



Addis Ababa Institute of Technology
School of Civil and Environmental Engineering

**Effect of Ballast Bonding and Stabilized Soil Modulus on Railway
Track Transition zone Settlement**

By

Sewbesew Tarekegn

**Thesis Submitted to School of Graduate studies of Addis Ababa University in
Partial Fulfillment of The Requirement for Degree of Master of Science**

In

Railway Engineering (Civil Engineering)

Advisor :- Dr.ing Henoke Fikre

Co advisor :- Mequanenet Mulugeta

December, 2016

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Abstract

Railroad substructure deforms and degrades progressively under heavy cyclic loading. The track subsoil and ballast have the most significant contribution for the substructure deterioration. Track degradation and settlement occurs throughout the track but particularly sensitive are transition areas between ballast track and ballast less track, switch and crossing areas, turn out areas and rail joints due to dynamic impacts that come from the abrupt change in track stiffness. Track stiffness has a profound significant in design and construction stages of the railway track. Safe travel and life time performance of a track depend on the unvarying track stiffness.

In spite of that, varying the track stiffness is bound to happen, particularly in the transition zone, where the rigid track connects to a conventional ballasted track. In this critical point track stiffness varies suddenly and it causes differential settlement, which is the major source for deterioration of tracks and sub structures at transition zones. Different solutions have been applied on the super structure of the track to make gradual stiffness transition, such as the use of gradual pad stiffness long sleepers and auxiliary rail.

This critical railway infrastructure problem demand repeated track preservation work, especially frequent ballast bed maintenance. In order to increase the performance of railway track, to avoid frequent maintenance works and to reduce costs the better solution is track substructure reinforcement. Reinforcement of the track by bonding ballast using polyurethane geocomposite and stabilizing the subsoil is a candidate solution to these problems. This paper focuses on the applicability and potential benefits of ballast bonding technology and soil stabilization to railroad bridge approach transition zones. The prominence of this study is conducted on the investigation of the characteristics of track substructure at transition zone under the train moving loads by improving ballast and subsoil strength. For that reason, well-known commercial finite-element method package ABACUS- CAE has been used to investigate the dynamic behavior of the transition zone under the passage of trains. The results of the dynamic analysis are presented and compared in two set of conditions; one the non-improved or low strength substructure without gradual stiffness change and the other by considering the improvement in the substructure by intensifying the substructure performance through constructing two-part transition section. These are improved and non-improved parts. The geometry of improved parts of the ballast and subsoil changes gradually to mitigate stiffness variation. Finally conclusion and recommendation are presented based on the finite element results. From the finite element result the vertical displacement of the ballast and the sub grade has been lowered to the acceptable range due to the improved modulus of elasticity of the substructure. The vertical acceleration on the rail is also absorbed to zero when the substructure is improved.

Keywords: Track transition zone, Track stiffness, Ballast bonding, Soil stabilization

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CHAPTER 1

1 Introduction

1.1 General Back ground

Efficient transport is a critical component of economic development, globally and nationally. Transport availability affects global development patterns and can be a boost or a barrier to economic growth within individual nations.

Railway transportation is recognized as the most reliable, safe and energy efficient means of transport for passengers and goods. In an era of increasing environmental concern, railway transport is also the most sustainable choice with the lowest carbon dioxide emissions per km per ton transported. With this in mind, the railway sector has been the subject of renewed interest and rapid development.

The Ethiopian government has planned to connect different parts of the country each other and to the ports via railways. The rail tracks which currently under construction are conventional ballasted tracks and they are for both passenger and freight trains.

Railway track structures contribute a crucial role within the transportation infrastructure of a country in providing a significant contribution to create a sustainable and stable economy. To attain optimal long term performance of the rail track, it is mandatory to understand how track structure function and degrade. Besides detail understanding of rail track problematic zones and providing appropriate mitigations is also inevitable in order to attain this goal. In the past, the train and track superstructure, such as rails and sleepers were the focus of attention of railway engineers. Less attention was given to the substructure such as ballast, sub ballast and sub grade even though they are as important as the superstructure. While the superstructure provides the

main function of the railway, the substructure provides the foundation to support the superstructure and to help the superstructure to reach its optimum performance.

The increase in speed, axle-loads and traffic has led to higher-rates of degradation of the ballasted railway tracks. Due to this a considerable effort is necessary for maintenance of the tracks, with corresponding increase in costs for the infrastructure managers. According to Schmitt (2006), 40-50% of these costs are spent to maintain the quality of the track geometry. The primary component of ballasted track, on which maintenance is concentrated, is the ballast itself. The main cause for the loss of track geometry is deformation and densification of the ballast layer, representing 75% of the total track position maintenance [31]. Track settlement also occurs after long-term service. Ballast contributes the most to track settlement even though one of the functions of ballast is to restrain track geometry. Excessive settlement can cause poor passenger comfort, speed restriction, and potential derailment. The most conventional method of restoring the track geometry is tamping. However, tamping has negative effect on the ballast in addition to the impact from traffic loading.

It has been recognized that the performance of railway track depends crucially on the behavior of the underlying natural ground. As mentioned deterioration of the track geometry is an important contribution to the maintenance costs. This deterioration is mainly caused by the settlement of the substructure which tends to depend on site conditions. For a weak subsoil layer the sub grade will be the main cause of failure and the general mitigation to restore the track stiffness is to increase the depth of the granular layers to minimize the sub grade stresses and reach acceptable track geometry. However, if the sub grade has too low stiffness that the track with any depth of granular material will not achieve the allowable track geometry under a specific load, and then enhancing the strength of the sub grade soil is required.

One of the major sources of problems for the track geometry are transition zones between the normal free track and stiff structures such as bridges ,tunnels, culverts and special track work transitions. The rate at which the track geometry degrades on these transition zones is frequently higher than on the normal free track, leading to higher maintenance frequency and sometimes speed restrictions. According to Lopez-Pita et al. (2007) the frequency of maintenance at transitions is three times that of normal plain track. Transition zones represent an area where significant improvements might be achieved by understanding the mechanics that are

contributing for the acceleration of degradation. To mitigate the effect, transition zones are designed and built with the aim of providing a gradual change in track support stiffness between the normal line and the structure. However, renewal and maintenance costs are disproportionately high on transition zones, indicating that current design procedures are ineffective and there is no coherent understanding of the mechanisms involved. Switches and crossings suffer from similar support problems, due mainly to the practical difficulties of maintaining the substructure underneath a complex mechanism that is particularly sensitive to differential movements. A poor switch substructure leads to high levels of vibration in the switch and drive mechanism. These vibrations are the root cause of a significant number of failures and hence train delays.

Improvement of track design and maintenance will lead to a reduction of total life costs with major benefits with the railway system owners, operators and users.

Despite the problems associated with ballast, ballast is still a preferable choice for substructure material over other alternatives such as concrete slabs or asphalt. This is because ballast provides less stiff support (which is an important factor in case of differential settlement or sub grade failure), is more economical, and produces less noise.

Thus, it is important to study problematic track zones, degradation of ballast and subsoil and efficient maintenance methods to increase track life, reduce waste ballast, minimize the frequency and cost of ballast replacement, and lead to further developments in the railway industry.

1.2 Problem Statement

In the context of Ethiopian geography pattern of settlement and economic activity transport plays a vital role in facilitating economic development. In particular railway transport can provide the means for bulk transport of goods and mass transportation of peoples. There for the railway transport system supports social and economic growth and plays a key role as a catalyst to meet poverty reduction targets in Ethiopia.

However the experience in design, construction and maintenance of the railway track in Ethiopia is at starting stage. Therefore it is mandatory to assess and explore the practices and procedures developed in other countries.

In rail road systems, at-grade ballasted track frequently changes to a non-ballasted track configuration or to ballasted track on a structure. The abrupt change in track support that can occur at these locations is often associated with accelerated rates of track geometry and component degradation, high maintenance demand, and poor ride quality. This is one of the main problems that occurred frequently at railway track that need apparent solution.

Track geometry problems at railway transitions are well recognized all over the world. The Association of American Railroad reported an annual expenditure of approximately \$200 million to maintain track transitions whereas more than \$110 million was spent annually on transition zones in Europe by 1999. Therefore, additional research on railway transitions will allow the development of optimized maintenance procedures, and improved transition zone solutions for new railway lines or for the up-grade of existing ones. Accordingly, a number of mitigation techniques have been suggested to enhance track performance by providing a transition to smooth the stiffness interface between the dissimilar track types. In order to avoid frequent maintenance works and to reduce costs, some railway companies started applying ballast bonding technique as well as soil strength improvement solutions to ensure durability of track substructure components. Then after, this technology was used to prevent track deflection which led to improvement of driving behavior and thus travel comfort as well.

Modeling transition zones with finite element software and observing the effects of stiffness variation with the application of different transition zone mitigations enables to understand better transition zone solutions.

1.3 Objectives of Thesis

The primary purposes of this thesis are

- To explore and assess the knowledge on cause of transition zone degradation and mitigation techniques.

- To analyze the settlement of railway track components at transition zones by improving the modulus property of ballast and subsoil of the track substructure using finite element analysis and modeling software ABAQUS.
- To see the effect of moving load and train speed on the vertical displacement of track transitions along the path of the train.

1.4 Research Questions

In doing this research the following questions have been answered:

- How the track substructure reinforcement reduce the track settlement at transition zones
- How to create gradual change in stiffness at transition zones by using ballast bonding and reinforced soil to mitigate stiffness variations
- What the response of track dynamic analysis implies on track transition zone settlement

1.5 Methodology

Finite element is one of the most powerful and acceptable method to analyze the dynamic behaviour of the track structure. By creating models in the finite element program ABAQUS responses to dynamic loading have been studied. The model is railway track transition zone model by incorporating transition mitigations techniques. In this study finite element modelling is performed using the material properties of track components. The effect of the mechanical properties of ballast and soil on the vertical displacement of the track components is studied by varying the parameters of elastic modulus of ballast and soil.

For the improved cases, the elastic modulus parameters of geocomposite reinforced ballast and cement stabilised soil are used.

In the study the performance of track transition zones by using reinforced ballast and soil is analysed using finite element modelling software Abaqus.

1.6 Scope and limitations

The scope of the research presented in this thesis includes:

- The thesis presents literature review about track transition zone problems and mitigations techniques besides to this experience on transition zone problems and application methods for mitigations also included.
- The finite element modeling is 2D and it doesn't include discrete element method for the modeling of the ballast condition.
- This study has been supported by secondary resources and findings should be considered as indicative rather than definitive for field applications.

1.7 Structure of the Thesis

This thesis is composed of six chapters. In chapter one the introduction and back ground of the thesis are established, including problem statement, purpose and scope/limitation.

Chapter two covers literature review of the theoretical foundations part focusing mainly on the review of rail terminology, track stiffness, track performance, modeling, transition zone degradation and mitigations, track reinforcement techniques (including ballast bonding and soil stabilization methods).

Chapter three research methodologies presented to outline the method used in this thesis in developing transition zone model in ABAQUS. Here the material properties of the modeled track components, the 2D geometry of the transition section and the cases for the finite element modeling are presented. By using the methods described in the previous chapter in chapter four finite element analysis and discussion of the results presented. The results from the explicit dynamic analysis software ABAQUS are put for discussion and interpretation giving way for the next chapter to make important conclusions.

Chapter five concludes the thesis results and recommends based on the findings either for further research or for considerations for making the results more acceptable and understandable.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Railway Track Structure

2.1.1 The Track

The aim of a railway track is to ensure safe and affordable train transportation. This requires the track to provide a suitable guide way with proper horizontal and vertical alignment to attain this role each component of the track must perform its particular function satisfactorily in response to the traffic loadings and external impacts imposed on the system. The track and the switches should allow smooth passage of the trains. If the track is not perfectly leveled and aligned, the irregularities will cause oscillations or vibrations of the train and this may induce discomfort for passengers and damage for goods.

The main components of ballasted track structure may be grouped in to two main categories:

- 1) Superstructure: The super structure consists of the rails, the rail pads, the fastening systems and the sleepers.
- 2) Substructure. : The substructure consists of the ballast, the sub ballast and the sub grade.

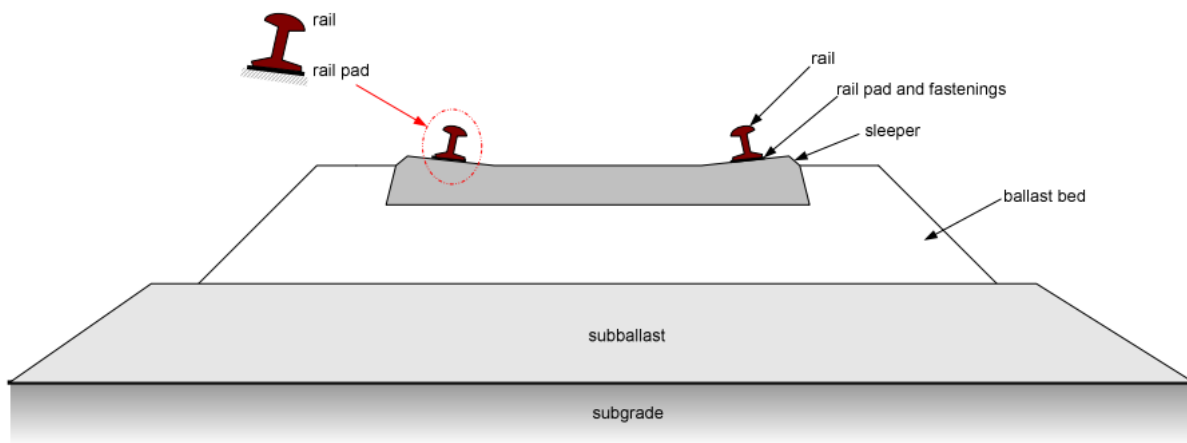


Figure 1: Typical ballasted track structure [13]

2.1.2 Rail

Rails are the longitudinal steel members that directly guide the train wheels evenly and continuously. They must have sufficient stiffness to serve as beams that transfer the concentrated wheel loads to the spaced sleeper supports without excessive deflection between supports.

The rails should provide smooth running surfaces for the train wheels and they should guide the wheel sets in the direction of the track. Esveld presented that a modern rail track also conveys signals and acts as a conductor on an electrified line [12, 13].

2.1.3 Rail fastening systems

The rail fastening system or fastenings includes every component that connects the rail to the sleeper including fastener and rail pad. Fastenings clamp the rail gauge within acceptable tolerances and then absorb forces from the rails and transfer them to the sleepers [12, 13]. Fastenings retain the rails against the sleepers and resist vertical, lateral, and longitudinal and over turning movements of the rail. Fastenings also act as electrical insulation between the rail and the sleepers. The principal components of the fastenings are fastener and rail pad [12, 18]. The typical fastening system for concrete sleeper is consisting of rail pads, fasteners clip, Y-type shoulders.

2.1.4 Rail pads

Rail pads in a railway track with concrete sleepers, rail pads are placed between the steel rails and the sleepers. The rail pads protect the sleepers from wear and impact damage, and they provide electrical insulation of the rails. Wooden sleeper tracks may not have rail pads. From a track dynamics point of view, the rail pads play an important role. They influence the overall track stiffness. When the track is loaded by the train, a soft rail pad permits a larger deflection of the rails and the axle load from the train is distributed over more sleepers. Also, soft rail pads isolate high-frequency vibrations. They suppress the transmission of high-frequency vibrations down to the sleeper sand further down into the ballast.

2.1.5 Sleepers

Sleepers are essentially beams that span across and tie together the two rails. The sleepers provide support of rails and preserve gauge, level and alignment of the track. The sleepers transmit vertical, lateral and longitudinal forces from the rail down to the ballast bed. They should also provide electrical insulation between the two rails.

Wooden sleepers were used in the past because timber was used in several countries [12, 18]. However, pre-stressed or reinforced concrete sleepers, and to a limited extent steel sleeper, have been adopted in modern railway tracks over the past decades because of their durability and long service life. Concrete sleepers are described as either twin-block or mono-block. The concrete sleepers are widely used, because they are relatively not affected by environmental effect [12, 18]

2.1.6 Ballast

Ballast is selected crushed granular material placed as the top layer of the substructure on which the sleepers rest [18]. The ballast is an elastic support layer to support the track (the rails and the sleepers) against vertical and lateral forces from the trains. It is tightly compacted or tamped around the sleepers to keep the track precisely leveled and aligned.

Ballast is an elastic support layer to support sleepers and transfer the forces from the rail and sleeper to the sub-ballast and over the sub grade [12, 18]. This layer comprises graded crushed stone, gravel, and crushed gravel such as granite and basalt and it also drains water from the rails and sleeper.



Figure2: Typical construction of a ballasted track [13]

2.1.6 Sub ballast

Sub-ballast is material chosen as a transition layer between the upper layer of large-particle, good quality ballast and the lower layer of fine-graded sub grade. The Sub-ballast assists in reducing the stress at the bottom of the ballast layer to a tolerable level for the top of the sub grade.

2.1.7 Sub grade

Sub grade, or formation, is a surface of earth or rock leveled off to receive a foundation for the track bed. Sometimes an extra layer, a formation layer, is put on the earth so as to give the correct profile of the track bed. On this material the sub-ballast and ballast layers rest. The sub grade offers the final support to the track structure.

2.2 Influence of Track Stiffness on Track performance

Track performance can be determined according to the response of the track structure to traffic loading. The extent of particular loads and repetition of loading are the main aspects that affect the loading of the track. The main problem for the track substructure is routine traffic and it is typically the cycling of loading [5].

The integration of the track components control the transmission of traffic loads through the track structure and ultimately ensure the performance of the track. The deterioration of track superstructure components, densification and breakage of the ballast, and sub grade deterioration are the main factors that affect track degradation.

Track support stiffness (wheel load divided by track deflection) is a vital parameter of track design and maintenance that affect the performance of track, vehicle mechanism, and the quality and service life of track components [30, 29]. The high track stiffness is generally effective that it provides sufficient track. High track stiffness increase resistance to applied loads and reduced the track deflection, i.e., affect track deterioration [29, 22]. However, dynamic forces on wheel–rail contact surface and sleepers and ballast increase with track stiffness increased [22, 20]. The variation of the track support stiffness along the track has significant influence on track

performance. It leads to variations in vehicle–track interaction forces and differential settlement; consequently it could lead to the differential track deterioration problems [18].

2.2.1 The Effect of Track Stiffness variation on Track settlement

The extent of degradation of track structure components and track settlement will depend on the intensity of the stiffness variation. As the track geometry starts to degrade, the train-track interaction forces show incremental change, and this speeds up the track degradation rate. Therefore, the influence of track stiffness irregularities on the development of track settlement and on the deterioration of track components and materials cannot be ignored.

The track stiffness can vary due to a variety of reasons such as:

Track stiffness irregularities may have its origin in the track superstructure (rails, rail pads, sleeper, and ballast) or substructure (foundation, sub grade soil, etc.).

A passing train will be exposed to variable track stiffness along the track. The stiffness variation expected to be large within a short distance on the following cases [33].

- (1) Equally unsupported sleeper: Track stiffness is concentrated at that sleeper, not significant.
- (2) Rail joints: the bending stiffness of the rail has a discontinuity suggest the joint also of the track stiffness.
- (3) Transition from free track to ridge track
- (4) At switches both mass and stiffness vary abruptly.

Variation of track stiffness will create changes in the wheel/rail contact force. The variation of the stiffness will speed up track degradation such as wear, fatigue, track settlement due to intended deformation of the ballast and the substructure.

Problems at track transitions due to stiffness variation can be divided into three categories these are differential Settlement, track stiffness case and track damping case.

Differential settlement is where two segments of track settle at different rates, such as the bridge to bridge approach track transition and ballasted track to ballast less track. Railroad bridges are built on deep foundations and are relatively immune to sub grade settlement. In contrast, the approach consists of fill and has a large amount of settlement compared with the bridge structure. This common bridge to bridge approach construction method can result in what is commonly known as a “dipped approach.” The running surface deviation that develops in a dipped approach

area can contribute to high dynamic loads as high as three times the static wheel load. The track stiffness case is the abrupt stiffness change that occurs in the track transition areas. A concrete span ballasted deck bridge with concrete ties can have a very high track modulus compared with the surrounding track. The abrupt stiffness change by itself does not contribute to higher dynamic loads, but coupled with a running surface deviation can induce high impact loads. The abrupt stiffness change does contribute to the degradation cycle promoting differential settlement at track transitions. This case has the more fundamental problem of a significant mismatch in track stiffness. Open deck bridges lack the ballast and sub grade layers found in conventional track. However, the problem also exists on ballasted deck bridges. Here, relatively short and stiff concrete spans can produce track with stiffness about double that of open track. This can result in poor ride quality and additional stress on track components on the bridge and its approaches, as well as higher dynamic loading on the bridge. The track damping case addresses energy dissipation of high dynamic loads. Track damping differs between different track structures at a track transition. For example, on a bridge approach energy is dissipated through the track structure, sub grade, and surrounding ground. On a bridge structure, some energy is dissipated in the ballast layer, but much of the energy can reach the bridge structure. It is important to understand the types of impacts and design damping into the track structure to alleviate potential damage. There are two types of impacts generated at track transitions with running surface defects, wheel impact and bounce.

Wheel impact is a high frequency impact due the wheel traversing a running surface deviation. The higher frequency content results from the vibration of the wheel set on the wheel/rail contact surface. This type of impact loading can be responsible for broken components, cracked concrete ties, and damage higher in the structure. These vibrations can be minimized by enhancing damping higher in the structure. Wheel bounce is a low frequency secondary impact. These transient vibrations are highly influenced by track stiffness. They may resonate with the movement of rails and ties on the ballast elasticity and contribute to surface and alignment degradation and ballast and sub grade deterioration.

These vibrations can be minimized by enhancing damping lower in the structure. The relative importance assigned by researchers to different mechanisms contributing to differential movement at track transitions varies from one study to another. For example, from the investigation of four bridge approaches with concrete ballast-deck bridges and concrete ties, Li

and Davis [13] reported inadequate ballast and sub ballast layer performance to be the primary cause of track geometry degradation. Using settlement rods installed in the test sections, they observed no significant sub grade movements, but instead they reported significant track geometry deterioration for a site with cement-stabilized backfill. On the other hand, Selig and Li [14] identified sub grade stiffness to be the most influential parameter affecting the module of ballasted tracks. As track transition problems are often related to the stiffness of the approach track bed, this would indicate that the sub grade layer plays the most significant role in governing the differential movement at track transitions.

2.3 Mathematical Model of the Railway Track

The railway track can be considered as an assembly of structural components with specific mechanical properties. Depending on what one wants to investigate these components may be modeled in a simpler or more sophisticated manner.

Models of track dynamic behavior can be classified into two categories: Those that represent the track as a continuously supported rail beam and those that represent the track as a discretely supported rail beam.

Continuously supported models of infinite length are based on the beam on elastic foundation theory. The rail, pads, fastenings, sleepers, ballast, sub-ballast and sub grade are components that define the value of the modulus of track elasticity.

Discretely supported models are similar to the continuously supported models and often have multiple layers representing the rail pads, sleepers, ballast, sub-ballast and sub grade.

According to this work, a model for the entire railway system can be developed consisting of mass and spring and dashpot.

2.4 Railway Track Transition Zone Characteristics

Transition zones are zones in which the track stiffness changes abruptly. Transition zones can usually be found near bridges, abutments and tunnels. Usually the following transition areas exist on railway track: At grade – bridge transition, at grade – tunnel transition, at grade – culverts transition, ballast less track – ballasted track transition, special Track work Transitions (Crossing, switches and turnouts) [31].

Transition zones between rigid track and free rail tracks exposed to early failure due to poor interaction between rail vehicles and abrupt variation of stiffness. This becomes continuous and challenging problem to the rail way infrastructure and still no well-organized and technical studies appear to have been taken to provide a gradually smoothening transition to alleviate forces between the rigid track and the free track. Imbalance settlement between the rigid track and free rail track in the transition zone is the principal issue, which affects the rail industry by causing unsafe travel and passenger discomfort, early failure on track structure and train components, speed limitation, and repeated periodical maintenance. The mechanics at railway track transition zone due to the interaction between the vehicle and the track can be described in three steps.

(1).at transition points the train wheel will experience rapid changes in elevation (either up or down) due to abrupt changes in track stiffness

(2).the vehicle components start to excite (wheel, bogies and car body)

(3).the excitation of the track components leads to vertical vehicle – track interaction forces, depending on: the elevation change, which is related to the change of the stiffness, the train speed, the vehicle mass and the suspension characteristics of the vehicle in the transition zone. The track may settle more on the plain line track (before entering the bridge or the tunnel) than at the rigid base (bridge or tunnel), where the track is stiffer. This can lead to dips in the track position (running surface) and hanging sleepers. In cases of soft sub grade soils and or poor drainage, the settlement close to the transition zone can be significantly accelerated.

In this study, a comprehensive analysis of the available literature has been done to set out remedial solutions for the track transition zone problems.

2.4.1 Causes of Track Degradation at Transitions

Mechanical and physical characteristics of the three key regions include rigid track Part (Bridge, tunnel and slab track), superstructure and substructure of its approach have significant role on maintaining track geometry of transition zones. Generally weak performance of mechanical and physical characteristics of track structure and inherent speculations of available design frameworks are causes for Poor track geometry, differential vertical settlement and lateral

displacement of the train track within the transition zone. In most cases, the causes of track deterioration at transition zone can be grouped into two: primary and secondary according to their impact on the track deterioration rate.

Varying stiffness and damping between rigid track and its approach and geotechnical causes are the key primary causes of track deterioration at the track transition zone.

The track stiffness experienced by a train will vary along the track. Sometimes the stiffness variation may be large within a very short distance. The variation of track stiffness will induce variations in the wheel/rail contact force. The track stiffness irregularities may have their origin from the support structures such as bridges and slabs, in the superstructure (rails, rail pads, sleepers and ballast) or in the substructure (foundation, sub grade soil, etc.)

The train movement direction has remarkable impact on such extra dynamic load, where extra dynamic load applies on low-stiffer transition approach zone, if the train movement is from rigid track to lower stiffness zone. The expected dynamic load within the bridge transition zone, which can cause ballast flowing and tie movement, is double of the quasi-static load. This uneven stiffness variation is vital to establish a differential track settlement within the track transition zone, by investigating numerous techniques. This assumption indicates the inclusion of geotechnical factors and soil-water response for controlling track deterioration rate at track transition zone.

Rail ballast layer, sub ballast layer, and sub grade control the performance of track transition zone in the short and long term situations. As reported in literature, the track differential movement may be a result of the combined action of one or more of the following mechanisms: Excessive deformations of ballast layer, fill settlement, and sub grade settlement.

A particular awareness on viable failure modes of sub grade is therefore crucial to ease sub grade induced problems in the track transition zone. Continuous shear failure and extreme plastic settlement are the foremost failure modes in sub grade. Rail track foundation design frameworks should consider outcomes of these two critical failure modes, especially in the superstructure where dynamic load is significant. It is observed that all the failure modes induced from the geotechnical causes and this can be critical in the railway bridge transition zone which is exposed to higher axial load and massive dynamic load effects compared to the road system. Reduction of effective shear strength of soil due to increase in water content resulted from poor drainage conditions, can catalyze these sub grade failure modes.

Soil-water response in construction infrastructures which use the ground as a major support stratum like highways and rail tracks is severely problematic, especially in bridge transition zones. In unsaturated soil arrange of complexity reveal than saturated soil which may lead to instant failure mechanism by moistening and shrinkage cycles. Shear strength and soil deformation are controlled by metric suction of unsaturated soil whereas the soil metric suction is strongly depend on soil moisture which is highly responsive to climate changes. Particle size distribution, clay ratio, soil type, soil structure orientation, and drainage boundary conditions further influence metric suction as well as pore water pressure increment by the dynamic load. Pore-water pressure decreases soil suction and as well as the effective shears strength.

2.4.2 Existing mitigation techniques

Rail track at transition zone is generally exposed to a high stress circumstances and hence it demands cyclic maintenance and acceptable remedies for the long term. The fundamental concept of any mitigation technique is to ease this high stress state and alleviate the differential settlement between the rigid track and free ballasted track. Kerr and Moroney (1993) suggested two postulates to consider when applying a new remedial technique for track transition zone:

(1) Assure to cause the constant vertical rail deflection along the track for the train wheel of each truck, in a moving train

(2) If this is not achievable, assure to ease abrupt change of vertical rail deflection, which can induce sever dynamic wheel load by remarkable wheel vertical acceleration. The existing mitigation techniques can be categorized into two groups based on their functions:

(1) Lowering the vertical stiffness or improve the damping on the high stiffness rigid track.

The under Sleeper pad, rail seat pad, ballast mat and slab mat can be used to reduce the vertical stiffness.

(2) Controlling the settlement in transition zone by enhancing the stiffness of the track structure on the weak stiffness region of the transition zone.

The following mitigation techniques can increase the stiffness of the low stiff region.

- Additional rail
- Long/Wide sleeper
- Reducing sleeper spacing
- Approach slab

- Ballast bonding using Polyurethane geocomposites
- Ballast reinforcement using geogrid and geocell
- Hot mix asphalt underlayment
- Soil strengthen techniques(improved soil wedge)

Smoothing the stiffness (k) distribution on the “soft” side of the transition can be achieved by varying the thickness of ballast bonding and sleeper length.

2.4.3 Track Substructure improvement

The track substructure consisting of the ballast, sub ballast and sub grade layers have a profound influence on track performance. To prevent substructure degradation several well designed geosynthetic materials are available that can be used to perform various functions within the substructure of rail tracks, to ultimately improve track performance to deformation. Separating the ballast layer from the sub grade to intercept ballast entry is one of the functions of these geosynthetic products. Strengthen the ballast layer to reduce ballast settlement and filtration to prevent sub grade pumping and drainage to prevent excessive moisture of the sub grade. These solutions can minimize the depth of the required granular layer and also reduce the frequency of the required preservation.

One of the most advanced stabilization system is the use of geosynthetics within the granular layers of the track structure.

Polyurethane (PUR) geocomposites created with the reaction of polymeric isocyanate and polyol alcohol with necessary catalyst and additives. PURs are the polymer materials whose physical properties can be changed in wide ranges by engineering their components. This versatility makes them replaceable for materials as soft as rubber to materials as hard as metals. Two examples of polyurethane materials used for ballast reinforcement are Elastotrack and Xitrack developed by BASF and Dow chemical companies, respectively [34]. Polyurethane geocomposites are used for this study to reinforce the ballast.

2.4.4 Ballast Bonding

In the last 150 years the railway system in the transportation sector has gone through significant development and as result of this considerably reformed. The demand gets bigger immutably, especially those concerning increment of travel speed, number of passengers, transferred freight and travel comfort. In order to achieve the required demands without blocking the traffic safety it is necessary to enhance railway traffic safety standards. The continuous increase in speed leads to increase the frequency of traffic loading which creates a significant impact on the track due to this extent the usual technical and technological solutions are not satisfactory to realize the traffic safety measures. That phenomenon causes lifting of fragment of ballast layer which has a negative impact on the trains driving in the opposite direction. To mitigate this circumstance from happening ballast bonding technique was put in place. This technical solution opened new point of view on technological field in railways. Stabilization of ballast bed using ballast bonding technique is a method that bind ballast stones each other at their edges and contact points (figure7 and figure8). Two-component mixture bonds the ballast bed in the position that the ballast stones took before bonding. It is necessary to refer that ballast bonding is not to be recognize as injecting. Injecting completely fills the cavities between the ballast stones on the contrary this method bonds the aggregates together only on contact points between them. [36]

Accordingly, water can percolate through the available cavities between the ballast stones. After the adhering chemical applied, ballast stabilization is achieved shortly (30 min to 3 hours, depending on the type of adhesive).

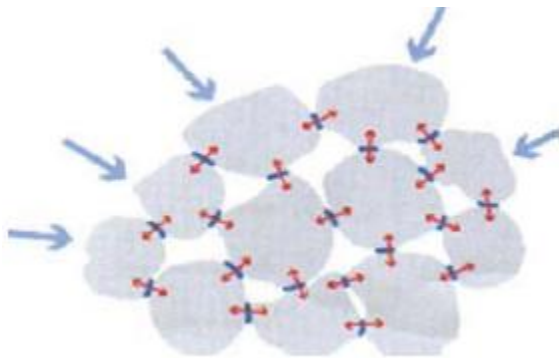


Figure 7: Schematic illustration of ballast bonding [36]

There are two basic bonding techniques applied on the ballast layer. Those are surface and structural bonding. The difference between the two is on the thickness of the stabilized layer [36].

(1). Surface bonding

The aim of surface bonding is to restrain flow of the ballast stones in the surface part of the ballast layer. It hasn't direct contribution to enhance the mechanical bearing properties.

Main reasons for using such a solution are:

- Prevention of lifting the smaller ballast stones by high speed trains
- Simplifying surface maintenance of ballast bed using the industrial vacuum cleaners (application at railway tracks and stations).
- Side ward stabilization of ballast bed to perform maintenance and development works.

(2). Structural bonding

In addition to preventing of the uplift of smaller ballast stones, the main aim of structural bonding is to improve the mechanical properties of the ballast bed. The adhesive chemical will acts as a load transfer with the track structure components. The thickness of the bonded ballast stones for structural bonding varies between 10 and 25 cm per layer. Structural bonding is used for:

- Application of so called transitional areas between the free ballasted track and a rigid track part.
- Sharp curves with small radius to restrain lateral stability of the track
- Enhancement of stability and durability of isolated joints
- Enhancement of track support capacity

To perform the expected bonding of ballast stones, in addition to the properly used bonding mechanism, following situations have to be addressed: preparation of sub grade properly, clean and tightly packed ballast bed and suitable track geometry. Adhesive material for bonding of ballast bed can be applied in a number of methods, depending on the scale of the intervention and field conditions. If the ballast bed needs to be stabilized on a longer way of track an adhesive application is performed by a wagon or a truck placed alongside the track. Shorter sections of track can be accomplished using movable machine and in case of short, local, interventions, stabilization can be achieved manually.

Ballast bonding can be effective in critical zones of a railway track as illustrated in the following cases on figure 9.

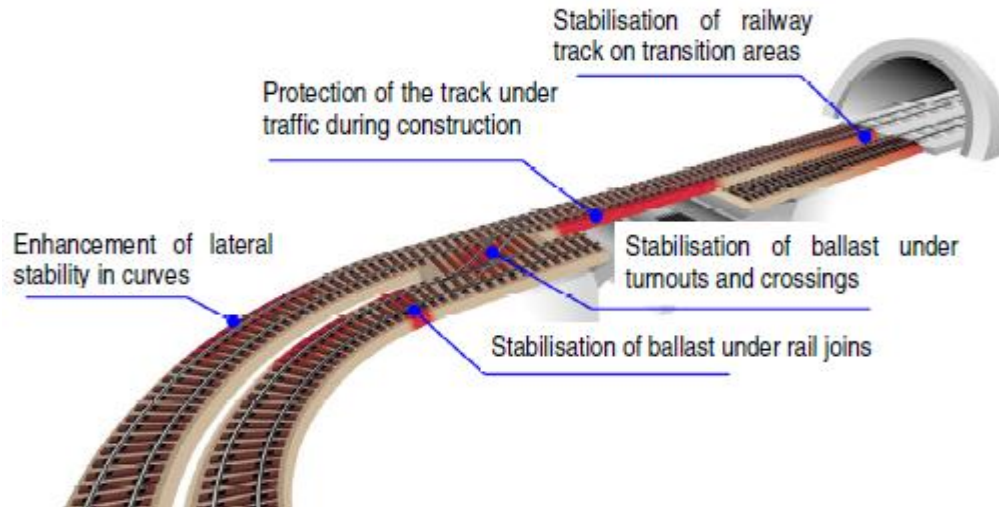


Figure 8: Location on a railway track for possible implementation of ballast bonding [36]

2.4.5 Recent Studies on ballast bonding

Dersch et al. (2010) and Boler (2012) used rigid-compact polyurethane to coat the ballast particles. The direct-shear box test was conducted under varying normal stresses to measure shear strength of the reinforced ballast. Depending on the test results, the shear strength of coated ballast specimen was 40-60% greater than uncoated clean ballast. After direct share test, a powdering test was conducted and results showed that coated ballast samples had 3-5% less breakage than untreated ballast. As a result, polyurethane treatment greatly increases shear strength of ballast and reduces fouling due to the breakage of ballast particles under loading.

Kennedy et al. (2009) conducted full-scale model tests to determine the deformational characteristics of the ballast layer with and without polyurethane. Rigid-compact polyurethane, which is similar to the type used in the study by Dersch et al. (2010), was injected on and into the ballast layer. In their study, 500,000 loading repetitions which simulate railway traffic loading conditions was applied to full-scale model to measure plastic strain of ballast. The results showed the settlement of the ballast layer in the model was 95-98% less for the treated full-scale model substructure than the untreated substructure modeled at their facility.

Ebrahimi et al. (2011): A Large-scale, cyclic triaxial equipment and testing protocol were developed to measure plastic deformation of fouled railway ballast. Different type of fouling, fouling index, moisture, and state of stress were applied in the ballast. FI was calculated by summing percent particles passing 4.75 mm (P4) and percent particles passing 0.075 mm (P200). When the FI is above 20%, ballast was considered to be highly fouled. Large-scale cyclic triaxial was conducted and 200,000 loading repetitions were applied. The results indicated that the plastic strain, ϵ_p of the clean ballast was 0.75%. However, the ballast with 20% FI, plastic strain was found as 6.9%. This clearly shows that the amount of fouling content increases the plastic strain of the ballast layer. The ballast fouled with 20% FI was tested with different water contents (3%, 8%, 10% and 14%). According to test results the amount of water content increases the plastic strain of the ballast layer.

Keene et al. (2012) studied the mitigating ballast fouling impact and enhancing rail freight capacity. The rigid polyurethane foam (RPF) was injected in to the clean ballast. Polyurethane stabilized ballast (PSB) specimens were prepared by refining the polyurethane injection methodology. The cyclic triaxial tests were conducted stabilized specimens at a deviator stress of 300 KPA. PSB deformational behavior varied as RPF density varied. The PSB specimen with no confinement had cumulative plastic stain of 0.43% or 63% less than clean ballast over 200,000 loading cycles. The PSB specimens with full confinement of 90 KPA had cumulative plastic strain of 0.15%, i.e., 87% less than the clean ballast. Monotonic-flexural loading was also conducted on beam specimens to measure the rupture strength. From the flexural tests conducted, the flexural strength increased as the percent RPF by weight of the specimen increased. Unconfined compression was conducted to measure the PSB strength and Young's modulus. The average strength of the PSB prisms (half of the beam specimen) was 2.60 MPA. The average Young's modulus determined from the unconfined compression strength (UCS) tests was 89.7 MPA. This study also compared the failure mode of PSB to concrete showing that concrete yields around 0.002 m/m, whereas PSB yields around 0.02 m/m (i.e., an order of magnitude greater); however, the minimal yield strength of concrete is designed around 21 MPA and the PSB yielded around 1.5 MPA, 90% less. Based on these attributes, the compliance (i.e., yield strain) of PSB is much more than concrete.

Jozsef Szabo. (2011) performed different assessments and analysis to determine on scientific basis new scientific relationships, properties and technical parameters which have not been determined but are essential in the planning, building and maintenance of the railway tracks with ballast bed stabilized by ballast bonding technology. Based on the results and experiences of the executed of laboratory tests and the detailed analysis of the results (K [kN/mm] vertical spring rates) he determined that during the usage of the ballast bonding technology, the vertical rigidity of the ballast bed is increased. Based on the experiences of the executed laboratory tests he determined that during the structural bonding, the definition of a lower and an upper threshold limit regarding the quantity of the specific bonding material is necessary for the (successful And high quality, as well as reasonable and economic) development of one bonding layer with complete thickness of 25cm. Based on the results of the executed laboratory test and detailed analysis of the results, during the structural bonding at the development of one bonding layer with complete thickness of 25 cm he determined the lower threshold limit in the value of 4 kg/m² and the upper threshold limit in the value of 14kg/m². So the quantity of the specific bonding material is between 4kg/m² and 14kg/m².

During the usage of ballast bonding technology the vertical rigidity of the ballast bed is increased. In case of the upper bonding ($K=46$ kN/mm) developed with 3kg/m² specific bonding material and 20cm bonding thickness, in case of under bonding ($K=47.9$) developed with 5kg/m² specific bonding material and 30 cm bonding thickness and in case of under bonding ($K=76.4$) developed with 8kg/m² specific bonding material and 50 cm bonding thickness compared to the condition without bonding ($K=28.5$ kN/mm) in case of constant technical parameters.

2.4.6 Xitrack Reinforcement of Ballast

Xitrack is a 3D polymer technique applied to boost the structural performance of ballasted track. This ballast bonding technique enhances the load transferring mechanism of ballast bed by forming very resilient geocomposite over the formation. Though, remarkably reduces long-term deformation at critical loading points along the railway track [35]. The adhering polymer used is a urethane-cross linked type and it is applied to the surface of the ballast through mixing equipment that can apply the two component (isocyanate and polypol) rapidly-reacting polymer

in a controlled manner to achieve proper distribution. The polymer percolates through the ballast and it forms a reinforcing fabric that enables the track to move in the proper way. In a classic stabilization case around 26% of the void structure is filled by polymer, which still permits to drain out water within the ballast formation in an acceptable range [36]. The rheology of the polymer can be adjusted for different track stabilization requirements. Its engineering properties to can be pre-defined to correspond with the required track application and the catalyst level can be altered to determine the perforation depth [36]. Inmost cases, the polymer makes better bond within 10 to 15 seconds, with around 90% of its stiffness gained within one hour. Besides to this, xitrack is versatile and it can be applied to improve lower levels of ballast to provide formation preservation, enabling maintenance to still take place, or a side beam could be reinforced to enhance lateral stability.

Xitrack compared to ballast glue the method of gluing ballast together is known to many track engineers as it has been around for a number of years. Its use is normally associated with increasing lateral resistance, either on curves, through switch and crossing and at locations where ballast shoulders fall away. Glue is an epoxy resin system which relies on forming a bond between the individual stones. It is important to be aware that xitrack is not ballast glue. Xitrack is unique and is very different to glue both in its mechanism and in its various uses. Xitrack is a polymer system that holds the ballast in place by means of adding a very strong web of polyurethane. This web absorbs energy and has a slight damping effect because of its inherent flexibility. Therefore, typically xitrack will not break up if the untreated ballast above or adjacent to it is tamped or renewed. Xitrack has a very long service life. Xitrack can normally be applied in any temperature or weather. Numerous tests have determined the characteristics and strength the polymer and therefore installations are specifically designed such that a measured amount of material is applied. This enables an installation to continue working below the fatigue perimeters of the material and thus offer confidence in its service life.

Xitrack polyurethane ballast reinforcement has been used to address a wide range of track engineering problems:

- Managing stiffness transitions from ballasted track to slab track
- Reduction of settlement due to soft sub grade
- Vertical and lateral stabilization of switch and crossing
- Protecting critical parts from shock and vibration

- Reducing Critical Track Velocity effects
- Increase of lateral resistance for plain line
- Reduction of dynamic loading on under-track services
- Prevention of ballast washout during flooding

The improvement in track stiffness by applying Xitrack bonding technique was shown by [36] where FE analysis indicates that a 400mm Xitrack layer overlain by 100mm of normal ballast enhanced the track stiffness by 53% when related with an unreinforced 500mm ballast layer. Xitrack increases the young's modulus of ballast by more than 50%. In addition, xitrack has been implemented to many railway sites in the UK specially on critical zones including bridge transitions, cross-overs, turnouts, clearance issues, tunnel formations, track over poor ground, concrete slab-track transitions, lateral stability issues etc. and it has been shown to significantly minimize maintenance by restraining the ballast densification process and substructure bearing pressures[36]. Significant steps in strengthening and stiffening the ballast have been proven through the application of polyurethane polymer reinforcement of the ballast [28]. In this technique a rapidly reacting exother-micvisco-elastic polymer is applied to the surface of the ballast. The polymer penetrates to a predefined depth set by a catalyst to form a3-dimensional ballast polymer matrix. Forming this Geocomposite across the width, length and depth of the ballast will then form a geopavement over the track area. This geopavement slab has a high degree of strength and resiliency [28]. In order to test the engineering characteristics of the Geocomposite, especially its resulting settlement and stiffness behavior, it is ideally best to use a railway test rig capable of loading a ballast structure to realistic axle loads and hence stresses levels [37].

The literature presented in this paper uses the result of full-scale GRAFT I (Geopavement and Railways Accelerated Fatigue Testing) facility at Herriot-Watt University to investigate the track stiffness improvement of the xitrack polyurethane polymer technique. The paper builds upon the work in Kennedy et al. (2 where the settlement characteristics of the geocomposite tests were presented. The results show the track stiffness improvement from the non-reinforced control tests to the geocomposite tests. [28]

According to Kennedy et al. [28] within GRAFT the full 300mm ballast depth was stabilized to improve the formation layer and to minimize ballast settlement, in addition to this some other

tests were performed with GRAFT to check at the side beam application. The comparison of xitrack stabilized to un stabilized ballast tests is presented in Figure 5.5. As it is shown that the settlement of the xitrack reinforced track is markedly less than CT1 and CT2, even though both tests were performed with an improved sub grade modulus and by reducing the exerted load for CT2. As it is indicated on the estimated settlement curve remarkable reduction in track settlement is noticed (99% over 500,000 cycles or 18.5MGT) that can be gained by applying xitrack reinforcement on track that has heavy axle loads (44.4 tones including DAF) running over weak subsoil on the bottom layer (sub grade tangent modulus of 25MPa). For an unreinforced track to achieve the same level of settlement in GRAFT as shown in the xitrack test the sub grade modulus required would be 814MP. Basically xitrack formed the track performance elastic. [28]

The average GRAFT track stiffness gained from the LOS actuator displacement readings for the xitrack test over the 500,000 applied cycles was 47.1kN/mm/wheel with an average GRAFT track modulus value of 25.7MPa. Comparing this result to the GRAFT stiffness values found for the GRAFT unreinforced control tests, it is considered that xitrack enhances the track stiffness by around 43% when compared to unreinforced track with the same sub grade modulus as the xitrack test. When considering the maximum exerted load in the xitrack experiment, the stiffness enhancement raised to around 55%. [28]

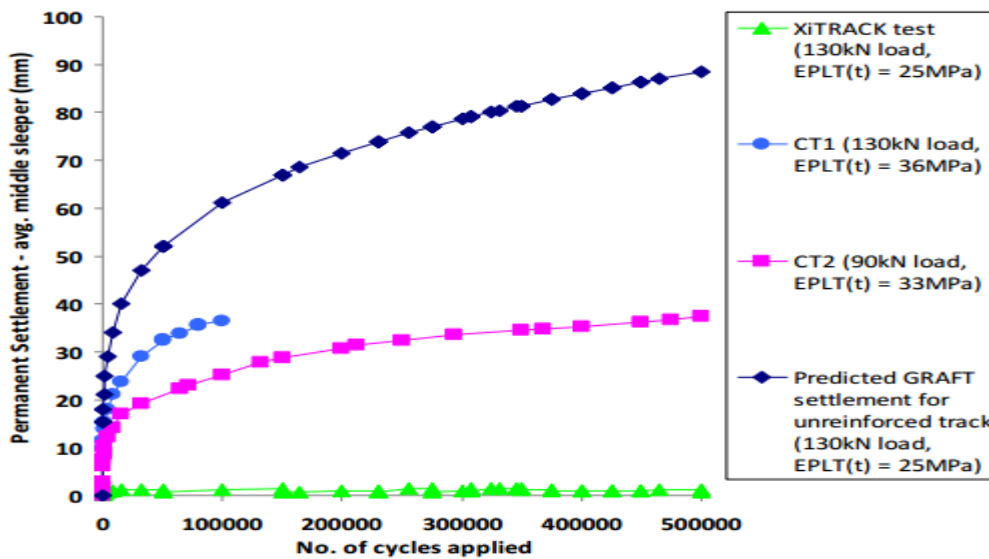


Figure 9: Comparison of xitrack reinforcement to unreinforced track [28]

Using this test result for unreinforced track in GRAFT it can be considered that xitrack reinforcement has enhanced the stiffness by around 65%. As a result, stiffness xitrack reinforced track shows increment by between 55 and 65% over 500,000 cycles, additionally lowering track settlement by around 99%. After the test accomplished the reinforced track structure sample was taken in one section and any mark of wear or crack did not noticed on the section. Finally the sample checked for water permeability to ensure its functionality for drainage. As a result, the xitrack sample allowed free water percolation after the 500,000 applied load frequencies.

2.4.7 Effect of bonding on the permeability of the ballast bed

The primary criteria during the establishment of the ballast bonding system was to ensure the ballast stones have bond at their contact surfaces as well as to allow holes between the ballast stones that can facilitate the desired percolation for the drainage of rain water. Laboratory tests at the Technical University Budapest (Hungary) were carried out to determine the influence of ballast bonding on the permeability of the ballast bed for drainage purpose. For the purpose of the permeability analysis of the ballast bed with and without the adhesive, a container with sealed sides, a lattice bottom and a collector flat tray directly below, has been set. The permeability test was performed out in two phases. [36]

In the first phase the container has been filled with ballast without adhesive material. Certain amount of water has been poured on the surface of the ballast in a limited time. The time taken for the water to drain out on the collection tray and the quantity of percolated water has been measured.

Second phase processed in a similar method but undertaken on ballast that has been bonded with the adhesive. Results of the performed tests can be observed at Figure 10

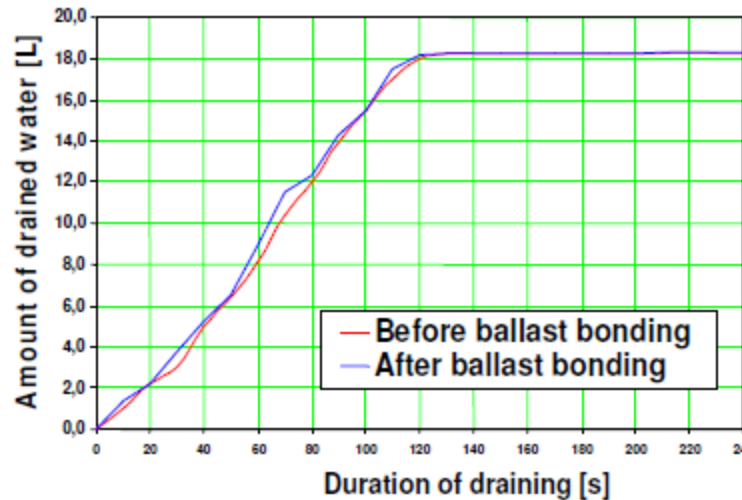


Figure 10: Results of the permeability tests [36]

The test result shows a non-significant difference between the free ballast and ballast stones with adhesive. As it is seen on the chart it is clear that better draining speed is observed in case of bonded ballast stones. Such result can be explained by the fact that the ballast stones are coated with a thin adhesive film which has reduced roughness compared to non-bonded dry ballast stones. As a result, very little resistance to permeability of water through ballast bed is obtained. Results of the undertaken laboratory testing obviously demonstrate that ballast bonding has no significant consequence on the permeability of the ballast bed. [36].

2.4.8 Track subsoil Reinforcement

Soils are naturally occurring materials that are used for road construction and other civil engineering works. Soils are used for the construction of all layers of pavements except the surface which is made of concrete or asphalt. Soils are, therefore, a critical element influencing the success of a construction project. However, not all naturally occurring materials are suitable for construction of railway track beds especially at transition zones.

Mechanically improved soil is a better remedial option if groundwater table and weak sub soil are the causes for the imbalance track settlement around transition zone between the slab track on bridge deck and the approach free track. D Li and Davis (2005) however claimed that if remedial techniques induced to reinforce the sub grade are unable to yield consistent and allowable track stiffness in regard to the bridge and the approach, they can be inefficient. If the

track stiffness at the track transition zone is so stiff, improving the stiffness of approach zone is not relevant compared to lowering stiffness of the rigid track further extended this idea; stiff subsoil improved by hot mix asphalt layer, geocell, and cement stabilized fill soil are unable to give allowable performance than managing bridge transition zone only with ballast and sub ballast layers.

2.4.8.1 Soil Stabilization

Many geotechnical structures are constructed on weak and loose soil deposits. Thus for safe design this formation needs improvement before construction starts. A popular technique to improve such soil condition is to use cement and lime in the soil. This technique is now being used all over the world in various applications such as embankment, foundations, road and railway subsoil construction. The soil properties need to be improved by using cement and lime admixtures. In a broad sense, stabilization incorporates the various methods employed for modifying the properties of a soil to improve its engineering performance.

Methods of soil stabilization may be achieved through modification or improvement of soil property of the existing soil with the help of admixtures or without any admixture.

(1) Mechanical Stabilization

Mechanical stabilization can be defined as a process of improving the stability and shear strength characteristics of the soil without altering the chemical properties of the soil.

Mechanical stabilization is termed as granular stabilization. It involves two operations changing the composition of soil by adding or removal of certain constituent sand densification or compaction. In this process, gradation of soil aggregate mixture is the only factor which controls the stability of the engineering behaviors of a soil. For mechanical stabilization, where the primary purposes is to have a soil resistance to deformation and displacement under loads, soil materials can be divided into two fraction: the granular fraction retain on a 75micron ASTM sieve and the soil fraction passing a 75micron sieve.

The granular fractions impart strength and hardness. The fine fraction provide cohesion or binding property, water retention capacity and also act as filter for the voids of the coarse

fraction. Mechanical stabilization has been largely used in the construction of less important roads.

(2) Chemical Stabilization

Chemical stabilization is a method of improving the engineering properties of a material by adding chemical substances. Chemical stabilization is used for a wide range of purposes including: improving the bearing capacity and strength of pavement layers, dry temporary by passes during rainy periods, delay certain chemical reactions that are detrimental to road soils or aggregates, dry out soil where the moisture content is too high for successful compaction, make soil less permeable where necessary, reduce the plasticity of soils used in construction and thereby reducing the effect of moisture variations, changing clay to a more granular and workable material and reducing swelling and shrinkage properties.

When stabilization of soil is done by mixing cement with soil it is known as soil cement stabilization. Soil-cement is a mixture of pulverized soil and measured amount of cement and water, compacted to the desired density and cured. Portland cement is comprised of calcium-silicates and calcium-aluminates that hydrate to form cementitious products (AASHTO, 2008). The role of cement is to improve the engineering properties of available soil such as strength compressibility, permeability, swelling potential, frost susceptibility and sensitivity to changes in moisture content.

Soil cement materials range from semi flexible to semi rigid depending on the type of soil and amount of cement used. When granular soils are used and the concentration of cement is increased the mixture approaches a rigid behavior. Cement stabilization is ideally suited for well graded aggregates with sufficient amount of fines to effectively fill void space and float the coarse aggregate particles. The goal of mixture design using cement stabilization is to find the lowest cement content that will produce the desired strength. The strength of soil cement increases linearly with the quantity of cement added to the soil. Two types of soils stabilized with cement, cement-treated soil (2 to 3% cement content) and soil cement (5 to 11% cement content) were adopted [37].an analysis was done with a set of tests, carried out by different authors and concerning the soils treated with cement. Thus it was possible to plot the figure 14 as well as to obtain a relationship that allows relating the elastic modulus with the content of the cement. The remaining values were properly referenced in the dissertation and are shown in table 3. When stabilization of soil is done by mixing lime in proper proportion, the process is known

as soil lime stabilization. The two primary types of lime used in construction today are quick lime (calcium oxide) and hydrated lime (calcium hydroxide). Lime is an excellent choice for short term modification of soil properties. Lime can modify almost all fine grained soils but the most dramatic improvement occurs in clay soils of moderate to high plasticity. Modification occurs as calcium captions supplied by the hydrated lime replace the captions normally present on the surface of the clay mineral, promoted by the high pH environment of the lime water system.

Lime treatment of soil facilitates the construction activity in three ways. First, a decrease in the liquid limit and an increase in the plastic limit results in a significant reduction in plasticity index. Reduction in plasticity index facilitates higher workability of the treated soil. Second, as a result of chemical reaction between soil and lime a reduction in water content occurs. This facilitates compaction of very wet soils. Further, lime addition increases the optimum water content but decreases the maximum dry density and finally immediate increase in strength and modulus results in a stable platform that facilitates the mobility of equipment.

The graph in figure 14 relates the elastic modulus with its lime content in various soils stabilized with lime, and it was made by the application of expressions, which correlates these two values, to a set of tests of soil treated with lime made by several authors who sought to obtain compressive strength. [37]

CHAPTER 3

3. Methodology and Finite Element Modeling

3.1. Introduction

The primary purpose of a railway track dynamic analysis model is to combine the components of the vehicle and track structure subsystems to each other with the intention of appropriately representing their complex interaction so that the effect of traffic load on stresses, strains and deformations in the components of the railway system can be determined. Such a model offers a foundation for predicting the track performance and serves as a technical and economical device for track design and maintenance.

In this chapter the development of a dynamic analysis model by which the vertical response of railway track subjected to a moving train load is discussed. There are three sub systems, in this model namely the track, the vehicle wheel, and the contact between the track components at which they interact with each other. Based on this model result stress and displacements in various track components have been studied. Using these models study on how parameters such as stiffness, axle load and train speed influence the track components has been undertaken.

3.2. Modeling in ABAQUS

The ABAQUS environment is divided into different modules, where each module defines a logical aspect of the modeling procedure; for instance, specify the geometry, assigning the material properties, and creating a mesh. The GUI interface generates an input file with all information of the model, to be submitted to the solver, using ABAQUS/Standard or ABAQUS/Explicit routines. The solver performs the analysis and sends the information back to ABAQUS for evaluation of the results.

In this paper using ABACUS the 2D geometry of the model is developed by the appropriate elements and materials that represent the different components of the model most accurately and with simplified conditions.

The elements used for modeling the different components of the track are; BEAM element used for the rail, spring and dashpot for each rail pads, Solid elements for each sleeper, ballast, sub grade and bridge slab. The vehicle wheel is modeled by means of analytical rigid element.

3.3. Analysis Types

3.3.1. Linear Eigen value Analysis

Linear Eigen value analysis is used to estimate an Eigen value extraction to determine the natural perturbation and corresponding mode shapes of the model. The analysis can be performed using two different Eigen solver algorithms, Lanczos or subspace.

3.3.2. Steady-state Dynamic Analysis

One approach to investigate the dynamic properties of a railway track is to load the track with a sinusoidal force. At frequencies up to about 200Hz, this can be done by using hydraulic cylinders. If one wants to investigate the track response at higher frequencies, the track may be excited by an impact load, for example from a sledge-hammer. [3]

3.3.3. General Static Analysis

The general static analysis can include both linear and nonlinear results and is performed to analyze static properties such as deflection that can be induced due to a static load. A criterion for the analysis to be Possible is that it is stable. A static step uses time increments, not in a manner of dynamic steps but rather as a fraction of the applied load. The nonlinear effects are expected, such as large displacements, material nonlinearities, boundary nonlinearities, contact or friction, the nlgeom command should be used. [19]

3.3.4 Dynamic Implicit Analysis

The dynamic implicit analysis method is used to calculate the transient dynamic response of a structure. A direct-integration dynamic analysis in Abaqus must be used when nonlinear dynamic response is being studied. [1]

3.4. Methods of Modeling Railway Track Transition Zone

The track used in this model is the conventional ballasted track and modeled as discretely supported beam. Each component will be appropriately modeled using the elements that best represent them. In this model the track length is 12m of which 4m is the bridge structure and 8m is the bridge approach track and the sleepers set at 0.6 m spacing.

3.4.1 Rail

The track component consisted of 50kg/m rail to a gauge of 1435mm supported by concrete sleepers and a length of 12m. The rail is represented as a continuous deformable body by means of two dimensional finite elements model. In this model the rail is represented as a continuous beam element and modeled by wire base feature. The profile of the rail is simplified to I-beam cross section with equivalent moment of inertia. The geometry of the I-beam cross section and material properties of the rail used in the finite element modeling are described below.

Table 2. Material properties of rail

density	Young's modulus	Poisson ratio
7800kg/m ³	210 MPa	0.3

3.4.2. Fastening system

The rail fastening system often encompasses a flexible spring fastener, functioning correspondingly with a rail pad having stiffer material property. In this model Rail pads are effective remedies to prevent cracking of sleepers at rail seat area. The fastening system between the rail and the sleeper is modeled using spring and dashpot system in abaqus. The spring and dashpot system is characterized by stiffness and damping parameters.

Table 3. Stiffness and damping properties of spring and dashpot system

Stiffness	Damping
100MPa	0.015MNS/m

3.4.3. Sleeper

The sleeper is modeled as 2D, deformable and as base feature of shell and it has 0.25 m width, 2.5 m length and 0.2m height. The sleepers are considered as pre stressed concrete components that have mass and stiffness. There are 13 sleepers positioned in the horizontal plane just below the rail. The sleepers are positioned only on the bridge approach track and on the bridge they are considered as monolithically casted in to the slab.

Table 4. Material properties of sleeper

density	Young's modulus	Poisson ratio
2400kg/m ³	35000MPa	0.3

3.4.4. Ballast

The ballast has 40cm thickness, 8m length and modeled as 2D deformable parts a base feature of shell. In this model the ballast is considered as elasto-plastic material and modeled with drucker prager material property in abaqus. The ballast is modeled in the improved and the non-improved case by changing its material property. In the improved case the ballast is considered as fully stabilized under the first four sleepers, half depth stabilized under the next four sleepers and quarter depth stablised under the last four sleepers. In the improved case the ballast is considered as reinforced by xitrack geocomposite. When ballast is reinforced by geocomposites the most influential property is it's young's modulus. Xitrack increase the young's modulus of ballast by more than 50% as it is studied by professor peter wood ward of Herriotwatt university of united kingdom jointly with balfour beaty rail company and Dow chemical company. The young's modulus of the reinforced ballast is increased by 50%.The amount of geocomposite for complete bonding, half bonding and under sleeper bonding is determined by jozsef szabo in Budapest university of Portugal.

Table.5 material properties of ballast

density	Young's modulus	Poisson ratio
1600 kg/m ³	130 MPa	0.35

3.4.5. Subsoil

The subsoil has a height of 3m and 8m length. The sub grade modeled as deformable body by using shell as a base feature. The soil wedge will be constructed according to the Chinese standard. The plastic property of the soil is modeled in drucker prager. The soil is modeled in the improved and non-improved case as that of the ballast. In the improved case the soil is considered as cement stabilized. The improved soil behind the abutment has 5m length at the top and it goes down with 1: 2 slope up to the bottom. The modulus of elasticity of soil increases as the cement content increase. The material properties of engineering fill of class A according to Chinese standard (100-130Mpa young's modulus) are described in table 5.

Table 6. Material properties of soil

Density	Young's modulus	Poisson ratio
2100kg/m ³	100MPa	0.3

3.5. Modeling Bridge Approach Transition Zone

In order to investigate the effects of ballast bonding and reinforced soil on settlement and dynamic response of a two dimensional finite element model of the track wheel system is built. The finite element model is on a section of railway track bridge approach transition zone.

One of the best standard solutions for transition areas is to apply ballast bonding and transition soil wedges placed in-between subsoil and the track superstructure and additional elastic layers on the more stiff side [33]. In this study only the substructure is improved i.e. the ballast and subsoil. The modeling plan of the transition soil wedge shaped based on the subsoil and the characteristics of the subsoil like the bearing capacity of the soil. To smooth the stiffness variation the stabilized ballast bed depth and width vary along the transition length as shown in Fig 15 and 16 but this is for 3D modeling. To achieve balanced settlement behavior in the rigid track structure and the free track structure zone, the same type of foundation should be implemented on both sides. Behind the abutment backfill of cement mixed soil should be arranged to balance the stiffness variation (figure 13). The bridge approach transition zone is modeled as shown in figure 13 and 14 both longitudinally and transversally. The finite element modeling is performed in different cases by varying the material properties of the ballast and subsoil. In addition to this the effect of varying speed on settlement is also considered in the modeling analysis and discussion part.

To mitigate the sudden stiffness change at the transition zone the thickness of the reinforced ballast has been decreased gradually this implies that the stiffness is also gradually decreases. As shown in figure 13 the reinforced ballast thickness changes after four sleepers. The soil also has two sections i.e. the stabilized and none stabilized. The stabilized section is a soil wedge with better strength behind the bridge abutment. The improved soil behind the abutment has 5m length at the top and it goes down with 1:2 slopes up to the bottom. The improved soil also has influence on mitigating the stiffness change.

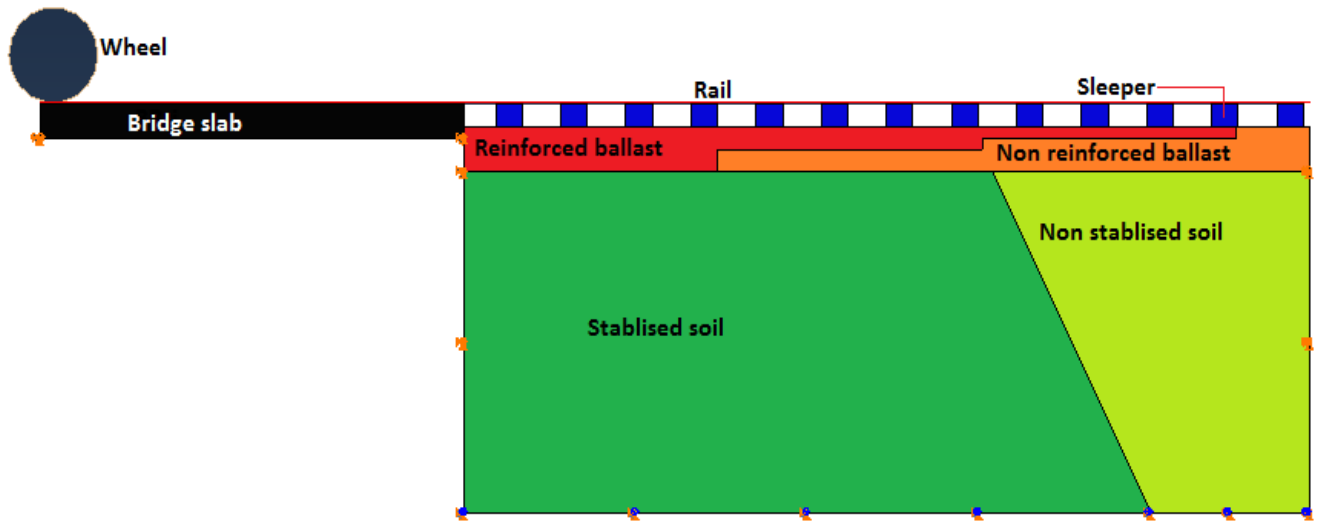


Figure 13: Transition zone at section of abutment end and boundary condition

The transition between track structures that have different stiffness property – ballasted track and free track – with regard to the necessary rigidity variation the track structure must be very smooth.

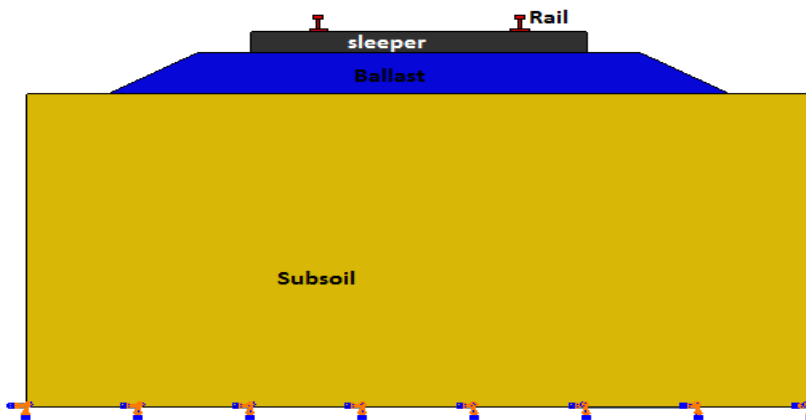


Figure14. Cross section of the track at transition section of the abutment end

Track component	Length [m]	Height[m]
Sleeper	2.5	0.25
Ballast top	3.31	0.4
Ballast bottom	4.85	
Subsoil	5.85	3

Table 2: Track component dimensions at transition section of abutment end in figure 14

3.5.1. Boundary Condition and Surface Interactions

Two types of boundary conditions are applied on the model as shown in figure 13 and 14. Velocity/Angular velocity boundary condition is applied to both translational and rotational degree of freedom at the center of the wheel with train speed of 120km/h and 160km/h.

In the displacement/rotation boundary condition the bottom of the subsoil is fixed with translational and rotational degrees of freedom while the sides of the subsoil and ballast are pinned with translational degree of freedom. As shown in the model the abutment /support of the bridge slab is removed to simplify the model and the bridge slab is supported with pinned boundary conditions on both ends. The interaction property between subsoil and ballast as well as between ballast and sleeper is rough. Rough contact is selected to prevent longitudinal movement of track components on each other. Linear contact stiffness has been applied between wheel and rail.

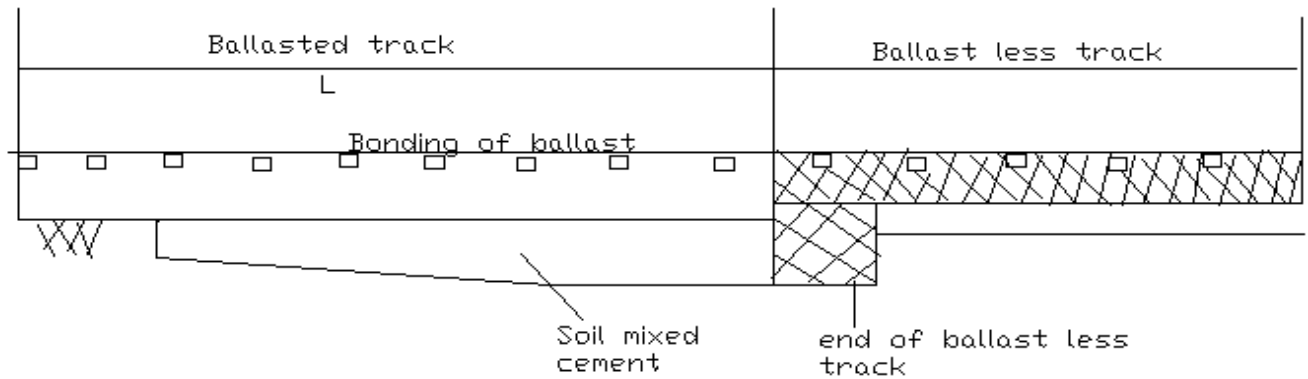


Figure 15: Transition between ballasted and ballast less track

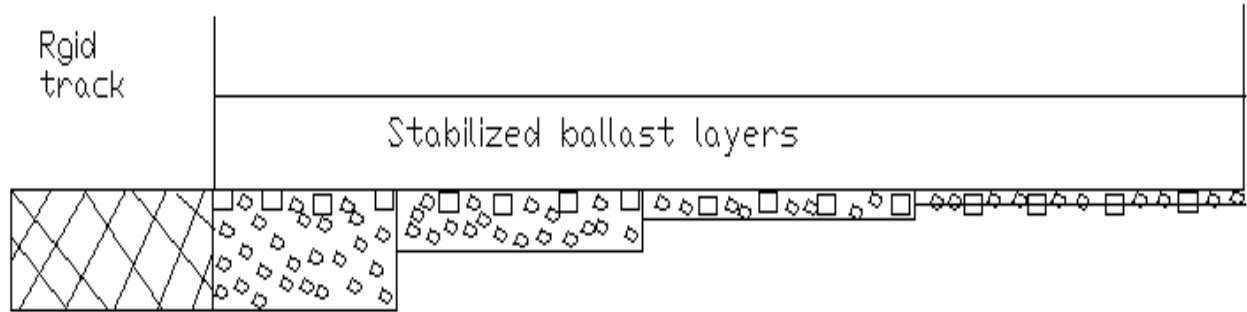


Figure 16: Section of ballast bonding at transition zone

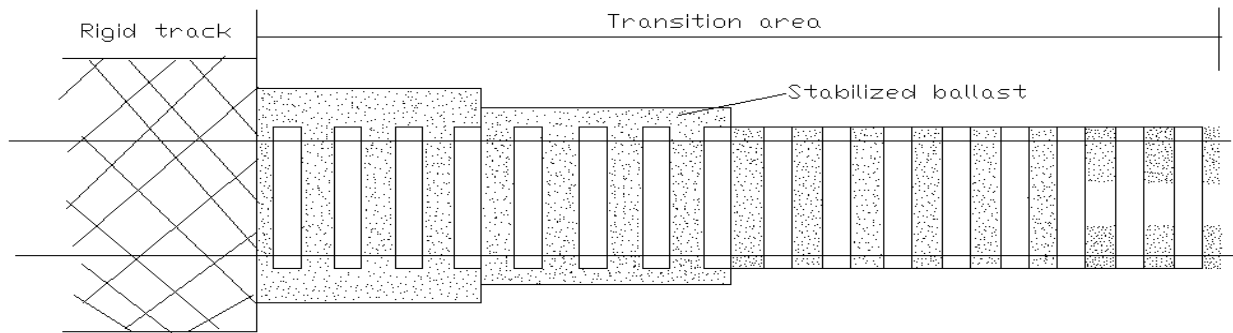


Figure 17: Plan of ballast bonding at transition zone [36]

3.5.2. Cases for the finite element modeling

The modulus of substructure components of railway track has magnified effect on the settlement of the free track near structures. The effect of subsoil and ballast modulus has been evaluated in two cases namely A and B.

Case A: represents the non- improved ballast and subsoil.

Case B: represents the improved ballast and subsoil. The modulus of ballast is increased by half when it is reinforced by using geocomposite chemicals. The subsoil modulus is changed from 100 MPA to 500 MPA and by increasing the cement content young's modulus of greater than 1000 MPA can be achieved i.e. from poor to good modulus of elasticity. [37]

The modulus of ballast and soil in part one (figure 20) varies in the two cases as shown below.

Table 4: modulus of ballast and soil

Modulus	Ballast modulus		Soil modulus	
	Part one	Part two	Part one	Part two
Case A	130MPa	130MPa	100MPa	100MPa
Case B	195MPa	130MPa	500MPa	100MPa

Bridge slab



Figure 20: Improved and non-improved parts of ballast and subsoil

Chapter 4

4. Results and Discussions

4.1 Dynamic Analysis

In this chapter the results from the finite element modeling in ABAQUS are presented. The purpose of the modeling is to study the effect of dynamic loading on the settlement of track transition zone. Dynamic explicit analysis has been carried out by varying the material properties of track substructure components and train speed. The displacement of the track bed with improved and non-improved materials has been evaluated and compared. Each part of the assembled model both longitudinally and transversally has been meshed separately for the dynamic explicit analysis as shown in the figures below. The dynamic analysis on the track has been carried out both cross sectional and longitudinally.

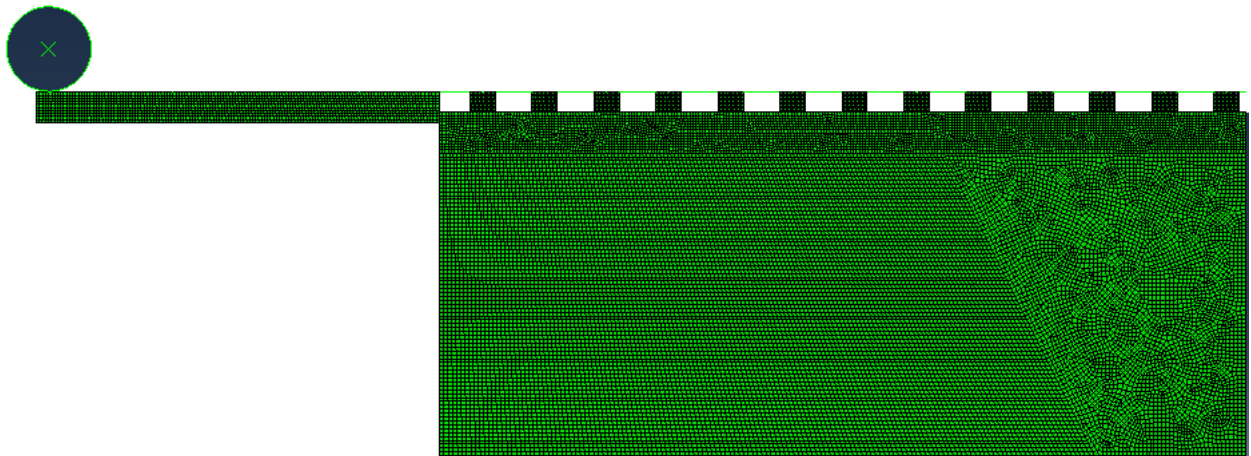


Figure 18: Longitudinal view of the track: Meshed geometry

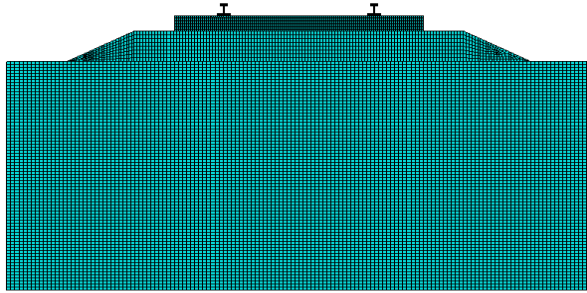


Figure 19: Cross sectional view of the track: meshed geometry

4.1.1 Effect of Track substructure

First dynamic analysis was carried out in the case of moving load at constant speed of 120 km/hr with improved and non-improved substructures. The result in terms of stress field distribution and vertical displacement in the different layers when the train is moving have been obtained and visualized. These pictures clearly show the foot path of the train wheels in the structure and the propagation of and extension of the displacement field in the different track layers. The dynamic effects are plotted along the path of the moving load. The effect of vertical acceleration of the rail in the two cases along the path of the moving load is indicated in figure 21 below. The graph shows the effect of vertical acceleration when the wheel with 125kN load and speed of 120km/h moves along the track starting from the bridge to the end of the free ballasted track.

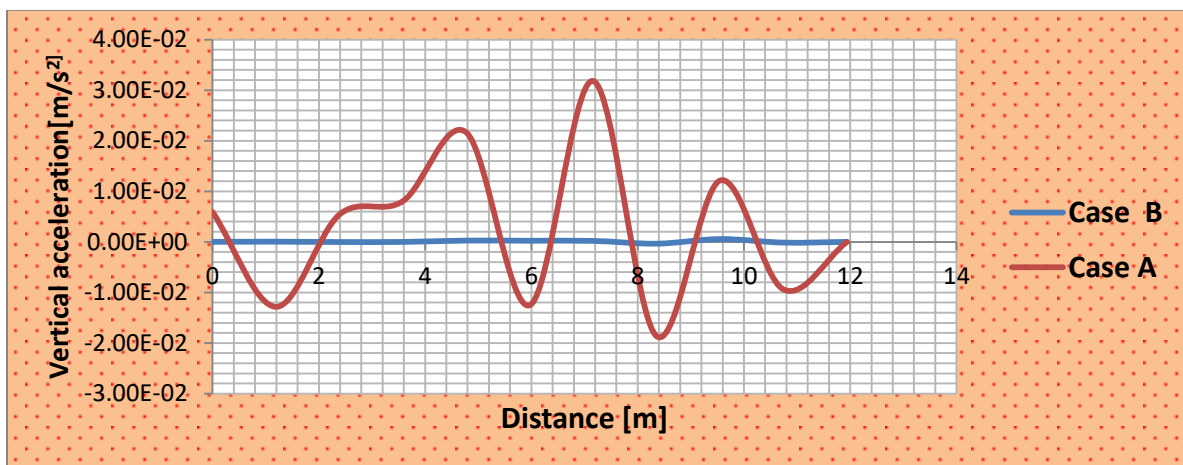


Figure 21: Vertical acceleration of rail

As shown in figure21. The higher acceleration values are recorded in case A which have wide difference with the values in case B. The vertical vibration acceleration of the rail in case B is almost absorbed to zero due to the improved ballast and sub grade modulus. The increased modulus results in lowering the dynamic effects on the rail. Vertical acceleration has direct relationship with vertical displacement as shown in figure21there is peak acceleration value on the free trackside. The free track behind the bridge slab is exposed to sudden settlement.

The graph in figure 22 and the contour pictures in figure 23 show the vertical displacement of the rail along the track in the two cases with a moving wheel load of 125KN and speed of 120Km/h.

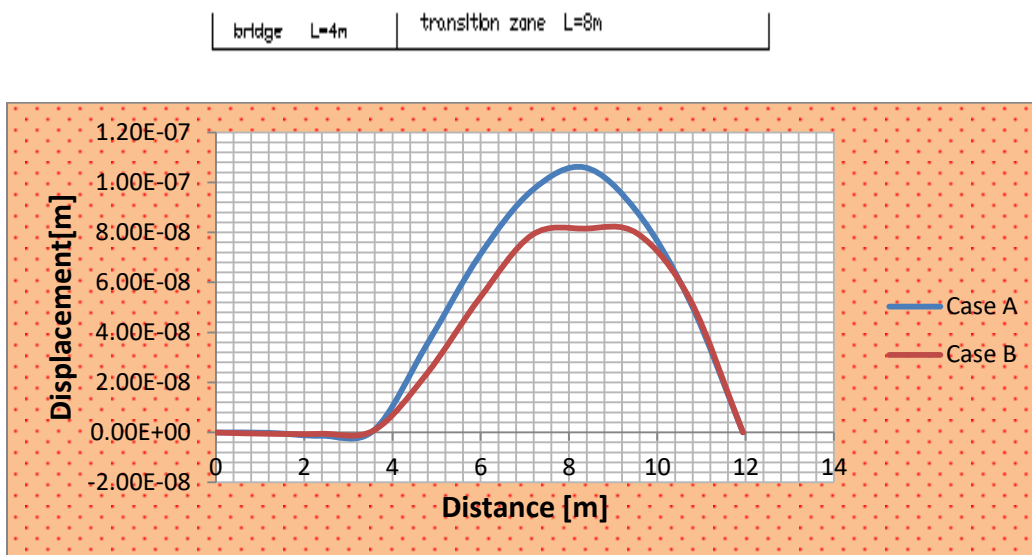


Figure 22: Rail deflection with varying subgrade and ballast stiffness

The deflection of the rail in the two cases in figure 22 shows the effect of varying substructure modulus gradually. In case A the rail deflection is very high because of the lowest modulus values of ballast and subsoil when compared with case B good modulus values respectively. The rail deflection in case A is sharp and wide which may cause sudden bump along the track while in case B the deflection range is short and increase smoothly.

Figure 24 below shows the vertical displacement of the subsoil along the path of the subsoil in the two cases under the moving wheel of 125KN and speed of 120Km/h.

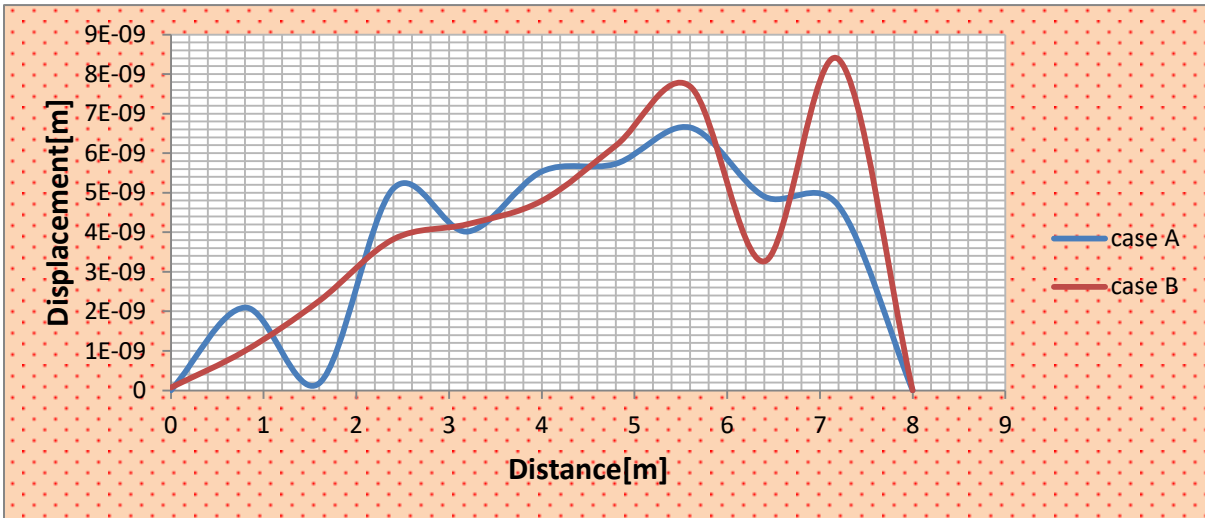
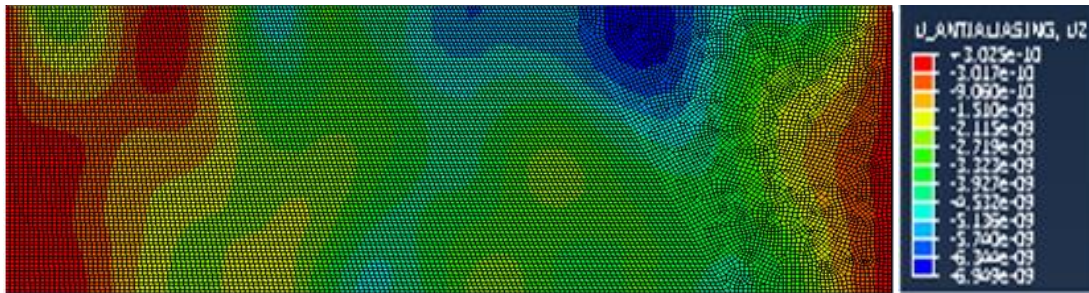
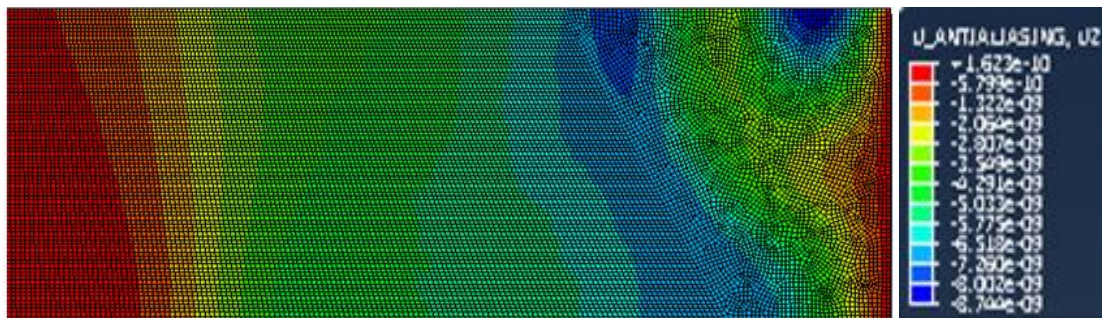


Figure 23: subgrade displacement



(a)



(b)

Figure 24: Displacement of subgrade a) case A b) Case B

The sub grade displacement increases as the stiffness decrease as shown in figure 24. In case A the sub grade displacement is higher near the bridge slab which may suffer the track to sudden bump while in case B the displacement changes gradually up to the low modulus soil section. As shown in the displacement counter figure 25(b) the displacement in case B increases gradually with uniform change from low displacement section to high displacement section of the subsoil while in case A the displacement has non uniform change specially on the top section of the sub grade. High modulus value can be obtained by increasing the cement content of the soil.

The graph below shows the effect of high modulus value of soil on vertical displacement.

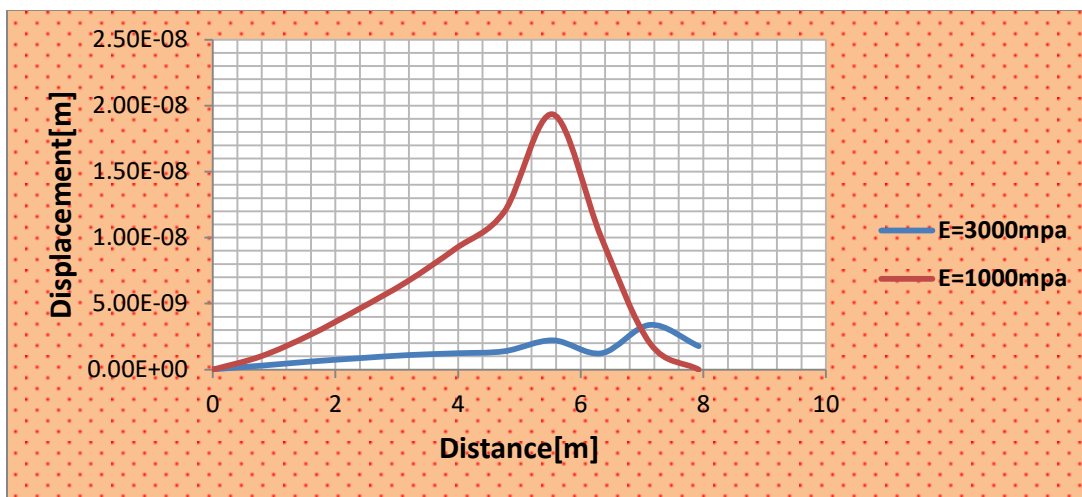
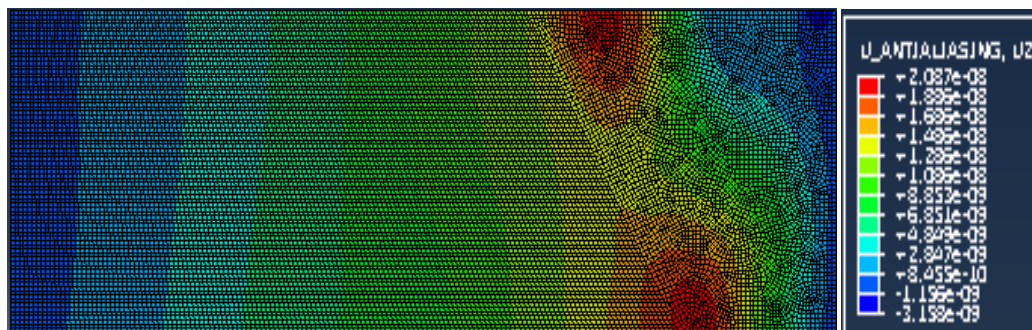
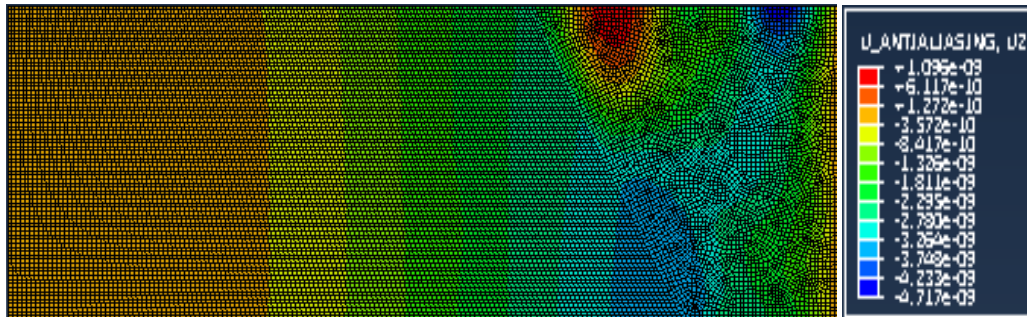


Figure 25. Subsoil displacement at E=3000 mpa and E=1000 mpa



(a)



(b)

Figure 26: subsoil displacement at different modulus [MPa] a) E=1000 b) E=3000

The figure below shows the effect of ballast and soil young's modulus on the vertical displacement of the ballast layer along the path of the wheel load with 250KN. The graph plotted along the path of the ballast layer starting from the bridge slab end.

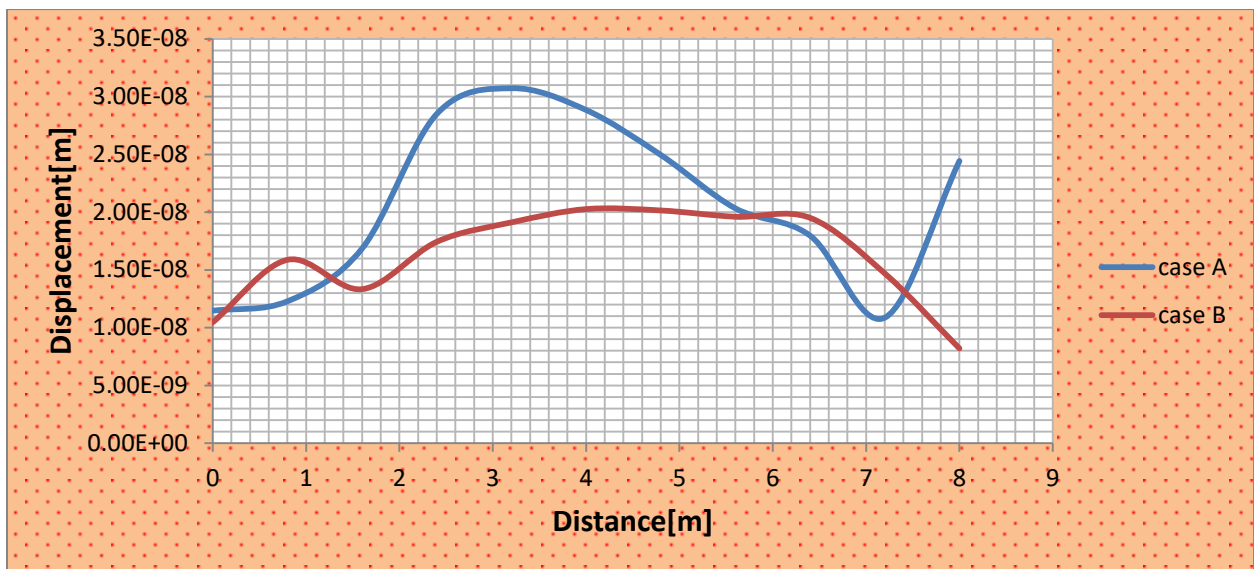


Figure 27: Ballast displacement along the path

From figure 26 the ballast in case A without reinforcement has peak displacement value compared to case B. The increase in ballast modulus by 50% using polyurethane geocomposite decreases the maximum settlement by 33%.

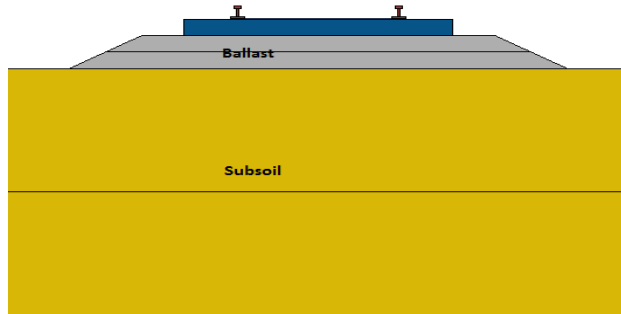


Figure 28: Cross sectional view of the modeled track

In addition to the longitudinal 2D model the cross section of the track has also been modeled for two cases A and B. For Case A, half part of ballast and subsoil (figure 27) modulus is improved while for case B full section of ballast and subsoil modulus is improved. For case A the top half part of the ballast and the bottom half part of the soil are improved. The vertical displacement effects on the subsoil and the ballast are presented in figure 28 and figure 30. For the cross sectional model a concentrated load of 125kN is applied on the top of the two rails.

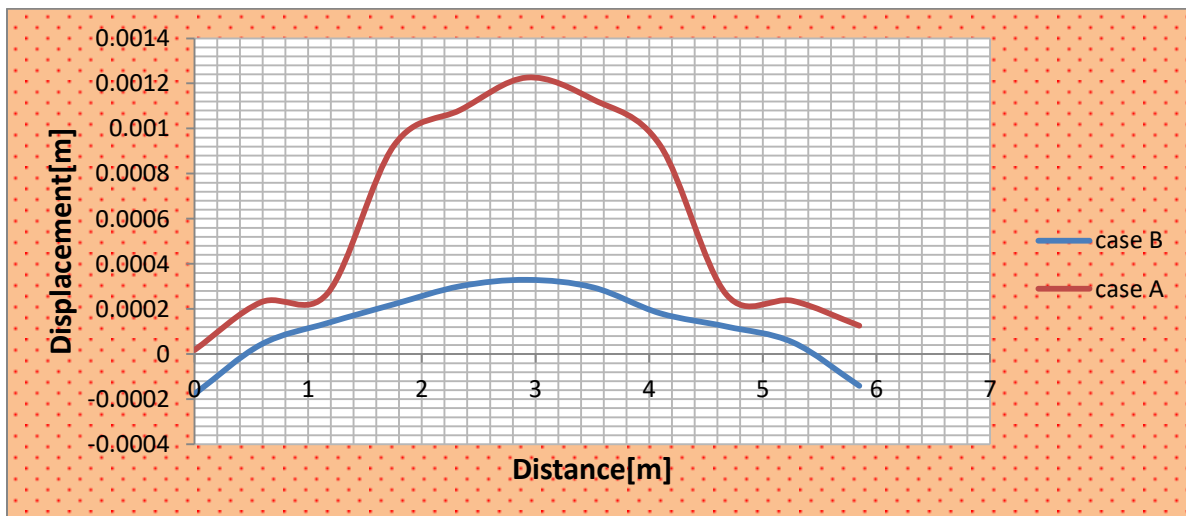
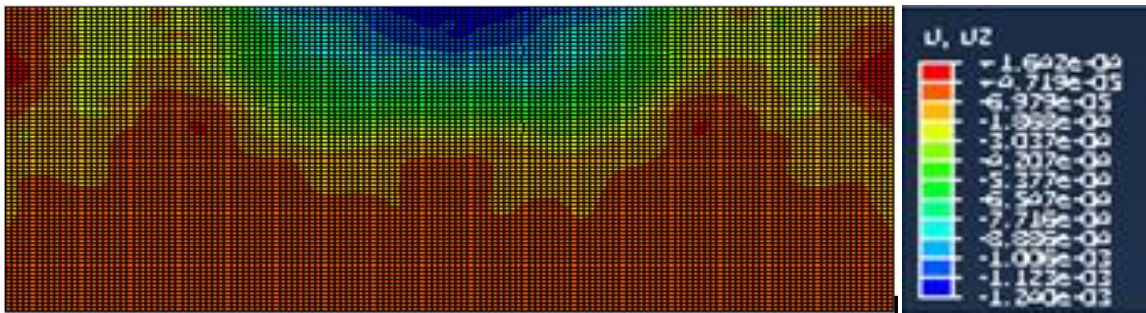
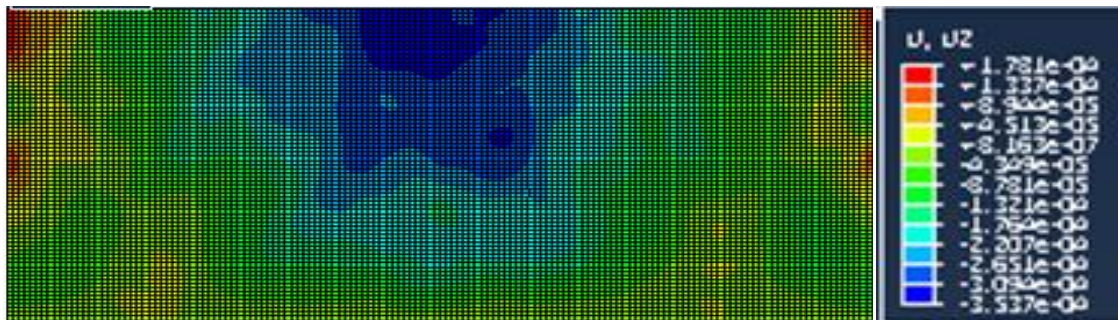


Figure 29: Subsoil displacement



(a)



(b)

Figure 30: Cross section of the track a) case A b) case B

AS shown in figure 28 case A has high peak value than case B. In case B the vertical displacement has lowered more than by half compared to case A. The change in displacement in case B is smooth while in case A it changes abruptly and it may cause embankment slope failure.

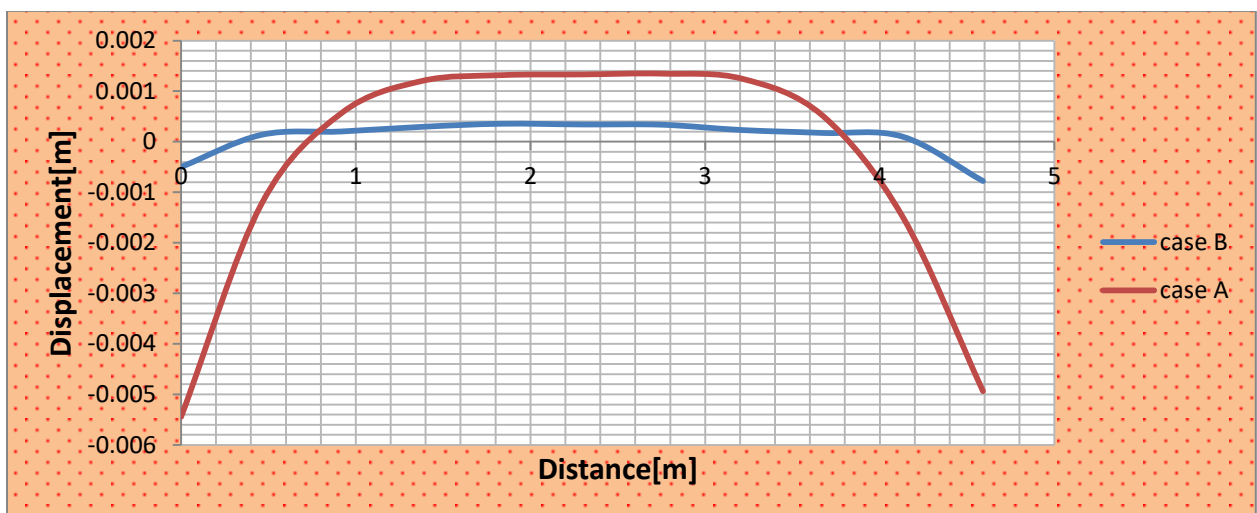


Figure 31: Ballast displacement

The ballast in case A has peak displacement values at the start, middle and end points while in case B the displacement is almost absorbed to zero due to the improvement of the ballast and subsoil modulus.

4.1.2. Effect of speed

The increase in train speed induces high levels of vibration in the track structure and it has direct relation to the sub grade deformation. The figure below shows the effect of train speed on the displacement of rail.

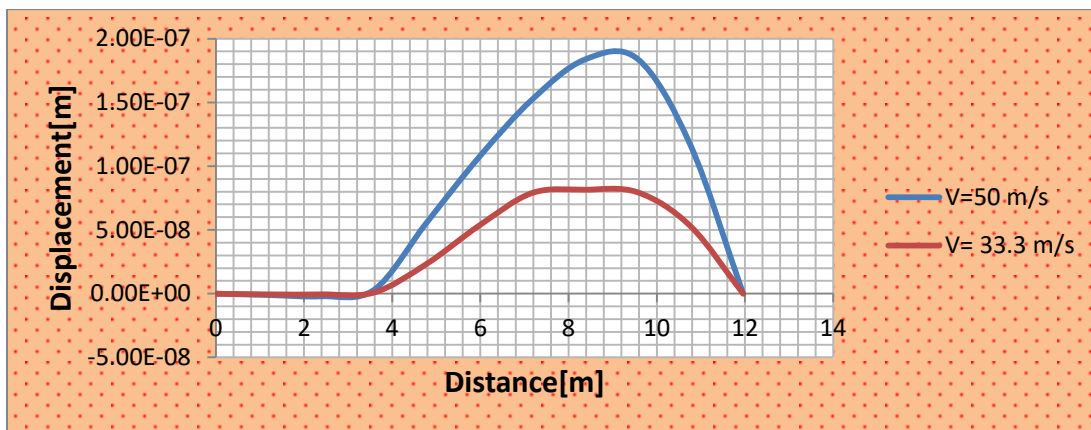
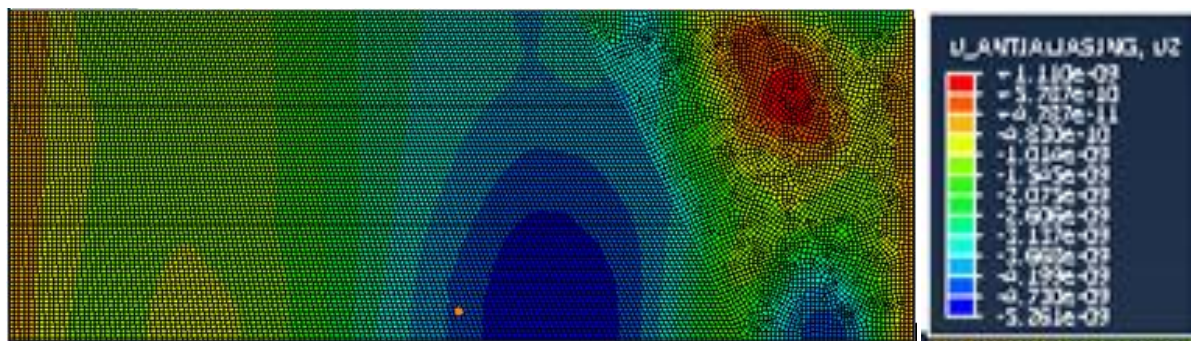
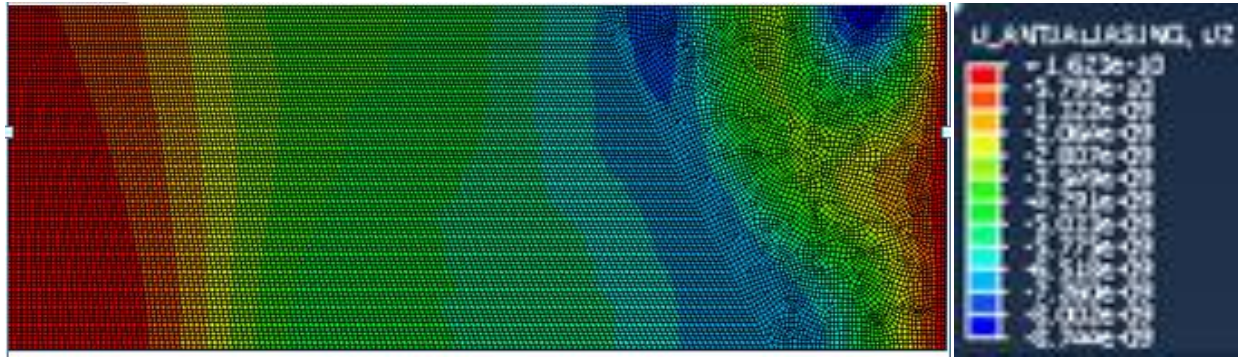


Figure 32: Rail deflection at different speed for case A



(a)



(b)

Figure 33: sub grade displacement at speed of a) 50m/s b) 33.33m/s

As the train speed increase its impact on the track components also increases. High train speeds induces high levels of vibration in the track and the surrounding area. These vibrations can result in the rapid deterioration of the track structure, causing settlement and ground failure. As shown in figure the rail deflection at train speed 50m/s has sharp and high displacement values compared with train speed of 33.3m/s.

The train speed has a direct relation with the sub grade deformation. As shown in the figure 13 there is a variation in deflection of the subsoil from 33.3m/s to 50m/s train speed. The subsoil is very sensitive to speed changes as shown in figure (b) for 50m/s train speed the deformation is very high even at the bottom region of the subsoil.

CHAPTER 5

5. Conclusion and Recommendation

5.1. Conclusion

Two dimensional finite element model has been developed to study the vertical settlement of transition zones between ballasted and ballast less track under passage of train load. Improved and non-improved ballast and subsoil have been adopted for the comparison.

The two most crucial substructure components of a track ballast and subsoil transition systems which mostly constructed in transition zones in bridge approaches has been used with modification of cross section and material properties.

The conclusion has been made on the basis of vertical displacement, vertical acceleration and vertical stress on the rail, ballast and sub grade.

In general the improved substructure of abridge approach show good track dynamic improvement. It provides smother transformation to reduce impact causing due to sudden abrupt change in stiffness while the modified ballast and subsoil system shows considerable effects on the vertical displacement of the track system at bridge approach transition. It suggests that it has a high potential to apply stiffness improvement in the track transition.

The first analysis in Abaqus was done in two cases with different young's modulus value for ballast and subsoil. As there is gradual change in stiffness of ballast and subsoil from the rigid track to the free track the vertical displacement on the track components reduce smoothly with the acceptable range.

The dynamic vibration of the rail absorbed due to the effect of ballast bonding and soil reinforcement. The rail on the bridge slab has the same deflection for both cases while for the improved case it increases smoothly and its abrupt change is low compared with the non-improved case. The rail displacement in the improved substructure case reduced by 44% compared with the non-improved case.

Different speeds of train are analyzed showing that a higher speed created a larger dynamic loading on the track components. This higher dynamic load increases the settlement rate of the

track structure. The subsoil is sensitive to higher speeds and speed has a direct relation with the subsoil deformation.

Speed effects are also clearly seen on the rail deflection. Two types of speed were analyzed and the higher speed yields rail deflection which exceeds the lower by more than 50%.

5.2. Future Research

The following areas are recommended for future research.

- The dynamic effect on transition zones can also be mitigated by using rail pad, under sleeper pad, longer sleeper and auxiliary rail so the railway track transition zone settlement and dynamic effects can be analyzed with additional mitigation techniques on the superstructure with 3D modeling.
- Laboratory test can be performed to investigate and analyze the material properties of ballast by implementing stabilization using polyurethane geocomposites.

5.3. Recommendation

As it is seen in the finite element modeling railway track transition zones are sensitive for degradation besides to this from the experience of the railway industry the maintenance cycle and cost is higher compare to the free track. The maintenance cycle and cost can be reduced by taking better mitigations at these locations.

Ballast bonding using geocomposite chemicals and soil reinforcement using cement with gradual change in material property as well as geometry are recommended as better mitigation techniques for the track substructure at transition zones.

In the case of Ethiopian railway projects there are many crossing structures due to the difficulty of the terrain of the country. The track at these locations may suffer from sudden bump due to the abrupt stiffness change therefore it is better to apply these mitigation techniques during the construction and maintenance periods.

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