United States, USA.

Zhang, S., Sheng, D., Zhao, G., Niu, F., & He, Z. (2016). Analysis of frost heave mechanisms in a high-speed railway embankment. *Canadian Geotechnical Journal, 53*(3), 520-529. doi:10.1139/cgj-2014-0456

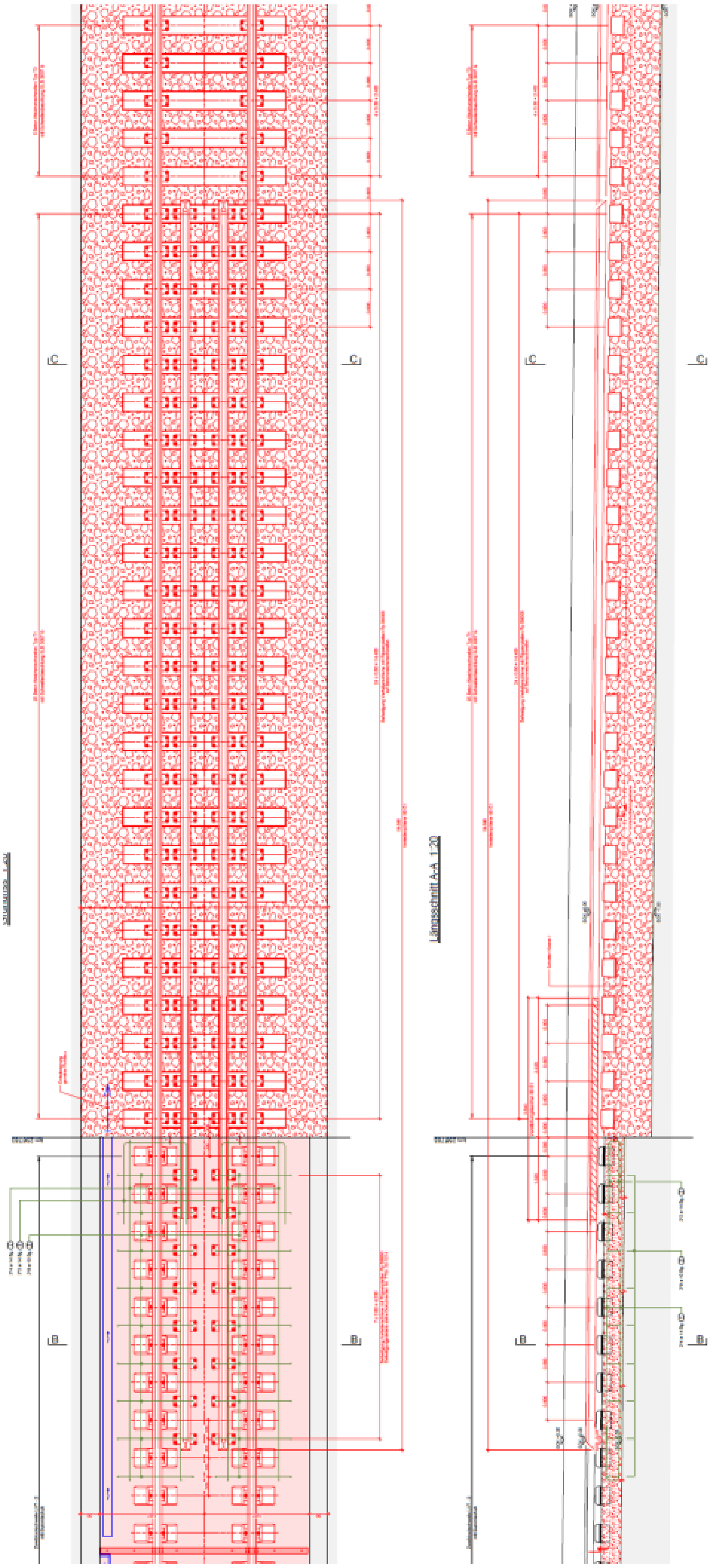
Zhang, T., Barry, R. G., Knowles, K., Ling, F., & Armstrong, R. L. (2003). *Distribution of seasonally and perennially frozen ground in the Northern Hemisphere*. Paper presented at the 8th International Conference on Permafrost, Zürich, Switzerland. http://research.iarc.uaf.edu/NICOP/DVD/ICOP%202003%20Permafrost/Pdf/Chapter_226.pdf

Zottl, W. (2012). *Staffposition, Research & Development (R&D).* Paper presented at the Workshops on Research and Development, Intelligent Transport Systems, Road/Rail Intermodal Innovations and Road Safety Ankara.

10 Annex

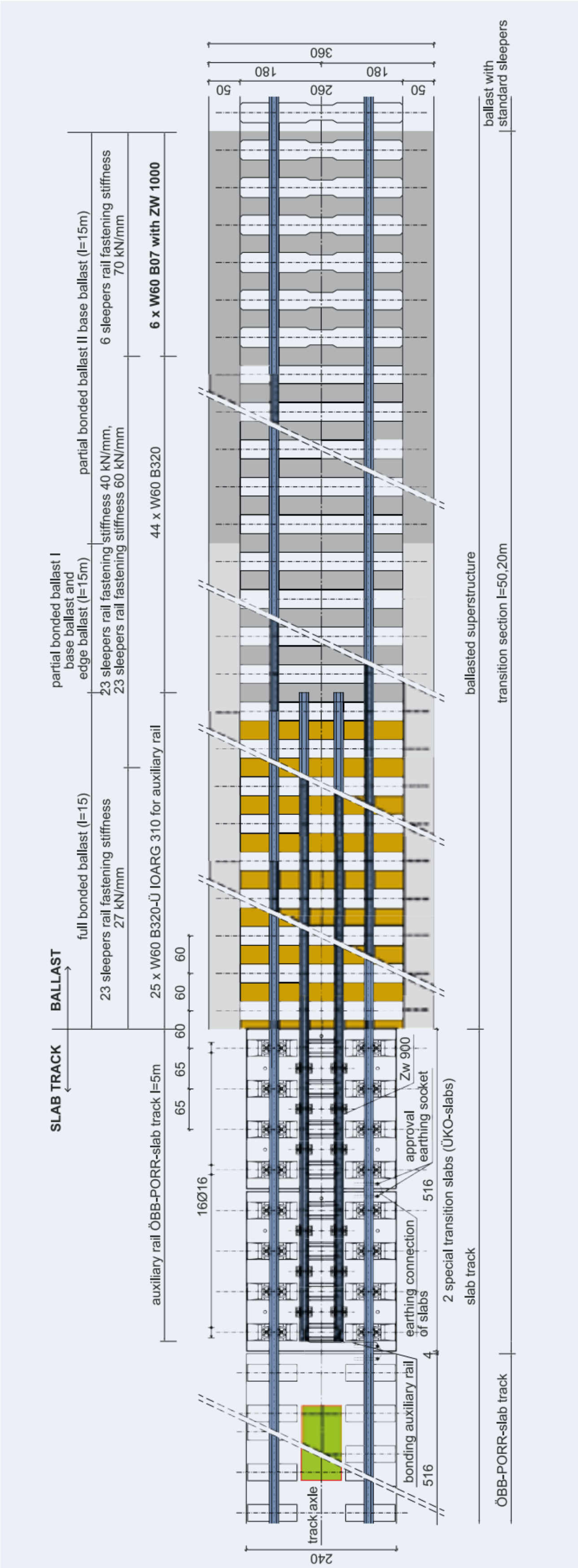
Annex 1

LVT Transition zone (Laborenz, 2019b)



Annex 2

ÖBB-PORR Transition zone (PORR Bau GmbH, 2016)



Annex 3

Rheda 2000 transition zone (Esveld, 2001)