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University of Birmingham

The Adaptability of Slab Track Systems to Unstable Areas

The Author: ALPER CEBECİ

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Supervisor: DERMOT KELLY & FELIX SCHMID

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Executive Summary

The purpose of this thesis is to demonstrate the potential positive impacts of applying slab track systems in unstable areas and the advantages of using them for mitigating earthquake effects. This aim is addressed under four major headings. Firstly, the author characterises different track systems, with their advantages and drawbacks in terms of reliability, availability, maintainability and safety. Secondly, types of slab track systems, their features, requirements, advantages and disadvantages are examined. He documents how the track systems are built in unstable regions or areas with active seismic behaviour. Finally, he discusses the applicability of slab track systems to deal with Turkish ground conditions.

Together with advantages in terms of journey times, the widespread adoption of high speed trains in many countries brings some requirements in terms of safety due to speeds rising above 250 km/h. This being said, in order to address these requirements track system selection is becoming more and more important. Therefore, this selection leads one to evaluate products supplied by companies that produce slab track. Many companies supply slab track products and solutions. Various types of concrete slab track are in use in Japan, Europe and North America. The use of slab track provides benefits to the operators in terms of RAMS (reliability, availability, maintainability and safety) as well as life cycle cost despite its high initial cost. In Japan, the maintenance cost of slab track is a quarter of that of ballasted track. However, recent surveys show that slab track construction costs are 30% to 50% higher than standard ballasted track.

Slab track companies have introduced innovations that result in reductions of maintenance and life cycle cost. This type of track can provide better level crossing for the mixture traffic zones or emergency access. Moreover, slab track systems have been used for reducing the tunnel height, track construction depth and increasing the availability of the systems in specific circumstances. However, not every country have same ground conditions; while some of them are struggling with extreme weather conditions, others must cope with seismic behaviour of the ground that has to be considered during design processes.

There are a great variety of organisations which include national railways and specific major projects that suffer from weak ground and that are a very difficult problem for both high speed and heavy freight train operations. Failures can cause major incidents. In case of an accident, millions of pounds of damage can occur and people may be killed or injured. Earthquakes can be very dangerous where the ground is weak, which is a very common problem occurring in many parts of the world and it can have devastating impacts on transportation systems, buildings or the habitat of the people.

Earthquakes may result in soil liquefaction that has major hazardous effects on the structures. There are also other earthquake impacts that can affect the people such as surface ruptures or land sliding. Earthquake effect mitigation methods have been described for many years by engineers. However, engineers have still not developed sufficient methods to tackle ground ruptures and land sliding, except for some basic methods.

Liquefaction is a phenomenon where a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic, or shock loading and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance.

There are a number of different options, as shown in Section 5.4, which suggest the retrofitting of the sub-structure conditions to the railway systems in the case of soil liquefactions occurring, whether for new or already existing track. Spread footing systems and pile foundation systems bring many advantages for the slab track systems. The author shows the advantages of slab track for unstable areas by the way of using these methods. Furthermore, even if other mitigation methods are available for unstable ground conditions they are very expensive and difficult to apply for many railways.

The author suggests that Turkish State Railways use feasibility studies for the high speed lines. If the line consists of many special parts such as tunnels, viaducts or substructures, slab track is the best option for construction. For example, tunnel heights or bridge loads can be reduced with slab track systems. Therefore, the economic advantage may be caught. The slab track systems should also be used for busy networks as it is a good option thanks to the availability issues. In general, the embedded track systems and floating slab track systems are better options for the Turkish State railway. Both types allow changing some part of the structure. Moreover, nowadays the new developed BBEST systems present opportunities to reduce installation and maintenance cost. It should be considered as a noteworthy suggestion for TCDD.

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Glossary of Terms / List of Abbreviations

Term	Explanation / Meaning / Definition
AREMA	American Railway Engineering and Maintenance-of-Way Association
BBEST	Balfour Beatty Embedded Slab Track
CA	Cement-Emulsified Asphalt
CBR	California Bearing Ratio
CPR	Canadian Pacific Railway
CWR	Continuous Welded Rail
DART	Dallas Area Rapid Transit
DB	Deutsche Bahn
ERS	Embedded Rail Slab Track
FFB	Feste Fahrbahn Bögl
GB	Great Britain (England, Scotland and Wales)
JMA	Japanese Meteorological Company
JNR	Japanese National Railways
LCC	Life Cycle Cost
LVT	Sonne-ville Low Vibration Track
MTA	The Los Angeles County Metropolitan Transportation Authority
NR	Network Rail (Infrastructure Company)
ÖBB	Österreichische Bundesbahnen
RAMS	Reliability, Availability, Maintainability and Safety
RFF	French Railway Infrastructure Company
SNCF	French State Railway Operator Company
TCDD	Turkish State railways (Infrastructure and Operator)
UK	United Kingdom (Great Britain and Northern Ireland
USGS	U.S. Geological Surveys

1 Introduction

1.1 Brief

In order to enhance competition with road transport and airlines, among other efforts railways are increasing their speed and making their system safer, more reliable and available. In this regard, high speed lines are becoming more and more important. To use high speed trains, railway infrastructure companies must construct better railways to provide safety, reliability and maximum availability for services. The densely-populated areas in the world are mostly formed of level layer, often alluvial in nature, whose subsoil has geo-technical characteristics that range from weak to strong. Building railway structures on weak ground conditions would require a substantial improvement of the bearing capacity.

High speed trains have begun to be adopted by countries thanks to its quality, safety and speed. Various types of concrete slab track are in service in Japan, Europe and North America. Conventional ballasted track has been used in many parts across the world since the early years of railway, but significant competition from slab track introduction started after 1972. According to Bilow et al., (n.d.), in Japan, where slab track has been used for thirty years, recent slab track construction costs are 30% to 50% higher than these of standard ballasted track. However, in Japan the maintenance costs for slab track are a quarter of those for ballasted track (Bilow, P.E., S.E., & Randich).

Slab track suppliers have achieved very important developments of these systems. At the beginning of the process, slab track systems were used solely for reducing life cycle cost and for providing more reliable track operation. Today, they are also used to reduce the tunnel height, track height and to increase the availability of the systems. In applying slab track, different countries have the different ground stability features or economic conditions; some of them are struggling with extreme weather conditions while others have to cope with seismic behaviour of the ground. This affects slab track companies' competition.

There are many countries whose transportation systems suffering from low ground stability. It is a very difficult problem for both high speed and heavy freight operations. In case of an accident, failures can cost millions of pound and people may be killed or injured. Earthquakes are a very common problem, which occurs in many countries across the world e.g., most recently, in New Zealand. They can have devastating impacts on the transportation systems. Earthquakes may result in soil liquefaction that is very dangerous for structures. There are also other earthquake impacts that can affect people, such as volcanic eruptions or land sliding. Unfortunately, engineers have still not developed sufficient methods to tackle ground ruptures and land sliding, but some basic methods exists such as using retaining walls or forestation to mitigate the land sliding impacts.

The author of this thesis develops and utilises existing data and methods to characterise slab track systems. For the purposes of supporting railway infrastructure managers, this thesis suggests approaches for designers to choose the best option of track for un-stable zones planning. To this end, the track systems selection is given an important place in this thesis, which also describes active seismic zones and examines the ways of mitigating its risks for slab track systems. These methods can be described as follows:

To manage soil liquefaction, ground remediation may be done using piled foundations, spread footing, reduction of ground water and changing the soil in the liquefaction zones.

To prevent land sliding, retaining walls can be built in railway area to protect the track from unforeseen sliding. Moreover, planting the slopes is a very common and easy method to mitigate the land sliding impacts.

The ground ruptures present a very complex situation for the engineers, because there are no methods to mitigate its impacts. To avoid constructing railway lines near fault zones may be the only solution.

Turkish State Railways, responsible for operation and infrastructure, deal with high speed railway lines construction throughout the country. However, Turkish ground has had all failure modes which are referred in above in case of earthquakes. To mitigate these failures, the author gives some beneficial advice inside this study. The small city Pamukova, along the route of the Ankara-Istanbul high speed line, has soil liquefaction risks in the ground. These beneficial suggestions could be used in this high speed line construction.

The thesis is aimed at four major goals;

First, the author presents the characteristics of different track systems, with their advantages and drawbacks in terms of reliability, availability, safety and maintainability.

Second, he shows the types of slab track systems and characterisation of their specialities, requirements, advantages and disadvantages at a glance.

Third, he discusses how track systems may be built in an unstable zone or area with active seismic behaviour. The broader purpose of this thesis is to demonstrate the potential positive impacts of applying slab track systems in unstable zones and its advantages in terms of mitigating earthquake effects.

Finally, the author discusses the ground conditions in Turkey and the respective applicability of slab track systems.

1.2 Scope

This thesis presents information related to ballasted and slab track. The ballasted track systems will be investigated in terms of their components, requirements, advantages and

drawbacks. The ballast-less track systems which are known as slab track systems are examined in more detail. Each different type of slab track systems will also be discussed briefly. In the case study and elsewhere in the thesis the earthquake impacts on the structures and the railways will also be described. There are various methods that have been suggested to mitigate these impacts. There will also be mentioned. With the idea of providing some beneficial information for Turkey, some discussion will be included about earthquakes and Turkish State Railways (TCDD). Briefly, the author of this thesis will investigate several subjects: railway tracks (slab track-ballast track), earthquake, and impacts of the earthquake and mitigation of these impacts on the railway lines.

1.3 Methodology

The use of slab track systems brings several benefits. Therefore, it is not surprising that there are a number of slab track types that have been produced by different companies. For this reason, the author has faced a serious obstacle during this research. It is the difficulty of finding an independent source which has not been prepared as advertising material for a company. Most of the sources available are in support of some products manufactured by companies. As such, the author has taken much care to stay neutral.

Although the secondary literature on the various aspects of earthquakes is in abundance and broad, specific studies on the understanding of slab track behaviours in the case of earthquakes can be counted on the fingers of one hand. Nevertheless, the present literature still provides some hints to understand general earthquake behaviour, and ideas for retrofitting the slab track. Drawing upon the information provided by these sources, the author focuses on the adaptation of the earthquake mitigation methods, especially soil liquefaction methods that deal with railway infrastructure, such as foot spreading and pile foundation methods.

1.4 Dissertation Structure

At the beginning of the thesis, the author gives a brief background to the nature of ballasted tracks, slab track, earthquakes and the impacts of earthquakes. Then in Section 3, the author describes ballasted track for the railway infrastructure, including its advantages, drawbacks and system components. After that, in Section 4, he presents the history, requirements, and components of the slab track systems. This section also introduces the types of slab track systems. Then, the nature of the earthquake and the impact of seismic movements on the railway lines are explained in section 5 as a case study. In section 6, there is a brief discussion about slab track systems that are available for the Turkish ground conditions. Finally, there follow some recommendations provided in the conclusion.

2 Background and Literature Review

2.1 Background

According to the UIC regulation, a line is described as a high speed line, if the designed train operation in where speeds above 250 km/h. Conventional lines which are upgraded to a speed of 200-220 km/h can also be considered as high speed. The technical requirements such as reliability and availability indicate that track type selection is one of the most important things which should be taken into the consideration. Since the beginning of the railways, the principle of the ballasted track structure has not changed significantly despite the innovations that have taken place in other parts of the railway.

In the railway organisations the selection of the track is an argumentative issue. It becomes more and more difficult to apply maintenance and renewal work with the new growth of traffic intensity. Against this background, ballasted track concepts have lost their attractiveness in comparison to slab track systems. Using of slab track brings several advantages for the construction sides, such as tunnel or bridge construction, while traditional ballasted superstructure can still satisfy high demands, as demonstrated by the TGV-tracks in France. Life cycle cost, construction time, availability and durability play crucial roles in the design of railway lines. In this case non-ballasted track concepts introduce good opportunities.

Certain railways such as those of Germany (DB), France (SNCF) and Japan (JR) have developed high-speed ballast-less track. Especially, in Germany the authorities have made decisions to build sections of high speed lines by using non-ballasted track to reduce high maintenance cost because they need more reliable tracks in order not to meet serious problem in their busy networks. However, France still utilise ballasted track systems for its high speed lines. Because, the French railway companies, RFF, consider the labour skills and using the existing machines of the ballasted track systems.

There are number of factors that play crucial roles in calculating the capital expenditure for particular track frames; installation cost, maintenance cost, and so on. Building slab tracks costs are much higher, and this cost can be from 50% to 75% higher than ballasted track does. However, experience shows that, especially in tunnels and bridges, the maintenance costs are less than the costs associated with ballasted track. These systems reduce the maintenance time and cost in the tunnels. Smaller construction depth and drainage opportunities are also strong advantages for choosing track types.

Slab track systems can provide well-improved track geometry with greater lateral stability. Yet, slab track systems have several disadvantages as well as benefits. Substantially, higher initial cost is one of the most important drawbacks. Furthermore, the rigid structure of the slab track allows only limited improvements in future. Adaptations to changed conditions,

such as changes in track geometry, can be difficult to perform, and at high cost. However, some of the system products are available that reduce the initial cost of the system, such as embedded slab track systems. Moreover, the floating slab track systems have been introduced to provide less transmission and propagation of vibration and noise. The railway concepts require less rigid systems in railway track. However, rigid track structure may not be solved in slab track systems. There are number of factors covering the design of ballast-less track;

- Absorbing railway track vibrations and noise
- Supporting layer should have sufficient bearing capacity and elasticity.
- The Soil settlement should be expected to have fixed depth; and precaution should be taken to deal with extra settlement.

In general, slab track systems have four important types, namely Direct fixation, Indirect fixation, Floating slab technology, and Embedded rail systems.

Slab track systems have had a rapid development in many countries, for instance, Germany's Deutsche Bahn (DB) has been carrying out test works for 7 types of ballasted track since 1996. The best known German slab track designs are Rheda and Zublin and their types. In both of these systems, the sleepers are cast into a concrete slab.

Figure 1: Sonne-Ville Low Vibration Track simulated for Marmaray project/Istanbul (Sonneville, 2010)

The French Stedef system is generally used in tunnels in France. This system has been used for metro systems and the high speed networks. Furthermore, this system provides a high degree of elasticity, which ensures good noise and vibration insulation. The Sonneville Low Vibration track has an important place in the slab track systems competition. Beside the channel tunnel LVT will be used in the tunnel crossing the Bosporus as part of the Marmaray project. This is a 12 km long line with double-track consists out of tubes under the European and Asian side of the city of Istanbul connected by an immersed tube.

Japan was effectively the birthplace of high speed rail. Development work on the Shinkansen network started at the end of the 1950s between Tokyo and Osaka, and this was opened in 1964 as a first slab track line in Japan. The Japanese high speed network has a 3,500 km of double track. In Japan, ballast-less track always consists of prefabricated slab track, using slabs just under 5 m long.

Ballast-less track has not been used much in Italy. In 1992, The Ferrovie dello Stato (Italian State Railways) had less than 100 km of ballast-less track. This track was supplied to the Japanese system which is referred to above. ÖBB (Österreichische Bundesbahnen) which is the Austrian Federal Railway uses another slab track system, which is very popular in Austria. The ÖBB-Porr system, comprising embedded mono-block sleepers, is very similar to the Züblin design that is mentioned above. A continuously supported rail system has been in use in the Netherlands since 1976. The system is known as the Embedded Rail Structure (ERS), and involves providing continuous support for the rail by a special mixture of asphalt or concrete, depending on type. The Figure 2 indicates the Edilon slab track system and its special mixture which is known as Corkelast.

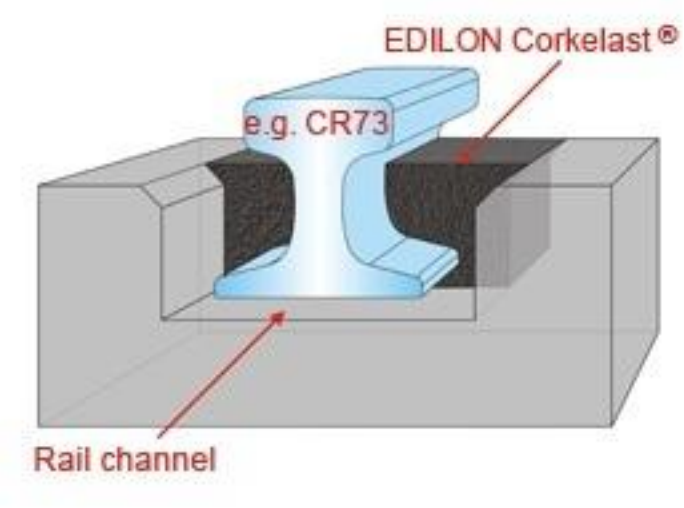

Figure 2: Edilon slab track and its corkelast mixture (Goldschmidt-Thermit Group, 2010)

The investigation of unstable areas constitutes the main part of this paper. Therefore, an earthquake investigation will be undertaken. Briefly, an earthquake is an event that should be considered before the railway tracks are being constructed. There are a number of different impacts that earthquakes may cause, such as soil liquefaction, land sliding and volcanic eruptions. The most dangerous impact of the earthquake is soil liquefaction, which is a phenomenon where in a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic, or shock loading and then flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance (Sladen, D'Hollander, & Krahn, 1985).

Methods of mitigation of the earthquake impacts have been determined by engineers. Additionally, there are different methods which may be used in the future. This paper presents these methods and investigates the availability of these for the railway structure, particularly the slab track systems structures. These methods are ground remediation methods which are removing the ground water with pipe systems and changing the soft liquefiable soil, and the other methods for the different earthquake impacts, such as land sliding.

2.2 Literature Review

This study is based on the studies that have been conducted in three different fields of research: the investigation of the track systems, the characterisation of unstable areas, and mitigation of earthquake impacts on the railway lines constructed with slab track.

The first field of research is the investigation of the track systems which focuses on slab track, particularly. The importance of slab track systems for the railway infrastructure has been the subject to much research. Esveld, (2001) presents ground-breaking studies in terms of comparing slab track and ballasted track can be counted as the best known ones. He analysed the slab track types and its material features which are used in the world currently. Moreover, in his book, he allocates a section for the requirements of special parts of the slab track systems, such as track resilient layer, usage in tunnel and bridges. Furthermore, the maintenance statistics of the slab track have been referred in the study inclusively. Drawing upon Esveld, (2001) study, Lichtberger, (2005) has worked on the track systems' components, but he has mainly focused on slab track systems. He has detailed his study with presenting the requirements of the slab track in terms of subsoil, sound protection, transition areas, signalling and energy supply at the beginning of his study. After that, the comparison of slab and ballasted track with its advantages and drawbacks in both systems follow. Then, he discusses the economic efficiency and cost of slab track systems. He has appended a very comprehensive table to show differences between the slab track types.

Profillidis, (2006) has examined the selection of track types of the railway and provided some information about slab track systems and their usage. In his work, he also gives a comparison of slab tack with ballast track, albeit short. The railway tracks provide a structure to guide the train in position. The track on a railway which is also known as the permanent way, is a structure that includes the rails, fasteners, sleepers, ballast (or slab) and sub-grade. The track systems consist of two main structures. One of them is superstructure layer, which it includes rails, sleepers, ballast and the sub-ballast, which support and distribute the train loads into the sub-grade. The second layer is sub-grade layer which consists of formation layer and base. This layer enables the transfer of loads from superstructure to ground. While the track systems traditionally based on ballasted track, it may alternatively be supported by concrete

slab. Especially, slab track systems have been used successfully for high speed lines, urban tramways, and metro systems.

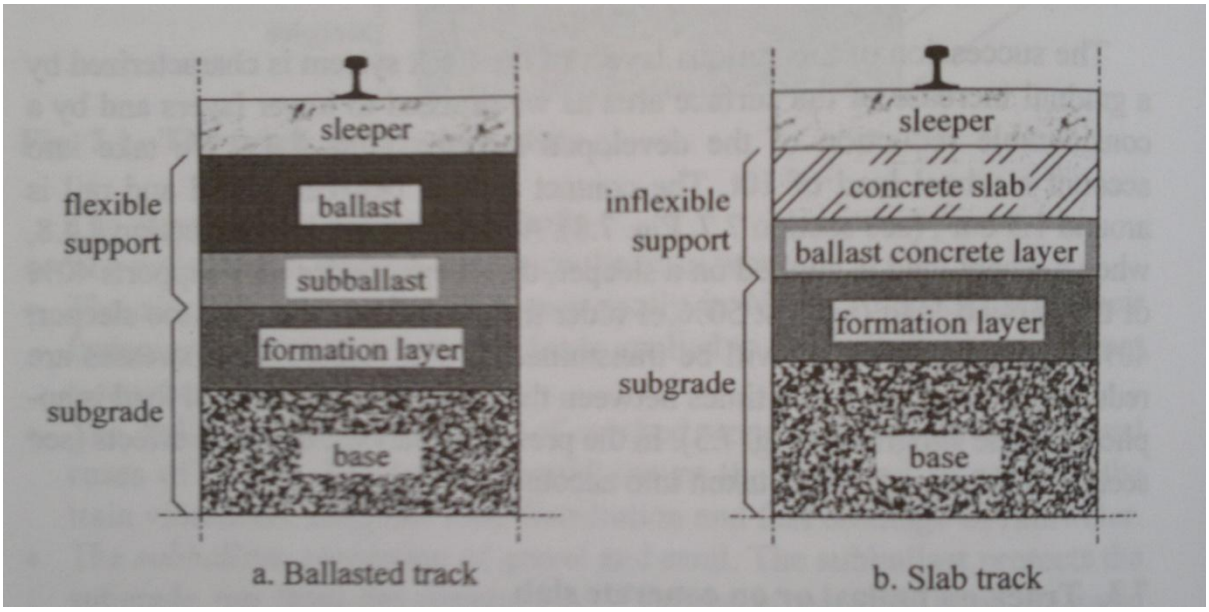

Figure 3: Differences between slab track and ballasted track (Profillidis, 2006)

The reports of TAV (2005) Rio de Janeiro to Sao Paulo high speed line and Lier, (2002) have also produced important studies of the slab track types and their advantages and drawbacks. There are another two important studies in the field. One of them has been studied by Yan-Chyuan Shiau, (2008). This introduces and discusses the features of quality management by Japanese enterprises on the production of slab tracks, which can act as a reference and application for the cement industry in Taiwan. The second one has been generated by Husseina and H.E.M.Huntb, (2009) where presents a new method for modelling floating-slab tracks with discontinuous slabs in underground railway tunnels which is very beneficial study for the literature. It helps to understand floating slab track behaviour and specialties.

Bilow et al., (n.d) has investigated the slab track systems in a detail which are commonly used in the world. Various slab track systems that have been used in the world. The Canadian Pacific Railway (CPR) constructed a test section whose patent name is PACT-TRACK near Rogers Pass in British Columbia to simulate and investigate slab track. Since the test was successful, the railway built slab track in the McDonald Tunnel. Both the test and tunnel sections are performing well. Concrete is placed using a specialised slip form paving machine. Concrete is fed into the front of the paving machine using a conveyer system. After the concrete has cured, the continuously welded rail is laid on a concrete layer. Thick rubber pad and the rail are clipped to inserts embedded in the slab.

Slab track is used extensively on high-speed rails in Japan. The high-speed rail requires a very accurate rail alignment to increase passenger comfort. Slab track systems have been

used on the Shinkansen and some of the narrow gauge lines since 1980 by Japanese National Railways (JNR). The JNR considered some of the issues that are direct selection criteria for slab track construction. Slab track construction cost should not be 30% more than the cost of ballasted track. Slab track should have equivalent behaviour with ballasted track in terms of damped sound and degree of resilience. Furthermore, it should allow for adjustments in the vertical and lateral directions to account for deformations of the sub-grade. (Bilow, P.E., S.E., & Randich)

According to Bilow et al.,(n.d.), slab track maintenance is found to cost much less than ballasted track on the Shinkansen lines, ranging from about 0.18 to 0.33 of the maintenance cost required for ballasted track. The average construction cost of slab track is 1.3 times that of ballasted track. The difference in construction costs will be recovered in 8 to 12 years.

Slab track has also been used in the Eurotunnel under the English Channel where the speed is 200 km/h. In this project, the slab track is called Low Vibration Track (LVT) and was developed by Sonne-Ville International Corporation. The LVT system has also been used for MTA (The Los Angeles County Metropolitan Transportation Authority), Metro Link - St. Louis and DART (Dallas Area Rapid Transit) transit systems in the United States, and in numerous other countries (Bilow, P.E., S.E., & Randich).

The Embedded Rail System (ERS) has been used since the 1970s in the Netherlands. This system uses a compound called Corkelast which consists of cork and polyurethane mixture to provide continuous support for rails on the slab track. This system is used extensively for light rail in Europe and has been used on bridges. In the ERS, the rail is temporarily suspended in a trough in the concrete slab and then the elastic material is placed around the rail and allowed to harden.

Recently, a 3 km length of the ERS concrete slab track placed on grade was built in the south of the Netherlands. The structure consists of a continuously reinforced concrete slab resting on a cement-stabilised base, which was placed on the sub-base (Bilow, P.E., S.E., & Randich).

Slab track use has been undergoing development in Germany for many years. In 1996, the German Railway began operating a test track in Karlsruhe consisting of seven new types of ballast-less tracks. Approximately 340 km of slab tracks has been constructed throughout the German Railway network. One of the best-known German designs is the Rheda compact design, developed during the 1970s, which uses a top down method of construction. After the rail is positioned to line and grade, concrete is placed below and around the ties, partially embedding the ties (Bilow, P.E., S.E., & Randich).

Approximately 147 km of slab track were constructed along the new 219 km Cologne-Rhine high speed line. The higher initial cost of the slab track was offset by the saving at

maintenance costs and greater availability of the tracks due to less downtime for track maintenance (Bilow, P.E., S.E., & Randich).

The second field of study that has been used within the context of this thesis is the description of earthquakes, and its impact on the ground structure which is a broad subject of its own. There are a number of studies that have been done by the communities and researchers to understand the earthquake's main impacts. The United States Geological Studies (2011) and Japanese Meteorological Agency (2008) have had significant studies in terms of investigating the historical impacts of the earthquake in the world. Both research groups have been following the earth movement continuously. They have come up with a very beneficial study for the literature of the earthquake.

As far as the mitigation of earthquake impacts on the railway lines constructed with slab track is concerned, there is limited number of articles in this field. Articles written on the mitigation of soil liquefaction by the American Railway Engineering and Maintenance-of-Way Association (AREMA), and Prucz and Pourbohloul, (2008) can be counted as an example to this. However, these articles refer to American ground conditions specifically. There is also a short article which was published by Japanese Railways, (2000) about Shinkansen derailment. The article, which is important to understand the earthquake's impacts on the railway structure, presents the earthquake vibration effects on the high speed lines constructed with slab track. However, the application of the earthquake mitigation methods in railway track system construction has not been taken into consideration by any authors. This constitutes an important deficiency in secondary literate. The aim of this work is to address this deficiency by examining the importance of the application of earthquake mitigation methods for railway lines construction.

3 Ballasted Track Systems

The present section deals with the principles of ballasted track which is called classical track or conventional track. As mentioned, the classical railway track basically consists of rails and sleepers which are supported by ballast. The ballast bed is laid on a sub-ballast layer which forms the transition layer to the formation. The rails and sleepers are connected by fastenings. These components and other structures, such as switches and crossings are all considered as part of the track.

The principle the ballasted track structure has not changed since the beginning of the railways. The most important developments in this area have been realised since the Second World War with continuous welded rail, concrete sleepers and elastic fastenings. With these improvements, the traditional ballasted superstructure can still satisfy the demands of high speed or conventional lines, as can be clearly seen on the TGV network in France. Conventional ballasted track brings many advantages as well as disadvantages.

Ballasted track has relatively low construction cost and requires only a very simple construction process. Also it allows small adjustments of the track layout in the curves. It has good noise and vibration characteristics, and its elasticity brings advantage for the whole structure. The type of the structure can be chosen not only taking into account axle loads and speeds, but also with the requirement of service life. Furthermore, the local condition for the maintenance is also very important for the selection of the most convenient track structure. Regarding the tunnels and bridges, both of them have difficult circumstances to provide regular maintenance. In this case, ballasted track systems bring difficulties from both economic and technical sides. Decision makers should consider that the busy networks, such as London Underground and Paris Metro systems needs more maintenance in the less time under the tunnel conditions. However, ballasted track systems require regular maintenance works on the line. At the beginning of both lines projects, project managers have considered these conditions and constructed a different type of track called ballast-less track.

3.1 Advantages and Drawbacks

As has been mentioned, ballasted track systems have been developed for a long time, and are still being used with very important applications such as TGV tracks in France. According to Esveld (2001) the ballasted tracks have proven technology since the first railway line. They bring important advantage in terms of cost, labour skills, materials and machines. They also provide good elasticity and damping noise.

The type of structure to be chosen depends not only on the expected axle loads and speeds, but also on the required service life, the type and amount of maintenance, local conditions,

and availability of basic materials. The relations between initial cost and maintenance cost are very important to make a correct evaluation in the choice of track form.

Figure 4: Ballasted track systems, Switzerland, 2011(By the author)

Figure 4 shows a ballasted track system with wooden sleepers which are still used in Switzerland. The disadvantages for ballasted track should be advantages for slab track systems. Slab track producer began to develop a competitive edge thanks to these drawbacks. At speed of 300 km/h, the small ballast grains, when lifted from the permanent way damage the rail and the wheels of the trains. The permeability of the contamination can reduce the sub grade structure strength and complicate the ballast cleaning works. Heavy and high track structures require stronger constructions for bridges and viaducts. The rate of maintenance intensity is very high and brings additional loads for the construction cost. In the long term, the life cycle cost becomes more and more important because of operational issues.

3.2 System Components

3.2.1 Track Formation

The substructure consists of the formations which include slopes, ditches, cuttings, embankments, straight way and so forth. The formation must have sufficient bearing capacity and stability, and must exhibit reasonable settlement behaviour. The formation structure must also provide good drainage for the rain or melted snow from the ballast bed. Finally, there should not big differences between design and construction sides.

There are a number of requirements that should be achieved in railway track. The measurement of formation can be California Bearing Ratio (CBR) and Standard Proctor Testing (SPT), and these are the significant requirements for the construction of ballasted track systems. In general, the formation layers require minimum 97% proctor and 5% CBR.

Furthermore, the deformation modulus may also be an important factor for the ballast track formation, and it should be more than 100 MN/m^2 (Esveld C. , Modern Railway Track, 2001).

3.2.2 Ballast Bed

Ballast plays a vital role for transmitting and distributing the train loads to the intermediate layer and sub-grade. The bearing capacity of the track, ride quality and passenger comfort may change spontaneously, depending on the stability of the ballast layer.

The ballast bed consists of a layer of loose, coarse grained material which, as a result of internal friction between the grains, can absorb considerable compressive stresses but not tensile stresses. Ballast requires good depot condition, and it should be always ready to use The Figure 5 shows the ballast depot and ballasted track. The ballast is generally carried by freight trains.

Figure 5: Ballast bed and depot for railway lines (Railway Technology, 2010)

The thickness of the ballast bed should be such that the sub-grade is loaded as uniformly as possible. The optimum thickness is usually 25 to 30 cm and measured from the lower side of the sleeper.

> *Contamination of the ballast bed may have external or internal causes, such as attrition and weathering of the ballast material or upwards penetration of fine particles in the form of a clay mixture referred to as slurry. The most important requirements to be met by the ballast material are hardness, wear resistance, and good particle size distribution. The particles themselves must be cubic and have sharp edges.* (Esveld, 2001)

A contaminated ballast bed is an obstacle for water drainage which results in reduced shear resistance and freezing during frost. The particles themselves must be cubic and have sharp edges to increase the materals friction rate. There are three common ballast types which are currently used; crushed stone, gravel and crushed gravel.

3.2.3 Sleepers

The rails lie on sleepers, and these are a built-up portion of the superstructure. There are three types of sleepers that are used, namely; timber, concrete and steel sleepers. In general, sleepers should provide support and fixing facilities for the rail. It should preserve the track gauge and rail inclination. Furthermore, it should provide adequate electrical insulation between both rails. Finally and most importantly, sleepers should transfer the loads from rail to ballast or concrete layer.

The timber sleepers are generally 15 cm high, 25 cm wide, and 2.50-2.70 m long. They are light weight at about 50-65 kg, which means that it can be replaced by hand. It is known as a traditional type of sleeper. This sleeper can be produced from soft or hard wood depending on the structure requirement. In the switch and crossing zones, the lengths of timber sleepers extend to 5.50 m. In the Figure 6, the application of three type sleepers (concrete, wooden and steel sleepers) can be seen in the picture that may be applied in same zone. These do not have impact on bearing capacity.

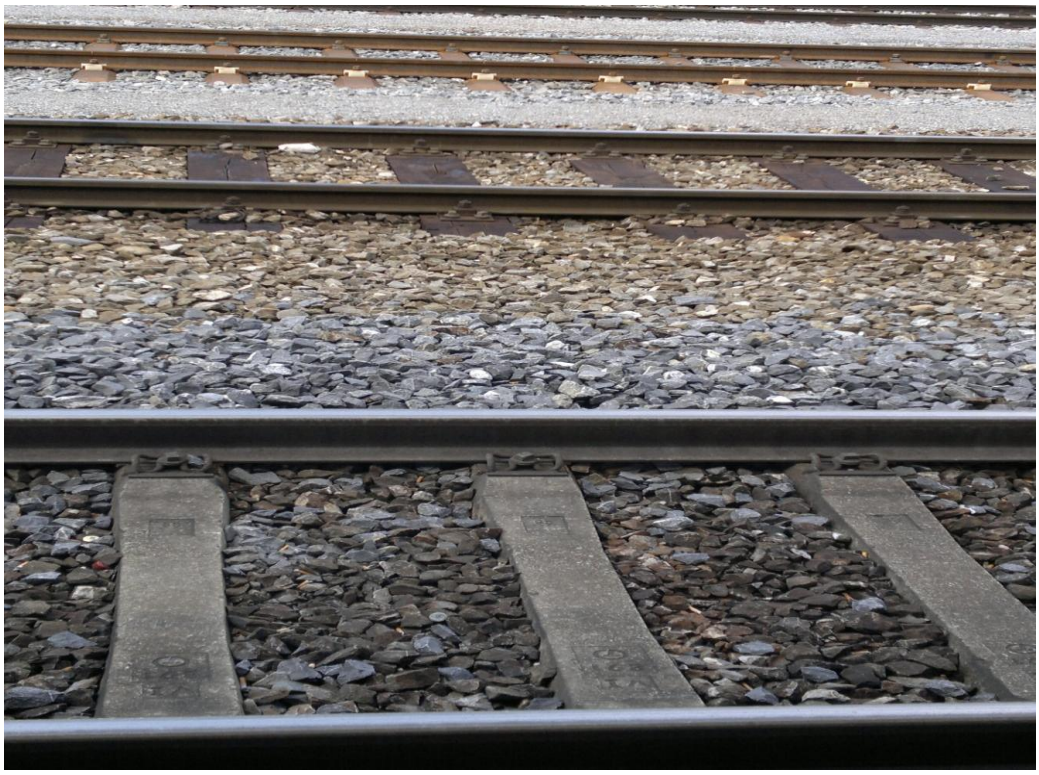

Figure 6: The Application of Concrete, Wooden and Steel Sleepers in Same Area (By author-Switzerland)

The advantage of the concrete sleeper is that climatic influences have little effect. Its service life is significantly higher than this of timber sleepers under certain conditions. These conditions require that the formation and ballast bed are that should be of good quality as well as the rail and weld geometry. (Esveld, 2001) This type of sleepers are heavy in weight (200-300 kg), and provide longer service life than the timber sleepers. One of the important disadvantages of this type of sleeper is its rigid structre and low residual value.

In last decades, the frame sleepers are becoming very popular in railway track systems. These are the formed of both lateral and longitudinal members in a single monolithic concrete casting. It is very important for the track systems which are the basics of ballast-less track system that intends to replace the load transmitting structure of a traditional ballast track (Esveld, 2001).

In many countries steel sleepers are only used on a very small scale because of problems such as insulation, maintenance and its higher price. However, it can present longer service life, great dimensional accuracy and positive residual value.

3.2.4 Fastening Systems

The term fastening systems is considered to include all the components which together form the structural connection between rail and sleeper. All over the world a great variety of fastenings existing and new ones are produced all the time to provide better performance. The choice of fastening also depends on the properties and structure of the sleeper. Figure 7 indicates typical rail fastening which is produced for ballasted track systems

Figure 7: Rail fastenings for ballasted track, Vossloh design (Vossloh, 2009)

These materials absorb the rail forces which are from the train wheels elastically and transfer them to the sleepers. In all circumstances such as while the vertical clamping force is applied on the rail, the sleeper must be sufficient to hold the rail in the exact place, even in case of wear, in order to provide the necessary longitudinal resistance. It also reduces the vibration and its impact. The main duty of the fastening system is maintaining the track gauge and rail inclination within certain tolerances.

The material which is known as rail pad provides electrical insulation between the rails and sleepers, especially in case of concrete and steel sleepers. According to Esveld (2001), the longitudinal resistance between rail and sleeper should be at least 15 kN so that it is much greater than the longitudinal shear resistance of the sleeper in the ballast bed. This would amount to 5 kN for half a sleeper. This means that in case of large axial rail forces the fastening remains intact and the sleepers move in the ballast bed (Esveld C. , Modern Railway Track, 2001).

4 Slab Track (Non Ballasted Track) Systems

The term “slab track” is used to describe non-ballasted track structures that usually consist of concrete slab, rails and fastenings. These systems are used where strength and durability are required. The slab track is becoming very popular for the high speed and low speed train operation which is constructed in the tunnels, bridges and straight ways. In English this type of track is called Slab Track (ST), in German the term Feste Fahrbahn (FF) and in French Voie sur Dalle (ISO).

4.1 Selection of Track Form

Slab track is commonly used for light rail transit systems as well as high speed railways. It can also be used for corridors where high-speed passenger trains share track with freight trains. In slab track, ballast as the load distributing element is replaced by another material which has a stable position, such as concrete or asphalt. The plastic deformation of these materials is very low in regular circumstances. The elasticity of the structure has to be provided by inserting elastic elements below the rail or the sleeper, as the concrete or asphalt layer is very stiff. In general, a slab track system provides a reduction in the structure height and weight, lower maintenance requirements and, hence, higher availability and increased service life.

Figure 8: Ballast-less track systems in Switzerland (By the author)

The general problem which occurs with conventional track or ballasted is the slow deterioration in the ballast layer under the traffic conditions. As stated earlier, the ballast layer consists of granular materials which can damage while it is under the influence of friction, and turn into fines. These fines can cause drainage problems. Therefore, the ballast

layer requires regular maintenance during the operation. This maintenance reduces the life of the ballast as well as having an impact on RAMS.

Maintenance work, such as tamping, ballast cleaning and track lining brings 20-30% extra cost for the ballasted track. The slab track systems eliminate most of this cost from the maintenance. Additionally, it should be considered that the drag force is becoming more and more important with increase in the speed of the trains. The flying ballast phenomena is taking place in high-speed train and difficult to cope with it. Very high speed trains should either use ballasted track by taking extra precaution or use slab track for the construction.

Slab track began to be used on Britain's the Southern Railway built with a concrete slab built in 1899 (Bilow, P.E., S.E., & Randich). At the beginning of the project, this track has built in order to stabilise a section of track on poor soil. Furthermore, widely accepted usages of these systems have started to be utilised on light rail transit systems in the United States and Canada. In these areas slab track is used extensively on corridors where light rail shares the slab track pavement with automobiles and buses.

The fundamental track type selection is quite open to debate nowadays. Both systems have several advantages and disadvantages. The table below illustrates the comparison of ballasted track and slab track systems on the similar areas in Germany. The maximum speed in NBS Frankfurt-Cologne high speed lines is 300 km/h and Wurzbuerg's is 250 km/h.

Parameter	NBS Frankfurt-Cologne (Slab Track)	Würzbuerg (ballasted track)
Maximum gradient	40/100	20/1000
Minimum curve radius	3350 m	7000
Maximum cant	170 mm	65 mm
Proportion of bridges	9%	3%
Proportion of tunnels	37%	21.5%

Table 1: Slab track vs. ballasted track (Bilow, P.E., S.E., & Randich)

The table shows that the maximum gradient can be obtained by slab track system and the system can reach minimum curve radius by 3,350 m. By increasing cant a better comfort and higher speed in the curves can be obtained. The slab track systems have great advantages for the structures. The author of this paper aims to prove primarily that slab track usage brings more and more advantages in terms of economic, technologic and safety. Several factors will be taken into account and show the better system in terms of track type selection.

4.2 The Characteristics of Slab Track

In the design of railway lines future such as life cycle cost, construction time, availability and durability play a vital role for the networks which have increasing traffic density. It becomes more and more difficult to complete maintenance and renewal works in night possession or 3 to 4 hours work during the day. These conditions increase the need for low maintenance track systems.

The slab track provides excellent performance by maintaining track geometry and reducing maintenance of track cost for very high speed lines (Esveld & Markine, 2008). The developed countries, such as France, Germany, Japan, Spain and so forth, have started to play important role in high speed railway development. However, not all use slab track. This section analyses high speed railway systems which are related to slab track. The great slab track advantages can be listed as follows;

- Requires less maintenance or is a maintenance-free structure. For example, The Rheda systems require 10% maintenance of the ballasted track (Esveld & Markine, 2008);
- Provides higher service life to compare with ballast track (Esveld C. , Modern Railway Track, 2001);
- Significantly reduces the dynamic stress on subsoil. It might be important unstable areas (Lichtberger, 2005);
- Allows higher value of cant and cant deficiency that permit small horizontal radii on passenger only high speed lines where trains are relatively short and light.
- Provides higher availability with lower possessions progress (Lichtberger, 2005);
- Provides hard surface for the drainage instead of a crumbled away ballast layer (Lichtberger, 2005);
- Permits emergency and maintenance machines access;
- Provides better ride quality for the passenger and driver;
- Reduces the track structure height; it thus brings several advantages for the tunnel height. The construction of the tunnels is very expensive, and the reduction of the tunnel height brings economic advantages approximately at £1 M reduction at cost by decreasing 0.1m diameter (Esveld C. , Modern Railway Track, 2001);
- Ballast particles can cause serious damage for the train wheel or rails as a result of churning high speed impacts (Lichtberger, 2005);
- Provides a cleanable track inside stations;
- The slab track systems reduce the track systems weight. It brings important serious advantage for the bridges;
- The slab track systems allows the use of effective and economic braking systems, such as eddy-current braking;

- Apart from these advantages each slab track design can have a special advantage, such as reduction of noise and vibration with the floating tack systems and so forth.

Besides of these advantages slab track systems have some drawbacks which should be considered in the construction progress. These general drawbacks of the slab track systems are summarised;

- The higher capital expenditure is one of the drawbacks. Even the politicians and commercial consideration often support lower initial cost during the design process;
- There is not sufficient test data to assess the rate of the deterioration of the slab tracks;
- The rail pad replacement and the application of preventative grindings problem have still not been solved yet;
- The ballasted track provides lower carbon footprint and re-usable recovered materials;
- Besides of these general drawbacks, the specific slab track designs may have special disadvantages. Some of them have not improved the life cycle cost and other technical requirements, to date yet.

4.3 System Requirements

The requirements for slab track systems are changeable depending on the country because of specific requirements concerning the superstructure and sub-structure and systems show different behaviour, especially in different areas, such as tunnels, embankments and bridges. However, some areas such as noise and vibration sensitive zones require extra work in the slab track construction. Very high speed line construction needs to consider dynamic forces while braking or accelerating.

The ballasted track systems do not allow easy access in case of emergency. Therefore, slab track systems must require easy access for rescue services. In this section, the requirements of the slab track systems are dealt with for different areas.

4.3.1 Requirements for the Substructure

Substructure requirements are becoming very important while slab track systems have been improved for the very high speed railways. The limited track geometry adjustments constrained to design sensitive substructure for the ground settlements, in particular embankments should be stable against settlements. Soft sub-grade can be remedied with the compacted soil. Alternatively, a very sophisticated solution is the use of mixture which includes cement, in another words slab track needs to be founded on ground that will not settle greatly.

Ballasted track requires embankments with a maximum of 2cm settlement in over 10m track length. These requirements are too low for the slab track. The substructure of the ballasted track has to be secured by earthworks measured until 0.5m depth below the frost protect

layer. However, the slab track needs to be secured at a depth of 2.5 m below the bearing plate. On the earthworks, these requirements have led to higher construction cost than ballasted track has. The small settlement can be controlled by fastening from +26 mm to -4mm (Esveld C. , Modern Railway Track, 2001).

The regular composition of layers consists of two important sub-layers; improved ground, and a frost-protection layer of granular material. On the top of these layers, either concrete roadbed or a layer of asphalt-concrete is applied, depending on the system. After that the actual slab track is constructed. Before the preparations for the embankment, the geotechnical research is very important to understand the ground conditions and the deformation behaviour (Esveld, 2001).

These works can be achieved by dynamic compacting and by mix-in-place ground-improvement. In some of the area, the weak ground layers are replaced with mixture of the better layers. The geotechnical requirements for the embankment can be provided by proctor densities which are between 98 and 95 per cent, depending on the age of the track.

4.3.2 Requirements for Slab Track in Tunnels

The first application of ballast-less tracks was the installation of slab tracks in tunnels. The low construction height of the track provides best conditions for using slab tracks. In case of enlargements of the tunnel gauge in existing tunnels, the small construction height is a major advantage to land use. The Figure 9 indicates the slab track construction inside the tunnel.

The reinforcement in the tunnel is becoming more important with the growing networks. Many tunnels are using both passenger and freight train passes, which require better tolerances for the structure. The electrification of some networks often requires the lowering of the track heights in the tunnel and can be done by slab track systems rather than ballasted ones. There are also other issues such as alignment design and vertical adjustability which should be considered in the tunnel construction

In tunnels, the total construction height is restricted because of cost and geological issues. The tunnels formations are very important in making sure that the slab track system is suitable because, tunnel formations can show different behaviours under loads such as extreme settlement that must be considered to select track type. The concrete layer with a thickness of 30 cm at grade may be reduced to 15 cm for the use in tunnels. Inside the tunnel, some specific requirements, such as drainage and emergency access, can also be met.

The ground properties in terms of rock/soil have to be appropriate for the installation of slab track. All structural types of ballast-less track used at different grade can be applied in tunnels. (SSF Ingenieure)

Figure 9: Installation of slab track in tunnel (By the author)

4.3.3 Requirements for Slab Track on Bridges

The slab track systems are always used on the bridges and viaducts. These systems can decrease the weight of the additional track load and maintenance issues.

Bridge and viaducts provide a solid foundation for slab track, but it is short and discontinuous. Moreover, bridges can be affected by external issues such as temperature and vibration. In this case, longitudinal movements of the bridge-structure will occur. It can affect the slab track structure as well as bridge structure. The slab track systems can solve many problems on the bridges and viaducts. For example, the derailment risks are reduced without the need for extra precautions, and the track is freely movable on top of a concrete or asphalt-concrete roadbed.

Bridge structures provide the required settlement-free base for slab tracks. Longitudinal deformation of the bridge structure is caused by temperature variation. Longitudinal dilatation has to absorb the energy without trigging high longitudinal rail stresses and in case of long bridges i.e. those over 25 meters, the track has to be fixed to the bridge structure.

Figure 10: Slab track systems on bridges (German Railway Consult Middle East, 2010)

In continuous welded rail (CWR) tracks on bridges, considerable longitudinal rail forces and relative displacements may develop due to the factors such as temperature variations, acceleration and braking. These stresses are caused by the interaction between the bridge deck and the track system, which have to be limited as they are adding additional stresses to the rail stresses appearing on a normal track section.

4.3.4 Requirements for slab track on the Embankment and Cuttings

The cuttings and embankments are the crucial part of the railway lines construction. The local settlement on the embankments should be reduced so that influence from the slab track structure is not seen. The earthwork construction should provide high stability and low settlement.

The subsoil has to be compacted in order to avoid long-term settlement. If the requirements cannot be satisfied by standard compaction methods, sub-grade treatment or methods for acceleration of settlement must be used. Moreover, the soil has to be exchanged if the bearing capacity of the existing soil is insufficient. Soft, cohesive or organic soil in the subsoil should be exchanged to a depth of at least 4 meter below top of rail. The influences of measures during construction, such as lowering the groundwater level, should be considered.

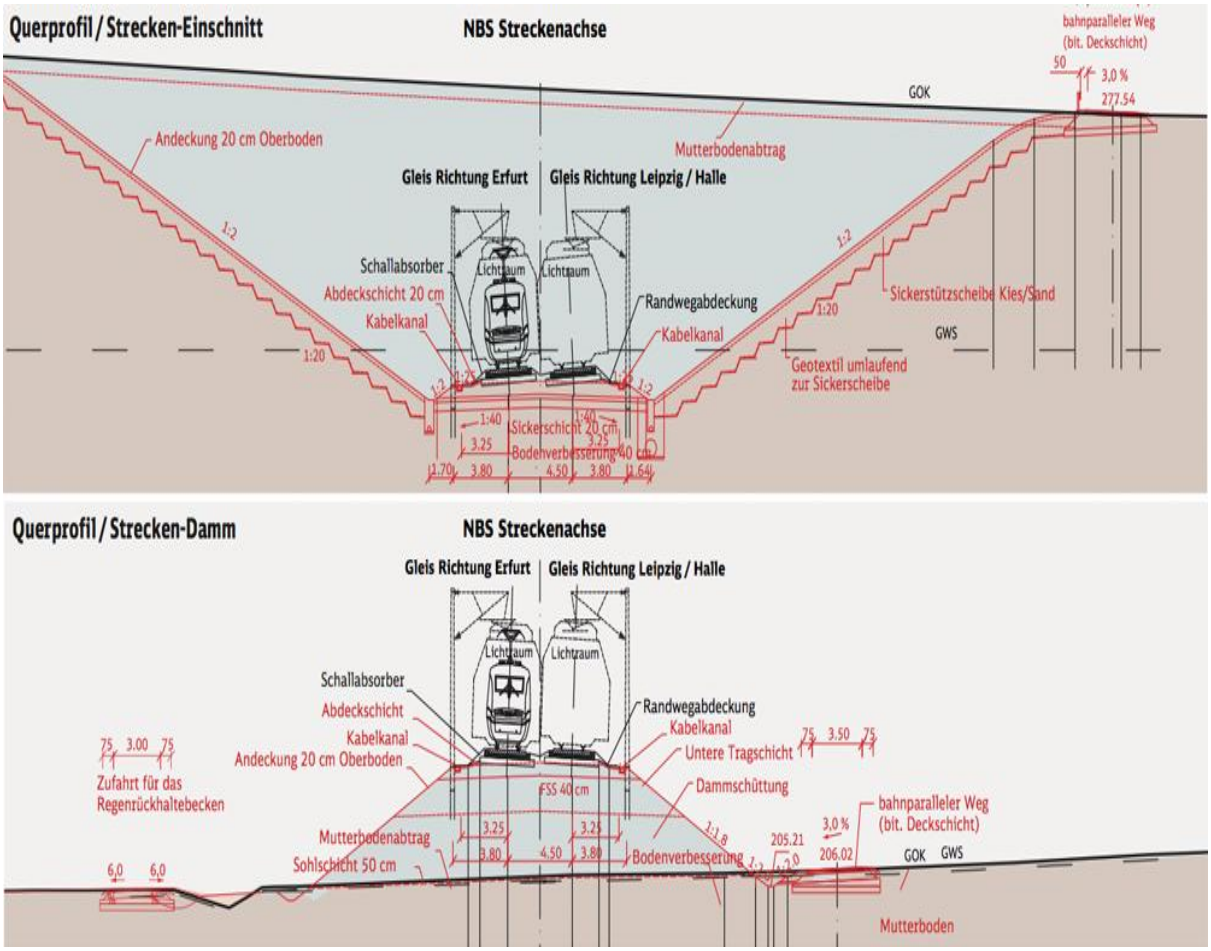

Figure 11: Slab track systems in cutting &embankments (Verkehrsprojekt der Deutschen Einheit 8, 2008)

The cuttings also have the same strict regulations as the embankments. The required arrangement of layers and compaction needs to be provided for 3 m under the rail. The subsoil needs to be durable and provide a suitable bearing capacity combined with small settlement behaviour. Soft, cohesive soil must be replaced or other treatment has to be provided in order to limit settlement.

4.3.5 Requirements for transitions

If the system consists of both ballasted and slab track systems, transitions in the superstructure occur on the railway line. Furthermore, in the substructure transitions between embankments, bridges, and tunnels occur. Transitions demand smooth passing out the difference in both track structures. In these zones, the temperature and other environmental issues are becoming important as they affect the structures preciously. Problems can also occur because of the different construction height and there are number of methods available to solve this problem. However, the author emphasises one method that is more widely known and also economic. In the case of transitions between track structures, the sleepers must be applied with direct rail fastenings or embedded sleepers, and the sleepers must be

placed on roadbed over a distance of at least 10 metres. The stiffness, flexibility, and settlement are very important issues for the transitions.

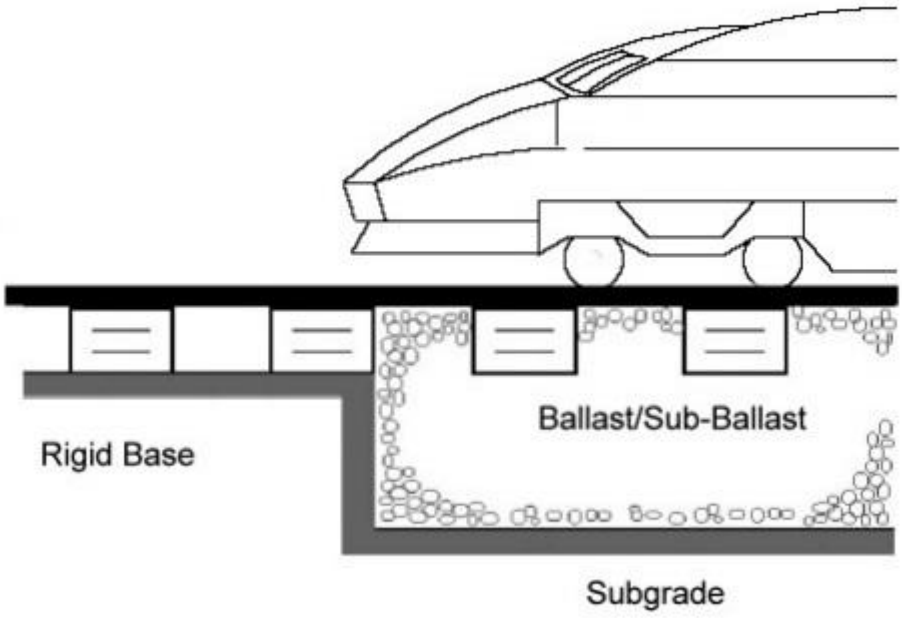

Figure 12: Railway transitions from ballasted to slab track (Xitrack, 2007)

The transition between bridges and slab track involves specific measurements too. There are differences between steel and concrete bridges, but the chosen solution is depending on the length of the bridge itself.

4.3.6 Other requirements

There are several other requirements that should be used in the slab track systems such as frost protective layers, sound protections, signalling systems and electro-technical requirements. The frost protective layer serves compensation for the stiffness of the other subsoil layers as it has to lead surface water away rapidly. For this reason, it should have $1*10^{-5}$ m/s permeability (Lichtberger, 2005).

The correction value for the slab track is +5dB and is significantly higher than ballasted track. Unlike the ballasted track, structure-borne noise on the rails is in the frequency range of 250-100 Hz (Lichtberger, 2005).

The space for the signalling equipment should be designed on the slab track in advance. In order to put extra equipment to improve the system, designers also create free space for signalling.

The slabs may be prefabricated or prepared on the site, depending on the site's condition. In this case, one of the important things that should be considered is concrete availability at the

right time and right place. It can directly affect the slabs' concrete quality and strength. Also the weather conditions should allow to construction on the site. The greatest savings will be achieved in tunnels and on bridges.

4.4 Slab Track Systems Types

4.4.1 Sleepers or Blocks Embedded in Concrete

- **Rheda 2000**

The Rheda system has been used since the first application of it in 1970, and it has been under continuous development. In the first design, mono-block sleepers are embedded in reinforced concrete. The Rheda 2000 Slab Track System has resulted from the on-going development of the well-known German Rheda system. The Rheda 2000 system was first installed in July 2000, as part of the German high-speed section between Leipzig and Halle. Moreover, these systems have also been designed for commuter traffic applications which are known as Rheda City. The track frameworks may be adjusted in lateral and longitudinal direction. The settlement is very important for this type slab track systems.

Figure 13: Rheda 2000 system in construction process (GTE Group)

> *The Rheda 2000 superstructure requires a settlement-free foundation because its reinforcing bars are applied at the centre of the concrete slab with as main function to regulate crack-width and transmit lateral forces, not with the purpose of providing a stiff slab.* (Esveld, 2001)

The Rheda systems can show different behaviours in different Rheda systems. In particular, Rheda 2000 systems eliminate all the previous designs. The main characteristic of the system is a cast-concrete track layer which consists of rail and frame work for the sleepers. It can be seen from the Figure 13 that the rails, sleepers and steels should be stable, while concrete layer is built.

Figure 14: Rheda 2000 system after construction (Flickr)

This technique can tolerate the unavoidable effects of track components. In addition, the rail fastening system allows for adjustments to compensate for long term differential settlements of the substructure. Figure 14 shows the mono-block sleepers that Rheda suppliers have still dealt with improving mono-block systems are embedded into concrete.

The primary development goal for the Rheda system is the improvement of the monolithic quality then, design optimisation and uniform architecture will be created. In order to enhance the monolithic quality of the concrete slab, the sleepers in the Rheda 2000 system were changed from a mono-block design to twin-block. The geometrically exact supporting points can stabilise the rails in their required position. Supporting points produced with high quality concrete provide a strain-resistant bond which is a stable point between the rail fastening system and the concrete track layer. This solution provides safe and long term transfers for the static and dynamic service loads in high-speed operations.

Rheda systems which have already been fitted will require the necessary maintenance measures to prevent reduction of service life. It is very important to think about long term service life.

> *The system configuration was done by eliminating the conventional concrete trough. As a result, the cross sections of the slab have become one monolithic component, whereas in the earlier trough configuration the filler concrete did not play a structural role. Due to the elimination of the trough and the use of twin-block sleepers, a considerable reduction of the structural height could be achieved as is revealed by the height* (Esveld C. , Modern Railway Track, 2001).

According to Esveld (2001) the reasons behind cost-effectiveness in planning are that the Rheda 2000 system design had to fit a variety of track situations in practice. Therefore, solutions have been developed for track systems on earthworks, bridges and tunnels.

- **Zublin System**

The Zublin system consists of concrete twin block or mono block sleepers which are embedded in a monolithic concrete slab. The designer of the Zublin system directly focused on finding a highly economic constructing method in 1974.

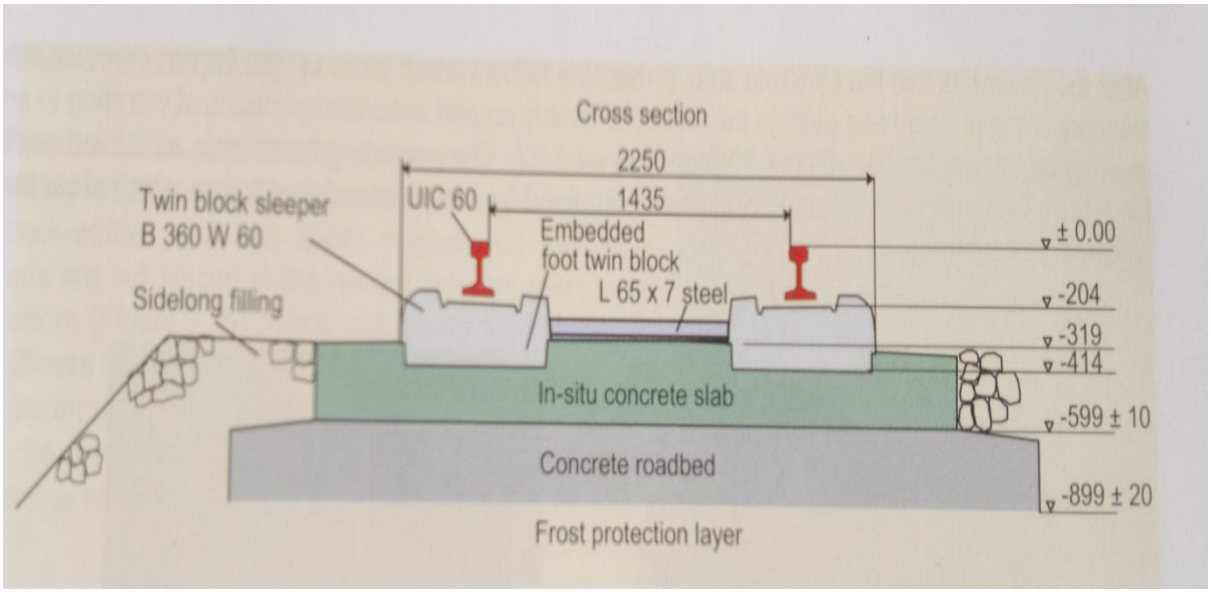

Figure 15: Cross section of Zublin slab track (Esveld C. , Modern Railway Track, 2001)

As Figure 15 indicates the basic design of the Zublin system is a 24 cm thick and 2.8 m wide load bearing slab with integrated twin-block sleepers. Two individual reinforced concrete sleeper heads are connected to form a twin-block sleeper. The reinforcing bars provide not only accurate geometry during installation but they also give the sleepers additional anchorage in the concrete.

The geometry of the sleepers is designed for Vossloh rail fastenings. The rail fasteners are pre-mounted on the twin-block sleepers prior to installation. The designer endeavours achieve a high level of mechanisation combined with a low cost of labour and a high daily turn out of track. The main difference between this method and other methods of slab track construction is the fact that the concrete sleepers are pushed into the fresh concrete by means of vibration.

After the soil improvement, the concrete road bed is constructed upon which the monolithic concrete slab is made with slip form paver. After the paver has laid the concrete slab, machine follows the pushing up the sleepers onto the concrete by means of vibration. The Zublin system can achieve 150-200 m in 8 hours a day. The construction steps of this system are:

- Preparation and construction of the sub-base and base course;
- Reinforcing, concreting and compacting of the concrete bearing slab without interference of the sleepers;
- Fixing the sleepers by compacting with pre-mounted fasteners;
- Installation of rails;
- Implementation of the surface of the slab by hand;
- Waiting for the concrete hardness;
- Disconnection of the frames from the sleepers.

Figure 16: Zublin slab track under construction (Esveld C. , Modern Railway Track, 2001)

4.4.2 Structure with Asphalt- Concrete Roadbed

In this ballast-less structure, sleepers are placed on top of a layer of asphalt-concrete roadbed. This roadbed is made by ordinary paving machines. It is possible to reach level accuracy of +/- 2 mm and cant-deficiencies of up to 180 mm. Thus, the asphalt provides a stiff and level base for the sleepers.

There is also the possibility of applying slabs on top of a layer of asphalt-concrete. Asphalt does not require hardening and can be subjected to loading immediately after cooling, so high construction productivity can be achieved (Esveld C. , Modern Railway Track, 2001).

> *Due to its specific material properties, asphalt can be suitable for slab track structures. Asphalt mixtures used in slab track system do need modification compared to the mixtures used for roads. In road construction, the important properties regarding the surface (high friction-resistance and resistance to wear and tear) are subordinate to resistance to deformation and stability. In the case of ballast-less superstructures, resistance to deformation and stability are the most required features* (Esveld C. , Modern Railway Track, 2001).

Figure 17: Asphalt- Concrete roadbed (Railway Technology, 2005)

4.4.3 Prefabricated Slabs

Prefabrication of track components can contribute to quality. These prefabricated slabs are applied in several places around the world. It brings several advantages in design and application of the projects. The mechanisation usage reached in higher level, so that these systems require less labour and the risk of failure. These types of systems are known as repair and innovation friendly.

Prefabricated slabs with direct rail fastening have mainly been used in Japan on the Shinkansen lines and in Italy with the IPA system. The use of prefabricated elements avoids

having to process wet concrete during construction. Many urban rail systems and inter regional high speed rail systems have compatible prefabricated slab systems installed on particular network. This system is being applied in convenient areas with respect to noise and vibration nuisance. Although this system is very effective, it brings considerable height for the track, and it is expensive.

- **Shinkansen Slab Track**

Many of people agree that Japan was the birthplace of high speed rail. Development work on the Shinkansen network started at the end of the 1950s, and the first line, between Tokyo and Osaka, was opened in Autumn 1964. Five lines are currently in service and the sixth one is under construction. South Korea is currently building a high speed line to link the capital, Seoul, with the port of Pusan. As in Japan, the line will include both ballasted and ballast-less track. The ballast-less track is based on the Japanese Shinkansen slab track. Ballast-less track has been little used in Italy.

> *The Japanese Shinkansen slab track consists of a sub-layer stabilised with cement (concrete roadbed), cylindrical bollards or dowels to prevent lateral and longitudinal movement, and reinforced pre-stressed concrete slabs measuring 4.93 m x 2.34 m x 0.19 m and only 0.16 m thick in tunnels. The slabs weigh approximately 5 tonnes. The slabs are adjusted on top of the concrete or asphalt-concrete roadbed with spindles* (Esveld C. , Modern Railway Track, 2001).

The rails which are welded in the depots and are 200 m long will be laid on the trolleys. These trolleys are driven by motor car running on temporarily laid rails which has gauging 1435 mm. These rails are used to follow the slabs as they are putting cement-emulsified asphalt mortar (CA mortar) under the slab in a neighbouring line. Slabs are transported to the site by rails which have 3000 mm track gauge. The CA mortar is transferred from the moving plant running on rails with gauge of 1435 mm onto the neighbouring track. This moving plant fabricates CA mortar at the site by mixing liquid asphalt, cement and sand. After this process, rails are put on the slabs and fastened with normal fasteners (Esveld C. , Modern Railway Track, 2001).

Figure 18: Shinkansen slab track station passing (Skyscraper City, 2008)

- **Bögl Design**

The first application of the Bögl slab track was at Karslfeld, Germany, in 1977. The purpose of producing this slab track is providing a long-endurance, maintenance-free operation. This track also brings many advantages for the high speed lines with highest track availability. As can be seen from the Figure 19 that Bögl design slab track systems can be developed with noise and vibration protection systems.

The Bögl slab track system is very similar to Shinkansen slabs and can be used on embankments, bridge structures, in tunnels and troughs. One modification of this structure built on a long bridge which is designed for a high-speed line section between Beijing - Tianjin (China). The FFB (Feste Fahrbahn Bögl) (China) structure is almost 116 km long, approximately 12 km of this structure is built on earth work and approximately 104 km is laid on bridges. Each bridge slab has a length of 31.5 m (Esveld & Markine, 2008).

The main difference of Bögl rather than Shinkansen is that slabs are made of B55 steel fibre reinforced concrete and are 20 cm thick, 6.45 m long and either 2.55 or 2.80 m wide. The slabs are pre-stressed in lateral direction and traditional reinforcement is applied in longitudinal direction. Spindles integrated in the slabs to provide an easy and quick adjustment of the slabs (Esveld C. , Modern Railway Track, 2001).

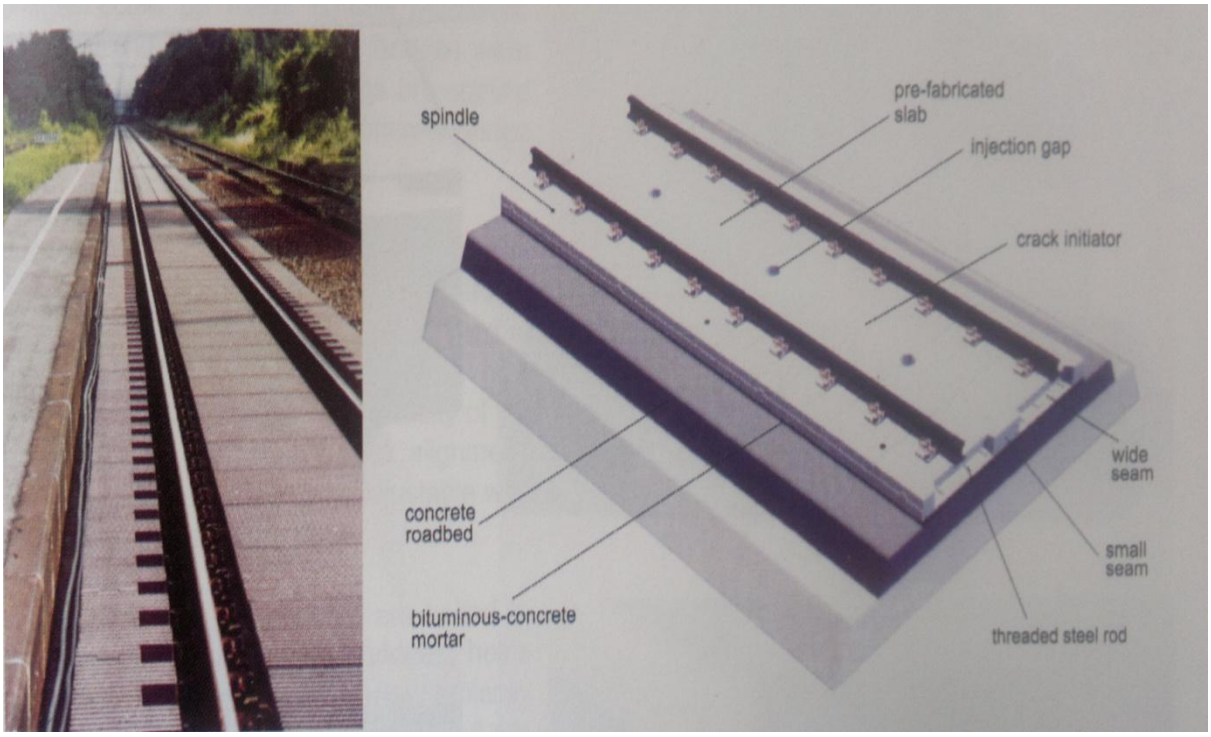

Figure 19: Bögl slab track design with noise absorbing concrete cover- detailed track layout (Esveld C. , Modern Railway Track, 2001)

A crane places the slabs on top of a concrete roadbed or an asphalt-concrete top layer. The longitudinal threaded reinforcement rods are connected to each other with the help of nut. After that the rails are put into position and fixed by fastenings (Esveld C. , Modern Railway Track, 2001).

A mortar is used to cover up the void at the edge between the slab and the roadbed. After hardening of this mortar, the slabs are rigidly connected to each other at the edges in two steps. The heads of the slabs are toothed and by first filling the smaller void in between the slabs with concrete, it becomes possible, after the concrete hardened, to wrench the extended nut over both rods in order to achieve pre-stress force across the joint (Esveld C. , Modern Railway Track, 2001).

4.4.4 Monolithic Slabs and Civil Structures

The direct rail fastening systems are bolted straight onto the concrete or steel decks or floors. The bridges or track on continuous monolithic slabs can be applied without sleepers. In this process, the direct fastening system can be used. The Vossloh OFF 300 system can be one of the example for the direct fixation the bridges or other special areas. This system can be adjusted by approximately 50 mm in vertical and 46 mm in lateral direction. The advantage of this structure is that it will become possible to apply slab track on top of weak and soft layers. The rigid slab spreads the loads across a much wider and longer surface and across

local defects. The minimum requirements for the substructure can be lowered, saving costs for ground improvements in certain situations (Esveld & Markine, 2008).

The rail is permanently fastened with two clips which have a long run elastic spring deflection. The steel base plate itself is fastened on the concrete slab with four screws in plastic dowels or, alternatively, with anchor bolts in steel decks. Several slab track systems with direct rail fastening have been developed over the years. A slip form paver places a monolithic slab on top of a concrete roadbed (Esveld C. , Modern Railway Track, 2001).

Figure 20: Slab track direct rail fastening Vossloh DFF 300 (Vossloh Fastening Systems, 2010)

This method of construction provides a continuous stiff and rigid slab, which consist of supported elastic beam. These type structures can also be applied on soils that have a great risk of local settlement on the subsoil.

4.4.5 Embedded Rail

Embedded Rail Structure (ERS) continues support of rail, which consists of cork and polyurethane with elastic materials surrounding the rail except for its head. Characteristic of this slab track is that rail is embedded underneath the concrete. There is no additional material to secure the track gauge under operational conditions. In the construction process,

the continuous support of the rail is provided by elastic materials. The rail fixes in the U-steel frame and is adjusted by means of top and down methods. Furthermore, the continuous concrete slab is made to allow free settlement on the soil.

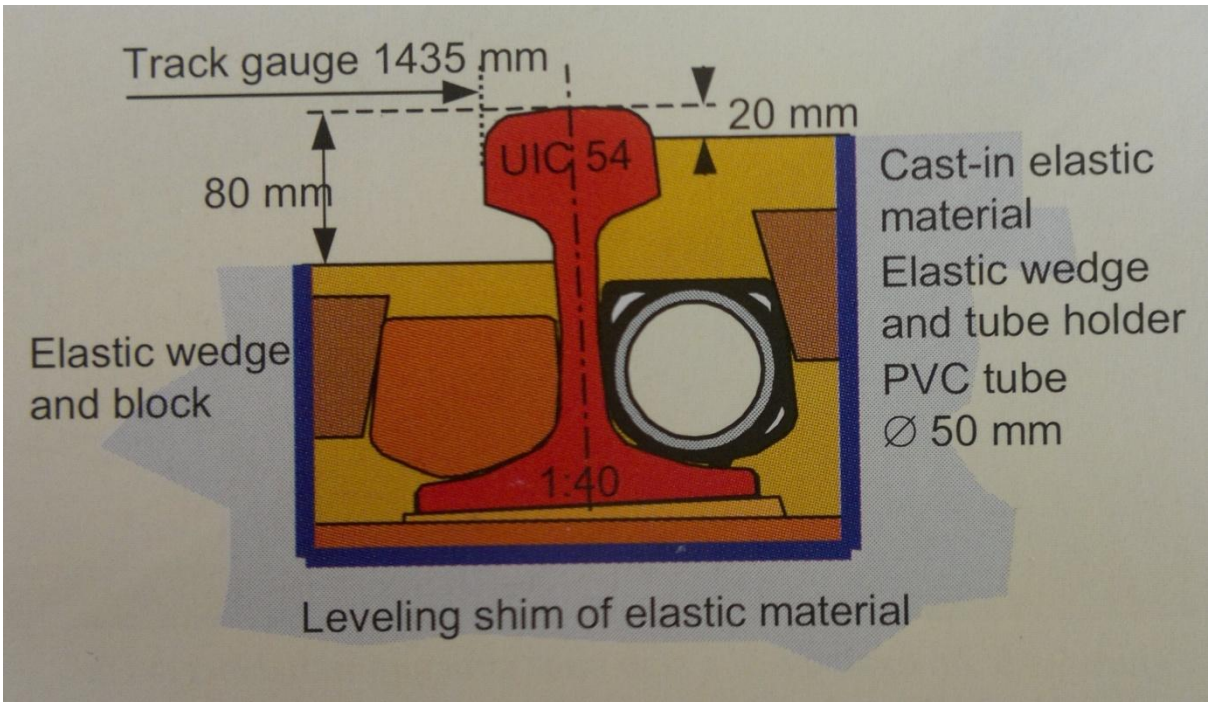

Figure 21: Details of an embedded rail inside a groove (Esveld C. , Modern Railway Track, 2001)

There are five advantages of an elastic continuous supported rail, which are absorbing of dynamic forces, reduction of noise production, increase in life span of the rails, reduction of maintenance and providing free settlement. The construction height can be reduced for road crossings, so that embedded rail provides a smooth surface for rail crossings.

In 1976 Netherlands, the pilot track was constructed for speeds up to 160 km/h and that was a very positive experience for the beginning. Another pilot track has been constructed in October 1999 with 3 km length, 0.6m height and 2.5 m width. According to Esveld (2001) the result of optimisation process and component testing reduces 5 dB noises. Furthermore, this system provides 60% of reduction for the UIC54 elastic design to secure the rails.

- **Deck track**

To reduce the settlement problems and life-cycle costs (LCC), the deck track systems can be a solution for the ballast-less systems for both high speed and heavy freight lines. Deck track is a new type of ballast-less track developed by Holland Rail Consults to use on relatively soft soils. The rails can be directly applied as an embedded rail or with direct fastening. The concrete deck can be considered as a hollow tube weighing the same mass as that of the

removed soil. This track provides less vibration and less settlement as a result of the structure weight.

After five years of use in the testing process, the settlements and the quality of the structure have been evaluated. The concrete structure and embedded track system did not show any sign of deterioration. The widest cracks in the concrete carrier those at locations at the beginning and end of a day's production (casting joints) that are less than 0.1mm wide, which is largely acceptable (Corporation, 2005).

Figure 22: T*est track in Rotterdam (Corporation, 2005)*

The test has shown that the track geometry remains at the same quality after construction for a long period and the track quality does not deteriorate significantly in spite of settlements of the structure. The track alignment is a very good quality; even the strict alignment requirements of a high-speed line can be met.

5 Seismic Movement on the Railway Lines

5.1 Earthquake and General Characteristics

Seismology is the study of Earth's elastic vibrations, the sources of these vibrations that generated by earthquake and are generally caused by rocks suddenly breaking away from the surface. It is also related to the structures through which they propagate. It is a geophysical discipline that has a considerable diversity of applications to critical issues facing society and involving Earth's dynamic systems (Sesmological grand challenges in understanding earth's dynamic systems, 2008). Seismology is directly relevant with earthquake and its effects on the earth. There are some technical parts which are directly related with the earthquakes.

Body waves, which are primary and secondary waves, penetrate the body of the earth and start to vibrate fast. Primary waves scatter at about 8 km per second, and it provides the initial jolt. These waves cause buildings to vibrate in an up and down motion. Secondary waves scatter about 4.5 km per second in a movement similar to spring work style. They are usually the most destructive and can vibrate the ground in both ways; horizontally and vertically.

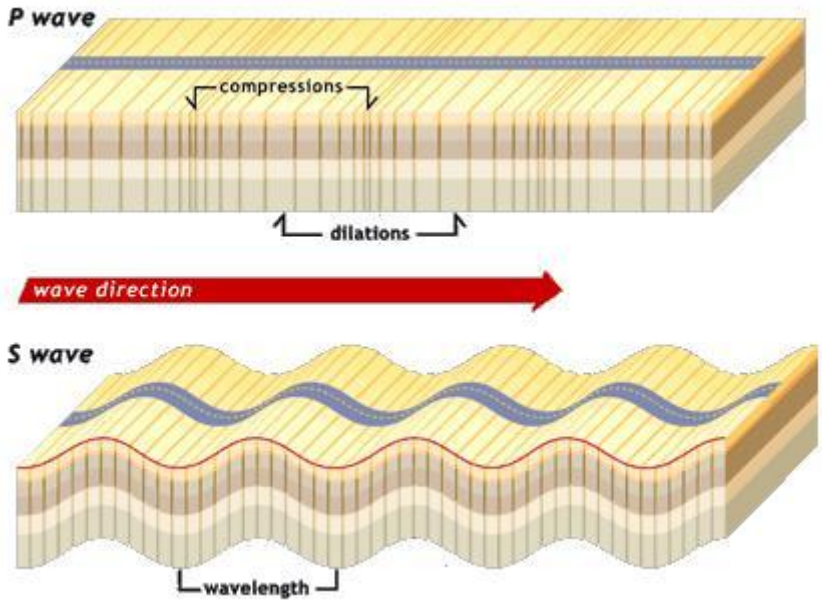

Figure 23: Primary and secondary waves (USGS Report)

According to the USGS reports (2002), earthquakes generate with the releasing of elastic energy by sudden slip on a fault that results ground shaking and radiated seismic energy caused by the slip. In case of large displacement, greater earth movement can occur. Earthquakes can be generated by the result of tectonic loading of faults and volcanic eruptions.

The global tectonic plates are created with lithosphere which is divided into a number of plates such Pacific or Arabian as in the Figure 24. They can interact with one another at their boundaries causing earthquakes, volcanism and deformation.

Through the fault, the point where the shearing action begins and earthquake energy occurs is called as a hypocentre. This point can place between 5 and 50 km in depth. The epicentre is the sketch of land directly above the hypocentre where the earthquake is felt the most.

A fault on the tectonic plate is not only cause of the earthquake; there are also volcanic eruptions, scientific explosions and collapse earthquakes. A volcanic earthquake is defined as one that occurs in conjunction with volcanic activity, but it is believed that eruptions and earthquakes both result from tectonic forces in the rocks and not together.

Explosion earthquakes are produced by detonation of chemicals or nuclear devices. Some of the larger scientific tests and nuclear investigations can trigger an earthquake with increasing or decreasing the temperature of the earth's layer.

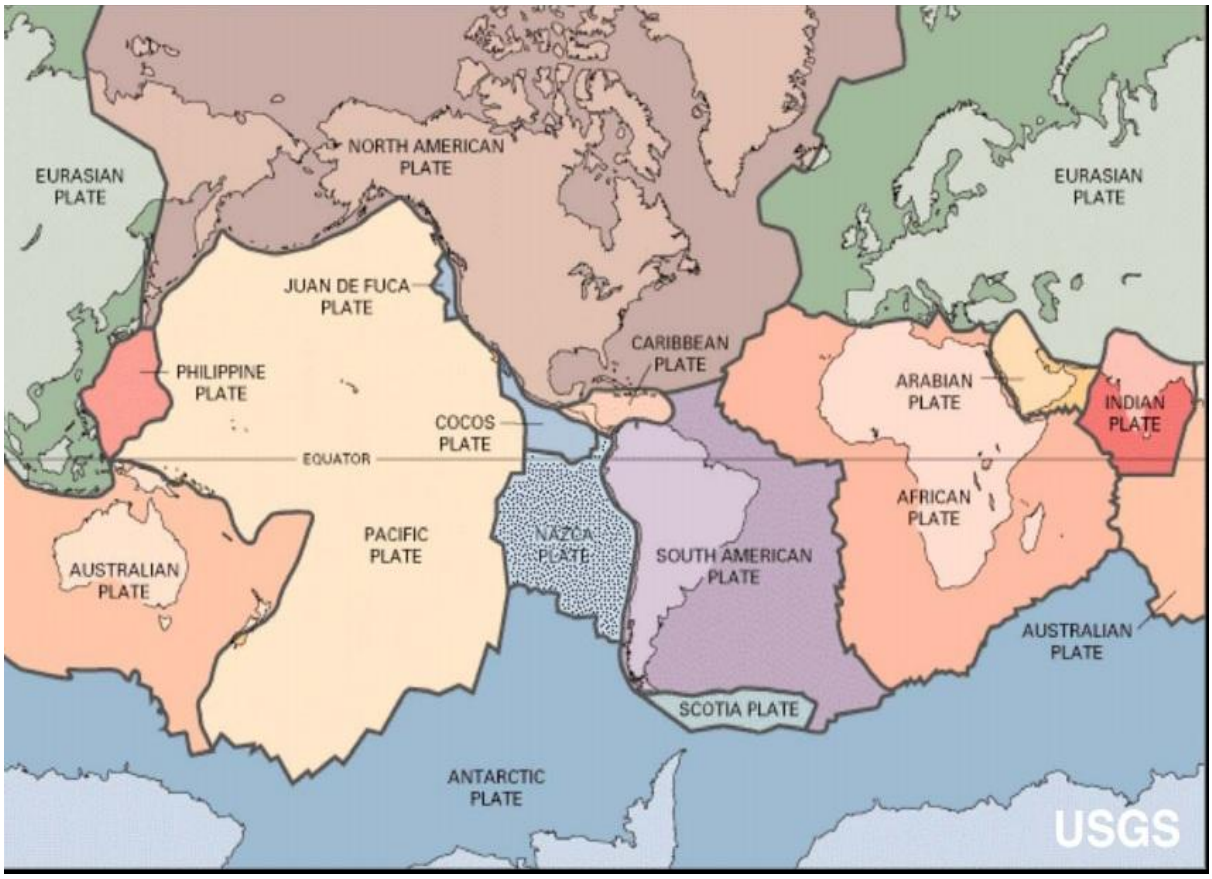

Figure 24: Tectonic plates (California, 2010)

Collapse earthquakes are small earthquakes occurring in regions of underground caverns and mines. The immediate cause of the ground shaking is the collapse of the roof of the mine or

caver as a result of the induced stress around the mine working because large masses of rock fly off the mine face explosively that produce seismic waves. Collapse earthquakes are also produced by massive land sliding (Rogers, 2000).

The earthquake can be measured importantly two important ways which are magnitude and intensity. Earthquake intensity is defined as the strength of seismic shaking at a given location. In general, closest areas to the epicentre have the highest intensities, and shaking diminishes in strength. The intensity of the earthquake can be measured by several methods however; the most familiar one is Mercalli intensity scale. It was developed in 1902 and modified in the 1930s. As can be seen from the Figure 24, there are 12 types of earthquakes have been described in the modified scale.

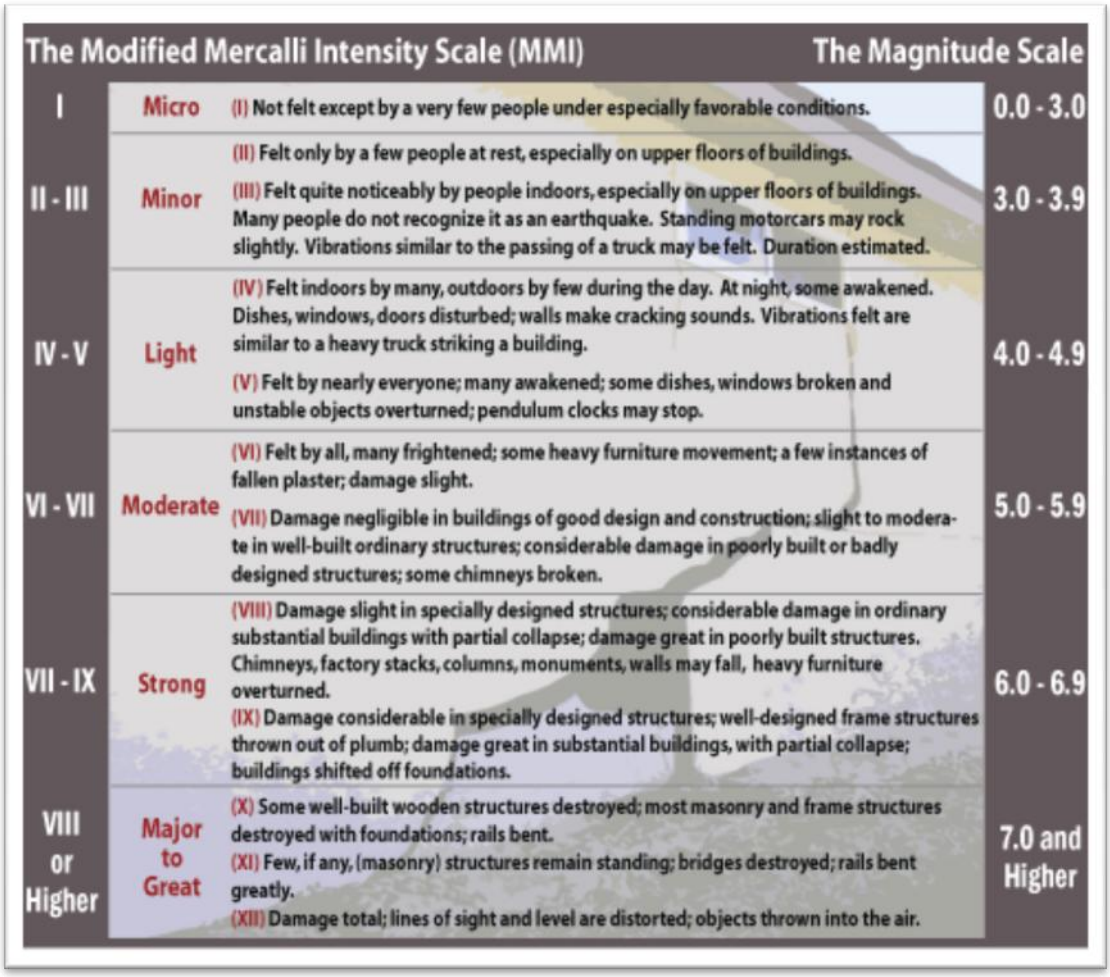

Figure 25: Modified Mercalli intensity scale (South Carolina Emergency Management Division, 2008)

Magnitude is a measurement of the energy produced by an earthquake. The first earthquake magnitude scale was the Richter scale, devised by Charles F. Richter who was the seismologist at the California Institute of Technology. The Richter scale is based on the amplitude of seismic waves and seismic vibrations. This scale consists of logarithmic scale,

where an increase of one in magnitude corresponds to a factor of ten increases in the amplitude of ground motion. For instance, the magnitude 6.7 of earthquakes can cause shaking 10 times greater in amplitude than a magnitude 5.7 earthquake and 100 times greater than a magnitude of 4.7 earthquakes.

The some of the fault zones have not been active for several years. These zones called as inactive zones which has not been produce an earthquake for more than 11000 years. In regards to important projects such as high speed rail lines or nuclear site, the activation time of the zones must be considered and the quantitative risk analyses can be done.

There several issue which can occur due to an earthquake;

- Soil liquefactions
- Surface fault rupture
- Landslides
- Tsunamis and Seiches

In this paper, the author will mention about all these issues at the following parts although the main subject is soil liquefaction taken in a great detail.

Earthquakes are inevitable for people. Some of them are caught by the earthquake while they are in daily life or work near the major faults that can produce strong ground shaking. Ground shaking can be affected by several things; the type of ground the earthquake waves travel through, the size of the earthquake, and the distance away from the earthquake source.

The land surface rupture occurs when movement on a fault breaks through to the surface. Rupture may occur suddenly during an earthquake or slowly in the form of fault creep. Fault rupture almost always follows pre-existing faults, which are zones of weakness.

A tsunami is an extreme wave that can be generated by an earthquake, landslide and volcanic eruption. These waves can move at a rate exceeding 800 km per hour. In smaller water bodies such as seas or lakes, tsunamis are most commonly created by underwater landslides. A seiche is a wave that sludge in an enclosed body of water, such as a lake or river.

5.2 Soil Liquefaction

When saturated sand deposits are subjected to earthquake-induced shaking, pore water pressures are built-up leading to liquefaction or loss of soil strength (Liyanapathirana & Poulo, 2004).

A more precise definition of soil liquefaction is given by Sladen, D'Hollander and Krahn, 1985:

> *"Liquefaction is a phenomenon where in a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic, or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance."*

The major earthquakes that have occurred during past years, such as the 1964 Niigata 1920 California Calvers, 1938 Montana Fort Peck, 1948 Fukui, 1971 California San Fernando, 1964 Alaska Anchorage, 1980 Mino-Owari, and 1999 Marmara-Turkey have demonstrated the effects of soil liquefaction. Thus, it is necessary to obtain a proper understanding of the nature of the soil liquefaction. Most major earthquakes occur around the boundaries of the tectonic plates such as Turkey, America or Japan.

One of the important questions in the liquefaction analysis is the circumstances in which soils can liquefy. As has been known for many years, the clean sands tend to liquefy in all circumstances. However, the tendency of the mixture of the sands which consist of clay or silt to liquefaction has been a debatable situation for many years.

Another important issue is the prediction of tendency of soil to liquefy in several earthquake circumstances. The possibility of liquefaction can be investigated in two parts; ground conditions and characteristics of earthquake that causes liquefaction. The low density of the particles and high water content can be evaluated in the ground conditions. Sometimes earthquakes which, have long duration of shaking, and their magnitudes are above 5 on the Richter scale, can directly cause soil liquefaction.

On the other hand, the reason of the liquefaction should be investigated technically, which is sometimes difficult. However, as is known in general, liquefaction can occur in saturated soils that consist of individual particles which are completely filled with water that makes a pressure on the soil particles, and influence how tightly the particles themselves are pressed together. Before earthquakes happen, water pressure is relatively low. However, earthquake shaking can cause an increase in water pressure and affect the soil particles when they can readily move with respect to each other.

When liquefaction occurs, the strength of the soil decreases and, the ability of a soil deposit to support foundations for buildings and bridges are reduced that can be seen in the Figure 25 in below of the overturned apartment complex buildings in Niigata in 1964.

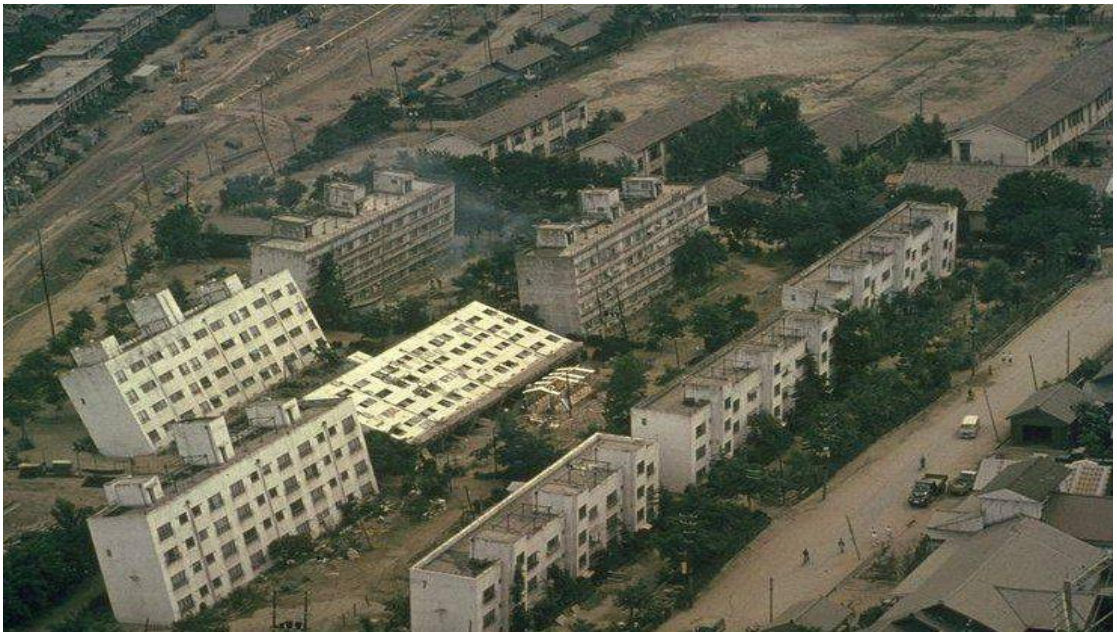

Figure 26: Overturned apartments in Niigata in 1964 (University of Washington)

Soil liquefaction has been identified as an engineering evaluation focus on the mode and magnitude of ground failures. The National Research Council lists eight types of failure commonly associated with soil liquefaction in earthquakes (Rauch, 2008):

- ***"Sand boils,*** *which usually result in subsidence and relatively minor damage.*
- ***Flow failures of slopes*** *involving very large down-slope movements of a soil mass.*
- ***Lateral spreads resulting*** *from the lateral displacements of gently sloping ground.*
- ***Ground oscillation*** *where liquefaction of a soil deposit beneath a level site leads to back and forth movements of intact blocks of surface soil.*
- ***Loss of bearing capacity*** *causing foundation failures.*
- *Buoyant rise of buried structures such as tanks.*
- ***Ground settlement,*** *often associated with some other failure mechanism.*
- ***Failure of retaining walls*** *due to increased lateral loads from liquefied backfill soil or loss of support from liquefied foundation soils.''*

There are several ways to mitigate the risk and severity of damage caused by soil liquefaction. The first and most obvious is to avoid construction on liquefaction susceptible soils. If it is necessary to construct on these places, the areas must be modified with several ways to make the structure more resistant to potential damage of the liquefaction. In addition to designing a liquefaction-resistant structure, improving the soil conditions and lowering the potential can reduce the liquefaction occurrence possibility. There are several type of ground modification techniques that are available to change the ground conditions. These methods

can increase soil drainage and density to generate lower liquefaction risk. These can be application of vibration to the ground, installation of stone columns, dynamic compaction with vertical stones, compaction grouting, and use of various drainage improvement techniques.

5.3 The Effects of Active Seismic Movements on the Railway

As mentioned, there are three primary seismic hazards that occur as a result of the presence of faults capable of generating earthquakes. These are ground rupture potential, strong ground motion, and liquefaction. The ground ruptures occurs when a fault ruptures at depth and movement along the fault propagates to the ground surface. The ground can move in two different ways both laterally and vertically. Ground motion occurs when faults rupture happens deep in the ground where pressures are high. Liquefactions are the result of ground motions where the rock or soil conditions are susceptible to collapse or flow.

The ground rupture and ground motions are very significant seismic hazards that can badly damage the railway structure. However, the designer of the railway infrastructure cannot take precaution for these events. They can only avoid constructing railway lines near active seismic zones.

A fault is geologically defined as active if a relative movement has taken place in a period less than two millions years before or if slip has occurred, variously in historical or Holocene or Quaternary time or earthquake foci are located. On the other hand, the service life of engineering structures could not generally be greater than 100-150 years. Taking this into consideration, there were new attempts to define active faults for engineering purposes by various US government agencies defined the active faults as given below (Ulusay, Aydan, & Hamada, 2001);

(1) It moved in the last 10000 years (Holocene),

(2) It moved in the last 35000 years (in nuclear power plant site selection)

(3) It moved in the last 150000 years,

(4) It moved twice in the last 500000 years.

These criteria can be used to construct railway line in the seismic zones whether it is active or non-active. The ruptures cannot be mitigated. However, the construction zones can be selected with regard to seismic zones activation.

The soil liquefaction is one of the important effects of the earthquake on the ground. It can be very significant depending on the ground conditions and ingredients. There are numerous examples for the liquefaction devastated effects on the transportation structure, especially for

the highways. As can be seen from the Figure 27, liquefaction can overturn the highway's ground.

Figure 27: Highway structure which is damaged by soil liquefaction in Costa Rica Earthquake (Magnitude 7.7, 1991) (Earthquake Engineering Research Institute, 2002)

Furthermore, soil liquefaction can have great impact to damage railway lines in several places. It can cause of derailment and death of hundreds of people. The nature of the railway allows carrying many of people or tons of goods at the same time. Therefore, the railway damages or incidents are becoming more and more important. In case of accident, lots of people or goods can be damaged, and this increases the importance of railway. The soil liquefaction affects the rail lines with spoiling the ground structure or giving extreme vibration to the track system. Figure 28 shows the rail buckling in 1976 Tangshan earthquake caused liquefaction and bending of the rails on the Beijing-Shanhaiguan railway. One of the biggest liquefaction examples happened in Alaska, USA and Niigata, Japan, in 1964. There are liquefaction areas in this earthquake and, it was trigged by earthquake. In some place, apartments were tilting, while the road beds have broken in both highway and railway.

The 1995 Great Hanshin Earthquake, magnitude is 6.9 and commonly referred as the Kobe earthquake, was one of the most devastating earthquakes in Japan; more than 5,500 were killed and over 26,000 were injured.

Figure 28: The soil liquefaction damaged railway lines the embankment (USGS Report)

The Figure 29 shows the impact of the soil liquefaction Kobe earthquake in 1995. The highway viaduct has damaged while other buildings were stable. It shows the impact of the soil liquefaction.

Figure 29: Soil liquefaction affects in Kobe 1995 (University of Washington)

Potentially unstable slope areas are also important for the railway structure. It should be considered while railway is being constructed. These zones can be damaged where there are slopes of a gradient more perpendicular than 33 per cent slope gradient but are not underlain by strong geologic rock formations. According to the California high speed train reports (2004), the station or the railway lines should be avoid to construct in 60 m unstable zones and the ranking system is described as follows:

"Unstable Slopes = per cent of segment within 60 m buffer of potentially unstable zones"

5.4 The Effects of the Seismically Active Zones on the Slab Track Systems

Improving the various facilities of the whole system to protect the railway property and passenger against earthquake is becoming more and more important, especially for the active seismic zones. There are various safety counter measures that may be helpful to improve earthquake safety. The track quality might be increased with slab track systems. It helps to improve strengthening of the track. Furthermore, there are many varieties of Earthquake early warning systems which can be adapted to the railway like Japanese railway. This system will provide a warning for trains which are under operation. However, this system might be applied with very effective braking systems. The early warning system works greater with reduced operating speed. According to researchers, some precautions should be taken in active seismic zones;

- Strengthening the tracks
- Retrofitting the rail viaduct
- Installing earthquake early warning systems
- Improving braking systems
- Reducing the operating speed

Furthermore, there are interactive relationships between the counter-measures in terms of earthquake risk reduction. If the track condition is very good like in the extreme condition, the track cannot be broken by the earthquake shakings and we need no warning system, we need not substantial investment on braking systems. On the other hand, if earthquake warning systems has been applied, the requirement for the braking systems could be relatively lower. These interactive relationships make the optimization analysis more interesting and complex.

In this context, the purpose of this study is to show the necessity of slab track systems for railway systems which is located in active seismic zones. There are two main track types to make selection for the active seismic areas; slab track and conventional ballasted track. Ballasted track systems have several advantages and disadvantages compared to slab track systems. However, in case of earthquake the behaviour of ballasted track is weak and the maintenance after the earthquake's potential damage is very difficult as in slab track.

The maintenance issues are very important for the busy lines in terms of cutting the traffic long times and economic justifications. The previous earthquakes such as Golcuk-Turkey (1999) in the Figure 30 shows that rail tracks can be affected by the ground movement easily. Furthermore, the rails can be damaged easily in ballasted track systems. The energy which is provided by earthquake is very high and it is not possible to absorb this energy in the track. Therefore, the designers do not need to use elastic structure for the rails. Even if they use stiffer track, it is better to protect rail damage in the long way. If there is a rail or track breaking, it is easy and fast to maintain this line that may be cheaper because maintainer do not need to maintain long lines.

Figure 30: Damaged railway in Izmit-Turkey 1999(TCDD, 2008)

As mentioned previously, the emergency braking should be improved with the use of greater braking systems such as eddy-current braking. Eddy current brake is a contactless brake system, brake force is produced between magnet assembly and rail that means working independent of adhesion between wheel and rail. Thus, brake performance of the vehicle is increased. However, this system may require the use of slab track system as when it is used the heating of the rail becomes an important factor. This has led to restriction of the use of eddy current brakes in Germany to slab track only. It is not only the heating of the rail head and the longitudinal force that is of importance but also the uplift of the track panel leading to a reduction in lateral stability and increased risk of track distortion or buckling. The rigid slab track is able to assimilate these additional forces in a much higher amount. Ballast superstructure is less suitable for these additional loads or respectively has to be especially upgraded for this purpose (Railway Gazzette, 2008).

One of the most destructive effects of earthquakes is liquefaction. When liquefaction occurs in loose saturated sands, the soil loses shear strength and temporarily acts as a liquid. Liquefaction has resulted in significant damage in transportation systems in nearly every major earthquake event. For example, liquefaction resulted in nearly $1 billion worth of damage during the 1964 Niigata Japan earthquake, $99 million damage in the 1989 Loma Prieta earthquake, and over $11 billion in damage just to ports and wharf facilities in the 1995 Kobe earthquake (Rollins, 2004). During the earthquake, the slab track systems can have different behaviours. The liquefaction can devastate the structure of railway with producing extreme vibrations and settlements. As it can be understood from the Shinkansen derailment in 1964, the liquefaction can give extreme vibration to derail the trains from the slab track systems.

Figure 31: Earthquake was the cause of Shinkansen derailment in 1964 (Web-Japan, 2005)

5.5 Mitigation of Seismic Movement under the Slab Track Systems

5.5.1 Methodology of Soil Liquefactions Mitigation Methods

The earthquake has devastated impacts on the railway structure. It can sometimes overturn the bridges or viaducts, generate extreme settlement of the railway sub-structure or make deformation the track structure whether it is small or big. There are three important impacts which can cause deformation on the railway lines; soil liquefactions, settlements and land sliding.

As mentioned, soil liquefaction is very destructive for the railway lines. There are a number of various precautions that can be taken to mitigate the effects of liquefaction on railway lines. However, we should investigate first the following questions;

- Do these grounds seismic have a history?
- Do the ground characteristics have to liquefy in the small earthquake or aftershocks?
- If the answer yes, what is the characteristics of the earthquake that can cause of liquefaction?
- What are the possible effects of the liquefaction on up-structure?
- What precautions can be taken to mitigate the liquefaction impacts?
- How can the best method be chosen?
- How can it be applied if there are some impacts on the other existing structure?

Afterwards, some of the criteria should be investigated to decide whether the soil liquefaction will generate or not. These are:

- Relative density of the soil.
- Rate of increasing pore water pressure.
- Grain size of the soil.
- Void rate of the ground.
- Standard penetration.
- The time which is the ground under the stress.
- Seismic history of the area.
- The vibration under normal conditions.

The mitigation of the liquefaction can be evaluated in two main parts while some of the methods can be applied as structural measures, some of the precaution known as ground stability remediation.

5.5.2 Structural Measures

The purpose of these methods is to increase the strength of the structure for liquefaction. The foundation of the structure can be designed depending on the bearing capacity of the ground. It a very difficult process in railway, but there can be possible solutions.

Option 1: With using shallow foundation, the liquefaction impacts can be reduced. It is a very common method in buildings to separate the loads from weak ground to strong ones. The spread footing is very beneficial for the structure foundation to create more strength in structure. The difficulties of the work lie in the adaptation of the spread footing systems to railway lines.

The areas that have been chosen to construct railway on and the bearing capacity should be investigated deeply. In this system, loads which are from the track structure will spread onto the ground by foundation. This foundation will be very wide and some parts can be in liquefaction weak zone and other parts should be in strong zones. The working principle is to transfer the loads while ground is liquefying from weak zones to strong zones.

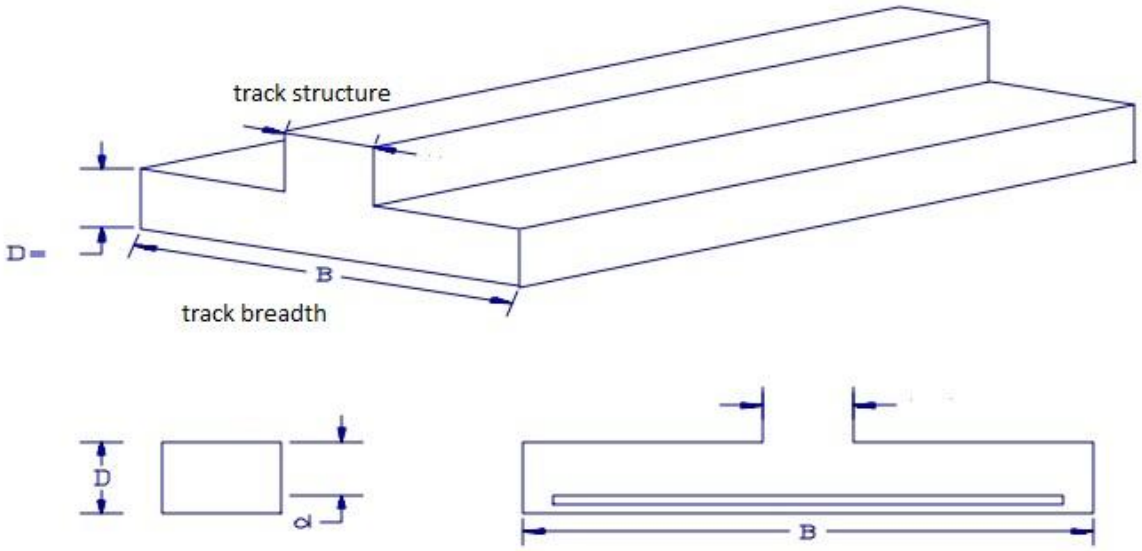

Figure 32: The adaption of spread footing system to railway lines (By the author)

It can be seen from the Figure 32 that these foundations can be used in railway structure. The track breadth (B), height of the foundation (D) and the reinforced concrete specialities can be investigated depending on bearing capacity of the ground. This system will provide uniform settlement and it will not affect the structure of the slab track deeply by reducing the shear force on the track structure. Furthermore, the floating slab track system may absorb the small vibrations from the foundation. The small adjustment will be done with fully adapted foundation for the railway.

Option 2: The second option is to use deep foundations under the railway track. This method is also known as pile foundation. The bearing capacity of the ground can be increased with using pile foundation under the track formations. The piles will reach to the firm ground or rock layer. The piles will support the bearing layer and track structure in case of the liquefaction. The important thing that should be considered is the determination of the piles diameter, length and materials (the rate of the steel or concrete quality inside the reinforced concrete). The geotechnical designers will take everything into the consideration and define the piles specialities. In this system, the piles will resist the lateral force that can be obtained

by an earthquake as well as bearing the structure vertically. The merging point of the piles are very important in this system to provide elastic movement on the structure ,otherwise, the movement can cause un-effective working of system and generate the cracks on the structure in due course of small movement or settlements.

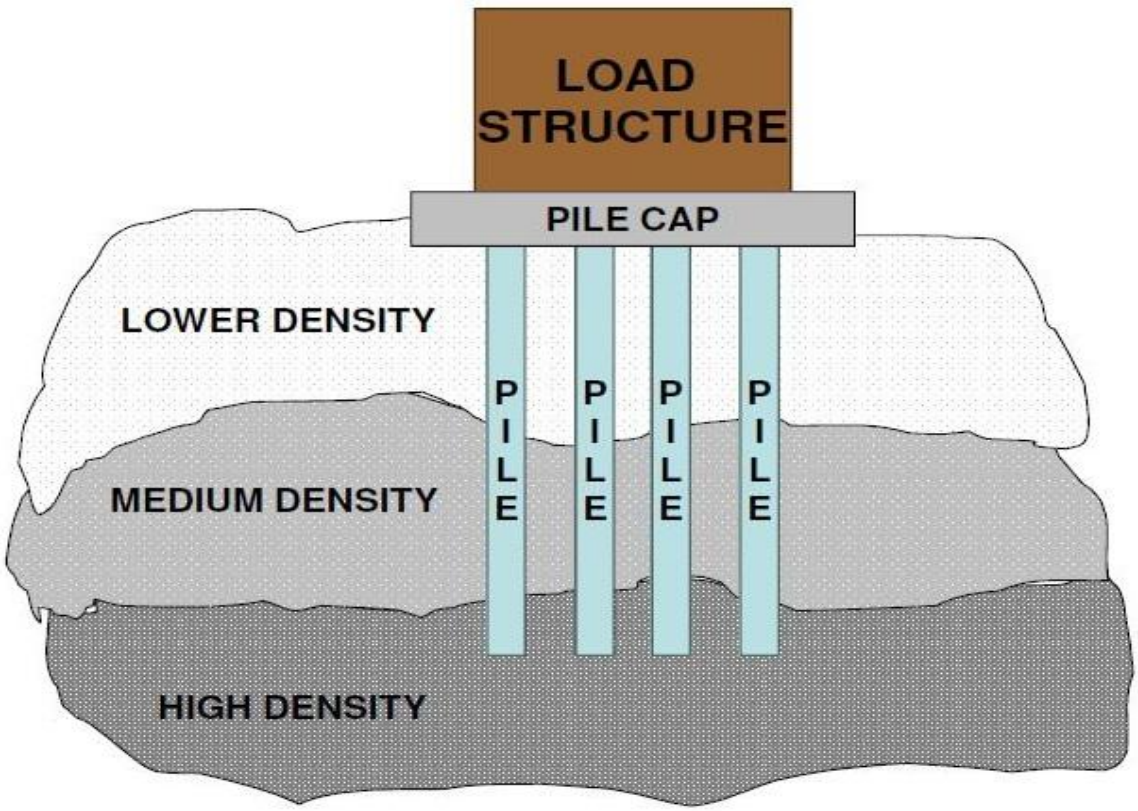

Figure 33: The basic principles of pile foundation for the railway structure (Mait Piling Rigs-India, 2010)

It can be seen from the Figure 33 that the pile foundations reach the strong layer and provide the better support to the track structure. This system is very compatible with the slab track systems as they provide better performance by the way of absorbing railway vibrations.

Figure 34: The application of pile foundation in the weak ground (Inova enerji, 2010)

Ground Remediation for Liquefaction:

To increase the resistance of the ground for soil liquefaction, there are several techniques that have been applied. The purpose of these methods is reducing the pressure of pore water. These methods are generally expensive and applied in wider areas in special projects.

The first method is dynamic compaction that is used to increase the density of the soil when certain subsurface constraints make other methods inappropriate. The process involves dropping a heavy weight from 10-30m height to the ground repeatedly on the ground at regularly spaced intervals. The weight is between 8 tonnes and 36 tonnes, depending on the degree of compaction desired. This method provides more compressed soil and reduced pore water pressure inside.

However, this method is not effective for the railway lines because railway lines need long and thin areas. Economically and structurally, it is not the method choice for the railway structures.

Figure 35: Dynamic compaction method for liquefaction (Liebherr, 2005)

The second method is that using vibro-flotation heads under the ground to penetrate granular soil to depths of over 100 feet. The vibrations of the probe cause the grain structure to collapse. Therefore, the soil densification can be provided.

The third method is replacing the weak ground with the strong one. The ground which has potential to liquefy can be removed carefully without damaging other structures. It a is very expensive method for the railway lines.

There are also some special drainage techniques that are used for the dewatering the soil. It is a very common method for the transportation projects. It can sometime be effective sometimes ineffective, depending on ground specialities.

5.5.3 Ground Settlements without Soil Liquefaction

Ground settlements are very important for all constructions. It can devastate the construction's nature in very short time. The precautions which are used for mitigation of the soil liquefaction can be used also for reduction of settlement during the operation. The most obvious and exact solution is to avoid constructing railway in zone which is potentially settlement area.

5.5.4 Land Sliding in near Railway Lines

The secondary effect of the earthquakes is land sliding. There are a number of methods to reduce the risk of land sliding such as shotcrete and retaining walls. These methods can increase the availability of slab track in railway lines. The prevention of slab track from the huge massive rocks can be an obstacle to damage the track structure.

Figure 36: Land sliding on railway in Turkey (Turkish State railway, 2011).

5.6 The Advantages of the Slab Track Systems in Unstable Areas

Slab track systems have great advantages in unstable areas compared to the ballast track systems. Moreover, slab track systems' adaptation for the unstable areas is easier and more economic. These advantages are listed below;

- According to Bilow et. al., (n.d.) there is a small table can be created with considering German railway lines in Table 1, and make justification about the gradient. This table shows that the maximum slab track gradient is 40/1000 and ballast track gradient is 20/1000. Therefore, Slab track systems allow using higher gradient in the systems. This advantage provides less earthworks; cuttings and embankments. The excessive earthworks can cause damage in the ground structure, and can be one of the reasons for the land sliding.
- The slab track systems may provide fewer tunnels work which require less tunnel height. It can reduce the deterioration of the ground. Using slab track is reasonable to mitigate land sliding possibility.
- Railway tracks bring additional loads for the bridges. If the loads are excessive, it can cause problems where the bridge footings are placed. In particular, weak grounds with small ground ruptures can be very sensitive for the excessive loading. The slab track systems are lighter than the ballast track.
- As mentioned, the emergency braking should be improved for earthquake situations. Improved braking systems, such as eddy-current braking systems, require slab track system. Regulating the speed of trains is done in specific situations such as earthquakes so that trains will use the service brake repeatedly in the same areas. This braking system also brings economic benefits for the operation.

- In case of the soil liquefaction in the ground, slab track systems come into prominence when compare with the slab track. As is mentioned, there are two important recommended mitigation methods for the liquefaction which show suitable behaviour with the slab track. In the first option, the track system can be generated without using soil layers. Figure 37 shows that the slab track systems put into the concrete layer directly and make connection between the layers with elastic concrete materials.

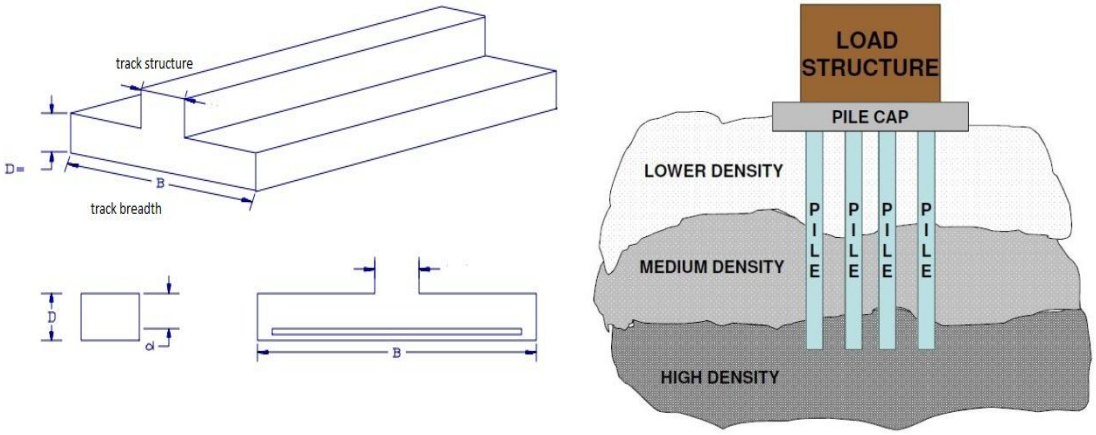

Figure 37: The spread footing and pile foundation (By the author)

There is also a second option namely pile foundation which is shown above. Naturally, the slab track systems are more suitable for the concrete layer (pile cap). Both methods are very effective and economic to mitigate soil liquefaction effects by using slab track systems. The reasons which are shown above may prove the slab track better behaviour in unstable areas.

6 Applicability of Slab Track Systems to Turkey Ground Conditions

6.1 Geological Structure of Turkey

Turkey has a various landscapes that generate complex earth movements. Anatolia has shaped over thousands of years with several earthquakes, liquefactions, and occasional volcanic eruptions. Turkey geologically is part of the great Alpine Lanes that extend from the Atlantic Ocean to the Himalaya Mountains. This belt was generated during the tertiary period from 65 million to 1.6 million B.C. The Arabian, African and Indian continental plates have begun to collide with the Eurasian plate during the tertiary period. This folding and faulting process is still at work and moving in south and southwest, respectively and it is still colliding. As a result, Turkey is one of the world's more active earthquake and volcano regions. The earthquake which has magnitude more than six can cause massive damage to buildings or transportation construction. If they occur on winter nights or transportation systems, it can cause more deaths and injuries.

The web-site which is called countryside defined the Turkish earth structure in more technically;

> *The ground conditions of Turkey are structurally complex. A central massif composed of uplifted blocks and down folded troughs, covered by recent deposits and giving the appearance of a plateau with rough terrain, is wedged between two folded mountain ranges that converge in the east. True lowland is confined to the Ergene Plain in Thrace, extending along rivers that discharge into the Aegean Sea or the Sea of Marmara, and to a few narrow coastal strips along the Black Sea and Mediterranean Sea coasts. Nearly 85 percent of the land is at an elevation of at least 450 meters; the median altitude of the country is 1,128 meters. In Asiatic Turkey, flat or gently sloping land is rare and largely confined to the deltas of the Kizilirmak River, the coastal plains of Antalya and Adana, and the valley floors of the Gediz River and the Büyükmenderes River, and some interior high plains in Anatolia, mainly around Tuz Gölü (Salt Lake) and Konya Ovasi (Konya Basin). Moderately sloping terrain is limited almost entirely outside Thrace to the hills of the Arabian Platform along the border with Syria.*
>
> *More than 80 per-cent of the land surface is rough, broken, and mountainous, and therefore is of limited agricultural value. The terrain's ruggedness is accentuated in the eastern part of the country, where the two mountain ranges converge into a lofty region with a median elevation of*

more than 1,500 meters, which reaches its highest point along the borders with Armenia, Azerbaijan, and Iran. Turkey's highest peak, Mount Ararat (Agri Dagi)--about 5,166 meters high--is situated near the point where the boundaries of the four countries meet. (http://countrystudies.us, 2009).

6.2 History of Earthquake in Turkey

The Turkey has been divided into 5 sections in terms of earthquake regions, and the hazards of the earthquake map have been drawn in the figure. This map prepared by the Ministry of Public Works and Settlement considering the latest knowledge and approved by the Government of Turkey and published in 1996. As can be seen from the Figure 38 there are 5 coloured sections that have been determined in Turkey. According to www.deprem.gov.tr (1996),

1st degree earthquake zone : more than 0.4g ----------Red zone

2nd degree earthquake zone : between 0.3g - 0.4g----------Lilac

3rd degree earthquake zone : between 0.2g - 0.3g----------Yellow

4th degree earthquake zone : between 0.2g - 0.1g----------light grey

5th degree earthquake zone : less than 0.1g----------white (g: gravity(981 cm/s*s)

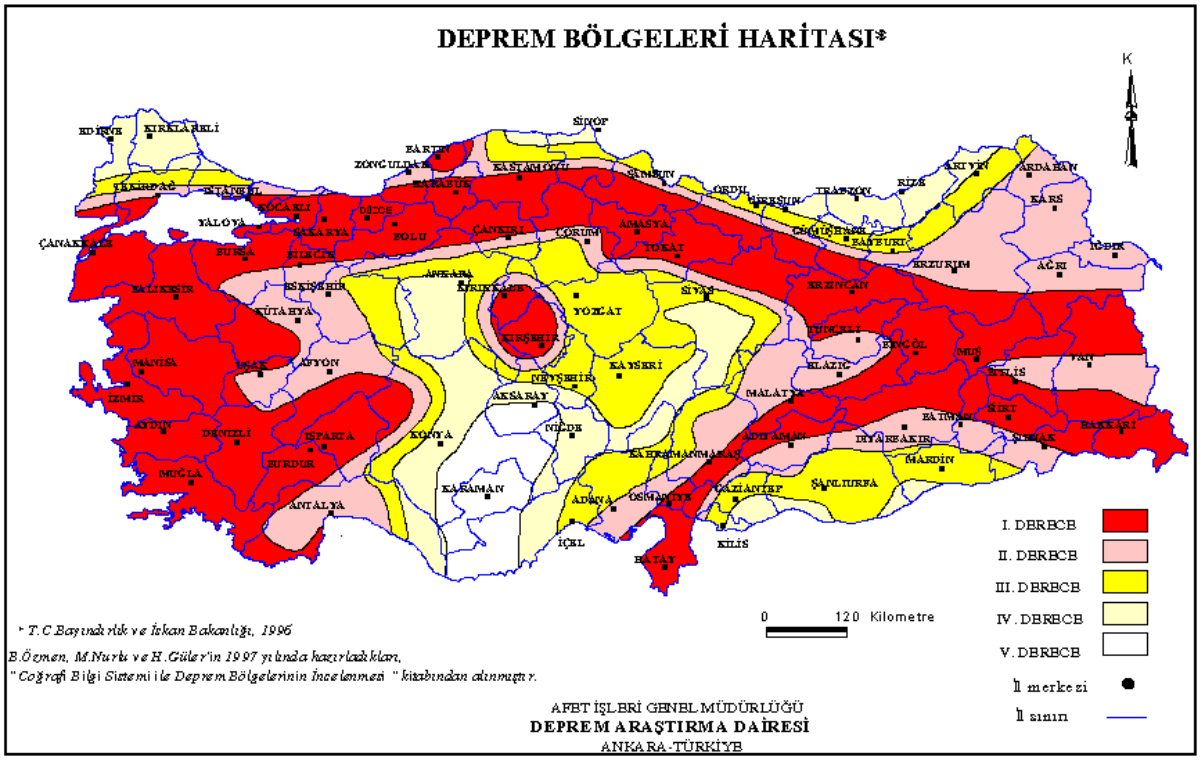

Figure 38: Turkey earthquake hazard map (Turkey Earthquake Surveys, 1996)

The biggest earthquake in Turkey has occurred in Erzincan on the one night of December in 1939. It devastated lots of the people in the city an estimated 160,000 deaths. The earthquake of seven violent shocks, the biggest one measuring 8.2 on the Richter scale, was the most powerful one to devastated event of Turkey.

The 1999 İzmit earthquake which is also known as the Kocaeli or Gölcük earthquake was a 7.6 magnitude earthquake on August 17, 1999. The event killed around 17,000 people while and approximately half a million people have been homeless. The nearby city of Izmit was very badly damaged. As it can be seen from the table in bellow, there were many earthquakes have occurred in very short time. Almost every earthquake has result with loss of life and properties. Transportation systems, building and other living space for the people have damaged. To mitigate these results, some kind of method has been used for many years such as using better foundation or making ground remediation. In this paper, some existing methods and new methods has been advised the Turkish railway systems. There is also comprehensive table which shows the serious earthquake in Turkey until 2005. These earthquakes indicate that Turkey ground is weak and potential earthquake area. Also people have been suffering from the all earth movements in Turkey. Many people have been killed and injured.

6.3 Expected Slab Track Revolution on Turkish State Railway Tracks

Turkish State Railways have been using ballasted track systems for about hundred years. After the government's comprehensive development, the higher speed trains have been becoming more and more important both small and big cities in Turkey. Turkish State Railways started building high-speed rail lines in 2003. In this purpose, the first line is between Ankara and Eskisehir which is the important part of Istanbul to Ankara high-speed rail line has been built completely.

The construction of three separate high-speed lines from Ankara to Istanbul, Konya and Sivas will finish soon. Turkey plans to construct a network of high-speed lines to extend the 1500 km network of high-speed lines by 2013 and a 4000 km network by the year 2023.

6.3.1 Evaluation of the Slab Track Systems in Terms of RAMS

In the existing projects such as Ankara-Konya and Ankara-Istanbul, the ballasted track systems have been used or planned. To think about long term benefits, preference of the ballasted track systems is negotiable. Turkish State Railway wants to increase the networks capacity and reduce the headway. In this process, the managers should consider RAMS (Reliability, Availability, Maintainability and Safety) process for the network.

Reliability engineering is dealing with ability of a system or component to perform its required functions under stated conditions for a specified period of time. Under operational

conditions, railway tracks should be reliable. Especially for busy networks, reliability is becoming very important position. Unreliable track systems can cause great delays and harm the entire operation process. The ballasted track systems are still a cause of important delays in Turkey. Sometimes, conventional lines are closed completely for the maintenance. Slab track systems present more reliable systems than conventional tracks do, because it requires less maintenance facilities.

Availability is the time period in which the system is functioning. This is often described as a mission capable rate. Mathematically, this can be calculated with unavailability. For the railway lines operation, availability is very important and it is also related to its maintenance process. The slab track systems have more availability than ballasted track with its maintenance facilities. Furthermore, the slab track systems can present more available systems in case of an earthquake with its easy access and rescue features.

Maintainability is a part of the lifecycle for all products in railway. Maintenance time and cost can increase the products maintainability option. Slab track systems require less maintenance than the slab track. The maintenance time can be reduced using prefabricated products and if whole product life is considered, maintenance costs will be less than ballasted track. Furthermore, in case of an accident railway tracks should provide easy access and easy change the products which are damaged.

Safety is the last part of the RAMS process that is a vital for all transportation systems. It is necessary to ensure safety for all components in railway systems. The railway tracks can cause of accidents which can result loss of people's lives and properties. Safer systems always increase the desirability of the components or products. It is general fact that both systems provide nearly the same safety facilities for high speed lines.

6.3.2 Evaluation of Slab Track Systems in Terms of Turkish Ground Conditions

As mentioned at the earlier section, Turkey has a weak ground condition to build railways on. In many parts of the country, new railway tracks needs remediation on the ground before it will be built. It is a very difficult process that can extend the project finish time, and increase the cost of the project. Sometimes manager should build new railway lines under the active seismic conditions. One of the important examples from Turkey which is called Pamukova passing for Ankara-Istanbul High speed railway construction, it shows the necessity for the consideration of active seismic zones. This critical passing length is about 15-20 km, but it is very important for the whole systems safety and operation. The tracks needs remediation, but it is expensive and it increases the project time. There are number of methods that can be used in this project. The important process is choosing the best method and check the adaptation of the track system.

The previous section of this paper shows the details about the slab track adaptation for earthquake or liquefaction zones. The author states that slab track systems can be adapted to the place where is under the earthquake or liquefaction risk. The elasticity of the ballast track can cause more damage on the rail and trains which is under operational conditions. Furthermore, slab track systems show better behaviour under emergency conditions in terms of braking and accessibility.

6.3.3 Economic justification for choosing track systems

As it is mentioned in this study, there are a number of different slab track types available for the railway lines both high speed and light rails. In this thesis, the author deals with high speed lines' slab track. Lichtberger (2005) has drawn very comprehensive graph for the slab track systems in Figure 39. There are two types of slab track systems; one of them has support in points, another one has continuous support system. After that, the first group can be evaluated with its sleeper or sleeper-less system.

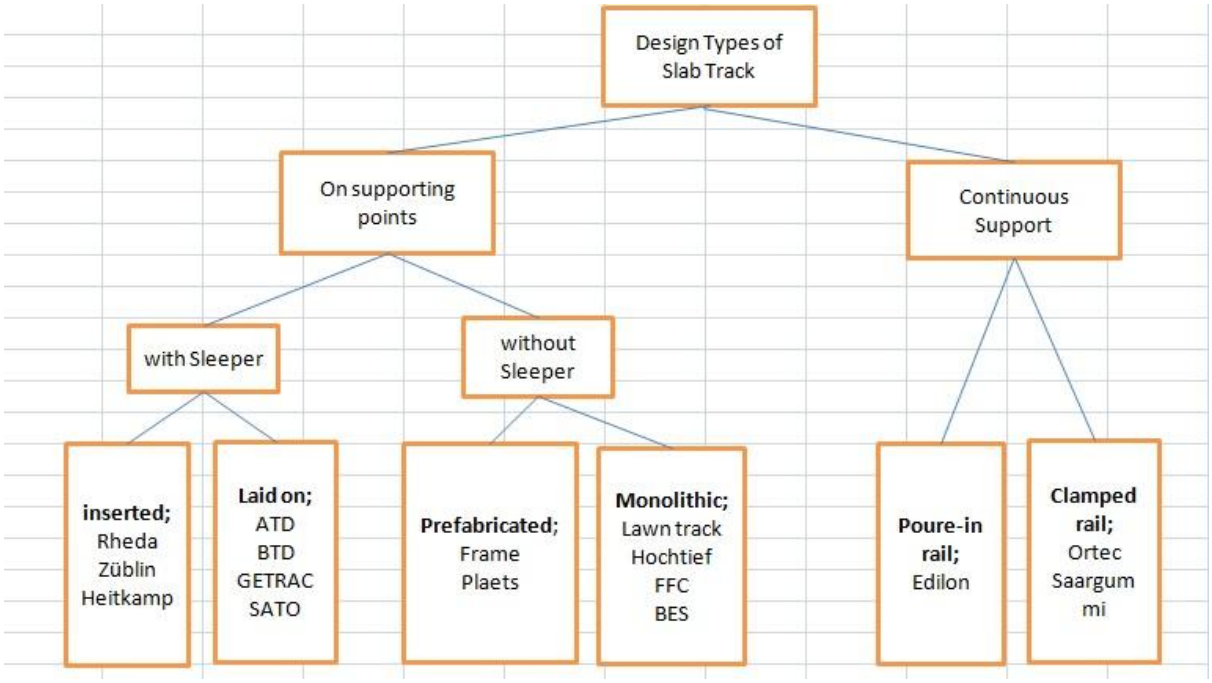

Figure 39: The slab track types (Lichtberger, 2005)

According to Lichtberger (2005), the slab track will be profitable only if its construction costs are no more than 30% above the construction costs for ballasted track. Construction costs of the slab track still amount to 1.5 times or more than that of ballasted track. However, some of the slab track types such as BBEST have achieved the less installation cost, as it can be seen from the Figure 40.

The initial cost of the slab track on average is more expensive than ballasted track. Ballasted track initial cost is about 350 Euros, and slab track is 500 Euros for 1m track. More recent studies show that the cost of slab track is reduced with increasing line length. .

Economic efficiency of slab track against ballasted track can be calculated only from the increased maintenance expenses required for ballasted track.

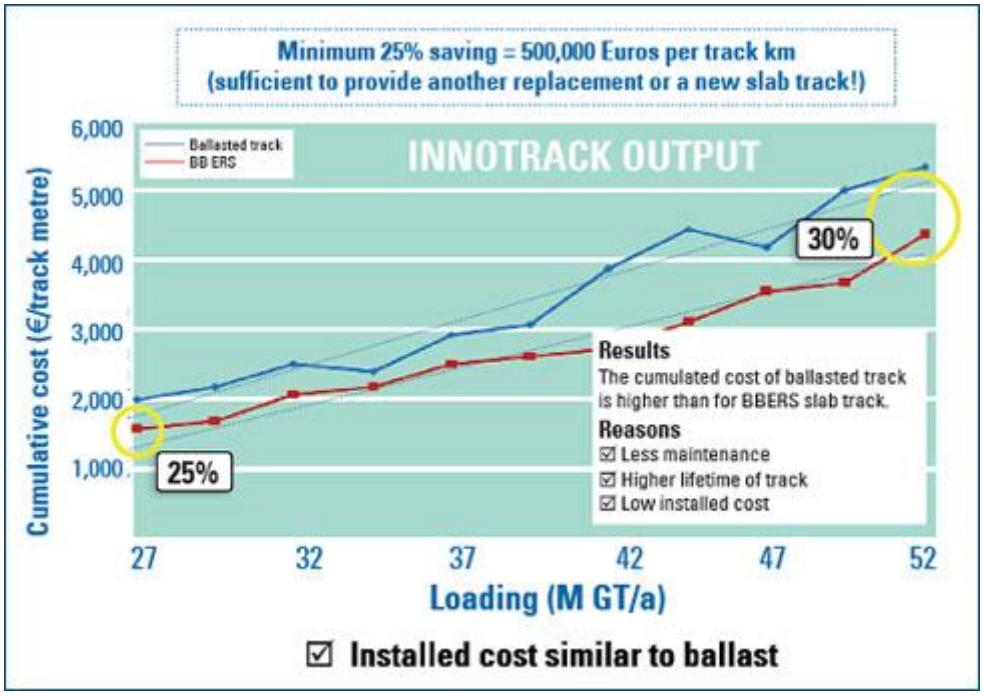

Figure 40: Slab track (BBEST) systems- ballasted track systems life cycle cost comparison (Balfour Beatty)

The graph which is shown above presents the life cycle cost of both a typical conventional track and slab track example, Balfour Beatty system. In this example, BBEST systems achieve lower higher installation cost than ballasted. Therefore, one of the biggest disadvantages of the slab track, high installation cost, has been rebutted.

The ballast-less permanent way machineries are economically efficient in comparison to the ballasted track in tunnels and circumstances which is necessary for the specifically unstable areas. The earth structures of the ballast-less track is not economically efficient compared to the ballasted track, when looking at it on short term.

The Figure 41 shows the slab track types installation cost, maximum speeds, heights and costs. It indicates that the Zublin and FFC designs have less cost than the others. The Heitkamp is very popular slab track system notwithstanding; it is not effective for high speed lines. Furthermore, several special evaluations noise and renewals have been done by Lichtberger (2005).

type of design	year of con-struction	v [km/h]	overall [height] [cm]	assessment noise	Q	assess-ment Q	cost €/rm	daily performance [m]	assessment renewal
Rheda	1972	300	63	2	15	1	1198	172	3
Rheda Berlin	1997	300	67	3	6	1	630	170	3
Züblin with sleepers	1988	300	60	2	30	3	550	200	2
Züblin BTE	1996	300	44	1	25	2	475	200	1
FTR	1988	-	-	-	-	-	1750	-	3
ATD	1993	300	~70	2	25	2	600	200	2
BTD	1994	300	63	2	14	1	-	350	2
Getrac	1995	300	72	2	20	2	625	270	2
SATO, FFYS	1984	200	61	2	35	3	600	350	1
lawn track	1998	160	80	2	28	3	-	-	-
Heitkamp	1998	160	78	3	5	1	-	200	3
FFC	1998	300	48	1	30	3	470	200	1
INFUNDO	1995	160	-	1	-	-	470	200	1
Saargummi	-	160	-	2	-	-	-	-	-

assessments: 1 = advisable, 2 = satisfactory, 3 = needs improvement
manufacturing cost: given from the upper edge of the hydraulically bonded bearing layer, tunnel sole or the substructure of the bridge
Q-figure: Track quality figure, at 100 maintenance has to be carried out
overall height: from the upper edge of the hydraulically bonded bearing layer to the upper edge of the rail
daily performance: refers to an 8-hour shift

Figure 41: Technical and economic comparison of various slab track designs (Lichtberger, 2005)

Turkish State Railway might do feasibility studies for all the high speed lines. It means that the ground investigations and available track structure should be described before planning the high speed lines. This can bring extra burden for the budget. If the line consists of special parts such as tunnels, viaducts or substructures, the slab track is the best option for construction. The slab track systems also should be used in busy networks. It is better way because of the availability issues. In general, the embedded track systems and floating slab track systems are the better options for the Turkish State Railway. This is because both types allow change in the some part of the structure. Moreover, the current BBEST systems have an important improvement to reduce installation cost, maintenance cost and the other disadvantages of the slab track. It should be considered as a one of the important suggestion for the Turkish State Railways.

7 Conclusions

The broader purpose of this thesis is to demonstrate the potential positive impacts of applying slab track systems in unstable zones and its advantages in terms of mitigating earthquake effects. At the beginning, the author indicated the characteristics of different track systems, with their advantages and drawbacks in terms of reliability, availability, safety and maintainability. After that, the types of slab track systems and characterisation of their specialities, requirements, advantages and disadvantages have been justified at a glance.

In the first part of the case study, the author showed how track systems may be built in an unstable zone or area with active seismic behaviour. The second part of the case study, the author justified the ground conditions in Turkey and the respective applicability of slab track systems.

7.1 Findings

At the beginning of the thesis, the author has presented the comprehensive background and literature review to understand the context of this paper. Afterwards, the track systems which are very important for the railway lines have been examined to understand the solutions for some railway problems.

At the beginning of Section 4, ballasted track systems were analysed in general and some evaluation has been made about the advantage and disadvantages of the system components. In this context, the ballasted track systems have been regulated by International Union of Railways (UIC) in order to provide international standards. The values given in Section 4 have been provided from the UIC from regulations.

In the Section 5, the slab track systems were investigated in details. These systems are very important for the high speed lines. There are a number of different examples that have been shown in this paper. The requirements of the slab track systems have been investigated for tunnels, substructures, bridges, cuttings and embankments and transitions. There are many types of slab track systems that are used in railway lines such as Shinkansen, Rheda and Bögl design. In this paper, these systems have been examined.

In the case study, the author sought and obtained more realistic and objective information for the slab track systems and investigations for the seismic movement zones. Earthquakes and their general characteristics have been described; afterwards, a description of earthquake measurements scales. Some of mentioned methods were discovered by US scientists and others by Japan scientists. Specifically, the author reviewed the impacts of seismic waves such as soil liquefaction, ruptures and landslides. In particularly, the author took the soil liquefaction into consideration as a how to reduce its impacts.

The author has started to investigate these impacts' definitions and mitigation methods for the railway lines. Then, he has showed the effects of the seismically active zones on the slab track systems. There are a number of different methods, some new, some already known, have been indicated in deeply such as foot spreading, pile foundation and dewatering.

Particularly, the options which are the retrofitting of the structural measures to the railway systems are shown in this thesis. The most known methods which are the spread footing systems and pile foundation systems bring many advantages for the slab track systems. The author wants to show the advantage of the slab track systems when these methods are used. Furthermore, other mitigation methods are available for the un-stable ground conditions. For example, the removing the soil layer which is under liquefaction can be replaced with the better soil layer. However, these methods are very expensive and difficult to apply for every place in railway.

7.2 Recommendations

The purpose of this thesis is to give track system recommendations for active seismic area when the track system is chosen. At the beginning of this paper, there is a description for choosing track systems in general. The explanations have been done to reveal the slab track systems advantages. Slab track systems nowadays provide lots of benefits in terms of the economy, less maintenance and less cost.

In the case study, the earthquake zones and its characteristics are investigated in detail. The most important part here is the determination of the system requirements and suggestion of the most suitable track types. As in the Section 5, the slab track systems have been determined as best systems for the high speed lines in active seismic zones. There are number of different requirements that have been considered before systems were suggested.

Inside the case study, there are also many of earthquake impacts mitigation methods have been suggested. The earthquake can have impacts on the ground structure and can directly affect the construction. These impacts can be soil liquefaction, tsunami, land sliding and ground rupture. Furthermore, some of the impacts cannot be reduced without precaution such as ground ruptures' impacts cannot be mitigated. As a result of this, designers should avoid construct railway in these type grounds. The soil liquefaction is one of the basic impacts of earthquakes. It can be mitigated by several methods. However, there are only two methods which are spread footing and pile foundations better than the others in terms of economy and application style. These methods can be very efficient for the soil liquefaction impacts.

The suggestion for the Turkish State Railway is that should always do feasibility study, which is known as a comprehensive study. This includes benefits, drawbacks, foreseen and unforeseen events before the application of project studies for all special high speed lines. If the line consists of special parts such as tunnels, viaducts or substructures, the slab track is

the best option for construction. The slab track systems also should use busy networks. It is better method because of availability issues. In general, the embedded track systems and floating slab track systems are the best options for the Turkish State Railway as both types allow changing the some part of the structure. For example, both systems can be improved by noise and vibration absorber materials. Moreover, the current BBEST systems have an important improvement to reduce installation costs, maintenance costs and the other disadvantages of the slab track. It should be considered as a one of the significant suggestion for the Turkish State Railway.

7.3 Review of Approach

In this paper, author tackled to find independent sources of information without using companies' advertising materials. Moreover, some of the sources have been written to support some of the products. In this situation, it can be very difficult to ensure that neutral comments are made.

The technical side of the thesis is very wide and can be difficult to understand. So that, the author has started from track type description, and following this the case study has been completed.

7.4 Word Count

There are 19407 words between sections introduction and conclusion.

8 References

8.1 Documents References

Bains, J. (2011). *Working with Word*. Frustration City: Hope Publishing.

Bilow, D.N., P.E., S.E. and Randich, G.M. (n.d). 'Slab Track Design for Next 100 Years'. *P.E. Portland Cement Association Skokie*.

Bloggs, J. (2010) New York: Rampant Publishing.

Coxa, S.J., Wanga, A., Morisona, C., Carelsb, P., Kellyb, R. and Bewesc, O.G. (2006). 'A test rig to investigate slab track structures for controlling ground vibration'. *Journal of Sound and Vibration*. no. 293. p. 901–909.

Esveld, C. (1999). 'Recent Developments in Slab Track Application'. *TU delf Faculty of Civil Engineering, Section of Roads & Railways*. February.

Esveld, C. (2001). *Modern Railway Track*. Second edition edition. MRT Production.

Esveld, C. (n.d). 'Innovations of railway track'. *TU Delf*.

Esveld, C. and Markine, V. (2008). ' Slab Track Design for High Speed '.

Lichtberger, B. (2005). *Track Compendium*. Eurail press.

Liyanapathirana, D.S. and Poulo, H.G. (2004). 'Assessment of soil liquefaction incorporating earthquake characteristics'. *Soil Dynamics and Earthquake Engineering*. no. 24. p. 867–875.

Nial, P. (2011) Brooklyn.

Profillidis, V.A. (2006). *Railway management and engineering*. 3rd edition. Greece: Asgate publishing company.

Prucz, Z. and Pourbohloul, A. (2008). 'Bridge Configurations and Details that Improve Seismic Performance'. *AREMA*. no. 9.

Report, F. (2009). 'Rail Operation and Technology '. vol. Part 2: Technology. JUNE.

Rollins, K.M. (2004). 'Liquefaction M¡t¡gation Using Vertical Composite Drains: Full Scale Testing'. *Final Report for Highway IDEA Project*. february.

'Sesmological grand challenges in understanding earth's dynamic systems'. *Long-Range Science Plan for Seismology Workshop* (16-18 september 2008).

Sladen, J.A., D'Hollander, R.D. and Krahn, J. (1985) *Canadian Geotechnic Journal*. no. 22. pp. 564-578.

Steenbergen, M.J.M.M., Metrikine, A.V. and Esveld, C. (2007). '306 (2007) 361–371'. *Journal of Sound and Vibration*. no. 306. pp. 361-371.

The King is Hot (1999). London: Big Bee Publishing.

Ulusay, R., Aydan, Ö. and Hamada, M. (2001). 'The Behaviour of Structures Built on Active Fault Zones: Examples From The Recent Earthquakes Of Turkey'. *Seismic Fault-induced Failures*. January. pp. 1-26.

Yan-Chyuan Shiau, C.-M.H.-T.W.-T.L. (2008). 'New Model of Cement Product – Precast Slab Track for THSR (Taiwan High Speed Rail)'. *25 th International symposium on automation and robotic construction*. June.

8.2 Web Site References

Balfour Beatty. [Online]. Available: http://www.bbrail.co.uk/Products-and-Services/Track/Embedded-Rail-System/Life-Cycle-Cost-Comparison [19 August 2011].

Belge-Net (2006). [Online]. Available: http://www.belgenet.com/deprem/depremt.html [17 August 2011].

California, u.o. (2010). *http://www.kitp.ucsb.edu/*. [Online]. Available: http://online.itp.ucsb.edu/online/earthq05/archuleta/pdf/Archuleta1_KITP.pdf [12 August 2011].

Corporation, S.-B.P. (2005). *http://findarticles.com/*. [Online]. Available: http://findarticles.com/p/articles/mi_m0BQQ/is_5_45/ai_n13784671/ [09 August 2011].

Country Studies Report (2009). [Online]. Available: http://countrystudies.us/turkey/20.htm [11 August 2011].

Earthquake Engineering Research Institute (2002). [Online]. Available: http://www.eeri.org/lfe/costa_rica_valle_de_la_estrella_photo_gallery.html [13 August 2011].

Flickr. [Online]. Available: http://www.flickr.com/ [23 July 2011].

German Railway Consult Middle East (2010). [Online]. Available: http://www.grcme.com/Competencies.35.0.html [20 August 2011].

Goldschmidt-Thermit Group (2010). [Online]. Available: http://www.goldschmidt-thermit.co.jp/en/partner/edilon-sedra.html [26 August 2011].

GTE Group. [Online]. Available: http://www.gte-group.de/Sites/frontend/Employee_references.php [07 June 2011].

Inova enerji (2010). [Online]. Available: http://www.inovaenerji.com/hizmetler3.aspx [15 August 2011].

Kayser Railway Sleepers (2008). [Online]. Available: http://www.kayserbuildingsupplies.co.uk/prod_category.php?sid=75 [20 August 2011].

Liebherr (2005). [Online]. Available: http://www.liebherr.com/en-GB/58520.wfw [15 August 2011].

Mait Piling Rigs-India (2010). September. [Online]. Available: http://maitindia.blogspot.com/2010/09/typical-pile-foundation.html [15 August 2011].

Railway Gazzette (2008). June. [Online]. Available: http://www.railwaygazette.com/news/single-view/view/eddy-current-braking-a-long-road-to-success.html [14 August 2011].

Railway Technology (2005). 05 June. [Online]. Available: http://www.railway-technology.com/contractors/engineering/pfleiderer2/press2.html [23 July 2011].

Railway Technology (2010). [Online]. Available: http://www.railway-technology.com/projects/alice/alice4.html [20 August 2011].

Rauch, A.F. (2008). *http://scholar.lib.vt.edu*. [Online]. Available: http://scholar.lib.vt.edu/theses/available/etd-219182249741411/unrestricted/Chp02.pdf [13 August 2011].

Rogers, D.V. (2000). *http://allshookup.org*. [Online]. Available: http://allshookup.org/quakes/earth.htm [12 august 2011].

Sangamon Country (2007). [Online]. Available: http://www.co.sangamon.il.us/NHMP/PDF/Earthquakes-Draft.pdf [11 August 2011].

Skyscraper City (2008). 04 August. [Online]. Available: http://www.skyscrapercity.com/showthread.php?t=194709&page=158 [08 August 2011].

Sonneville (2008). [Online]. Available: http://www.sonneville.com/range-of-application/lvt-in-tunnels/ [20 August 2011].

Sonneville (2010). [Online]. Available: http://www.sonneville.com/ [24 August 2011].

South Carolina Emergency Management Division (2008). [Online]. Available: http://www.scemd.org/news/publications/EQ%20Guide%202008/Common_New_EQ_Terms_08.html [12 August 2011].

SSF Ingenieure. [Online]. Available: www.ssf-ing.de [07 August 2011].

Turkey Earthquake Surveys (1996). [Online]. Available: http://www.deprem.gov.tr/sarbis/shared/DepremHaritalari.aspx [17 August 2011].

Turkish State railway (2011). February. [Online]. Available: www.tcdd.gov.tr [15 August 2011].

United States Geological Survey Reports (2002). [Online]. Available: http://earthquake.usgs.gov/ [12 August 2011].

University of Washington. [Online]. Available: http://www.ce.washington.edu/~liquefaction/html/what/what1.html [12 August 2011].

USGS Report. [Online]. Available: http://earthquake.usgs.gov/earthquakes/world/events/1976_07_27.php [13 August 2011].

Verkehrsprojekt der Deutschen Einheit 8 (2008). [Online]. Available: http://www.vde8.de/VDE-8-OVERALL-LINE-CONSTRUCTION------_site.site.html_dir._nav.10013_likecms.html [20 August 2011].

Vossloh (2009). [Online]. Available: http://www.vossloh.com/en/press/press_photos/press_rail_infrastructure/rail_infrastructure_1.html [20 August 2011].

Vossloh Fastening Systems (2010). [Online]. Available: http://www.vossloh-fastening-systems.com/en/produkte_2010/feste_fahrbahn/336_336sd/336_336sd.html [09 August 2011].

Web-Japan (2005). 15 June. [Online]. Available: http://web-japan.org/nipponia/nipponia33/en/feature/feature10.html [14 August 2011].

Xitrack (2007). [Online]. Available: http://www.xitrack.com/paper5.pdf [20 August 2011].

Appendix A: Earthquakes History of Turkey

Place	Date	Magnitude	Death	Injured
ÇANKIRI	09.03.1902	6	4	-
MALAZGİRT	24.04.1903	6,7	2626	-
MÜREFTE	09.08.1912	7,3	216	466
AFYON-BOLVADİN	04.10.1914	5,1	400	-
ÇAYKARA	13.05.1924	5,3	50	-
PASİNLER	13.09.1924	6,9	310	-
AFYON-DİNAR	07.08.1925	5,9	3	-
MİLAS	08.02.1926	4,7	2	-
FİNİKE	18.03.1926	6,9	27	-
KARS	22.10.1926	5,7	355	-
İZMİR-TORBALI	31.03.1928	7.0	50	-
SİVAS-SUŞEHRİ	18.05.1929	6,1	64	-
HAKKARİ SINIRI	06.05.1930	7,2	2514	-
DENİZLİ-ÇİVRİL	19.07.1933	5,7	20	-
BİNGÖL	15.12.1934	4,9	12	-
ERDEK	04.01.1935	6,7	5	30
DİGOR	01.05.1935	6,2	200	-
KIRŞEHİR	19.04.1938	6,6	149	-
İZMİR-DİKİLİ	22.09.1939	7,1	60	-
TERCAN	21.11.1939	5,9	43	-
ERZİNCAN	26.12.1939	7,9	32962	-
NİĞDE	10.01.1940	5	58	-
KAYSERİ-DEVELİ	20.02.1940	6,7	37	20
YOZGAT	13.04.1940	5,6	20	-
MUĞLA	23.05.1941	6.0	2	-
VAN-ERCİŞ	10.09.1941	5,9	194	-
ERZİNCAN	12.11.1941	5,9	15	-
MUĞLA	13.12.1941	5,7	-	-
BİGADİÇ-SINDIRGI	15.11.1942	6,1	7	-
OSMANCIK	21.11.1942	5,5	7	-
ÇORUM	11.12.1942	5,9	25	-
NİKSAR-ERBAA	20.12.1942	7	3000	-
ADAPAZARI-HENDEK	20.06.1943	6,6	336	-
TOSYA-LADİK	26.11.1943	7,2	2824	-
BOLU-GEREDE	01.02.1944	7,2	3959	-
DÜZCE	10.02.1944	5,4	-	-
MUDURNU	05.04.1944	5,6	30	-
GEDİZ-UŞAK	25.06.1944	6,2	21	-
AYVALIK-EDREMİT	06.10.1944	7.0	27	-
ADANA-CEYHAN	20.03.1945	6.0	10	-
VAN	20.11.1945	5,8	-	-

KADINHAN-ILGIN	21.02.1946	5,6	2	-
VARTO-HINIS	31.05.1946	5,7	839	349
İZMİR-KARABURUN	23.07.1949	7.0	1	7
İSKENDERUN	08.04.1951	5,7	6	10
KURŞUNLU	13.08.1951	6,9	52	208
YENİCE-GÖNEN	18.03.1953	7,4	265	366
BOLU-ABANT	26.05.1957	7,1	52	100
MARMARİS	23.05.1961	6,5	-	9
IĞDIR	04.09.1962	5,3	1	22
ÇINARCIK-YALOVA	18.09.1963	6,3	1	26
MALATYA	14.06.1964	6	8	36
MANYAS	06.10.1964	7	23	130
DENİZLİ-HONAZ	13.06.1965	5,7	14	217
VARTO	07.03.1966	5,6	14	75
VARTO	19.08.1966	6,9	2394	1489
ADAPAZARI	22.07.1967	7,2	89	235
PÜLÜMÜR	26.07.1967	6,2	97	268
AKYAZI	30.07.1967	6	2	40
BİNGÖL-ELAZIĞ	24.09.1968	5,1	2	40
BARTIN	03.09.1968	6,5	29	231
ALAŞEHİR	28.03.1969	6,6	41	186
KARABURUN	06.04.1969	5,6	-	3
GEDİZ	28.03.1970	7,2	1086	1260
ÇAVDARHİSAR	19.04.1970	5,9	-	2
DEMİRCİ	23.04.1970	5,7	-	43
BURDUR	12.05.1971	6,2	57	150
BİNGÖL	22.05.1971	6,7	878	700
İZMİR	01.02.1974	5,2	2	22
KARS-SUSUZ	25.03.1975	5,1	2	26
LİCE	06.09.1975	6,9	2385	3339
DOĞU BEYAZIT	02.04.1976	4,8	5	13
DENİZLİ	19.08.1976	4,9	4	28
ÇALDIRAN-MURADİYE	24.11.1976	7,2	3840	497
LİCE	25.03.1977	4,8	8	17
PALU	26.03.1977	5,2	8	26
ERZURUM	30.10.1983	6,8	1155	1142
ERZURUM-BALKAYA	18.09.1984	5,9	3	35
MALATYA-SÜRGÜ	06.06.1986	5,6	1	20
KARS-AKYAKA	07.12.1988	6,9	4	11
ERZİNCAN	13.03.1992	6,8	653	3850
DİNAR	01.10.1995	6.0	96	240
ÇORUM-AMASYA	14.08.1996	5,4	-	6
ADANA-CEYHAN	27.06.1998	6,3	145	1041
KOCAELİ	17.08.1999	7,4	17127	43953

BOLU-DÜZCE	12.11.1999	7,2	845	4948
ÇANKIRI-ORTA	06.06.2000	6,1	2	1766
SAKARYA-HENDEK	23.08.2000	5,8	-	9
AFYON-SULTANDAĞI	15.12.2000	5,8	6	547
TUNCELİ-PÜLÜMÜR	27.01.2003	6,2	1	7
BİNGÖL	01.05.2003	6,4	176	520
ERZURUM-ÇAT	25.03.2004	5,1	9	20
AĞRI-DOĞUBEYAZIT	02.07.2004	5,1	18	32
ELAZIĞ-SİVRİCE	11.08.2004	5,5	-	12
HAKKARİ	25.01.2005	5,5	2	5
BİNGÖL-KARLIOVA	12.03.2005	5,7	-	16

(http://www.belgenet.com, 2006)