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ANALYSIS OF ENHANCING THE PERFORMANCE OF BALLASTED RAILWAY WITH GEOGRID USING ABAQUS SOFTWARE- A CASE STUDY OF ADDIS ABABA PROJECT

By

Damiso Abire

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Approved By Board of Examiners

Argaw Asha (PhD)		23/09/17
Advisor	Signature	Date
Addisalem Zeleke (PhD)		28 Sept. 2017
External Examiner	Signature	Date
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Department Head	Signature	Date
Lemma Beressa (MSc.)		02/10/17
School Dean	Signature	Date

Lemma Beressa Gudeta
School Of Civil Engineering
& Architecture, Dean

Declarations

I, the undersigned, declare that this thesis is my work and that all sources of material used for the thesis have been properly acknowledged.

Name: Mr. Damiso Abire

Signature:

Phone: 0912811744

Date: August, 2017

Analysis Of Enhancing The Performance Of Ballasted Railway With Geogrid Using Abaqus - A Case Study Of Addis Ababa Project

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ASTU, Adama, Ethiopia by Mr. Damiso Abire.

Abstract

One very important issue is the need for significant improvement of railways passing over areas of poor soil conditions due to continuous deformation and a low bearing from the ballasted foundation. One general problems happened under substructure are vertical settlement and lateral settlement of the layers. In order to minimize these problems enhancing the bearing capacity of the subgrade soils can be the major solution. The subgrade soils is known by poor bearing capacity, high plasticity and high swelling factor. It is called black cotton soils. So, the bearing capacity of the soils can be improved by geotechnical ground improvement. Hence, geogrid reinforcement is used as a method of improving the performance of the railway tracks. Therefore; geogrid is reinforced in between Ballast and sub-ballast to minimize the layers vertical settlement and to minimize track lateral spreading of the materials. ABAQUS software package is used as a tools in analyzing the finite element models of a half of ballasted railway structures. Hence, a model embankments were simulated numerically using finite element procedures. Further numerical simulations were then performed on ballasted embankments reinforced with and without geogrid to model accurate ballasted track conditions and the effects of confinement on performance. The numerical simulations demonstrate that geogrid reinforcement effectively decrease vertical settlement and increase lateral confinement of a ballast embankment.

The results suggested that vertical deformation of ballasted railway is reduced by **17.79**%, when geogrid is reinforced in between ballast and sub-ballast, and due to the reinforcement of geogrid on ballasted track the lateral deformation of the track was rather stabilized to **50.89%.** The use of geogrid in ballast stabilization could demonstrate to a sustainable solution for a common and expensive problems of poor subgrade soils.

Keywords: ABAQUS, Geogrid, Biaxial Geogrid, cross machine direction, machine direction, and Finite element method.

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LIST OF ABBREVIATIONS AND SYMBOLS

ρ	Mass density.
δc	Uniaxial compressive strength.
$Ꞁ_f$	Shear strength at failure.
δ′n	Effective normal stress.
β, ɤ and α	Parameters describing the short-term and long term settlement behavior.
υ	Poisons Ratio
γ	Unit weight
ε	Strain
ν	Poisson's ratio
σ'c	Pre-consolidation pressure
τ	Shear stress component
φ	Angle between the radius of the wheel and the rail, called yaw rotation
Ø	Dimension Impact factor
θ	Angle between the principal axes.
3D	Three Dimension
ABAQUS	A software which solves the Finite element method
AREMA	American Railway Engineering and Maintenance of way Associations
B	Width of the sleeper
BOEF	Beam on Elastic Foundation
CIECC	China International Engineering Consulting Corporation
cmd	Cross machine direction.
CWR	Continues Welded Rail.

D_{50}	Diameter 50mm size of particle
E	Elastic Modulus
E_v	Modulus of elasticity taken from the second load plate test
ERC	Ethiopian Railway Corporation
F_2	Factor depending on the sleeper type and track maintenance
FEA	Finite element analysis.
FE	Finite Element
FEM	Finite Element Method
Fv	Design wheel load
G1 & G2	Geo-grid 1 and Geo-grid 2
HDPE	High Density Polyethylene
K 1, K2	Material properties of wheel and rail.
L	Effective length of the sleeper supporting load
md	machine direction
m, n	Dimensionless Constants
P_a	Average contact pressure
PD	Design wheel load
PET	Polyester
Pi	Initial pre stressing force
PP	Polypropylene
PSD	Particle size distribution
Ps	Static wheel load

q_r	Maximum rail seat load
Q_{static}	Static wheel load
Q_{wind}	Increase in wheel due to wind
R_w	Radius of the Wheel
UIC	International Union of Railways
USACE	United States Army Corps of Engineers
V	Design speed

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CHAPTER ONE

1. INTRODUCTION

Railway is one of the modes of transportation which is increasing in Ethiopia at recent period. Its purpose of a modern railway is to provide economical and comparatively rapid transportation. To achieve this, the railway track structure has to provide a safe and stable platform under severe vertical and horizontal alignment constraints. Therefore, it is important to identify the specific roles that each different component plays and how they combine and perform as an entity. There are two classifications of railway track. These are: Ballasted track and Slab track.

Ballasted track is a layer of broken stones, gravel, and any other granular materials placed and packed under and around the sleeper for distributing load from the sleepers to the formation. Whereas slab truck is constructed from concrete or from reinforced concrete.

1.1.Background of the Study

Different kinds of infrastructures are distributed in Ethiopia. Among these infrastructures, the construction of railway is one of the major types that are expanding through Ethiopian country. Now in our country the construction of railway track is started by calling National Railway Network from ballasted track with a total length of 2046km and 34 km Light Rail Transit system for the capital city of Addis Ababa. This railways will accelerate to sustain social and economic development of Ethiopia [ERC].

Before distributing such like construction; it is necessary to give a care for all works prior to start its building. Since, every activity is done on ground, knowing of the ground condition (properties of the soil) is the major one. Hence, this is the duty of geotechnical engineer that give a care during investigations and route selections.

This thesis concerns on ballasted railway truck. This ballasted rail truck probably build from soils and aggregates. Railway super-structure tracks (rails and sleepers) are normally placed on a sub-structure that consists of two or more layers of different materials. The top layer (below the sleepers) is a layer of railway ballast. Below the ballast there might be layers of sub-ballast, a formation layer and the subgrade (natural soil). Here, figure 1.1 below shows that the cross-section of the railway structures.

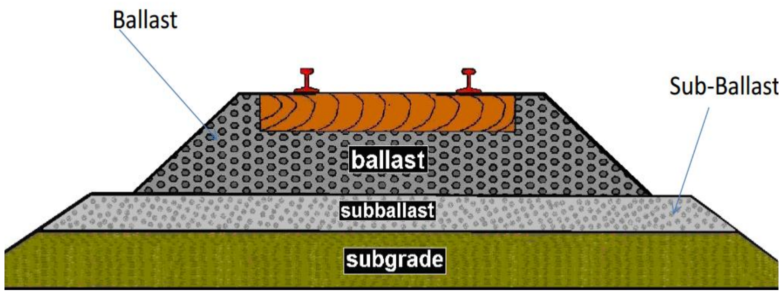


Figure 1.1 Component of railway cross sections [Huan Feng]

Ballasted railway is selected material because it is easily constructed and economical than slab track. It supports the track structure such as the rails and the sleepers against vertical, lateral and longitudinal forces from the trains. Conventional ballast is a coarse-sized, non-cohesive, granular material of a uniform gradation. It should be strong, hard-wearing, stable, drainable, easy to clean, workable, resistant to deformation, easily available, and reasonably cheap to purchase.

Hence, increasing the strength and stability of ballasted railway materials by using geotechnical improvement method is necessary. The rail track should be designed:

- ✓ To resist large repeated train loadings and provide protection to subgrade soils against both progressive shear failure and excessive plastic deformation.
- ✓ To account for the deterioration of ballast due to breakage and subsequent implications on the track deformations.

In order to have the above requirements, the potential use of geo-synthetics in the improvement of track stability and reducing the maintenance cost is well established. The research is very necessary particularly for area ballast underlying of soft soils and difficult to treat and replace it. So, the applications of ground improvement method is easy for improving rather than replacing them.

To deliver this broad variety of geotechnical functions, geo-synthesis have been established in mass of forms and material combinations. These include geo-grids, geotextile, geo-nets, geo-composites, geo-membranes and geo-cells.

Among all types of Geo-synthesis materials, Biaxial geo-grid is selected because of the geo-grid reinforcements performs the following functions:-

- It provided internal confinement (lateral stability) to the ballast layer, thus improving its vertical stress distribution characteristics.
- Confinement was achieved by the geo-grid restraining the lateral and vertical deformation of the ballast layer [Indraratna, B. & Nimbalkar, S].
- Create a rigid platform where horizontal shear strains and vertical settlements are controlled and minimized.
- Increase the bearing capacity and the load distribution by enlarging the foundation slip failure line, thus reducing vertical stresses,
- Provide a good drainage.

The potential use of geo-synthetics (i.e. geo-grid) in enhancing the performance of ballast under repeated loading analyzed using a FEA. A plane strain finite element analysis by ABAQUS is carried out and used to obtain the optimum location of geo-synthetics in railway track substructure.

The primary objectives of this research is to enhance the performance of ballasted materials in minimizing of the vertical settlement and lateral deformation of the ballast by inserting of geo-synthesis material called geo-grid. Literatures have been carefully reviewed and preliminary analysis were performed for typical sections of Addis Ababa railway networks using finite element method with the software ABAQUS.

ABAQUS is a suite of software for finite element analysis (FEA) is known for its high performance, quality and ability to solve more kinds of challenging simulations than any other software. This analysis is comprised for ballast embankment reinforced with or without geo-grids. Finally, their result model were compared to show the function of improvements and recommendation is given to it.

1.2.Problems of Study

The ballast layer is a basic constituent of the traditional track constructions**.** It is the selected crushed granular material placed as the top layer of the structure in which the sleepers embedded to support the rails. So that to resist the load applied by train the quality of Substructure materials are very necessary. But, some subgrade soils may not fit to resist such kinds of load which applied on it. Specially, poor subgrade soils. Hence, this paper concerns for the railway track passing over poor subgrade soils. Poor subgrade soils known by less bearing capacity, high vertical settlements, high liquid limits and less modulus of elasticity. Due to the failures of these subgrade soils, when load is applied on the upper layer, it highly start to affect the sub-layering of ballast. Hence, the railway sub-structure start to deform beyond the permissible settlement, laterally the material start to spread and the effects of differential settlement can be happened on the rail. As the results of these problems the effect can happen on the upper layers of the strata. These problems ae: Braking of the sleeper, misalignment of the rail, rotting of the sleeper failing, highly deformed of subgrade beyond allowable settlements and etc. are caused on the railway track.

i. Braking of the sleeper,

Figure 1.2. Sleeper braking of old railway found at Dire Dawa

ii. Misalignment of the rail,

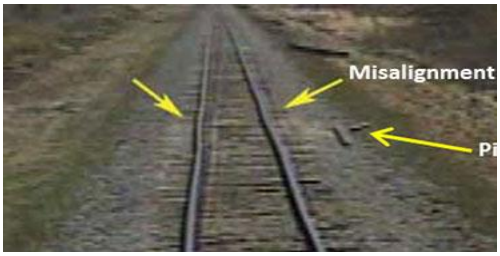


Figure 1.3 misalignment of rail of old railway found Adama

iii. Rotting of sleeper are failing.

Figure 1.4. Rotting of the sleeper failing old railway found Adama

Therefore, this research concerns on poor subgrade soils that found in our country called Ethiopia which are found in Addis Ababa along ASMERA Road construction site. The soil mass structure is easy to be deformed under external force. Mostly it is expansive soil with soft plasticity and low bearing capacity. It is recommended to calculate the bearing capacity and sedimentation of the layer in design for the purpose of checking and to remove and replace the layer with other fill. Hence, according to China International Engineering Consulting Corporation these layer should not be directly used as filling materials. It is suggested that crushed stone be used for replacement filling. But, rather than replacing the layer with other fill, using the application of ground improvement is the necessary one i.e. treating the soil rather than replacing them by geosynthesis material called geogrid.

So that, in order to minimize these problems reinforcing the ballast materials with welded biaxial geogrid material is selected on this thesis as a primary solutions. Welded biaxial Geogrid is a type of polymer geosynthetic usually placed between the layers to provide additional confining pressure and strengthen the ballast due to interlocking with surrounding ballast aggregate. It is discussed on topic 2.6.

1.3. Objective of the Study

1.3.1. General objectives

- To investigate the performance of geogrid reinforcement in minimizing the rate of settlement and to stabilize the tracks lateral deformation encountering on a weak foundation soils of ballasted rail track geometry.

1.3.2. Specific objectives

- Analyzing the settlement versus stress on the subgrade of the track due to the reinforcement of geogrid on ballasted rail track.
- To give the Comparison of the total deformation on subgrade between unreinforced and reinforced ballasted track.
- Compare the stress-strain distributed on Subgrade layer for both unreinforced and reinforced.
- The consequence of this research should provide awareness into future design methods for Railway Company and designers.

1.4. Scope and Limitation of the Study

The performance of the ballasted railway track can be improved by many geotechnical ground improvement methods. But, in this research; it is limited to geo-synthesis materials called geogrid. Geo-grids is selected because of its functions. To analysis the case study of Addis Abeba project, finite element analysis of static method is carried-out by using a software called ABAQUS. The data are from Ethio-Djibouti Railway Project and Addis Abeba Light Rail Transit Project Company along the directions of Asmera Road. Only a station which have a less bearing capacity or soft subgrade is selected. Immediate settlement is a major problems happened on the ballasted materials because of the materials majority is an aggregate. The dynamic load is not considered in this thesis; rather only static loads with its dynamic effect is considered instead.

1.5. Methodology

To understand the problem of railway foundation, first literature on railway foundation is reviewed. Specially, Subgrade is considered, because of it is the main part of the railway which carried the loads of the track and sustain the loads to come up on it. Hence, using geo-synthesis material improvement called geogrid the analysis of railway ballast is done by using a software called ABAQUS. Only geogrid reinforcement is done in between Ballast and Sub-ballast. The physical characteristics and technical specifications are listed by tables. While doing this, manuals and any publications are reviewed. The data sources are from Ethiopian railway Construction Corporation, Addis Ababa Light Rail Transit Project Company along the directions of Addis Ababa and American Railway Engineering and Maintenance of Way Associations (AREMA) manual. Generally the procedures are:

- Literature reviewing and Data collecting,
- Modelling and finite element analysis of the ballast with or without geo-grid material using a software package called ABAQUS,
- Considering the results of finite element analysis of the track section unreinforced and reinforced with geo-grid.
- Checking of the Subgrade settlement and giving of a conclusion and recommendation.

Initially, a literature survey from different books, papers and thesis on the topic are done. This serves as a good plat form to begin and frame the thesis properly. Then, all characteristics of the materials at the specific location are collected as input data.

Furthermore, the basic Static material properties, Load applied on it are modeled by employing the linear elastic model. The measured data from the site investigation carried out are incorporated in the model. The basic soil parameters and others are determined to be used in the subsequent steps.

Later, accurate condition is abstracted and a model of the layer system is produced. This is carried out a layer with and without geogrid reinforcement cases. This is the most important step in the thesis and serves as a bridge between the input data and the FEM analyses.

A FEM program-ABAQUS is used to analyze the problem. Models are developed and simulated in ABAQUS to perform 3D complex analyses. From the analysis, displacement values for different cases are determined as major output. Finally, comparisons and conclusions are drawn.

1.6. Organization of the Thesis

The thesis is organized in the following four main Chapters.

Chapter one introduces ballasted railway, problem of study, objective, limitation and scope of the study.

Chapter two presents the literature review giving an overview about ballasted track geometry, properties and load applied on it. The applications of geosynthetics in railroad tracks also critically reviewed and discussed.

Chapter two describes the general overview of the thesis, gives a picture of the study area, FE properties of ballasted materials, how to modeling by ABAQUS, step of analysis.

Chapter four refer with the discussion results and parameter study of the analysis.

Finally, Chapter five summarizes the main findings of this research study; conclusions have been made based on the result of the FEM analysis. Eventually, recommendations have been made for further research.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

Ballasted rail track is one of the types of railway. A ballasted rail track is categorized by two main divisions of components: the superstructure and the substructure. The superstructure comprises the rails, fastening system and the sleepers. The substructure covers the ballast, the sub-ballast and the subgrade [Cho Ching Joe Kwan].

The coarse strata on a railway track generally consist of an upper ballast layer comprised of large, angular particles (typically 20 - 60 mm) and a lower layer of capping material resembling road base. The main functions of the ballast layer are to control the stress intensity projected onto the weaker subgrade, to decrease the frequency of track maintenance by minimizing track settlement and sleeper movement, and to promote rapid drainage via the large pore structure [Indraratna, B., Lackenby, J.].

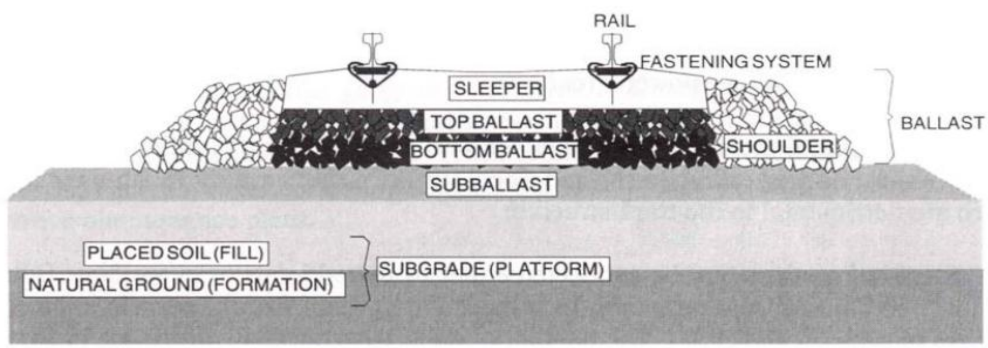


Figure 2.1 components of a ballasted rail track structure (transverse section) [Justin Kennedy]

2.1.1. Rail

The rails are the only part of the track component that comes into direct contact with the train. The main purpose of the rails is to guide train wheels. These longitudinal steel members must have sufficient stiffness to transfer the concentrated wheel loads onto the sleepers with minimum deflection between sleeper supports. Hence the rails must be of certain dimensions and profile. The profile of the rail coupled with the profile of the wheel has a significant bearing on the ride quality [Cho Ching Joe Kwan].

2.1.2. Fastening

The fastening system acts as a means of retaining the rails against the sleepers. The general functions and requirements of the fastenings are to absorb rail loads elastically and transfer them to the sleeper. The fastenings must be able to help the rails resist any vertical, lateral, longitudinal and overturning movements. The fastenings are also an aid to damp traffic vibrations, prevent or reduce rail/sleeper attrition as well as providing electrical insulation for track signals [Cho Ching Joe Kwan].

2.1.3. Sleeper

The general functions and requirements of the sleepers are to receive the rail loads and distribute them over the ballast. The sleepers also act as a restraint against any lateral, longitudinal and vertical rail movement through anchorage of the superstructure into the ballast. The sleeper must also be resistant to mechanical wear and weathering. The two most common types of sleepers are wood and concrete sleepers [Cho Ching Joe Kwan].

2.1.4. Ballast

Ballast is a crushed granular material placed as the top layer of the substructure in which the sleepers are embedded. A wide range of ballast materials can be found on the tracks, such as dolomite, rhyolite, gneiss, basalt, granite, quartzite, limestone, slag and gravel. The typical ballast material is gravel-size with most particles between 6 and 64mm diameter. The voids in the ballast layer provide essential drainage of water falling onto the track and also allow the maintenance requirement of rearranging ballast particles to adjust track geometry [Justin Kennedy], [Indraratna, B, Rujikiatkamjorn].

The engineering behavior of ballast have a key role in governing the stability and performance of railway tracks [Indraratna, B, Khabbaz]**.** Ballast is the largest component of the track by weight and volume. The thickness of the ballast should be such that the subgrade is loaded as uniformly possible. Good-quality railway ballast should have angular particles, high specific gravity, high shear strength, high toughness and hardness, high resistance to weathering, rough surface and minimum hairline cracks, good bearing capacity, good drainage capacity, and suitability for pacing [Justin Kennedy], [Chaitanya Calla]. The main functions of ballast are to distribute the load from the sleepers, to damp dynamic loads, and to provide lateral resistance and rapid drainage [Indraratna, B, Khabbaz], [Cho Ching Joe Kwan].

2.1.5. Sub-ballast

Sub-ballast is the granular layer of material separating the ballast and the subgrade and generally, sub-ballast materials consist of broadly graded sand-gravel mixtures or broadly graded crushed natural aggregates or slags. The sub-ballast layer further reduces the stress at the bottom of the ballast layer to an acceptable level for the top of the subgrade. Another important function of the sub-ballast layer, is to act as a separator and prevent interpenetration between the subgrade and the ballast. By acting as a separator the sub-ballast layer prevents the upward migration of fine material emanating from the subgrade, the attrition of subgrade by ballast and can provide drainage of water either flowing to the subgrade form the ballast or vice versa [Justin Kennedy],[Cho Ching Joe Kwan].

2.1.6. Subgrade

The subgrade is the foundation for the track structure and it can either consist of the existing natural soil, which is most likely to be a fine grained soil with silt and clay components, or placed fill. The main function of the subgrade is to provide a stable foundation for the track structure. Therefore, the subgrade has a significant influence on track performance and maintenance. The strength and stiffness of the subgrade ultimately dictates the amount of load that can be applied to the track and consequently controls the required depth of overlying granular materials [Justin Kennedy].

Table 2.1 Global requirements for the sub-ballast and subgrade layer [Ngo, Ngoc]

Parameters	**Required values**	
	Sub-ballast	**Subgrade**
California Bearing Ratio(CBR)[%]	>25	>5
E_{v2} [MPa]	100	35
Compaction through Proctor[%]	100	97
Maximum deviation from design subgrade profile [mm]	<10	<10

2.2.Geotechnical Properties of Ballasted Track

2.2.1. Physical Properties of Ballast

The physical properties of ballast are largely accountable for successful ballast performance in the field. They can be divided into two categories. The first group is concerned with the properties of individual particles, durability test, and shape and surface examination before the ballast can be declared suitable. The second category considers the physical properties of ballast particles that are in contact with each other, but not influencing deformation. These properties are permeability, void ratio, bulk density and specific gravity [Indraratna, B, Khabbaz].

The specific gravity and bulk density of the ballast are two properties that play pivotal roles in rail track safety. Bulk density is a function of the particle specific gravity and the void ratio [Indraratna, B, Khabbaz]. It has been shown that the higher the specific gravity of the parent rock, the greater the holding capacity of the ballast and the lower the degradation. The lateral stability of curved tracks, which is essential for track safety, can be improved by the use of ballast with high specific gravity. The bulk density and specific gravity control the stability of the track, and should be maximized without significant reduction in drainage [Indraratna, B, Khabbaz]. The Specific Gravity of the ballast was determined in the same way as the Kaolin clay, by dividing the mass of dry ballast particles in a large steel container by the mass of desired water displaced by the dry ballast particles. The test was repeated eight times for repeatability and to enable a representative sample of the large ballast particles to be tested [Justin Kennedy].

2.2.2. Mechanical Properties of Ballast with its Failures

Three important aspects of mechanical properties of ballast, namely shear strength, settlement and degradation [Indraratna, B, Khabbaz].

A. Shear Strength

When soils at high stresses and rocks at low normal stresses are tested, a non-linear shear strength response is obtained. Hence, one value set of cohesion intercept c, and the angle of shearing resistance, cannot be used to represent accurately the failure envelopes corresponding to the entire range of stresses [Indraratna, B, Khabbaz].

This non-linear shear strength envelope is represented by the following equation:

$$\frac{\tau_f}{\delta c} = m\left(\frac{\delta\prime n}{\delta c}\right)^n \qquad 2.1$$

Where δc is the uniaxial compressive strength of parent rock is determined from the point load test, m and n are dimensionless constants, τ_f is the shear strength at failure, and $\delta' n$ is the effective normal stress [Indraratna, B, Khabbaz].

B. Ballast Degradation

The main causes of ballast degradation are excessive repeated loading and vibration, temperature and moisture fluctuation, and impact load on ballast due to severe braking [Indraratna, B, Khabbaz]. The degradation of ballast can be lowered by:

a. using a finer grading (reduced D50),
b. choosing a ballast with as low production of fines as possible if there are options,
c. avoiding coarse grained rocks,
d. always using the ballast that has the lowest Los Angeles abrasion value,
e. Not using tamping more than absolutely necessary [Roar Nalsund].

C. Ballast Fouling

The life and performance of the railway track is very much dependent on the ballast layer. The ballast layer is subjected to deformation and degradation during traffic loading. Various sources of ballast fouling have been [Cho Ching Joe Kwan];

- Ballast Breakdown.
- Infiltration from ballast surface.
- Sleeper wear.
- Infiltration from underlying granular layers.
- Subgrade infiltration.

2.3. Load on Ballast

The forces imposed on the track structure could be classified as mechanical (both static and dynamic) and thermal. Types of forces and their sources are: a) Quasi-static loads induced by the self-weight of the vehicle and reaction forces in curves, b) dynamic loads resulting from track irregularities such as differential settlements in the ballast bed, corrugations, discontinuities and welds and joints together with vehicle defects, c) thermal loading due to temperature variations in continues welded rail [Ionescu, Daniela].The forces acting on the railway track structure can be classified broadly into:

2.3.1. Vertical Forces
2.3.2. Lateral Forces
2.3.3. Longitudinal Forces [Chaitanya Calla], [Ionescu, Daniela].

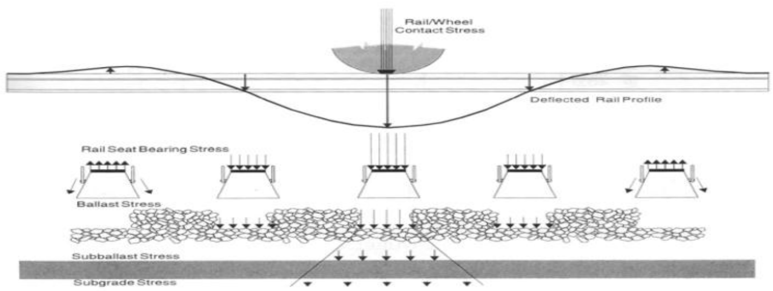


Figure 2.2 Types of Wheel Load distribution in tracks [Cho Ching Joe Kwan]

2.3.1. The Vertical Force

It is the combination of a static load and a dynamic component superimposed on the static load. The static load is the dead weight of the train and superstructure, while the dynamic component, which is known as the dynamic increment, depends on the train speed and the track condition [Huan Feng]. Vertical forces act perpendicular to the plane of the rail and the actual direction depends on the track level and grade [Chaitanya Calla], [Ionescu, Daniela].

For the purpose of design, the sleeper-ballast contact pressure is generally assumed to be inform and is given by equation [Hussaini, Syed Khaja Karimullah]:

$$\text{Pa} = F2\left(\frac{\text{qr}}{\text{BL}}\right) \tag{2.2}$$

Where P_a =average contact pressure, $\mathbf{q_r}$ = maximum rail seat load, B= width of the sleeper.

L= Effective length of the sleeper supporting the load qr, F_2= a factor depending on the sleeper type and track maintenance.

2.3.2. Lateral Forces

A lateral forces act perpendicular to the direction of traffic. Principal sources are the lateral wheel force which is due to lateral friction force between wheel and rail and force of wheel flange pushing against the rail [Chaitanya Calla]. The sources of lateral forces in the loaded track condition is as follows: (a) on straights, the lateral component of dynamic force due to geometry deviation; (b) on curves, the addition of non-compensated centrifugal forces; (c) wheel flange contact against the outer rail in curves; (d) cross-wind action for both straight and curved sections. Over all, the lateral forces are more dependent upon the track curvature than the vehicle speed [Ionescu, Daniela].

2.3.3. Longitudinal Forces

These forces are applied in direction parallel to the rails and can be caused due to: (a) braking or accelerating of the train, (b) thermal expansion and contraction of the rail, (c) track creep, (c) temperature effects, especially in CWR track [Chaitanya Calla],[Ionescu, Daniela].

2.4. Track Settlement

Railway track will settle with repeated traffic loading due to permanent deformation in the ballast and underlying soil. Hence, Traffic loading is the main cause for settlement and the intensity is often governed by the quality and behavior of ballast, sub-ballast and the subgrade [Cho Ching Joe Kwan].

Settlement occurs when stresses exceed the yield limit of the ballast and settlement can be accumulated and it is possible to model sleepers hanging from the rail [Chaitanya Calla].

Generally, Track settlement occurs in two major stages **[**Tore Dahlberg**]**.

1. Directly after tamping, when the track position has been adjusted to a straight level, the settlement is relatively fast until the gaps between the ballast particles have been reduced and the ballast is consolidated,
2. The second stage of settlement is slower and there is a more or less linear relationship between settlement and time (or load). This phase of settlement is caused by several basic mechanisms of ballast and subgrade behavior:
   - Continued (after the first phase) volume reduction, i.e. densification of the ballast and sub ground, caused by particle rearrangement produced by repeated train loading,

- Sub-ballast and/or subgrade penetration into ballast voids. This causes the ballast to sink into the sub-ballast and subgrade and the track level will change accordingly,
- Volume reduction caused by abrasive wear. A particle may diminish in volume due to abrasive wear at points in contact with other particles, i.e. originally cornered stones become rounded, thus occupying less space,
- Inelastic recovery on unloading. Due to micro-slip between ballast particles at loading, all deformations will not be fully recovered upon unloading the track. In this case the permanent deformation is a function of both stress history and stress state,
- Movement of ballast and subgrade particles away from under the sleepers. This causes the sleepers to sink into the ballast and subgrade.

2.4.1. Factors affecting the Settlement of Ballast

Under induced traffic loading, railway ballast aggregates experience numerous micromechanical processes i.e. slip, sliding, rotation and rolling take place which eventually leads to deformation. There are various factors governing ballast deformation under static loading conditions. These are loading amplitude, frequency, and number of load cycles, confining pressure, particle breakage, pore pressure and characteristics.

2.4.2. Settlement Model

The expression of track settlement *y* under repeated loading *x* is expressed in the form [Cho Ching Joe Kwan]:

$$y = \gamma\,(1 - e^{-\alpha x}) + \beta x \tag{2.3}$$

Where *x* = loading of the track either expressed as a number of load cycles or as tonnage carried by the track (see Figure 2.3). The constants γ, β and α are parameters describing the short-term and long term settlement behavior.

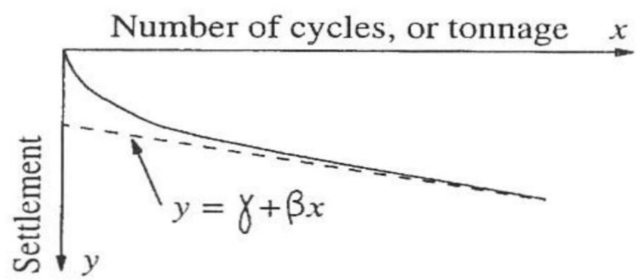


Figure 2.3 Track settlement as function of x [Cho Ching Joe Kwan]

2.5. Effect of Geo-Synthesis on the Performance of Ballasted Railway

One of the promising approaches to improve the track performance is to reinforce the ballast with geo-synthetics. Once in place, the geo-grid-reinforcement offers the following major benefits to the rail industry:

- ✓ It holds the ballast in place by restraining its lateral movement thereby preventing the track settlement and rail misalignment [Hussaini, S. K Karimullah].
- ✓ It increases the confining pressure on ballast thereby reducing particle degradation that helps maintaining the ballast angularity and track shear strength [Hussaini, S. K Karimullah]
- ✓ Increased ballast life (life cycle cost savings) [AREMA, 2010].
- ✓ Reduced roadbed thickness (initial cost saving) [AREMA, 2010].
- ✓ Transfer the load to subgrade like a slab action.

However, the effectiveness of reinforcement in providing the above mentioned benefits depends on the level of interaction between ballast and geogrid. In such a situation, the ballast-geogrid interface shear strength could be treated as a measure of the ability of geogrid to inhibit the lateral spread of particles; thus, providing guideline about its suitability as reinforcing material for stabilizing ballast [Hussaini, S. K Karimullah].

2.6. Geogrid

A geogrid is defined as a geosynthetics formed by a regular network of tensile elements with apertures of sufficient size to allow strike-through of surrounding soil, rock or other geotechnical materials. Geogrids are principally used for reinforcement purposes, they can also help to provide effective separation between two soil and granular fill layers [AREMA, 2010].

Geogrids are polymeric products formed by joining intersecting ribs. Geogrids are mainly made from polymeric materials, typically polypropylene (PP), high density polyethylene (HDPE) and polyester (PET). They have large open spaces also known as "apertures". The directions of the ribs are referred to as machine direction (md), orientated in the direction of the manufacturing process or cross machine direction (cmd) perpendicular to the machine direction ribs [www.naue.com].

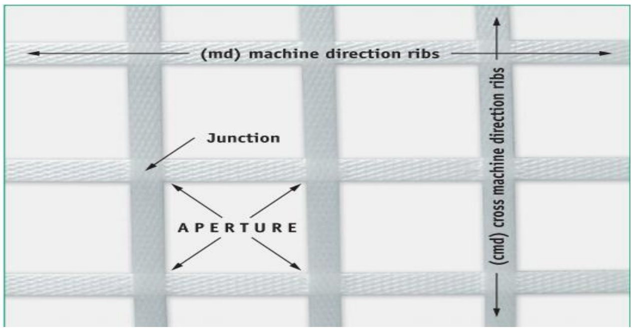


Figure 2.4 Geogrid definition [www.naue.com]

They are manufactured as either biaxial or uniaxial. Biaxial geogrids are those that exhibit the same strength in both machine and cross machine directions while uniaxial geogrids exhibit the primary strength in the machine direction with minimal strength, enough to maintain the aperture structure, in the cross machine direction [www.naue.com].

Biaxial geogrids are primarily used in base reinforcement applications, while the uniaxial geogrids are often used in the other markets. These are applications where an engineer is trying to improve the performance of a gravel base over poor soils [www.naue.com].

Geogrids are used under parking lots, airport runways, gravel construction roads, highways, dam levees and railroad tracks. The geogrid used in this study is a bi-oriented geogrid that is made of polypropylene and manufactured by extrusion and biaxial orientation to enhance its tensile properties. It is generally used for soil stabilization and embankment reinforcement. This geogrid has high tensile strength, high elastic modulus, and strong resistance to construction damage and environmental exposure. With its large apertures (>25 mm), this geogrid provides strong mechanical interlock with coarse ballast grains [Indraratna, B., Mohamed A].

The size of Geo-grid is taken from the recommendations of AREMA section 10.6 accordingly;

Size: The aperture size of geo-grid does not exceed the average (D50) particle size of the fill material being used when reinforcing at the sub-ballast layers. For ballast layers the use of a larger aperture geo-grid (greater than 1.7 inches (143 mm) almost always leads to optimum performance, irrespective of the particle size of the ballast as research said.

Welded biaxial geogrid is used among types of geogrid. Because it has the following functions [Amir Shahkolahi]:

- ✓ Higher pull-out resistance is mobilized due to its structured flat bars and strong junctions than woven geogrid, extruded geogrid etc.,
- ✓ Has higher stiffness in all directions,
- ✓ Has higher stiffness, torsional rigidity/aperture stability, higher interlocking effect and low installation damage than others.

According to AREMA the physical properties of Geo-grid used in Track stabilization is as follows [AREMA, 2010]:

Table 2.2. Physical Properties for Geogrid used in Track stabilizations [AREMA, 2010]

Properties	Test Method	Units	Minimum Value (sub-ballast reinforcement)	Minimum Value (Ballast Reinforcement)
Aperture Size (Min-Max)	Direct Measurement	Inches(mm)	0.7-1.60 (17.8-40.6)	1.70-2.50 (43.2-63.5)
Open Area	Direct Measurement	%	70	75
Rib thickness	ASTM D1777	Inches (mm)	0.05 (1.27)	0.05(1.27)
Junction thickness	ASTM D1777	Inches(mm)	0.16(4.0)	0.17(4.4)
Aperture stability modulus @ 20cm-kg	Us Army Corps of Engineers	Ib-ft/deg (kg-cm/deg)	0.47 (6.5)	0.419(5.8)
Flexural rigidity (Machine Direction)	ASTM D1388	(Ib-ft) (mg-cm)	0.0542 (750,000)	0.0335 (450,000)
Tensile Modulus @ 2% strain (machine x cross machine direction)	ASTM D6637-01	Ib/ft (kN/m)	18,500 x 30,000 (270 x 437)	19,000 x 32,500 (277 x 474)
Junction direction	GRI GG2-87	Ib/ft (kN/m)	1080 (15.7)	956 (13.9)
Junction efficiency	GRI GG2-87	%	90	90
Carbon Black	ASTM 4218	%	0.5	0.5

2.7. Application Locations of Geogrid

Geogrids tend to be used in one or both of two main locations within the roadbed section [AREMA, 2010];

a) At the bottom of, or within the ballast (Figure2.5) – this provides direct ballast reinforcement and thereby reduces the rate of track settlement; it therefore increases the length of the maintenance cycle. This approach is generally favored when the roadbed is founded on a relatively firm subgrade.

b) At the bottom of the sub-ballast, directly on the existing or prepared subgrade (Figure 2.6) this is done in order to increase the bearing capacity of the track foundation. This approach is generally favored when the roadbed is founded on a relatively soft subgrade

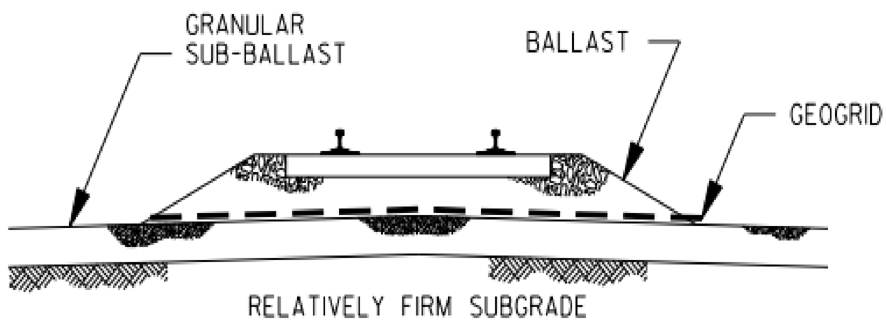


Figure 2.5 Geogrids at the bottom of, or within the ballast [AREMA, 2010]

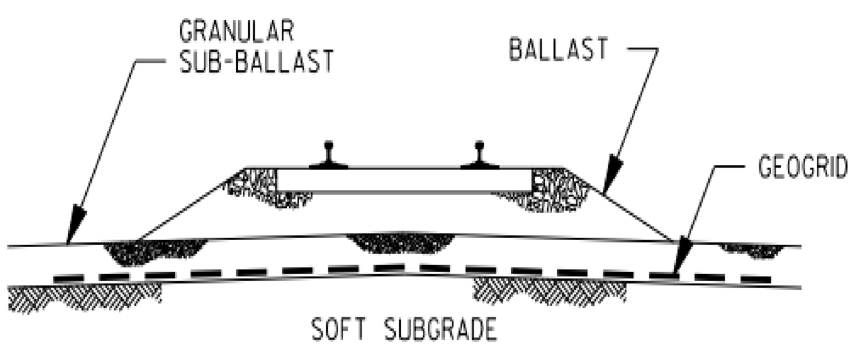


Figure 2.6 Geogrids at the bottom of the sub-ballast, directly on the existing or prepared subgrade [AREMA, 2010]

Figure 2.7 Mechanism of Geogrid reinforced in between Ballast and Sub-ballast [Mike Horton]

Figure 2.8 Mechanism of Biaxial Geogrid reinforced in between Sub-ballast and Subgrade [Mike Horton]

2.8. Ballast with Geogrid

Significant performance benefits have been documented when geogrids are included within the ballast or sub-ballast layers of a roadbed section. The effects of the reinforcement are particularly apparent where the roadbed is placed on soft or medium strength subgrades. Some of the documented benefits in the use of geogrid reinforcement within the roadbed section include the following [AREMA, 2010]:

- Increased ballast life,
- Reduced roadbed thickness (initial cost savings),

- Reduced track deflection resulting in less wear and tear of the mechanical components of the rail track,
- Maintenance of good drainage within the roadbed section,
- Smoother transitions between areas with differing subgrade strengths.

The reinforcement mechanism, often termed "mechanical stabilization", occurs when larger aggregate particles partially penetrate and interlock within the apertures of the geogrid. Subsequent compaction results in the aggregate and geogrid being "interlocked"; forming a semi rigid mat that helps to distribute train loads and thereby reducing stresses on the subgrade[AREMA, 2010]. See Figure 2.9

Geogrids work by interlocking with the granular or soil material placed over them. The apertures allow for strike-through of the cover soil material which then interlocks with the ribs (flat straps/bars) providing confinement of the overlaying granular/soil material due to the stiffness and strength of the ribs (figure 2.9) [www.naue.com].

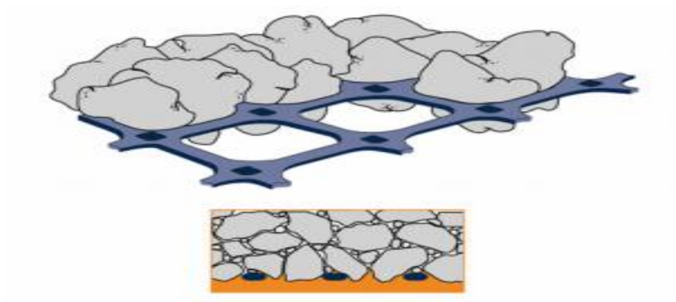


Figure 2.9 The Mechanism of Interlock [AREMA, 2010]

Figure 2.10 a geogrid an interlock with the soil aggregate [www.naue.com]

When reinforcing sub-ballast layers, it is recommended that the aperture size of the geogrid does not exceed the average (D_{50}) particle size of the fill material being used. For ballast layers however, research has shown that the use of a larger aperture geogrid (greater than 1.7 inches (43mm)) almost always leads to optimum performance, irrespective of the particle size of the ballast [AREMA, 2010].

The main objectives of this study were to investigate the effects of geogrid, and how its location and placement affected the deformation of ballast. The inclusion of geogrid within the ballast layer reduced the lateral and vertical deformation of ballast, which was attributed to the ballast particles interlocking and being confined by the geogrid [Ngo, Ngoc].

2.9. Reinforcement Mechanism of Geogrid

The foundation created for understanding the mechanism of geogrid reinforcement which was governed by the type of geogrid for a given particle gradation. The mechanism between geogrid and railway ballast is governed by the interlocking effect of attributed to the ballast particles partially penetrating through the apertures in the geogrid. Having incorporated geogrids within a ballast layer or at the interface of the ballast and sub-ballast, geogrids interact with the surrounding particles to carry the tensile loads induced by the rail vehicles [Ngo, Ngoc].

Through the interlocking and shear interaction between the ballast and geogrids, the ballast particles are restrained laterally and tensile forces are transmitted from the ballast to the geogrids. The vertical load applied through the ballast aggregates above the geogrid can now generate tensile resistance in the ribs with very small deflection. As the geogrids are much stiffer in tension than the ballast, lateral stress in the geogrid-reinforced ballast is decreased and reduced settlement can be observed. This interaction between geogrid and ballast aggregates increases the shear strength and thereby increases the load distribution capacity of the track substructure [Ngo, Ngoc].

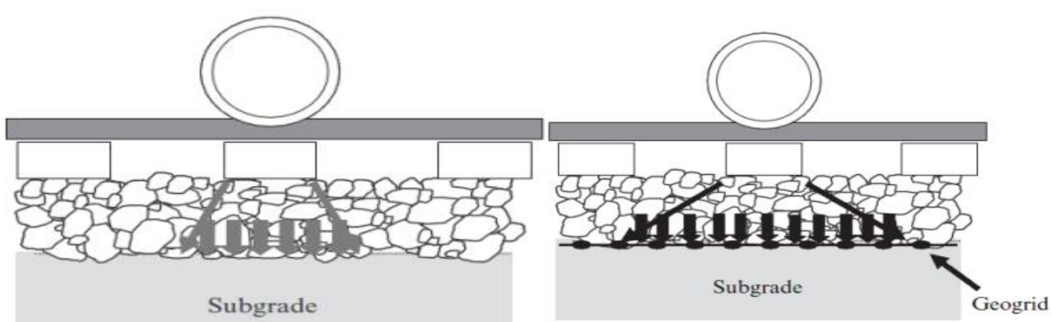


Figure 2.11 Load distribution with and without geogrid reinforcement [Ngo, Ngoc]

2.10. Summary

Track geometry is the main concern to reduce the rate of settlements for poor subgrade soils. These geometries are Subgrade, sub-ballast, ballast, sleeper, rail, and fastener. Hence, to minimize the deformation occurred because of small elastic modulus of such soils; many expensive, disturbing and common repair operations are often required to maintain the ballast characteristics. Because of this, a geosynthetic (geogrid) has to be a simple and economical method of reinforcing track ballast for performing it. The literature review presented in this chapter provided understanding and appreciation of how a geogrid is reinforced in between these geometry to enhance its performance of the materials. The ballast specifications and its typical characteristics were discussed. The review also indicated good understanding on the subject regarding track component and track forces and the effects of Geosynthesis on the performance of ballast.

This literature also covers in depth ballast degradation, the influence of the driving forces of ballast and ballast settlement. The functions of geosynthetics (geogrid), its characteristics and requirements, significance and use, application location and reinforcement principles are reviewed. The remainder of this thesis will examine and discuss the result of the analysis and modeling of railway ballast reinforced by geogrid with the aid of FEA package ABAQUS.

CHAPTER THREE

3. MODELING AND FINITE ELEMENT ANALYSIS OF RAILWAY WITH GEOGRID

3.1. Introduction

General evidence of experimental consequences from Finite Element modeling and stimulating implications from parametric studies automatically directed to the numerical modeling and simulation of geogrid reinforcement with actual ballasted railway foundation geometry and conditions.

Upcoming work and correspondence with ERC (Ethiopian Railway Corporation), in addition to consultation of current CIECC (China International Engineering Consulting Corporation) code has resulted in standard railroad ballast design and geometry specifications, allowing numerical studies of the effects of Geogrid on track settlement, subgrade stress distribution under various conditions.

A plane strain slice of the cross-section of a half of a ballasted railway substructure was modeled with a finite element mesh refined to observe important behavior of the foundation under loading, with or without geogrid reinforcing the sub-ballast-ballast interface. The parametric studies examined the effects of subgrade stiffness, geogrid stiffness, and ballast strength. The selection of material properties, loading of the track and Finite element analysis can be carried out.

Hence, ABAQUS is used as a finite element solver software package to formulate the finite element model for Rail track with geogrid reinforced bases. The results of the analysis were compared with an unreinforced rail track sections at the same geometry and material properties. At the end, the comparison between reinforced and unreinforced of the ballast summary have been given.

3.2. General Overview of the Project

The project is located in Addis Ababa, the capital of Ethiopia, which was the location of the head office of African Union. The altitude of the plateau is 2,400m. With an urban population of over 3,400,000, it takes 24% of the total population of Ethiopia. The urban area is 530.14 km^2, and the density reached 5,607.96/km^2. To effectively solve the problem of urban transportation, especially that of the downtown area, the government of Ethiopia decides to build a light rail in the city of Addis Ababa. Currently this project has planned two lines, the east-west line and the south-north line. About 3 km is the sharing section for both E-W route and N-S route, which has the greatest passenger current.

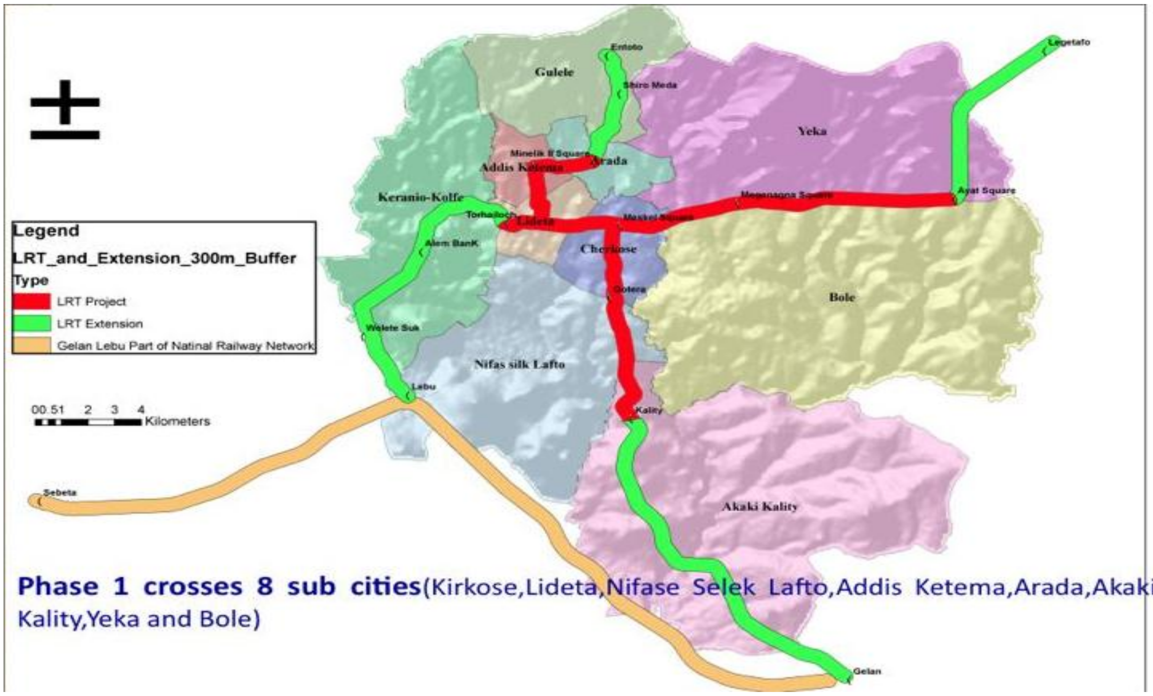


Figure 3.1 Design Alignment of Addis Ababa Light Rail Transit [ERC]

The area selected for this thesis is the station between YDK21+010 to YDK21+070. The station center mileage is YDK21+040 with a length of 60m.

3.2.2 Topography and landform of the Area

This station belongs to Ethiopian Plateau terrace landform and the terrain is flat, wide and undulating slightly, with the altitude of 2,402 to 2,404m and relative height difference of about 2m. The vegetation is sparse and residential areas on both sides are dense. This line, along which the traffic is heavy, is located at the reserved corridor in the central ASMERA ROAD, with a width of about 10m. Refer to figure 3.2 for the topography and landform.

Figure 3.2 Topography and Landform of Survey Area [ERC]

3.2.3. Recommendations for engineering design of the area after all tests

The station exploration reveals that the overburden layer of the survey area is very thick (1~6m) and contains 5 kinds of rock-soil layers in all, which specifically are:

Stratum Code	Name of Rocks and Soil	Depth	Depth
<1-2>	Plain crushed stone fill		0.0-1.00m
<2-2>	Clay		0.00-2.00m
<2-2-1>	Clay		2.00-5.00m
<5-1>	Completely weathered tuff		5.00-6.00
<5-2>	Strongly Weathered tuff		>6.00m

Figure 3.3. Borehole log Sheet [ERC]

The soil layers are generally known as clay soils called Black cotton soils according to local peoples. These black cotton soils have the properties of swelling during summer or when it get moisture and shrink during dry time. It has known by high plasticity index, high free swelling ratio and very small vertical compressive modulus (E_v) according to laboratory results. These suggested that the soils bearing capacity is very poor to resist the load coming on it. Hence, it is recommended to replace these layers by crushed aggregate as per CIECC (China International Engineering Consulting Corporation).

3.3. Geometry and Cross-Section

The Embankment is 7.70 meters in width at the crest, 9.70 meters at the base of sub-ballast, and 0.60 meters in height. (See figure 3.4)

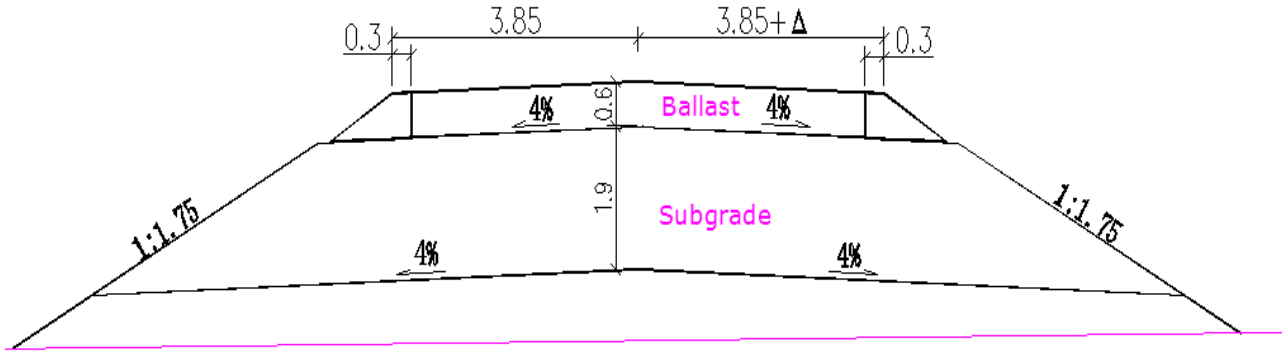


Figure 3.4 Embankment cross-section [ERC]

3.4. Cross Sections of Ballasted Materials

3.4.1. Rail Section

Table 3.1. Rail profile used is UIC50 [Kedir Abdu]

Rail Profile	**UIC50**
Section weight Kg/m	54.77
Rail height mm	152.00
Head width mm	70.00
Web thickness mm	15.50
Foot width mm	132.00
Moment of inertia I_{xx} mm^4	2337.90
Moment of inertia I_{yy} mm^4	419.20
Section modulus of the head mm^3	278752.83
Section modulus of the base mm^3	311180.62

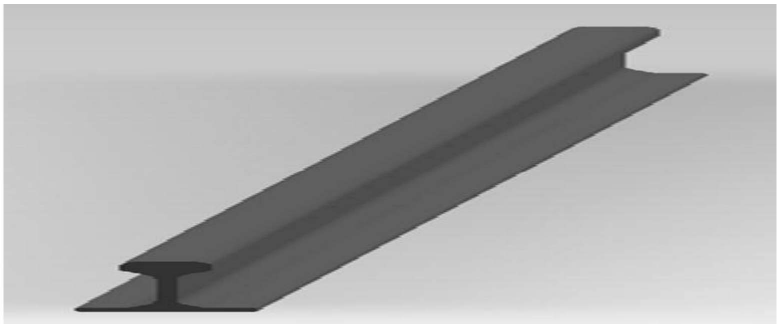


Figure 3.5 3D model of rail profile UIC50

3.4.2. Rail Pad Type-II Section [Kedir Abdu]

The rail pad for the case study is modeled as the following dimensions:

Length, L =240mm, Width, W= 140mm, Thickness, t = 5mm

3.4.3. Sleeper section

The Sleeper is modeled with the following dimensions shown below (Sleeper type B58) [Kedir Abdu]

Table 3.2. Sleeper profile used [Kedir Abdu]

Parameters	Value
Concrete Volume	Approx. 0.127m3
Length (L)	2520 mm
Width (W)	300 mm
Sleeper height (H)	233 mm
Height of center of rail base (h1)	225 mm
Height sleeper center (h2)	175 mm
Support surface (total)	639.2 cm

3.5. Geo-Synthetics

The dimensions of geo-synthetics is selected based on the recommendations stated in AREMA and based on verified dimensions from literatures.

Table 3.3 Physical and strength characteristics of geogrid used [Indraratna, B., Mohamed A]

Characteristics	Unit	Data
Material	-	Polypropylene
Mass	g/m2	420
Aperture size (rectangular)	mm/mm	24 x 23
Tensile strength at 2% strain	KN/m	10.5
Tensile strength at 5% strain	KN/m	21
Peak tensile strength for the weakest soil strength CBR values	KN/m	60

3.6. Analysis Using a Finite Element Model

3.6.1 Introduction

Finite element modeling of reinforced Railway foundation includes geometry modeling, load modeling and material modeling. The commercial FEM program ABAQUS /CAE was used in this study. ABAQUS is a powerful finite element software package. It can deal with bodies with various loads, temperatures, contacts, impacts, and other environmental conditions.

3.6.2. Analysis using ABAQUS/CAE

ABAQUS is a suite of powerful engineering simulation programs, based on the finite element method that can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations. It has an equally extensive list of material models that can simulate the behavior of most typical engineering materials including metals, rubber, polymers, composites, reinforced concrete, crushable and resilient foams, and geotechnical materials such as soils and rock [ABAQUS 6. 12].

Designed as a general-purpose simulation tool, ABAQUS can be used to study more than just structural (stress/displacement) problems. The element functions are gathered in the global equation system containing material and geometrical data. The forces applied on the element geometry are represented by load vectors that act in the nodes. The matrixes quickly increase in size and demand high computer performance to be solved. The nodal deflections are the solution to the equation system. The values between the nodes are received by interpolation with either linearly approximations or polynomials of n degrees.

A complete ABAQUS analysis usually consists of three distinct stages: preprocessing, simulation, and post-processing. These three stages are linked together by files as shown below [ABAQUS 6. 12]:

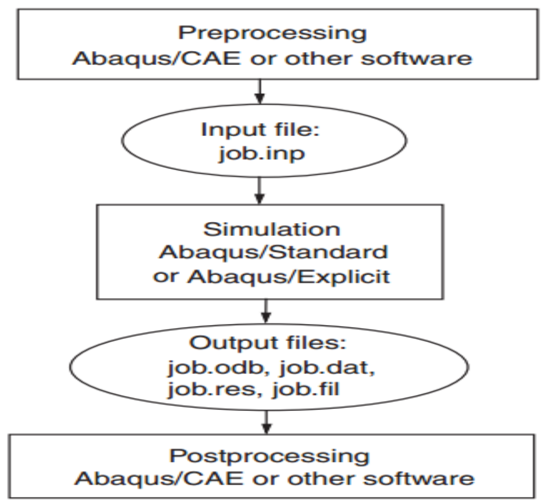


Figure 3.6 ABAQUS Analysis stages [ABAQUS 6. 12]

3.6.2.1 Preprocessing

It comprises all the steps to create the model with ABAQUS/CAE. The following principal steps are taken sequentially:

- Creating a part/defining the model geometry
- Defining the material and section properties.
- Creating an assembly.
- Configuring the analysis.
- Assigning interaction properties.
- Applying boundary conditions and loads
- Designing the mesh.
- Creating, running, and monitoring a job.

Below are discussions of procedures and assumptions made for the preceding steps in modeling the Railway layer system. Before starting of ABAQUS/CAE, the dimension can be set, because ABAQUS/CAE has no its own Unit by default.

Before starting to define this or any model, deciding which system of units used. Because of ABAQUS has no built-in system of units. All input data must be specified in consistent units. Thus, in this model SI (mm) is used as shown in Table 3.4

Table 3.4: Consistent units used in the model input and outputs [Yalelet Endalemaw]

Quantity	Length	Force	Mass	Elastic Modulus	Time	Stress	Density
SI(mm)	mm	N	Tone(10^3Kg)	MPa	S	MPa	10^3kg/mm^3

3.6.2.1.1. Creating a Part /Defining the Model Parameters of Railway Geometry

The model is created with a three-dimensional, deformable body with a solid, extruded base feature. Parts can be created as native to ABAQUS/CAE, or can be imported created by other applications either as a geometric representation or as a finite element meshes. Thus, for this thesis a model native to ABAQUS/CAE using the sketcher, by a deformed 3D extrusion option is created. The following dimensions are used:

i. Modeling of Rail

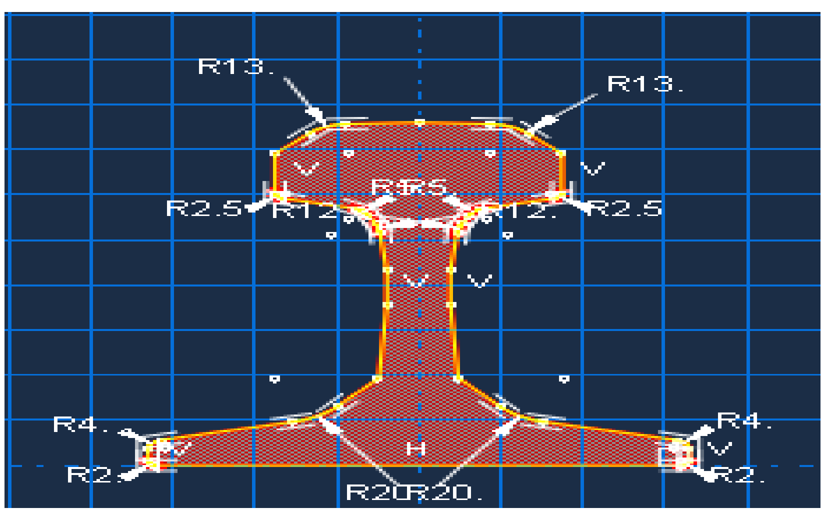


Figure 3.7 Modeling in ABAQUS sketcher of Rail.

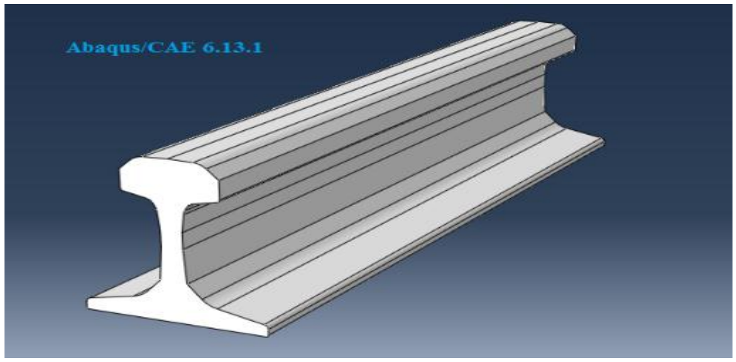


Figure 3.8 Modeling in ABAQUS 3D of Rail profile.

All materials are modeled according to this procedures. It is noted in appendix B of this thesis. The next step in creating the model involves defining and assigning material and section properties to the part. Each region of a deformable body must refer to a section property, which includes the material definition. In this model the rail, sleeper are made of steel and assumed to be linear elastic with its own young's module and a poisons ratio. Similar to the above ballast, sub-ballast are made of rock or crushed aggregate and sub-grade is made of soil. Geogrid is made of polypropylene materials with its own material properties. Thus a single linear elastic material are created with properties tabulated below.

3.6.2.1.2. Material Properties

The material properties used for FEA listed under are from manuals, manufacturer's specifications and design specification of Addis Ababa/Sebeta-Djibouti railway project.

1. **Rail: UIC50 Properties [ERC]**

Table 3.5 FE properties of Rail

Profile	**UIC50**		
Property	Unit	Value	Remark
Mass Density, ρ	kg/mm^3	$7.729*10^5$	
Elastic Modulus, E	MPa	206000	
Poisons Ratio, υ	-	0.3	
Tensile Strength, Rm	MPa	>1180	Standard High Strength Steel
Elongation at Rapture, in 2 inches	%	≥ 10	

2. Sleeper: Type-II S58 concrete sleeper[ERC]

Table 3.6 Type-II S58 concrete Sleeper FE Properties [14]

Profile	Unit	Value	Remark
Concrete Grade	MPa	50/60	
Mass Density, ρ	kg/mm^3	$2.3*10^5$	
Elastic Modulus, E	MPa	36000	
Poisons Ratio, υ	-	0.3	
Unit Weight, ɤ	Kg/m^3	2400	
Weight	Kg	Approx. 312	

3. Ballast, Sub-Ballast and Subgrade properties [ERC]

Table 3.7 FE properties of Ballast, sub-ballast and subgrade.

	Unit	Ballast	Sub-Ballast	Subgrade	Remark
		Value			
Mass Density, ρ	kg/mm^3	$1.8*10^5$	$1.8*10^5$	$1.6*10^5$	
Elastic Modulus, E	MPa	170	170	6.28	
Poisons Ratio, υ	-	0.3	0.3	0.25	
Internal Friction angle(Ø)	%	48^0-55^0	48^0-55^0	16.5^0	Justin Kennedy
Cohesion (c)	MPa	Approx.0	Approx.0	$73.3x10^{-3}$	ERC

The Subgrade is supposed to be quite soft to show the consequence of geosynthetics reinforcement and this is the type of Subgrade that exist at the Chainage YDK21+010 to YDK21+070 along the route of Addis railway project.

4. **Geogrid Properties**

Table 3.8 FE properties of Geogrid [14]

Property	Unit	Value	Remark
Mass density, ρ	Kg/mm3	≥0.94	
Elastic Modulus, E	MPa	350	
Poisons Ratio, υ	-	0.35	
Ultimate Elongation(min)	%	500	
Tensile strength	MPa	60	
Seam Peel Strength	N	-	
Flexural rigidity (machine direction)	Mg-cm	750000	
Junction strength,	N/mm	15.7	

3.6.2.1.3. Creating an Assembly

Each part created is oriented in its own coordinate system and is independent of the other parts in the model. Although a model may contain many parts, it contains only one assembly. The geometry of the assembly is defined by creating instances of a part and then positioning the instances relative to each other in a global coordinate system. Thus, the Rail, Sleeper, Ballast, Sub-ballast and Subgrade are assembled together with and without Geogrid Reinforcement. Therefore; based on the above geometric parameters, ballast embankment reinforced and unreinforced with geogrid are modeled with ABAQUS as shown below.

A. Unreinforced FE Model

The geogrid unreinforced model consisted of 23,735 number of nodes and 19,094 number of elements with Element types: C3D8R DASHPOTA SPRINGA

A three-dimensional axi-symmetric finite element model was developed as shown in Fig. 3.9. The Rail, Sleeper, Ballast, Sub-ballast, and Subgrade layers were used (Figure 3.9) to simulate the railway structure of the track. Eight-node elements were used throughout the mesh. The number of elements that were used for each material were as follows: Sleeper, 140; Ballast, 1710; Subgrade soil, 4446.

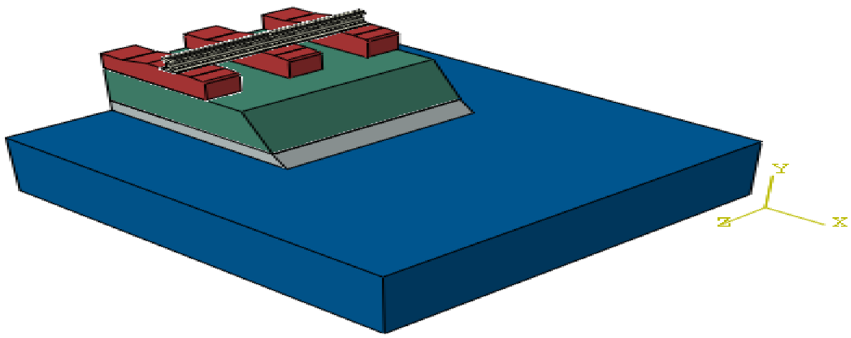


Figure 3.9 Unreinforced Railway track ABAQUS 3D-model

B. Reinforced with Geogrid

The geogrid reinforced model consisted of 26,717 number of nodes, 20,950 number of elements and Element types: C3D8R DASHPOTA SPRINGA. The large number of nodes and elements is because of more refinement is used around the geogrid. The volume of the model is 3.06841e+009 mm^3. Its mass is 1.60432e+015 tone

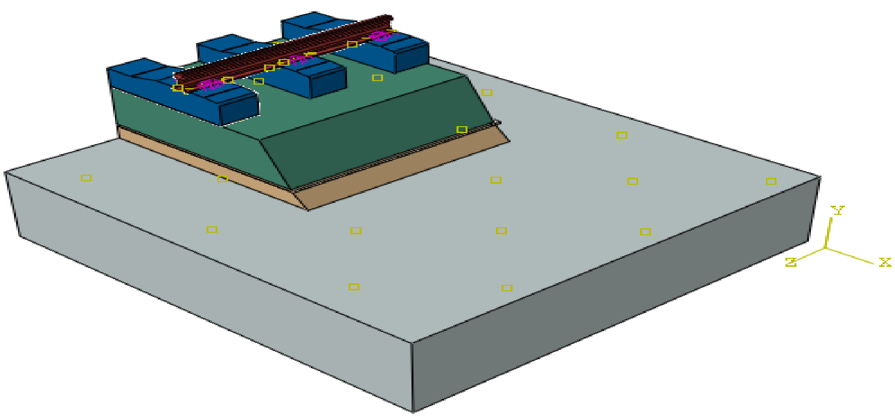


Figure 3.10 Reinforced railway track ABAQUS 3D-model

3.6.2.1.4. Configuring the Analysis

Analysis steps can be mostly characterized as an initial step and analysis steps. A cross-section of a half of a ballasted railway substructure was modeled with a finite element mesh refined to observe important behavior of the foundation under loading, with or without geogrid reinforcing the subgrade-ballast interface.

I. The initial step

ABAQUS/CAE creates a special initial step at the beginning of the model's step sequence and names it *Initial*. It allows defining boundary conditions, predefined fields, and interactions that are applicable at the very beginning of the analysis.

II. Analysis steps

The initial step is followed by one or more analysis steps.

Each analysis step is associated with a specific procedure that defines the type of analysis to be performed during the step. In this thesis, a static linear perturbation step is used. Where in the first analysis step the wheel load is applied.

3.6.2.1.5. Assigning Interaction Properties

The interaction between contacting surfaces consists of two components: one normal to the surfaces and one tangential to the surfaces. The tangential component consists of the relative motion (sliding) of the surfaces.

The contact constraint is applied in ABAQUS when the clearance between two surfaces becomes zero. The surfaces separate when the contact pressure between them becomes zero or negative, and the constraint is removed. The system is subjected to a small force which does not induce slip. Thus, for the tangential component, rough interaction is assumed as there is no slip between the surfaces.

For normal behavior and the tangential behavior “hard” and rough contacts respectively are used in all interactions. But, in this thesis a partition is created on the rail and at the mid span, the load, is applied to the parent rail and mesh. Then interaction is created between all materials i.e. between the rail and the sleepers, sleepers and Ballast, Ballast and Geogrid, Geogrid and Sub-ballast, and Sub-ballast and Subgrade with their interaction properties.

The Ballast-reinforcement interaction was simulated using two contact surface pairs above and below the reinforcement layer. The ABAQUS contact interaction feature uses the constraint approach to model the interaction between two deformable bodies. With this feature one surface definition provides the master surface and the other surface provides the slave surface. After this contact pair is defined, a family of surface contact elements is automatically generated. At each node, these elements construct series measures of clearance and relative shear sliding.

For embankment Ballast-geogrid interface, Normal interaction between geogrid-Ballast was simulated by a "hard" contact while shear interaction between them was modeled with two contact surface pairs above and below the geogrid. Master/slave surface definitions were used for the top and bottom contact surfaces of the geogrid.

Basic Coulomb friction model was used to model the shear interaction, which relates the maximum allowable frictional (shear) stress across an interface to the contact pressure between the contacting bodies. The general form of the coulomb friction model is given below:

$$\tau_{crit} = \mu\sigma \qquad 3.1$$

Where τ_{crit} is the critical shear stress along the interface; σ is the normal stress along the interface; μ is the interface friction coefficient (μ=tanδ, where δ is the interface friction angle).

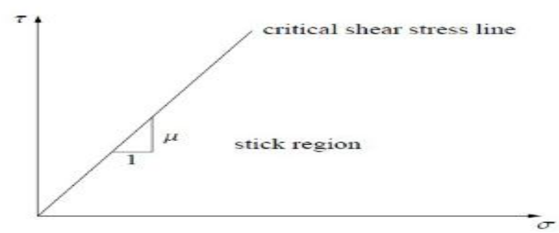


Figure 3.11 Basic Coulomb friction model [Jie Gu B.S]

3.6.2.1.6. Loading

The wheel load chosen for the geometry was very conservative in order to demonstrate track behavior under the worst conditions possible. When two bodies (wheel and rail) are in contact, stresses and strains appear. A large force from the first body (wheel) is transferred to the second body (rail) through a small contact patch of about lcm^2 [Yalelet Endalemaw].

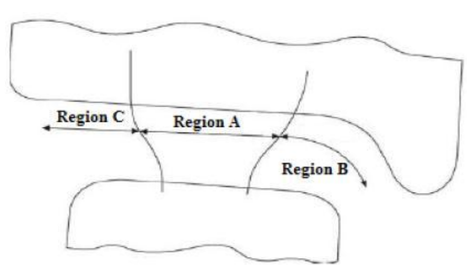


Figure 3.12 Wheel- Rail Contact Zones/Regions [Yalelet Endalemaw]

Wheel rail contact regions can be classified as shown in the above figure:

a) Region A - wheel tread -rail head contact: this contact zone is most common contact region with lower contact stress.

b) Region B - wheel flange- rail gauge corner: this contact zone is much smaller contact area and more severe; higher contact stresses and wear rates occurs.

c) Region C - wheel and rail outer sides contact: this contact zone is least likely contact region with high contact stress, and undesirable wear lead to incorrect steering of wheelset.

C. Rail-Wheel Contact Stress

The forces arising between wheel and rail contact generate contact stresses in a local volume of the two bodies. Hertzian-Contact-Model is most well-known calculation model for this local stresses. Hertzian model describes the local stresses with good accuracy for the most common wheel-rail contact problems. This model also provides a good understanding of general contact phenomena. Although Hertzian theory is valid only for elastic contacts it can be useful far beyond that. Limited plasticity will not affect the contact stresses very much. In wheel-rail contact the two bodies generally have a non- conformal contact **[**Yalelet Endalemaw**]**.

D. Hertzian Contact

The contact forces (stresses) from the wheel load are transferred at a small contact patch, in one or several contact locations.

According to Hertz theory, the normal pressure is distributed as an ellipsoid over the elliptic contact area [Yalelet Endalemaw].

When a wheel and a rail are brought into contact under the action of the static wheel load, the contact area and the pressure distribution are usually determined using the Hertz theory. In Hertz contact theory, no plastic deformation in the contact patch is assumed, and the radii of the curvature of wheel and rail profiles in the contact patch are assumed to be constant. The following formula for the calculation of the mean value of the rolling contact stress

$$\sigma\text{mean} = \frac{Ps\ x10^3}{2a\ x\ 2b} \qquad (3.2)$$

$$2a = 3.04\sqrt{\frac{\text{Ps Rwx1000}}{\text{2b. E}}} \qquad (3.3)$$

Where, b= width of wheel-rail contact area (2b=12mm), a =contact length, Rw= radius of the wheel.

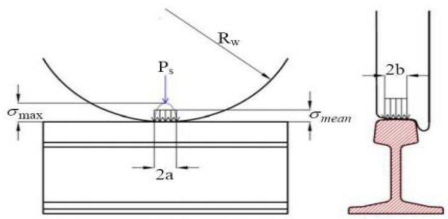


Figure 3.13 Uniform distribution of wheel-rail contact stress [J. Sadeghi]

$$\boldsymbol{a=m}\sqrt[3]{\frac{3\pi}{4}\frac{(K1+K2)N}{A+B}} \qquad (3.4)$$

$$\boldsymbol{b=n}\sqrt[3]{\frac{3\pi}{4}\frac{(K1+K2)N}{A+B}} \qquad (3.5)$$

Table 3.9: Hertz Coefficients n, m for different angle θ [Kalker J. J]

$\theta(deg)$	*M*	*N*	$\theta(deg)$	*M*	N	$\theta(deg)$	*m*	*n*
0.5	61.4	0.1018	10	6.604	0.3112	60	1.486	0.717
1	36.89	0.1314	20	3.813	0.4125	65	1.378	0.759
1.5	27.48	0.1522	30	2.731	0.493	70	1.284	0.802
2	22.26	0.1691	35	2.397	0.53	75	1.202	0.846
3	16.5	0.1964	40	2.136	0.567	80	1.061	0.893
4	13.31	0.2188	45	1.926	0.604	85	1	0.944
6	9.79	0.2552	50	1.754	0.641	90	1	1
8	7.86	0.285	55	1.611	0.678			

m, n- are geometric properties of the wheel and the rail.

φ-is the angle between the radius of the wheel and the rail, called yaw rotation

θ-is the angle between the principal axes.

Where the modulus K_l and K_2 are material properties of wheel and rail (the relative change in the volume of a body produced by unit compressive or tensile stress acting uniformly over its surface) and are given by:

$$\mathbf{K_i}=\frac{1-vi^2}{\pi Ei} \tag{3.6}$$

Then, the Hertzian coefficients can be obtained from Table 3.9 interpolation between 75° and 80° *m*=1.161; *n*=**0.872**

$$K_1=\frac{1-0.3^2}{3.14*2.1*10^{11}Pa}=1.38e^{12}$$

$$K_2=\frac{1-0.34^2}{3.14*1.9*10^{11}Pa}=1.48e^{12}$$

At this point it's possible to determine the contact patch elliptical geometric dimensions a and b

$$a=1.161*\sqrt[3]{\frac{3\pi}{4}\frac{(1.38e^{12}+1.48e^{12})N}{\frac{0.002754}{mm}}}=\mathbf{9.499mm}$$

$$b=0.872*\sqrt[3]{\frac{3\pi}{4}\frac{(1.38e^{12}+1.48e^{12})N}{0.002754/mm}}=\mathbf{7.135mm}$$

$$P_o=\frac{3*223.79e^3N}{2\pi 1.565*1.175}=\mathbf{1577.31MPa}$$

For the National railway network design the design axle load is 25Tone, thereby a 420mm radius standard wheel impose a 12.5Tone load on a 300mm radius wheel head.

So, the maximum contact pressure will be calculated from the Hertzian contact stress.

Design Wheel load (F_v)

$$F_v=ØPs \tag{3.7}$$

Where F_v= design wheel load (kN)

Ps= Static wheel load (kN)

Ø=dimensionless impact factor (>1). This factor is increase over static vertical loads to estimate the dynamic effect of wheel load and rail irregularities.

$$Ø = 1+5.21\frac{V}{D} \qquad (3.8)$$

Where V= Design Speed (km/h =120km/h), D=Wheel Diameter =840mm.

Therefore; Static wheel load is

$$P_S = \frac{axle\ load}{2} = mg = 12.5ton * \frac{1000Kg}{Ton} * 9.81m/s^2 = 122.625KN = 122625\ N$$

$$Ø = 1+5.21\frac{V}{D} = 1+5.21*\left(\frac{120km/h}{840}\right) = 1.744$$

$F_V = ØP_s$= 1.744*122625=**213,858N**

This load, however, is assumed to be applied as a static load and assumed to be transferred to the track surface through the contact pressure of a single tire.

E. Applying boundary conditions

Prescribed conditions, such as loads and boundary conditions, are step dependent, which means that the step or steps in which they become active is specified accordingly. A fixed support at the bottom of mesh was used to prevent horizontal and vertical movement. A roller support was used along both sides of the model to prevent the horizontal movement. See figure 3.14 below.

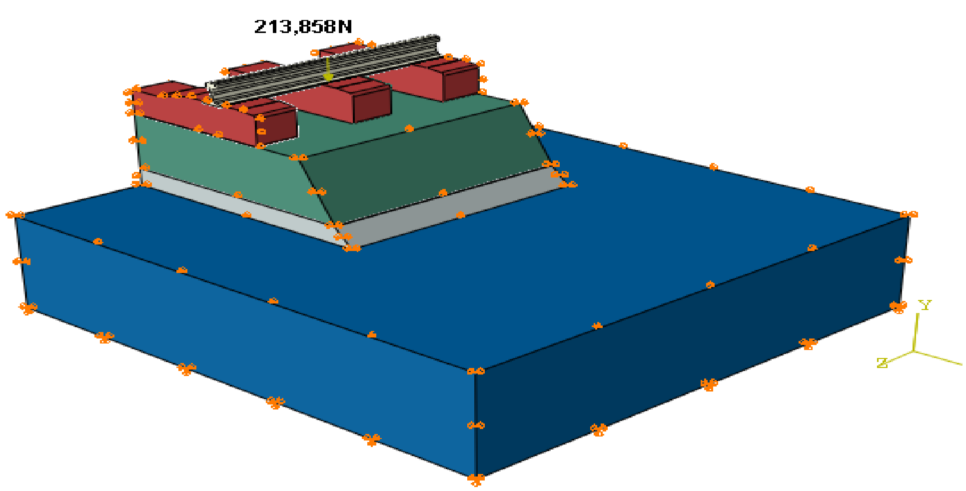


Figure 3.14 loading and boundary conditions of ABAQUS 3D-model

3.6.2.1.7. Designing the Mesh

The Mesh module contains tools that allow generating meshes on parts and assemblies created within ABAQUS/CAE. In the model, a structure meshing is used. Structure meshing is a technique that gives the most control over the mesh because it applies pre-established mesh patterns to particular model topologies. Considerable care is taken to optimize the mesh size so as to get reliable results. Fig 3.15 shows the mesh of the assembly.

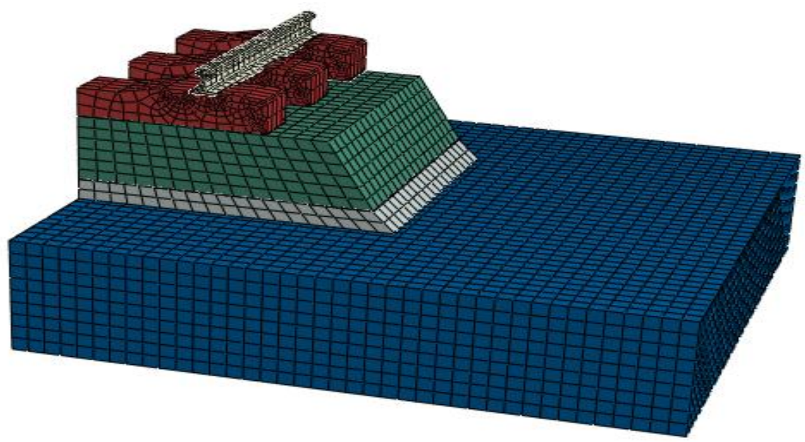


Figure 3.15 Meshing of unreinforced railway track of ABAQUS 3D-model

3.6.2.1.8. Creating, Running and Monitoring a Job

Once defining a model is finished, the model is analyzed using the Job module. The Job module allows interactively submitting a job for analysis and monitoring its progress.

3.6.2.2.Post Processing

The Visualization module provides graphical display of finite element models and results. It obtains model and result information from the output database; it is controlled what information is written to the output database by modifying output requests in the Step module.

3.7. Summary

This chapter also covers in general overview of the proposed area, all the steps and procedures of finite element analysis by ABAQUS were revealed, FE material properties and requirements, significance and use, application location and reinforcement principles are reviewed. The remainder of this thesis will examine and discuss the result of the analysis ballast reinforced by geogrid with the aid of FEA package ABAQUS.

CHAPTER FOUR

4. DISCUSSION OF RESULTS

A chains of simulations were performed on the railway geometry in order to determine the effects of foundation compressibility, settlement and geogrid effects. In order to compare the results, each situation was run with both geogrid reinforcement and no reinforcement for comparison. During the simulation, displacements, lateral deformation, stresses and strains were observed throughout the ballasted track substructure in order to determine the behavior and improvement due to geogrid reinforcement.

The results from the finite element modeling in ABAQUS are presented. The purpose of the modeling is to investigate some important parameters of the railway track. Three static analyses have been carried out:-

- Unreinforced ballast embankment,
- Ballast embankment reinforced geogrid in between Ballast and sub-ballast

The parameters analyzed are:

- Track settlement,
- Lateral Settlement and
- Effects on Subgrade due to unreinforced and reinforced of geogrid

4.1. Track Settlement

This thesis shall be limited only on the analysis of the followings parameters:

1. Vertical deformation (**U2**),
2. Lateral deformation (**U3**) and
3. Subgrade stress-strain distribution results.

Because of most of the time; due to these problems, failures of the track occurs. So, comparison and their results of conclusion are shown below.

4.1.1. Vertical Deformation of the Track

a. Vertical Deformation (U2, mm); without Geogrid reinforcement

Figure 4.1 shows the distribution of vertical deflection along the Railway cross-section for the case of an unreinforced Ballast system having weak subgrade layer.

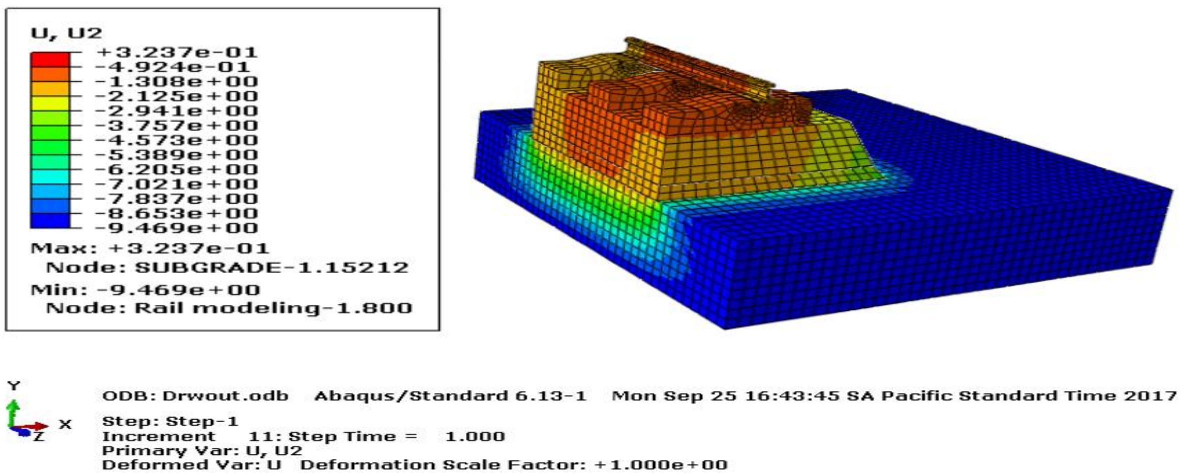


Figure 4.1 vertical deformation of unreinforced ballast system, ABAQUS/CAE.

b. Vertical Deformation (U2, mm); when Geogrid is in between Sub-ballast and ballast

Figure 4.2 shows the distribution of vertical deflection along the Railway cross-section for the case of a reinforced Ballast system having weak subgrade layer.

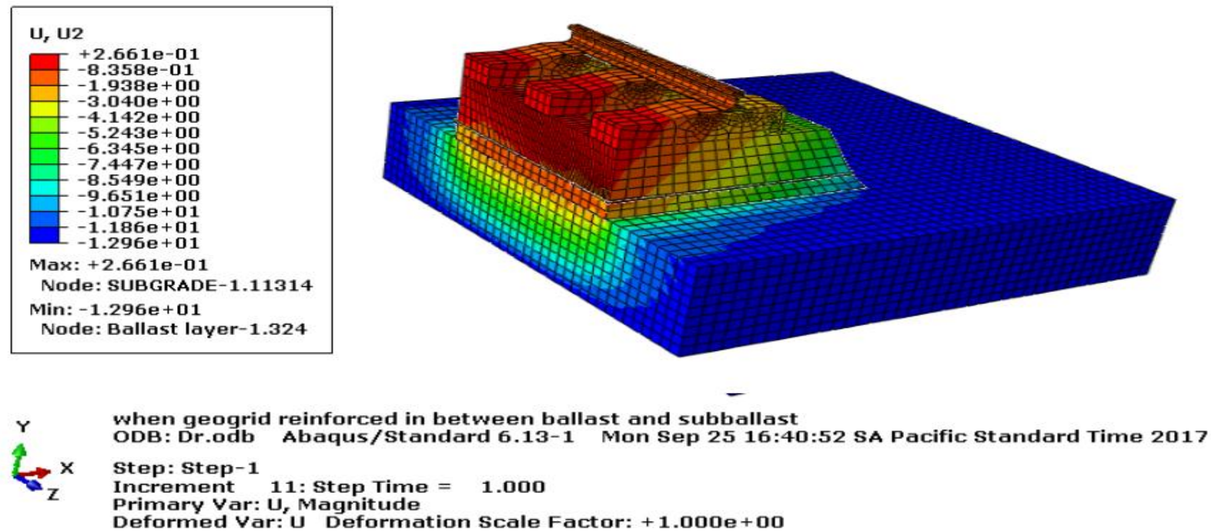


Figure 4.2 vertical deformation of reinforced ballast system; when geogrid is in between ballast and sub-ballast, ABAQUS/CAE.

In here the analysis results are compared and verified based on reinforced and unreinforced ballast. As it has been shown above, there are different kinds of deformation of the assembled railway due to the inclusion of reinforcement. By comparing the maximum deformation, the minimum deformation is occurred on railway foundation, when Geogrid is reinforced in between Sub-ballast and subgrade.

Table 4.1 vertical settlement comparison of unreinforced and reinforced ballasted rail track.

	Unreinforced Ballast	**When Geogrid is in between Sub-ballast and ballast**	**% reduction**
Maximum Vertical deformation, U2(mm)	**0.3237**	**0.2661**	**17.79**

Vertical settlement (%) : $$R_s = \frac{S_{(unreinforced)} - S_{(reinforced)}}{S_{(unreinforced)}} \times 100$$

$$R_s = \frac{(0.3237 - 0.2661)}{0.3237} \text{ x } 100 = \mathbf{17.79\%}$$

This means, reinforcing with geogrid minimize the rate of settlement. On this thesis, when geogrid is reinforced in between ballast and sub-ballast; the rate of track vertical settlement is minimized by **17.79**%.

4.2. Track Lateral Stabilization (U3, mm)

The track lateral deformation means the dispersion of the ballasted materials to both sides of the track. This is because of the ballasted rail track are made up of an aggregate materials which have filled by voids. This may initiate for the lateral instability of the ballasted rail track. Hence, due to the interaction between the geogrid and aggregate is too hard i.e. almost all of the aggregate which settled on the geogrid can be tied by its reinforcement. So that, it will minimize the movement of the aggregates while load applied on it. Due to this reason the aggregate are minimized from dispersion to the sides. Hence, the simulation results of ABAQUS is shown below with its numerical results.

- For Unreinforced railway Track.

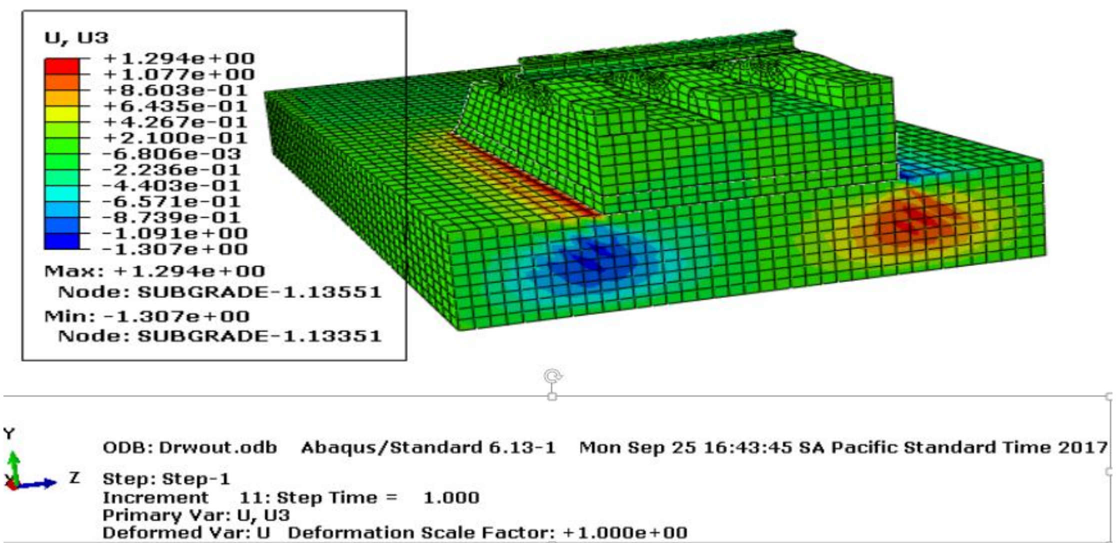


Figure 4.3 lateral deformation of unreinforced railway track, ABAQUS/CAE.

- **For reinforced railway Track; When Geogrid is in between ballast & sub-ballast:** its lateral deformation (U3) simulation is as shown below.

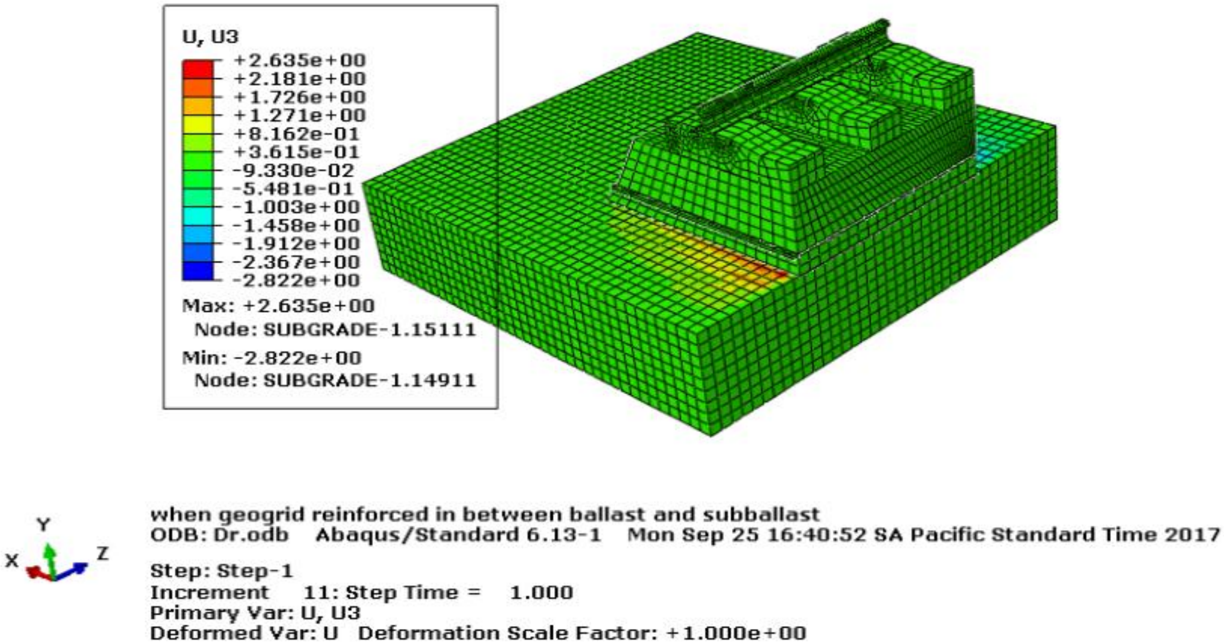


Figure 4.4 Lateral deformation of reinforced ballast system; when geogrid is in between ballast and sub-ballast, ABAQUS/CAE.

Table 4.2 Lateral settlement comparison of unreinforced and reinforced ballasted rail track when geogrid is below Sub-ballast.

	Unreinforced Ballast	**When Geogrid is in between Sub-ballast and ballast**	**% Stabilized laterally**
Maximum lateral deformed, U3 (mm)	**1.294**	**2.635**	**50.89**

Stabilized due to geogrid (Sg) = $\frac{(2.635-1.294)}{2.635}$ x 100= **<u>50.89</u>%**

Table 4.2 illustrates the analysis output for geogrid reinforced ballast embankment lateral Confinement was achieved by the geo-grid restraining the lateral deformation of the track. According to this thesis; Geogrid increase the stabilization of lateral deformation of the track by **50.89%**; when reinforced in between Sub-ballast and ballast.

4.3. Results of Subgrade due to unreinforced and reinforced of geogrid on ballasted rail track.

4.3.1. Subgrade Deformation (U $_{2,}$ mm) Results of unreinforced railway track.

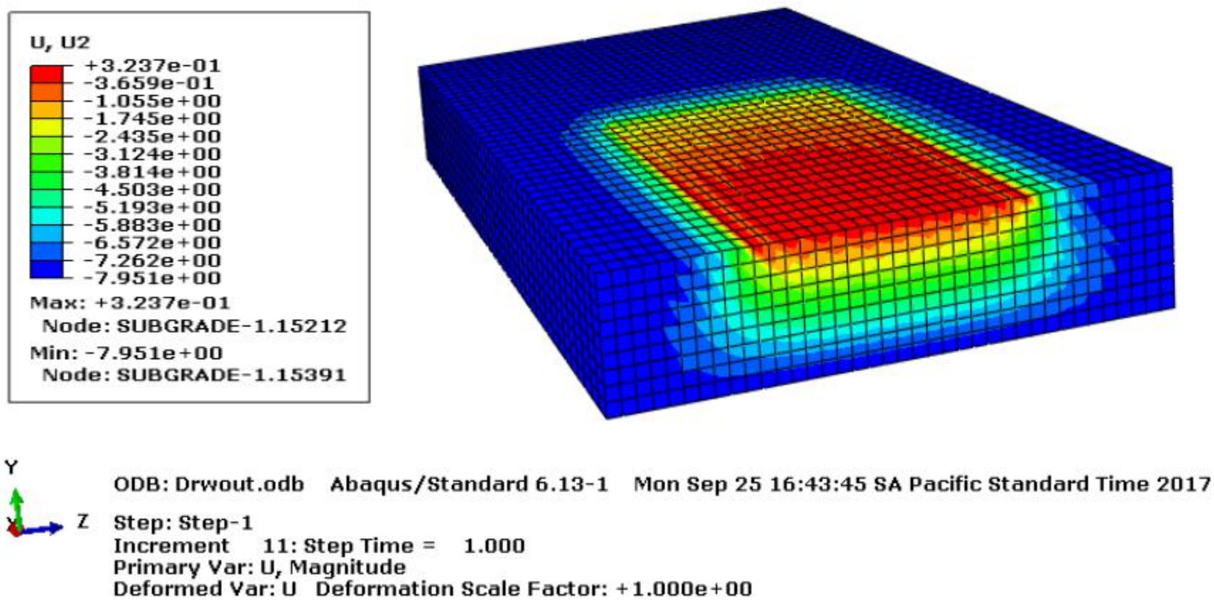


Figure 4.5 subgrade deformation for unreinforced results, ABAQUS/CAE.

4.3.2. **Subgrade Deformation (U $_{2,}$ mm) Results of reinforced railway track**

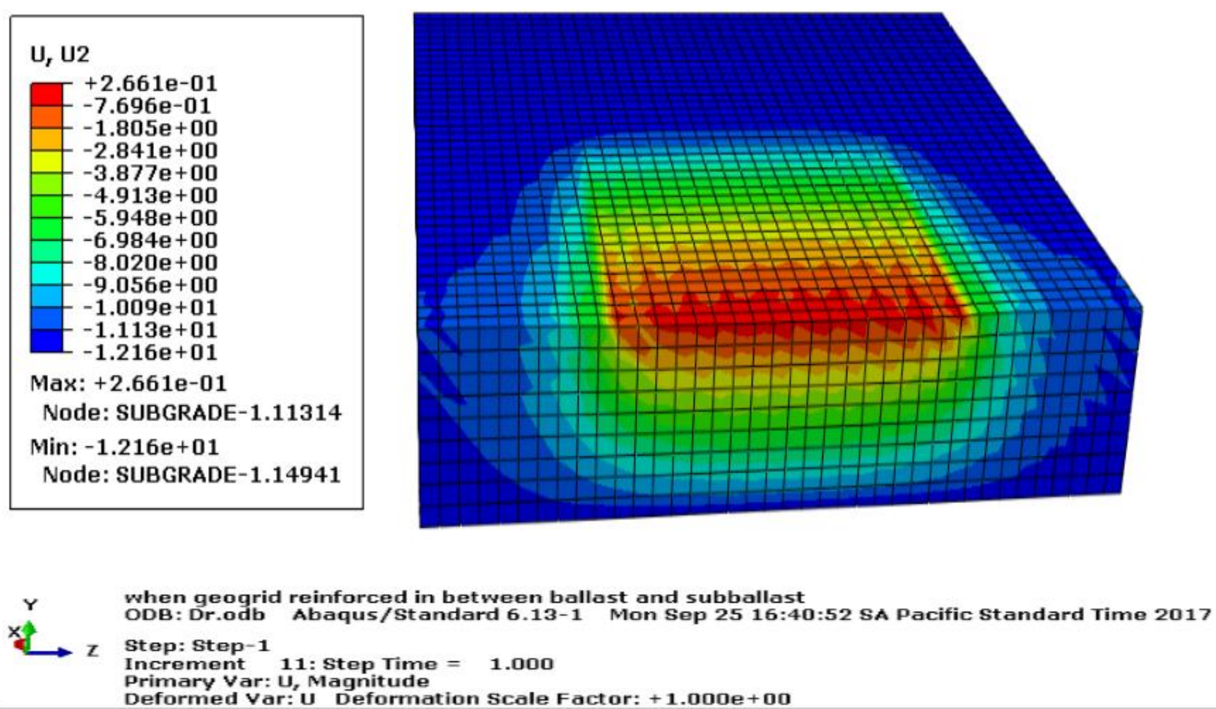


Figure 4.6 Subgrade deformation for geogrid reinforced between ballast and sub-ballast results, ABAQUS/CAE.

Table 4.3 Comparison table of unreinforced and reinforced ballasted track.

	Unreinforced Ballast	When Geogrid is in between Sub-ballast and ballast	% Reduction
Maximum deformation, U_2 (mm)	**0.3237**	**0.2661**	**17.79**

Figure 4.5 and figure 4.6 shows that, the increase in the geogrid tensile modulus (or stiffness) results in significant reduction of permanent deformation of the layer. Due to geogrid reinforcement the subgrade settlement can be minimized by **17.79%.** This means the geogrid reinforcement can extend the service life of track.

4.3. Stress-Strain Distribution Result

Usually, the preliminary point for stress analysis are a geometrical explanation of the structure, the properties of the materials used for its parts, how the parts are joined, and the maximum or typical forces that are expected to be applied to the structure. The output data is typically a quantitative description of how the applied forces spread throughout the structure, resulting in stresses, strains and the deflections of the entire structure and each component of that structure. The analysis may consider forces that vary with time, such as machine vibrations or the load of moving vehicles.

4.3.1. Stress-strain distribution of Subgrade for Unreinforced ballasted track.

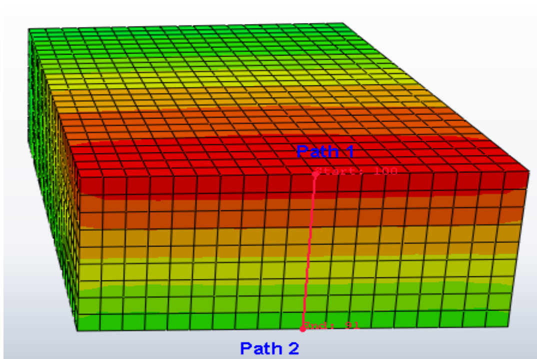


Figure 4.7 Subgrade path 1 and path 2 for stress versus strain Results

Table 4.4 Stress-strain through path 1 and path 2 of unreinforced ballasted track.

Stress(MPa)	0.000	13.85	13.796	13.611
Strain(mm/mm)	0.0000	0.000527944	0.000591752	0.000744485

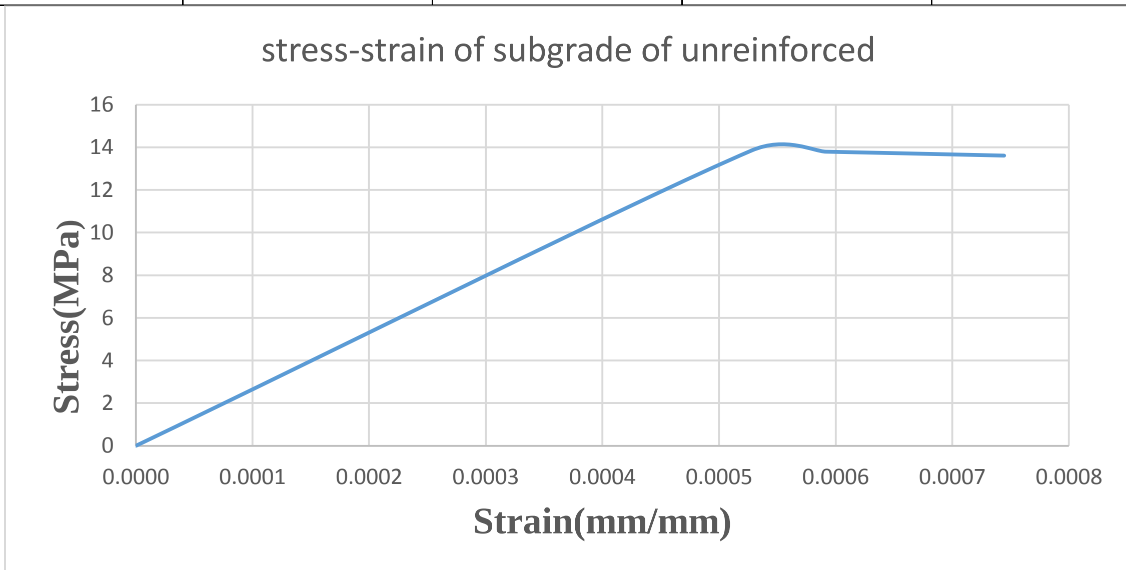


Figure 4.8 subgrade stress versus strain of unreinforced ballast, ABAQUS, CAE

Under a static loading, Figure 4.8 shows the analysis output for unreinforced ballast embankment subgrade stress as a function of the subgrade strain. As can be seen from this figure; the strain **εo** at maximum stress increases with curves for an increase in material strength.

4.3.2. Stress-strain distribution of Subgrade for reinforced ballasted track

The research is only done for only elastic settlements. Because, it is considered that crushed stone assumed to deform immediate than plastic settlement.

Table 4.5 Stress-strain through path 1 and path 2 of reinforced ballasted track

Stress(MPa)	**0.00**	13.85	13.796	13.611
Strain(mm/mm)	0.000	0.00067198	0.00072233	0.000742295

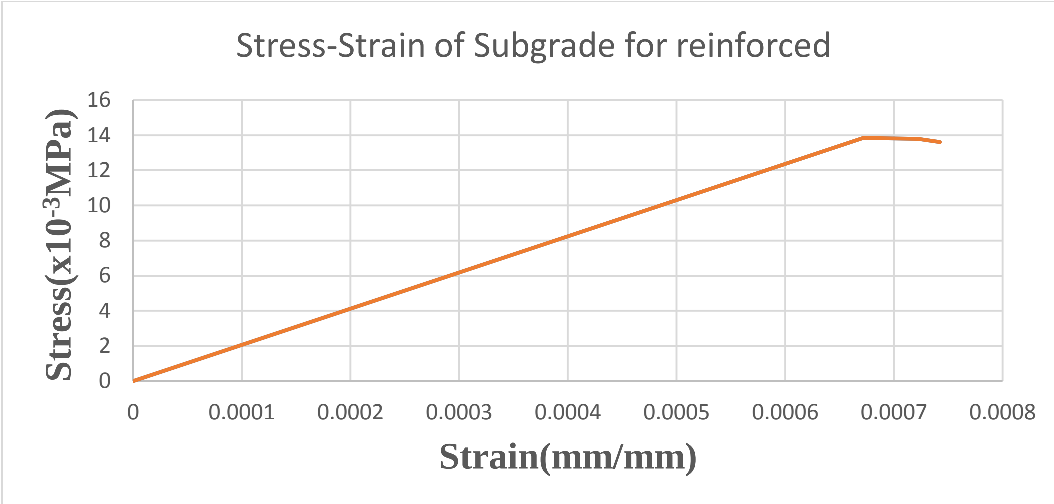


Figure 4.9 subgrade stress versus strain of reinforced ballast, ABAQUS, CAE

Under a static loading, Figure 4.9 shows the analysis output for reinforced ballast embankment subgrade stress as a function of the subgrade strain. As can be seen from this figure; the strain **εo** at maximum stress increases with curves for an increase in material strength. Generally; when the stress increase the strain also increase and start to decrease at a some pick point of stress the stress start to decrease.

4.3.3. Stress- Strain Comparison Results Between Unreinforced and Reinforced

The lateral strains profiles at different distances from the center of the wheel load predicted from the finite element analysis within the subgrade layer for unreinforced and reinforced. In these sections, the geogrid layer was placed at the bottom of ballast layer or in between ballast and sub-ballast layer. It can be seen that the geogrid layer significantly constrained the lateral strains within the subgrade layer as shown below (refer figure 4.10 and figure 4.11). And geogrid with higher tensile modulus has more reduction in lateral strains developed in the reinforced sections.

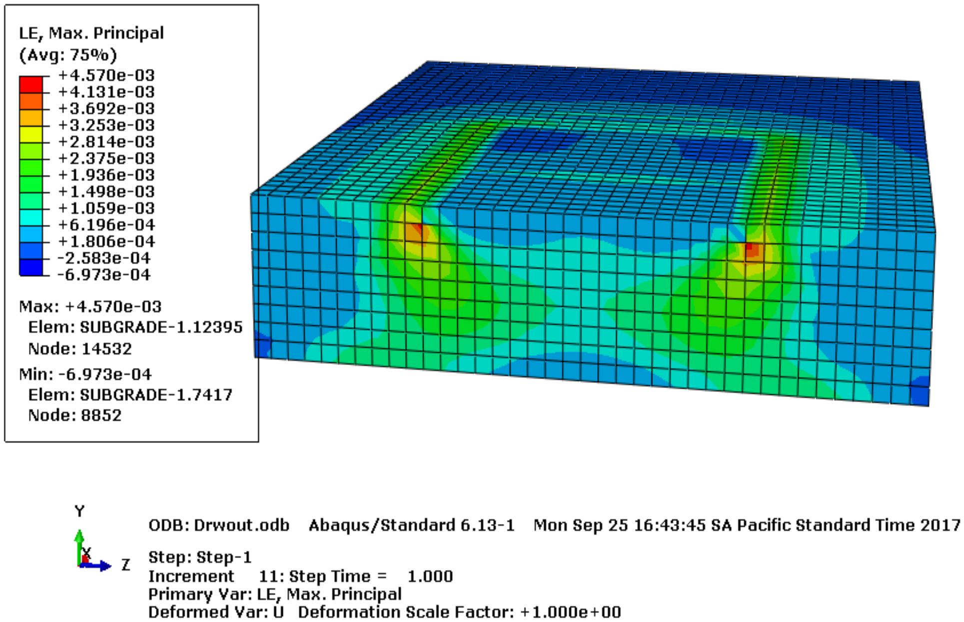


Figure 4.10 Lateral strain of unreinforced geogrid railway track output

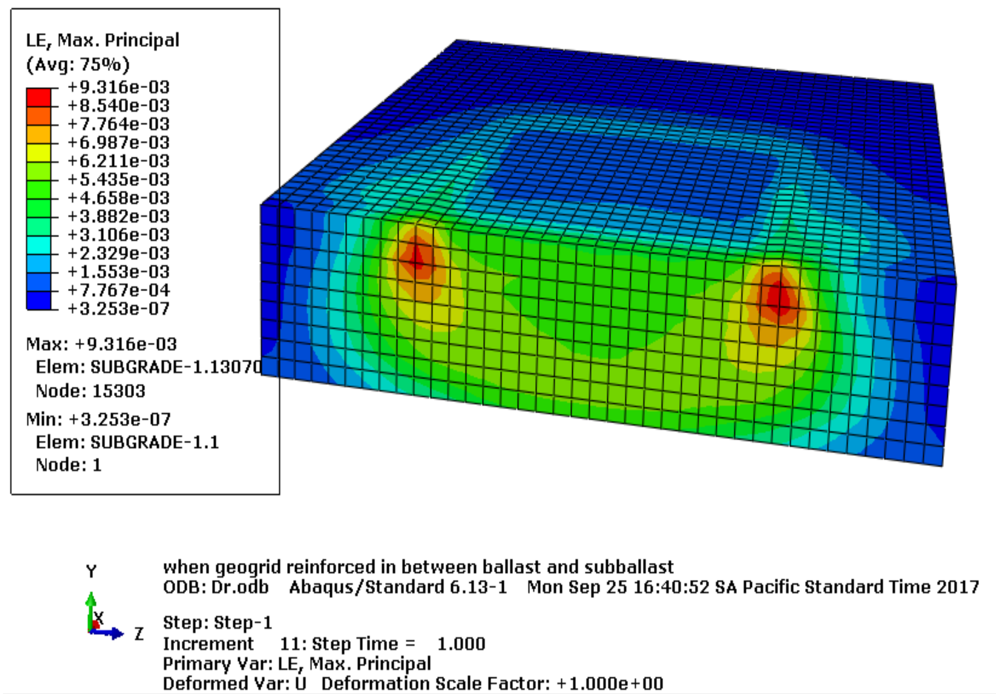


Figure 4.11 Lateral strain of reinforced by geogrid Railway track output

4.3.4. Stress versus Deformation results

4.3.4.1. Stress versus Deformation of subgrade for reinforced and Unreinforced Ballasted Track

Table 4.6 Stress versus displacement of subgrade of reinforced and unreinforced of railway at path 1-2

Stress(x10-3MPa)	Unreinforced Displacement(mm)	Reinforced Displacement(mm)
	7.70178	1.67879
13.796	7.07727	1.63517
13.611	5.93184	1.3805
13.6717	5.31866	1.30096
13.8138	4.18059	1.06496
14.1016	3.51757	0.939579
14.4306	2.45604	0.726814
15.2306	1.7248	0.544229
16.8361	0.792221	0.348202

Comparing the two above Table 4.6; at the same stress the deformation of unreinforced ballasted track is higher than the reinforced one. This means the reinforced ballasted track stiffer to deform than unreinforced ballasted track. This results shows that as it is possible to improve the poor subgrade soil by using geogrid reinforcement method easily.

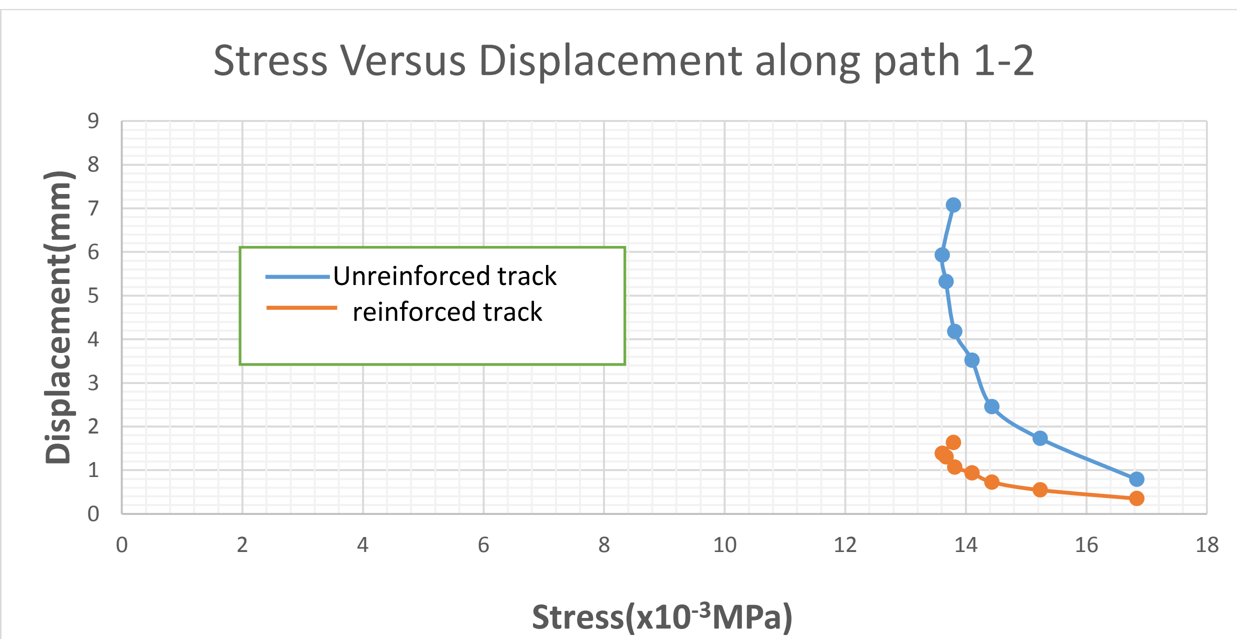


Figure 4.13 Stress versus Deformation of Subgrade results of unreinforced at through path1-2

Figure 4.13 shows that the Stress versus Deformation of subgrade for unreinforced at constant Stress of 16.8361×10^{-3} MPa is 0.792mm and that of the reinforced one is 0.348mm.

4.4. Summary

The benefits of using geo-synthetics to improve the ballasted track characteristics and durability of reinforced geogrid structures are widely recognized. Geogrids, as one of the most commonly used forms of reinforcement, offers improved interface resistance due to interlocking, in particular when compared to commonly used alternatives.

In the present study of geogrid reinforced structures geogrid reinforced ballasted track system were modeled by applying finite element analysis to investigate their potential improvements. For this purpose, the study, comprised of two distinctive parts, assessed the influences of different variables and parameters contributing to the improved performance of reinforced foundation and unreinforced ballasted track system. Based on the findings of the above analysis, finite element models that can simulate the performance of geogrid. Finite element analyses of different parameter combinations were run to investigate their influence on poor subgrade soils. The parameters studied included: settlement of the track and lateral deformation of the track, and subgrade stress versus strain. Finite element analyses that can simulate the behavior of ballasted track with reinforced.

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this thesis was to study the static effects and the performance of substructures of railway track by reinforcing with geogrid based on three dimensional finite element analysis methods. Considering the complexity, different models were created and compared. These models are unreinforced, reinforced with geogrid. Conclusions about the method and results are presented below.

5.1. Conclusion

Based on the results of the numerical modeling analysis of geogrid reinforced ballasted track system, the following conclusions can be drawn:

- The Reinforcement of the ballast using Geogrid was reasonably effective in reducing vertical deformations **17.79%**; when geogrid is reinforced in between Ballast and Sub-ballast.
- Due to the reinforcement of geogrid on ballasted track the lateral deformation of the track was rather stabilized to **50.89%.** The use of the geogrid more likely contributes resistance to deformation above, below and within the cell through frictional resistance and of the Ballasted composite. This means the lateral deformation of the ballasted track is minimized by reinforcement of geogrid.
- The increase in the geogrid tensile modulus (or stiffness) results in significant reduction of permanent deformation. Hence, the geogrid reinforcement extend the service life of ballasted track.
- Reinforced ballasted track can carry a stress almost more than unreinforced ballast track.
- When geogrid is reinforced in between the layer of the railway, it minimize the settlements of the foundation. So, in order to solve the problem of poor subgrade conditions, using geogrid reinforcement is one of the major key.

5.2. Recommendation

- The result of this paper can be a starting point to develop a methodology for further detail stabilization of poor subgrade soils rather than replacement of the ballasted track and Maintenance strategy.

5.3. Suggestions for Future Studies

Based on the findings of the present study, it is evident that further research in this field can yield practical and valuable result. Hence, future studies should focus on:

a. Extend the finite element work on geogrid reinforced ballasted track to reinforce more than two geogrid location, possibly using double georgic layer, etc.
b. Using the finite element model for the reinforced soil foundation to simulate a full scale geogrid reinforced approach slab embankment and compare the finite element results with field measurements from monitoring instrumental embankments.
c. The aperture size of the geogrid and the grain size needs a thorough investigation since the principles of reinforcement of the geogrid lies on the interlock of the geogrid and the ballast. Hence, it needs a more detail study.

REFERENCES

[1] Justin Kennedy; a full-scale laboratory investigation into railway track substructure performance and ballast reinforcement, January 2011.

[2] Indraratna, B, Khabbaz, H, Salim, W and Christie, D, Geotechnical Properties of Ballast and the Role of Geo-synthetics, Journal of Ground Improvement, 10(3), 2006, 91-102.

[3] Indraratna, B, Rujikiatkamjorn, C, Vinod, JS & Khabbaz, H, A review of ballast characteristics, geosynthetics, confining pressures and native vegetation in rail track stabilisation, Transport Engineering in Australia, 12(1), 2009, 25-35.

[4] Chaitanya Calla, Two Layered Ballast System for Improved Performance of Railway Track, A Thesis Submitted In Partial Fulfilment of the University's Requirements for the Degree Of Doctor Of Philosophy, December 2003.

[5] Huan Feng, 3D-models of Railway Track for Dynamic Analysis, Master thesis for Division of Highway and Railway Engineering, at the Royal Institute of Technology (KTH) in Stockholm. November 2011.

[6] Roar Nalsund, Railway Ballast Characteristics, Selection Criteria and Performance, Thesis for the degree of Philosophiae Doctor; Trondheim, September 2014.

[7] Indraratna, B. & Nimbalkar, S. (2013). Stress-strain degradation response of railway ballast stabilized with geo-synthetics. Journal of Geotechnical and Geo-environmental Engineering, 139 (5), 684-700.

[8] Ionescu, Daniela, Evaluation of the engineering behavior of railway ballast, PhD thesis, Civil Mining and Environmental Engineering, University of Wollongong, 2004.

[9] Hussaini, S. K Karimullah, Indraratna, B. & Vinod, J. S.; Performance of geosynthetically-reinforced rail ballast in direct shear conditions. In G. A. Narsilio, A. Arulrajah & J. Kodikara (Eds.), 11th Australia - New Zealand Conference on Geomechanics: Ground Engineering in a Changing World (pp. 1268-1273). Australia: Engineers Australia.

[10] M. Esmaeilia, J.A. Zakeria, A. Kavehb, A. Bakhtiaryc and M. Khayatazad, Designing granular layers for railway tracks using ray optimization algorithm.

[11] AREMA, 2010, American Railway Engineering and Maintenance of Way Association.

[12] Indraratna, B., Mohamed A. Shahin., Wadud Salim, Use of Geo-synthetics for Stabilizing Recycled Ballast in Railway Track Substructures, Journal of Geotechnical, Australia.

[13] Indraratna, B., Lackenby, J**.**, and Christie, D, Effect of Confining Pressure on the Degradation of Ballast under Cyclic Loading, Geotechnique, Institution of Civil Engineers, 55(4), 2005, 325-328.

[14] (ERC), E.R.; Final Evaluation Report on the Feasibility Study of Addis Ababa/Sebeta–Djibouti Railway Project, September 2012.

[15] J. Sadeghi, New Advances in Analysis and Design of Railway Track System,

[16] Kedir Abdu., Assessment of Degradation and Performance Improvement of Railway Ballast with Geosynthetics - A Case Study of National Railway Network

[17] ABAQUS 6. 12 Getting Started with ABAQUS; Interactive Edition.

[18] Cho Ching Joe Kwan, Geogrid Reinforcement of Railway Ballast.

[19] www.naue.com; Geogrid Introduction.

[20] Hussaini, Syed Khaja Karimullah, An experimental study on the deformation behavior of geosynthetically reinforced ballast, Doctor of Philosophy thesis, school of Civil, Mining and Environmental Engineering, University of Wollongong, 2013.

[21]National Standards of the People's Republic of China," Hot-rolled steel rails for railway", General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2007.

[22] Abdelaziz Ahmed Bohagr, M. S., Finite Element Modeling of Geosynthetic Reinforced Pavement Subgrades, Washington State University July 2013.

[23] Jie Gu B.S., Computational Modeling of Geogrid Reinforced Soil Foundation and Geogrid reinforced Base in Flexible Pavement, Hebei University of Technology, 2004 December, 2011.

[24] Kalker J. J.; Wheel-rail rolling contact theory. Wear, 144, 243-261, 1991.

[25] Ngo, Ngoc, Performance of geogrids stabilized fouled ballast in rail tracks, Doctor of Philosophy thesis, School of Civil, Mining and Environmental Engineering, University of Wollongong, 2012. http://ro.uow.edu.au/theses/3730

[26] Yalelet Endalemaw., Fatigue Life Analysis of Rail-Welds based on Linear Fracture Mechanics, Masters of Science thesis in Civil Engineering School of Civil and Environment Engineering, AAiT, February, 2016.

[27] Tore Dahlberg ., Railway track settlements - a literature review, Report for the EU project Super track, , Division of Solid Mechanics, IKP, Linköping University, SE-581 83 Linköping, and Sweden, July 2002.

[28] Mike Horton. Stiffness in Tensar Geogrids and Applications, Product and Technology Manager, stabilization System (EH) Tensar International Limited; Research Czech Technical University, Prague (2013).

[29] K. Minažek. et al, Simple Procedure of Geogrid-Soil Interaction Efficiency Assessment. Josip Juraj Strossmayer University of Osijek.

[30] Amir Shahkolahi., Advantages of Biaxial Welded Geogrids in Railway Rehabilitation and Upgrade. Conference of railway excellence at Adelaide Australia 5-7 may 2014

APPENDIX

A-1: Soil Exploration cores.

Figure A.1 Picture of Cores (MEZ2-S2-01) [ERC]

Table A-1 Summary of standard penetration test [ERC]

Summary of Standard Penetration Test <5-1> Table 5

Borehole No.	Depth of Standard Penetration Test Point (m)	Total Rod Length for Standard Penetration Test Point (m)	Measured Blow Count N63.5	Modification Coefficient of Rod Length α	Blow Count after Rod Length Modification N'	Stratum Code of Test Point	Lithologic Character of the Test Point
MEZ2-S2-01	4.30	5.60	31	0.92	28.5	<5-1>	Tuff

A-2: Summary of Laboratory Soil Test Results [ERC]

Table A-2: Summary of Soil test results

Bor e hole no	stratum code	sample depth	physical and Hydrological Indexes of soil in nature State											Free swelling ratio	Natural Quick Shear		Compression Coefficient		Compression Modulus		Coefficient of subgrade reaction	
			Natural Density	Specific gravity	Natural water	Natural Porosity	porosity	Saturation	Liquid limit	Plasticity limit	Plasticity Index	Liquidity Index	Dry Density		Cohesion	Inner friction angle						
			ρ	Gs	w	e	n	Sr	wL	wp	Ip	IL	pd	Fs	c		av	ah	Es(v)	Es(h)	Es(v)	Es(h)
		h(m)	(g/cm^3)		%		%	%	%	%		%	(g/cm^3)	%	(kPa)		Mpa^{-1}	Mpa^{-1}	Mpa	Mpa	Mpa	Mpa/m
MEZ2	<2-2-1>	1.6-2.0	1.81	273	38.3	1.086	52.1	96.3	60.2	31.8	28.4	0.23	1.31	115	73.3	16.5	0.32		6.28		20.5	

A-3: Rail and Wheel Profile

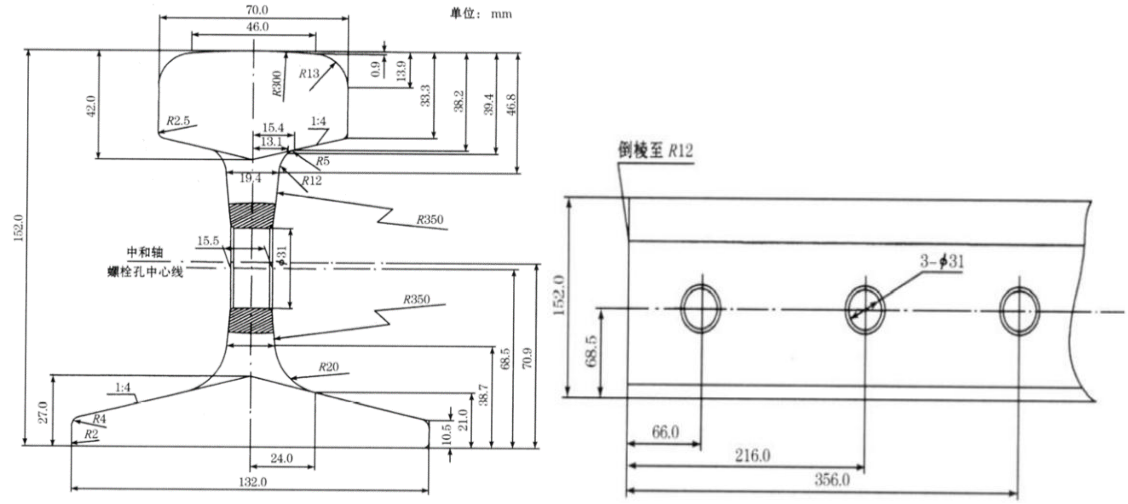


Figure A-3.1: Rail Section 50Kg/m **[ERC]**

A-4: ABAQUS/CAE model of Railway Cross-sections

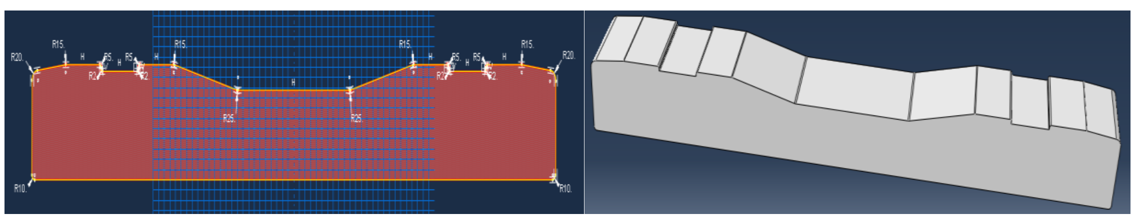


Figure A-4.1: Sleeper Modeling, ABAQUS/CAEA-2: Rail and Wheel Profile

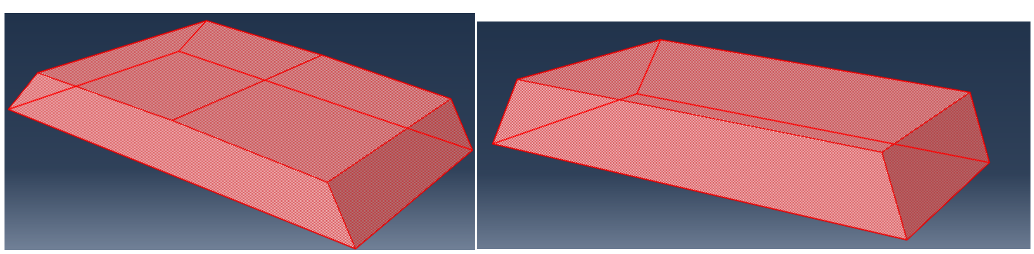


Figure A-4.2: Ballast and Sub-ballast Modeling respectively, ABAQUS/CAE

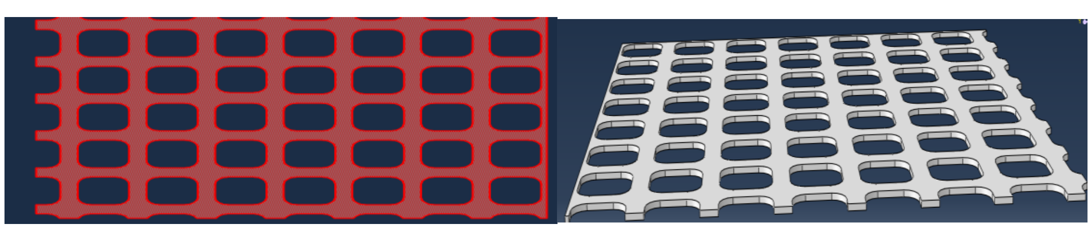


Figure A-4.3: Geogrid Modeling, ABAQUS/CAE**.**

A-5: Deformation Shape plot along Path 1 and path 2

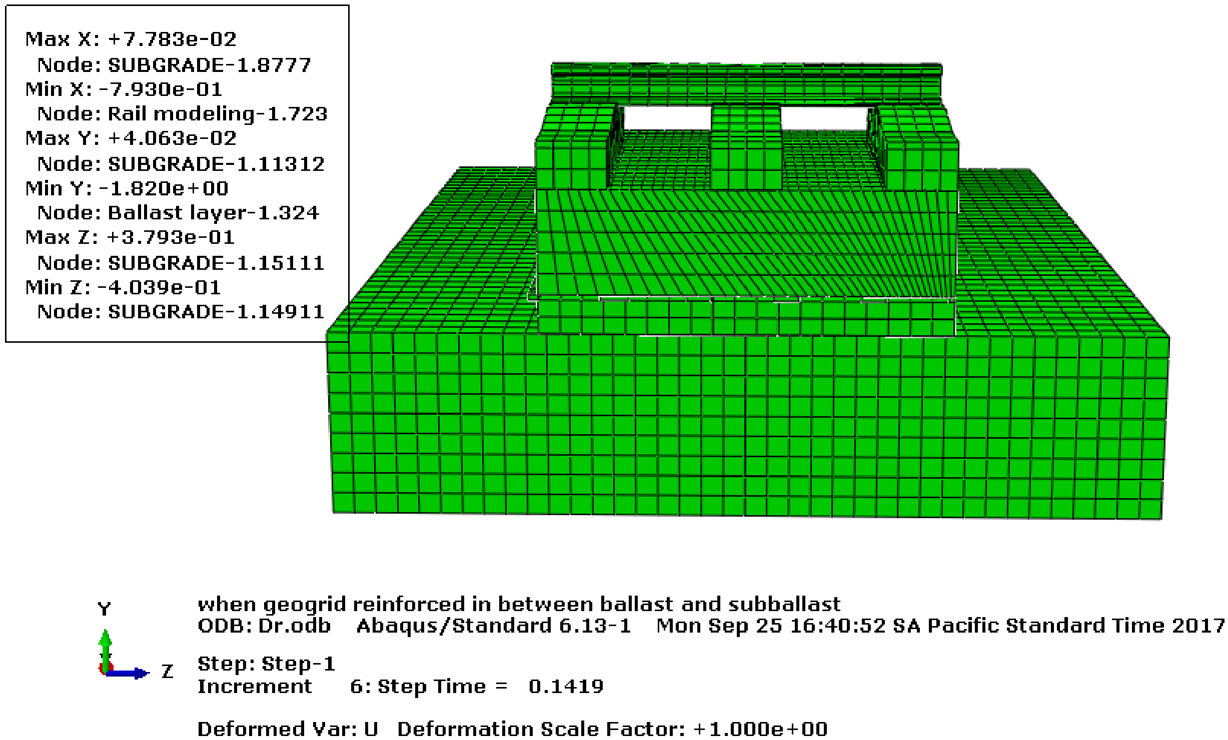


Figure A-5.1 Deformation shape plot result of ABAQUS/CAE for unreinforced.

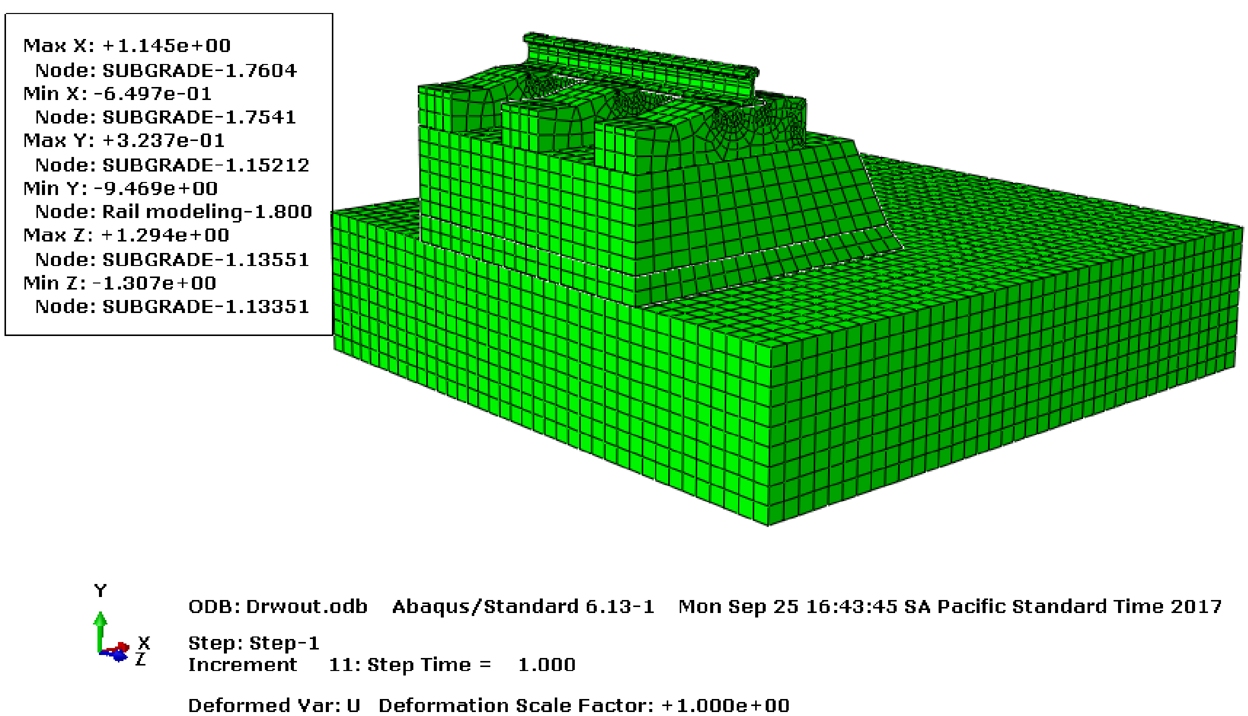


Figure A-5.1 Deformation shape plot result of ABAQUS/CAE for unreinforced.

A-6: Plot contours on deformed shape of unreinforced ballasted track

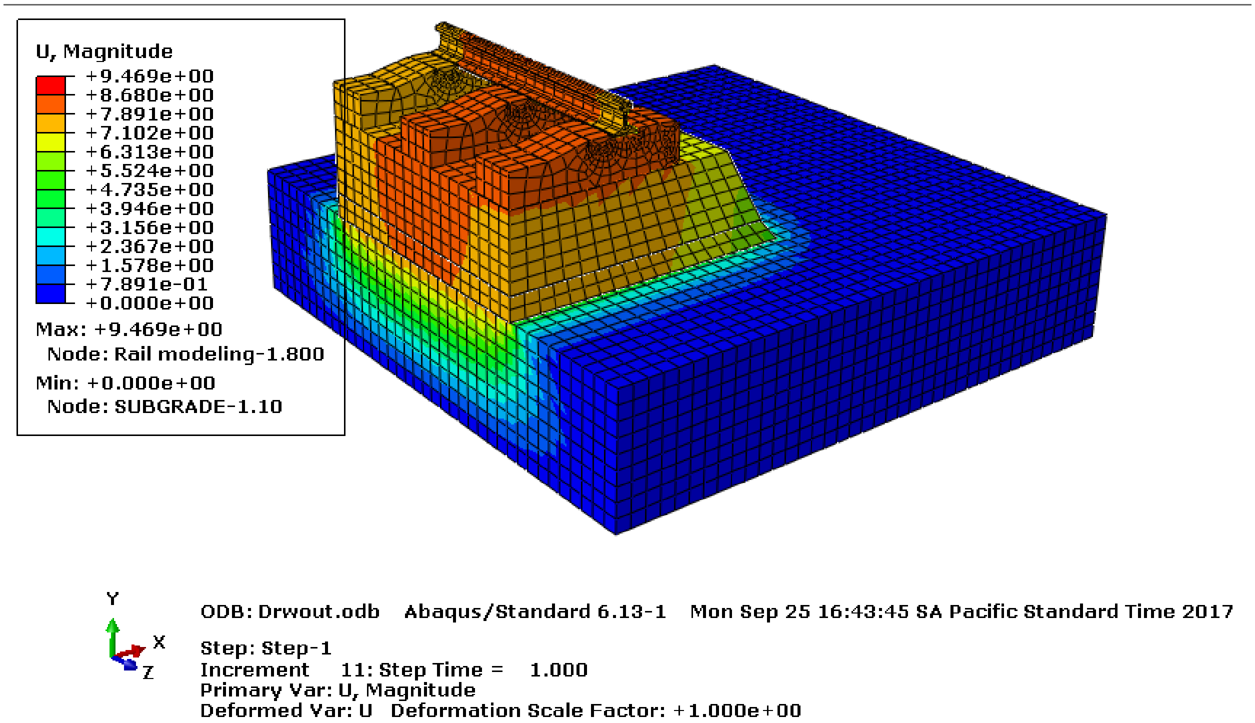


Figure A-6.1 Plot contours of deformed shape ABAQUS/CAE results for geogrid reinforced

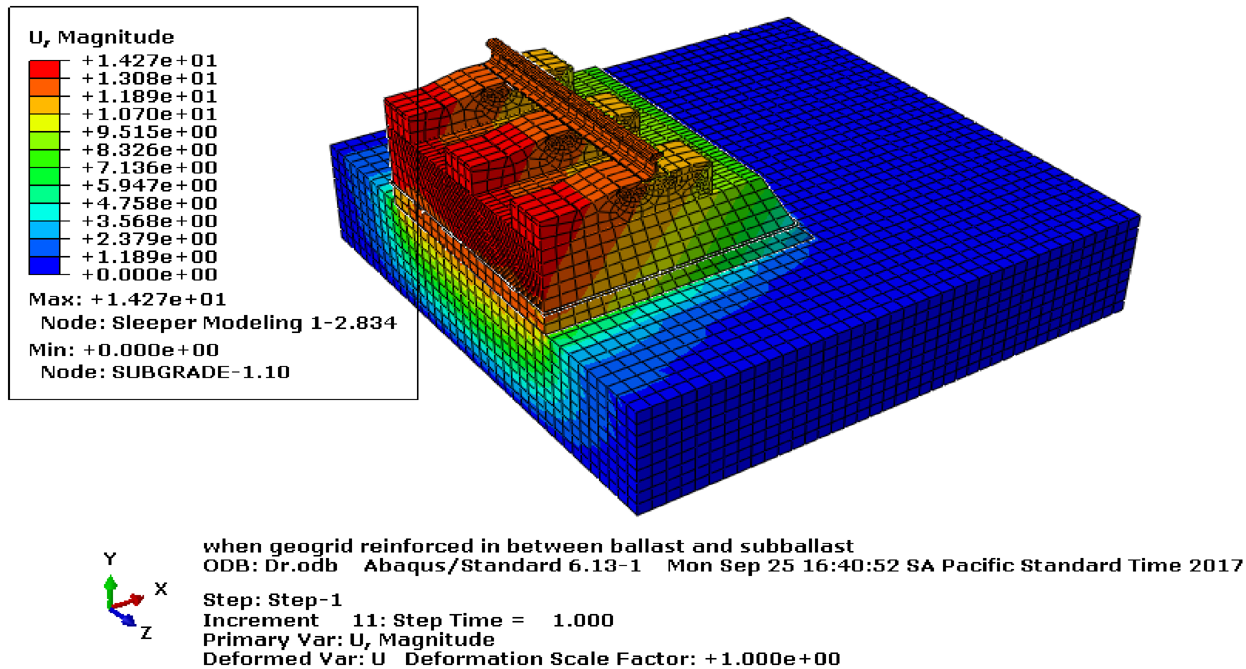
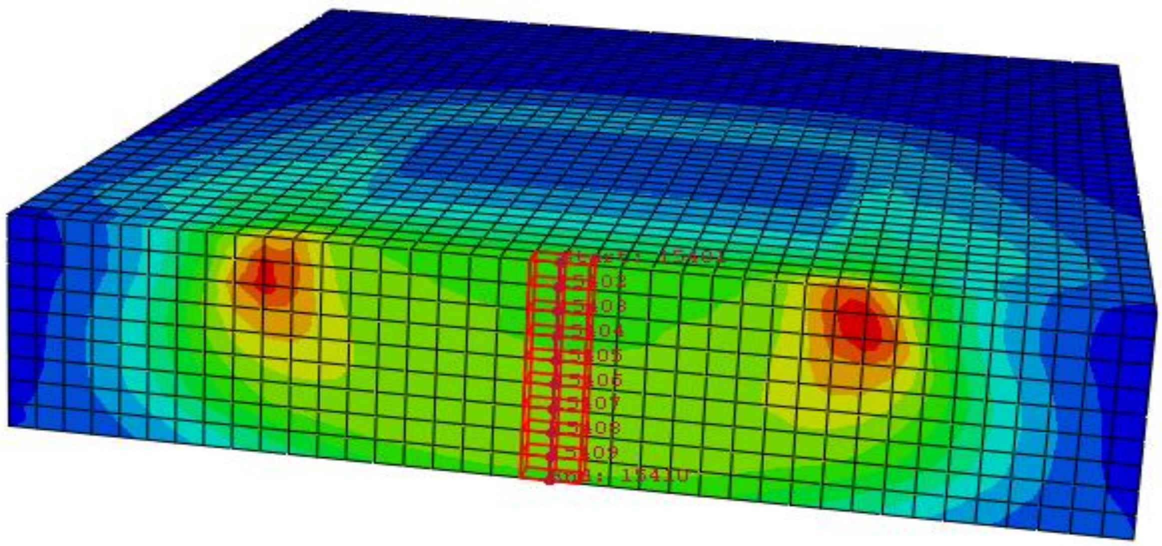


Figure A-6.2 Plot contours of deformed shape ABAQUS/CAE results for unreinforced

A-7: Subgrade strain versus True distance along path 1 and path 2 for reinforced and Unreinforced Ballasted track.



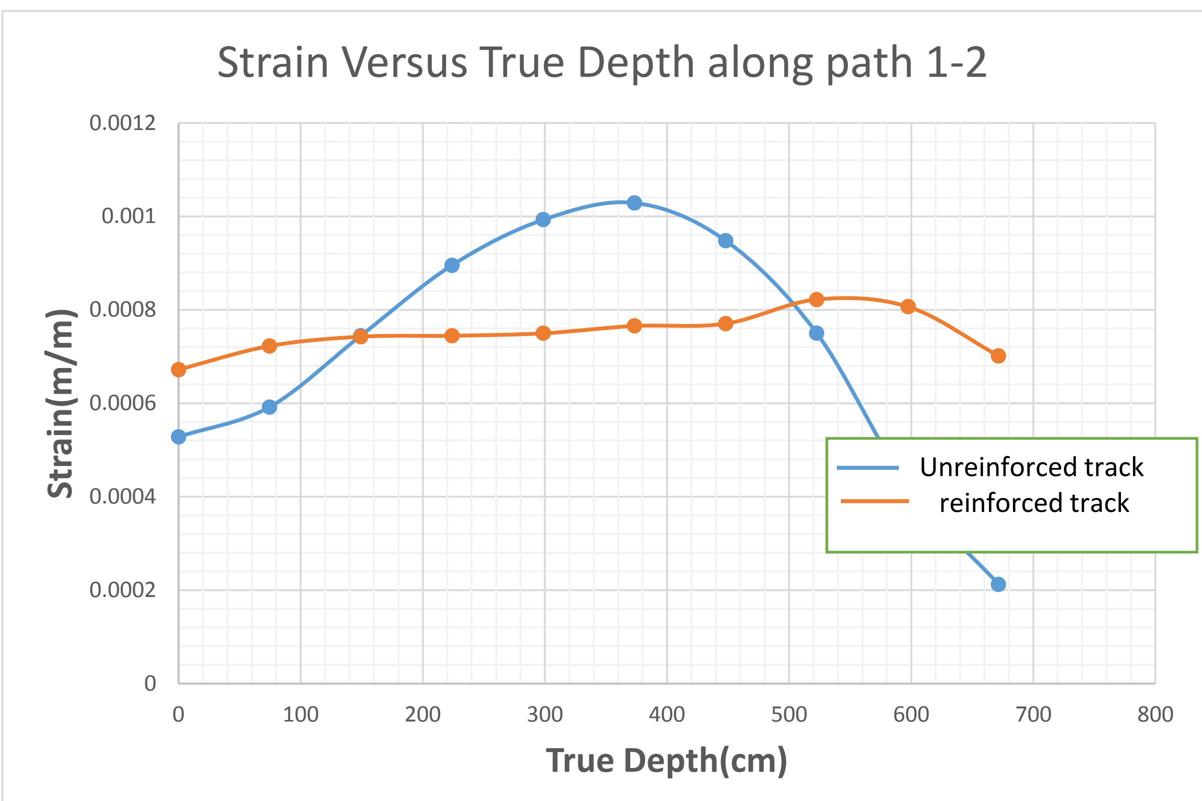


Figure A-7.1 Strain versus true depth along path 1 and path 2 of unreinforced and reinforced ballasted track.

Table A-3 Field Output reported at nodes for part: Reinforced Ballasted layer

ODB: C:/Temp/Dr.odb

Step: Step-1

Frame: Increment 11: Step Time = 1.000

Loc 1: Nodal values from source 1

Output sorted by column "Node Label".

Field Output reported at nodes for part: Ballast layer-1

Computation algorithm: EXTRAPOLATE_COMPUTE_AVERAGE

Averaged at nodes

Averaging regions: ODB_REGIONS

Node Label	U.Magnitude @Loc 1	U.U2 @Loc 1	LE.Max. Prin @Loc 1	S.Max. Prin @Loc 1	S.Pressure @Loc 1
1	13.7441	-12.6881	225.488E-06	-2.35266E-03	45.9878E-03
2	13.3886	-12.3140	240.283E-06	-4.39105E-03	51.7267E-03
3	13.1024	-12.0111	242.025E-06	-8.81793E-03	58.4497E-03
4	12.8102	-11.6932	207.252E-06	-16.9879E-03	63.6829E-03
5	12.4629	-11.3248	147.150E-06	-29.5259E-03	70.4414E-03
6	12.1895	-11.0139	90.1887E-06	-39.7970E-03	74.5192E-03
7	11.8997	-10.6963	72.2844E-06	-47.2108E-03	81.8472E-03
8	11.5839	-10.3297	60.7404E-06	-59.3317E-03	97.1746E-03
9	11.2864	-9.98700	41.2830E-06	-76.5366E-03	118.351E-03
10	11.0102	-9.64464	37.0361E-06	-99.5112E-03	150.734E-03
11	10.7358	-9.31078	34.4061E-06	-140.006E-03	208.729E-03
12	10.4535	-8.94146	25.4654E-06	-235.902E-03	345.558E-03
13	10.1919	-8.54151	357.306E-06	-169.235E-03	311.941E-03
14	9.29521	-7.28416	513.132E-06	-681.026E-06	97.9080E-03
15	8.81886	-6.74574	258.291E-06	17.1745E-03	23.9805E-0

Table A-4 Field Output reported at nodes for part: Unreinforced Ballasted layer

Field Output reported at nodes for part: Ballast layer-1

Computation algorithm: EXTRAPOLATE_COMPUTE_AVERAGE

Averaged at nodes

Averaging regions: ODB_REGIONS

Node Label	U.Magnitude @Loc 1	U.U2 @Loc 1	LE.Max. Prin @Loc 1	S.Max. Prin @Loc 1	S.Pressure @Loc 1
1	5.79398	-5.79398	274.746E-06	-90.5299E-03	182.662E-03
2	6.10526	-6.10422	212.333E-06	-76.0897E-03	150.015E-03
3	6.35524	-6.35304	177.278E-06	-54.0872E-03	111.612E-03
4	6.55578	-6.55184	223.634E-06	-38.6098E-03	98.0117E-03
5	6.81743	-6.81174	314.810E-06	-14.1224E-03	79.8631E-03
6	7.03279	-7.02754	405.637E-06	1.63245E-03	74.2623E-03
7	7.26262	-7.25787	427.748E-06	6.57330E-03	71.3019E-03
8	7.42948	-7.42545	414.237E-06	9.81545E-03	64.0670E-03
9	7.56534	-7.56328	372.245E-06	5.71976E-03	62.0511E-03
10	7.62706	-7.62527	337.741E-06	2.87212E-03	59.6469E-03
11	7.68764	-7.68688	301.757E-06	-180.480E-06	57.2593E-03
12	7.68534	-7.68476	265.845E-06	-5.39169E-03	58.0031E-03
13	7.71472	-7.71451	226.481E-06	-11.0138E-03	58.6886E-03
14	7.69760	-7.69748	193.691E-06	-15.6952E-03	59.2569E-03
15	7.71146	-7.71144	177.311E-06	-19.0960E-03	61.0753E-03
16	7.69853	-7.69853	163.771E-06	-20.0107E-03	59.8390E-03
17	5.81923	-5.81917	294.168E-06	-87.0853E-03	181.355E-03
18	6.11487	-6.11394	238.898E-06	-71.8390E-03	148.893E-03-06