



ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

**ANALYSIS OF RAILWAY TRACK STIFFNESS VARIATION AND ITS
INFLUENCE**

A Thesis Submitted to School of Civil and Environmental Engineering

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Master of Science in Civil Engineering (Railway Engineering)

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

(Master of Science in Civil Engineering under Railway Engineering)

Analysis of railway track stiffness variation and its influence

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ABSTRACT

Railway track stiffness is a basic parameter of track design which influences the bearing capacity and the dynamic behavior of passing vehicles. In particular, track geometry quality and the life of track components. The stiffness definition must include inelastic and non-linear behavior of the super structure and substructure elements as well as the existence of the stiffness under dynamic load. In most case track stiffness is a function of track superstructure and substructure material properties.

In this paper the influence of track component stiffness variation by using time and frequency domain of FEM (ABAQUS software) analyzed and discussed on the results observed. The Modeling analysis of track stiffness variation depends on the track component (rail-pads, sleeper, ballast and subgrade) stiffness variation and the Results for each track component stiffness variations. Interactive forces, track component displacements, Velocities and acceleration were presented. The analysis consider the influence of rail-pad stiffness, ballast stiffness, sleeper spacing, train speed and subgrade material on track structures. During operation and moving of the freight trains falling of small particles over the ballast layer causes an increase of stiffness in the layer of ballast and gradual deterioration of ballast effect on size of ballast grade and forming powder due to friction exists between stones rubbing together, which reduce the stiffness of ballast.

Using the software ABAQUS found that, decrease in sleeper spacing and increases in ballast young's modulus, ballast depth, sub grade young's modulus and rail moment of inertia increases the track stiffness at all. In general, relatively high track stiffness is beneficial as it provides sufficient track resistance to applied loads and results in decreased track deflection, which reduces track deterioration. On the other hand, very high track stiffness leads to increased dynamic forces in the wheel rail interfaces as well as on the sleepers and ballast which can cause wear and fatigue of track components.

Keywords: Vertical track stiffness, Rail bending stress, dynamic explicit, acceleration, sinusoidal load, stress, BOEF (Beam on Elastic Foundation)

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Notation

| | |
|-----------|--|
| K | stiffness |
| b | Density of the ballast |
| h_b | Depth of ballast |
| V2 | Vertical velocity |
| Qd | is dynamic load |
| | is factor of the quality conditions of the track and |
| l_e | effective supporting length of half sleeper |
| l_b | width of sleeper underside |
| | ballast stress distribution angle |
| EN | track settlement |
| K_{2mi} | measured average track stiffness on individual sleeper |
| K_{1-3} | constant factors |
| P_{dy} | dynamic wheel load |
| P_{ref} | reference wheel load |
| N | Number of load cycle |
| W | coefficient of track settlement |
| K_f | the K_{30} modulus of sub grade |
| t | is statistical security coefficient, |
| A2 | Vertical acceleration |
| U2 | Vertical displacement |

V is speed of the vehicle

Q_e is static vehicle load

Abbreviation

FEM Finite Element Method

BOEF Beam on Elastic Foundation

CHAPTER ONE

Introduction

Railway transport is currently one of the most important transportation systems. Which is efficient in moving people and cargo long distances and has better environmental features than most others available transportation alternatives railway transport administration have vision of travelling which is that all passengers will arrive easily environmentally friendly and safely.

Track stiffness variation may be more difficult to deal because even a track with an ideal track geometry may hide irregularities that are not discovered until the track is loaded by the train track stiffness irregularities may have its origin in the track superstructure (rails, rail pads, sleeper, ballast) or in the sub structure (foundation, sub grade soil etc.) due to an irregular stiffness of substructure and the ballast. For example, due to a non-uniformly compacted ballast lying on sub structure with properties varying along the track.

The track stiffness experienced by a train will also vary along the track quite often due to the sub structure there are large changes of the track stiffness with in short distance. Places along the track where track stiffness will change rapidly are at pile decks, embankments, bridges, transition zones etc. the transition area from an embankment to bridge is palace and turnouts especially at the crossings(the frogs) at insulation joints and at hanging sleepers the track stiffness changes very rapidly.

Changes in track stiffness will cause variations in the train/track interaction forces. The force variations give rise to track degradation such as track differential settlement due to permanent deformation of the ballast and in the underlying structure. The settlement is caused by the repeated loading and its severity is depends on the quality and the behavior of the ballast, sub structure and foundation (Berggren.E, 2009). The degradation of the track also occurs in the supper structure due to fatigue of rails and sleeper and due to wear and rolling contact fatigue of the rail surface (Selig, 1997).

In this paper the main focus is on vertical stiffness variations along a railway track. Track stiffness is defined as ratio of the load applied to the rail to vertical rail deflection. Track modulus on the other hand is a measure of the vertical stiffness of track foundation (Alain Robinet, 2004).

In the paper presented here problem emanating from stiffness variation are highlighted and its countermeasures are discussed in some cases geometric irregularities of the track may result in similar in conveniences with irregular track stiffness.

The rate of degradation of track components and the rate of track settlement will depends on the severity of the stiffness variation. As soon as the track geometry starts to deteriorate the variation of the train tack interaction forces increase and this speeds up the tracks degradation rate. Therefore one should be aware of the influence of

track stiffness irregularities on the development of track settlement and on the deterioration of track components and materials.

Also track stiffness irregularities will induces vibrations in the train in the track and in the surroundings. In many cases the stiffness variation is more or less random along the track. At abrupt changes of track stiffness, for example at turnout crossings or at transitions from ballast to slab track, transient and high frequency vibration will be induced in the track. Local track deterioration may takes places creating fatigue problems, cracks, wear, plastic deformation, hanging sleepers and so on.

1.1. Thesis objectives

General Objectives:-To analysis the railway tracks support stiffness variation, its influence on track components and its counter measures.

Specific Objectives:-

- ❖ To analysis the effect of vertical track stiffness variation along rail way track structure.
- ❖ To analysis the influence of track component stiffness variation.
- ❖ To identify the consequences of stiffness variation and its counter measures.
- ❖ To draw conclusions and recommendation based on research findings.

1.2. Statement of problem

Rail way track stiffness is a basic parameter of track design which influences the bearing capacity, the dynamic behavior of passing vehicle, track geometry quality and the life of track components. Deteriorations should also be a function of the properties of the track supper structure and sub structure. Good track support and its homogeneity (no stiffness variation) are very important parameters for long term stability of track geometry and good life cycle cost of the track. Weak modulus and non-uniform support from the track layers can cause poor track geometry under traffic loading.

However track stiffness depends on components of supper structure such as sleeper, rail fastening system and infrastructure such as ballast, sub-ballast and soil sub grades. At least a portion of the difficulty in the evaluation of sub grade is that so many factors affect its performance including classification properties, moisture contents, shear strength, consolidation, and stiffness parameters. Those parameters vary stiffness along track and lead to understand the problem with rail way maintenance, how maintenance is performed today, why it is needed and how it is measured.

1.3. Methodology

The selected methodology to follow in the research consists of five main stages. Each stage is properly developed and reported in this document.

1.3.1. Literature review

1.3.2. Track modelling by using FEM (ABAQUS) software

- Computational model
- Dynamic Explicit analysis
- Eigen Value analysis

1.3.2.1. *Computational model*

The first action is to propose a computational model of the track that behaves and responds as the actual track in the field. Literature review from Chapter 2 is used in this stage to design the model. The model is built using the FEM (ABAQUS) Software.

1.3.2.2. *Dynamic Explicit analysis*

Once the model has been verified, the subsequent action is to run a dynamic analysis. The analysis is designed to observe the response of the model under different stiffness of track components. The simulation will provide meaningful results that must be validated using standard data.

1.3.2.3. *Eigen Value analysis*

The model is also used to complete an Eigen value analysis and understand the influence of track stiffness variation on track components. The results observed and discussed under this section.

1.4. Structure of the thesis

A short description of chapter is presented below to get an overview of the general structure of the thesis. The introduction part, objective of the thesis, structure of the thesis and significance of the study clearly defined under **chapter 1**.

In **chapter 2**, selections of the literature reviews are presented, that constitute the basis of the calculations in this thesis. It also briefly describes dynamic properties of the railway track components and the models done by different researchers. We also describe present work of paper and inputs of the model in order to analysis track stiffness variation.

The well-known commercial software ABAQUS for railway track system has been introduced in **chapter 3** and the theories behind those programs have been briefly explained and some of its limitations have been discussed. The procedure of creating finite element models in ABAQUS/CAE is presented in this chapter. The algorithms within ABAQUS that are used in this thesis are briefly presented and the dynamic analysis approaches were explained.

The results of the finite element modeling in ABAQUS are presented in **chapter 4** and the dynamic analysis of track stiffness variation briefly presented and the effect of track support stiffness variation on vertical track stiffness has been evaluated.

Chapter 5 contains a discussion of the results and conclusion. Some recommendations for further research are suggested.

CHAPTER TWO

Literature review

General railway track stiffness concepts are reviewed in this chapter in order to introduce the reader to the research topic. The state-of-the art of specific subjects are included as well according to their relevance in the thesis.

2.1. Structure of railway tracks

Ballasted track is the most common railway track used now a day. The principal advantages over other track design are the relative low construction cost, larger elasticity and drainage (C.Esveld., 2001). The structure of the track consists of two parts: the superstructure and the substructure. The first one includes the rail, fastening system and sleeper; the second one is composed of granular materials placed by layers according to their mechanical properties. Figure 1 illustrates the elements that form the ballast track.

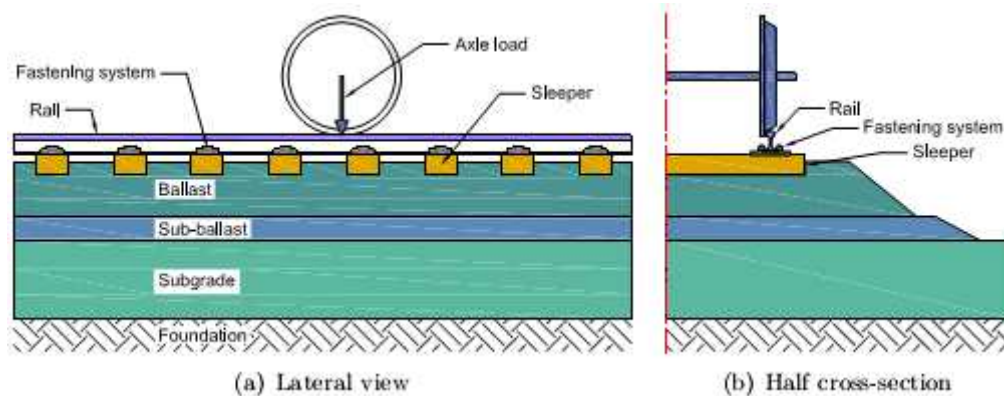


Figure 1 Ballast railway track components

The axle load is transferred from the top to the bottom of the structure. Each element of the track reduce the vertical stresses that the underneath element must resist. Consequently the geometry of the structure and the mechanical properties of each element have their own stiffness value.

2.1.1. Rail

The functions of the rails are to distribute dynamic and static loads from vehicle to sleeper function as a level surface for the wheel to minimize vibrations offer sufficiently low friction in wheel rail interaction and resist thermal expansion. To secure the functions there are high demands on the rails in the form of material hardness with a high ultimate stress limit. It should further have a good resistant to wear and good welding abilities. The rails also act as electrical conductor for the signaling system.

A modern steel rail has a flat bottom and its cross-section is derived from an [I] – profile. The upper flanges of the [I] - profile have been converted to form the rail profile UIC- 60 has been used for the finite element simulation in this thesis.

2.1.2. Rail pads

Rail pads are a provision of comforting element between the steel rail and concert surface. They transfer the rail load to the sleeper and filter out the high frequency force components. In a track the rails are fastened onto the sleeper. The rail pads provide electrical insulation of the rails and they protect the sleepers from wear. The rail pads stiffness should be as low as possible to a certain limit. Rail pads with a dynamic stiffness between 100 and 200 MN/M and static pads stiffness between 50 and 100 MN/M are commonly used.

2.1.3. Fastener system

Rail fastening are components which together form the structural connection between rail and sleeper. The fastening system is used to hold the rail onto the sleepers to ensure fixing of the rails. The choice of fastening greatly depends on the type of sleeper fastening are pandrol clip type fast clip which are fastened to a sleeper plat (Hosseingholian, 2009). The steel plate is fixed to the sleeper in the casting process.

2.1.4. Sleeper

The sleepers hold the rail and maintain track gauge, level and alignment. They distribute and transmit forces from the rail down to the ballast bed. Also they provide electrical insulation between the two rails (Witt, 2008). For ballast railway track there are wooden, steel and reinforced concrete sleeper available now days. Now in Ethiopia concrete sleepers is used now a days.

The choice usually depends on the speed of the train and economic reasons. For standard gauge tracks, the optimum spacing is 0.60m, which has been used for the modeling on this thesis. There are mainly two types of concrete sleepers. Reinforced twin block sleepers and pre-stressed mono-block sleepers in this thesis the later one was used.

2.1.5. Ballast

Ballast is a crushed granular material placed at the top layer of the substructure and between sleepers in a track and has many functions. The most important ones are to secure track stability in all directions, prevent excessive sleeper movement, absorb static and dynamic load and provide good drainage of water, to secure these functions, high quality ballast in terms of good vertical and horizontal load bearing capacity is required(chalmers university of technology, 2013). Further wear resistance good elastic characteristics and a good drainage capacity are important to meet these demands. It is important to fill the ballast embankment it is

also important to use hard stone material that carry large pore volumes and are angular. The angularity provides high friction between the grains. The ballast layer should be at least 300mm thick below a sleeper and the layer on bridge should be at least 400mm. the ballast layer should not cover the sleeper surface in order to minimize the risk of ballast spray. It also important for the sleeper ends to be surrounded with a sufficient amount of ballast to secure the sleeper's lateral stability.

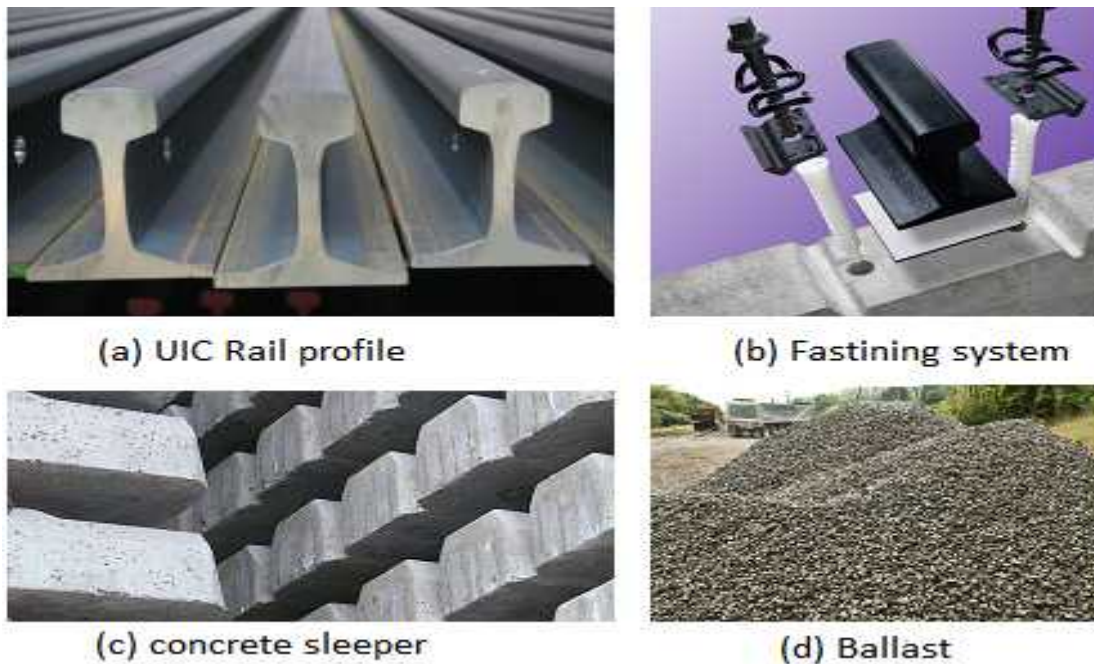


Figure 2 Ballasted Track elements

2.2. Track stiffness definition

There is no complete consensus definition of track stiffness; however the most general understanding seems to reflect the elastic rail deflection that takes place under a wheel loading. Thus this generic track stiffness is a function of the structural properties of the rail, resilient pads in the track structure, sleepers, ballast, and sub ballast and sub grade soils.

2.3. Vertical track stiffness

Vertical track stiffness is the relationship between vertical applied force and displacement response of the rails. Thus track stiffness is function of the structural properties of the rails, rail pads, sleepers, ballast, and sub ballast and sub grade soil. For example the vertical track stiffness is 7% greater for UIC60 rail than BS113A (Hunt.G, 2005). Furthermore, sleeper spacing influences track stiffness with reduced spacing resulting in an increase in track stiffness.

Reference (Hunt.G, 2005), notes that the sub grade is typically the primary determinant of overall track stiffness. Fundamental analysis and mathematical models of track stiffness are often based on the idealized Beam on Elastic foundation (BOEF) approach that considers the track as an infinite bending beam resting on a continuous linear elastic foundation. This approach introduces the concept of the track modulus which is the stiffness of a spring (k) per unit length of track.

Using the software of GEOTRACK, (Hunt.G, 2005) found that the track modulus can increase by around 10 to 20% for a decrease in sleeper spacing, as well as increases in ballast young's modulus, ballast depth and rail moment of inertia.

In general, relatively high track stiffness is beneficial as it provides sufficient track resistance to applied loads and results in decreased track deflection, which reduces track deterioration. Low track stiffness results in a flexible track with poor energy dissipation and ballast abrasion due to ballast flexural deformations. On the other hand, very high track stiffness leads to increased dynamic forces in the wheel- rail interface as well as on the sleepers and ballast, which can cause wear and fatigue of track components (Berggren.E, 2009).

An optimum track stiffness value is likely to occur at some intermediate value. Track stiffness can also be measured as sleeper end stiffness (I.e. track stiffness which does not include the rail pad stiffness). Based on reviews of track stiffness by(Berggren.E, 2009) vertical track stiffness(k) can be defined as the ratio between track load(F) and track deflection(Z) as a function of time(t), where the force can either be axle load or wheel load:

$$\text{Equation 1 } K(t) = \frac{F(t)}{Z(t)}$$

The stiffness of different components of the track structure is mostly non-linear, such as the rail pads and sub grade and can vary with temperature and moisture content for example. Furthermore, the sleepers may have voids beneath them, leading to large deflections at low load levels.

The secant stiffness is often used to eliminate the effect due to poor contact between ballast and sleeper and can be defined as

$$\text{Equation 2 } K(xy) = F / Z = (Fb - Fa) / (Zb - Za)$$

Where ΔF and ΔZ are the difference between the values obtained at two predefined points with point a being taken at the seating load. However the point "a" and "b" are selected based on various definitions to give both secant and tangent stiffness values.(Hosseingholian, 2009). Reference (Hunt.G, 2005) noted that for a realistic representation of non-linear behavior a tangent stiffness to the design axle loading is a reasonably relevant parameter.

If the track stiffness is too low then the ballast will undergo cyclic stress reversals leading to track settlement and hence track geometry faults. It is also likely that plastic strain accumulation in the formation will result in further track geometry issues (Hosseingholian, 2009) (if the track stiffness is low it is likely that the formation soil is weak). It is therefore clear that whatever methodology is used to determine the track stiffness, improvement of the track stiffness over poor (weak) ground is an important factor in railway track design and maintenance. This was discussed by (Allander H, 2004).

2.4. Influences on track stiffness irregularities and its origin

2.4.1. Direct influences of track stiffness

Parameters affecting direct track stiffness are:-a stiff rail distributes the load over a greater number of sleeper, where as a less stiff track modulus distributes the load over fewer sleeper (this would mean higher sleeper and rail fastening forces).a stiff rail result in lower rail fastening static bending stresses in the rail. A stiff track modulus results in lower (static) rail deflection and stresses. Low track bed stiffness directly produces an increase in ballast settlement.

2.4.2. Long-term influences of track stiffness

The three primary areas of influence of the track stiffness on track life-cycle behavior seem to be. Track geometry deterioration, rail fatigue, and other component deterioration. For track geometry, the track bed (and particularly the sub-soil) stiffness appears to be most relevant.

Differential track settlement is the primary cause of track geometry deterioration.

The track stiffness can vary due to a variety of reasons. Such as, geology, moisture content, embankment material, ballast and sub-soil layer depth, structures.

Track stiffness irregularities may have its origin in the Track super-structure (rails, rail pads, sleeper, ballast) or/and Substructure (foundation, sub grade soil, etc.).

An irregular stiffness of the substructure and of the ballast could be non-uniformly compacted ballast lying on substructure, with properties varying along the track. In this case, the track stiffness experienced by a train will also vary along the track. Irregularity of track Stiffness affects different component of track. The wheel will be influenced by the varying stiffness of track due to sleeper spacing and at switches (Witt, 2008).

The track is stiffer at the sleepers and softer in-between, so the wheel will be excited with a frequency 'f' that corresponding to the speed 'v' of the train and the sleeper spacing 'a' ($f=v/a$). Track stiffness varies at switch (turnouts) mainly due to (Allander H, 2004).

- The different lengths of the sleepers
- The different spacing of the sleeper
- The loss of symmetry: the left and right rail will have different stiffness's (the stock rail keeps the stiffness of the track, whereas the switch rail becomes stiffer because of the longer sleeper supporting that rail.)

The rail bending stiffness (EI) will change dramatically at the frog (diamond or crossing). Such a sudden change of the stiffness will induce transient and high- frequency vibrations in the train and in the track. The mass is also larger at the frog making inertia forces larger.

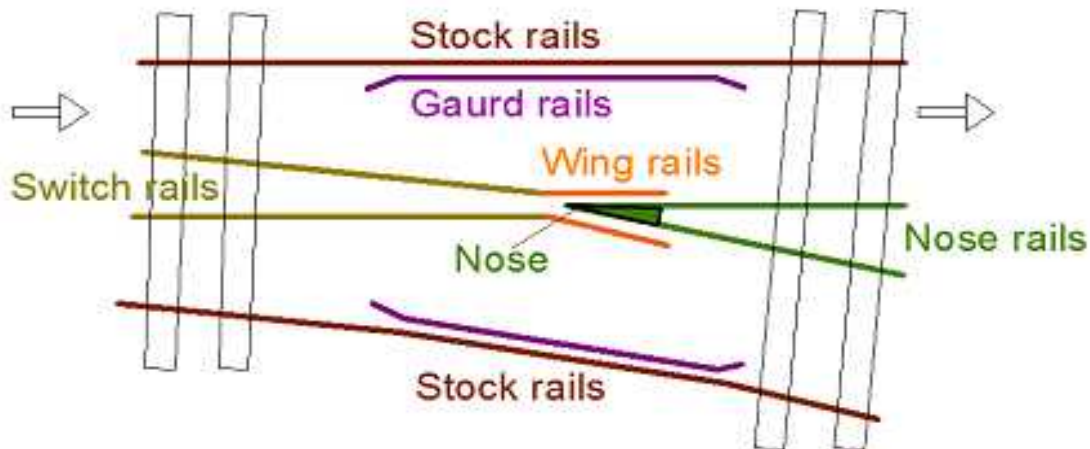


Figure 3 Railway switch at the frog area

2.5. Fundamental causes of track stiffness irregularity

2.5.1. Ballast Settlement

In a research program in Germany aiming at a better understanding of the dynamic interaction of vehicle, track, the components of the entire system long term behavior, settlement and distraction of the ballast and the sub grade were examined. It is also seen in this research the sub grade and ballast settlements have a large influence on the track stiffness. Uneven track will induces low-frequency oscillations of the train. Railway track will settle (Changes its position) as a result of permanent deformation in the ballast and underlying soil. The settlement is caused by the repeated traffic loading and the severity of the settlement depends on the quality and the behavior of the ballast, the sub-ballast and the sub grade.

The track support (ballast, sub grade) stiffness varies due to the ballast and sub grade settlement/permanent deformation. This happens that:-The Volume Reduction, i.e. densification of the ballast and sub ground, caused by particle rearrangement produced by reaped train loading. Sub-ballast and/or sub grade penetration in to ballast voids. This cause the ballast to sink in to the sub-ballast and sub grade and the track changed accordingly.

The Movement of ballast and sub grade particle a way from under the sleepers. This causes the sleepers to sink in to the ballast and sub grade. These conditions vary the ballast (ballast/sleeper contact) stiffness and affect the track performances.

The track stiffness irregularities happened and the track became deteriorated. The variation in ballast stiffness beneath under sleeper is generally stochastic. Due to poor drainage and the uneven settlement of a ballast the sleeper became unsupported this will speed up track deterioration processes.

The Research Performed by (Sun, 1992)shows that due to the deformation (unequally settlement of ballast, the track sleeper became unsupported of theirs ballast support) stiffness variation under sleeper. It was found that up to 50% of all sleepers are more or less unsupported. The length of unsupported sleepers section was found to be in the range 1m to 4m. The ranges of small gaps between sleepers and ballast were found to be between 2-4mm this is due to the ballast stiffness variation under the sleepers.

2.5.2. Sub grade deformation

Excessive sub-grade deformation frequently causes rapid track geometry degradation especially when a sub-grade is made up of clayey soil and heavy axle loads. It's important to realize that an effective remedy for track geometry deviation may largely depend on the source of deformation.

The sub-grade stiffness and plastic deformation controls have to meet a much higher standard in the design, construction and maintenance, which increase in cyclic number caused by the higher train speed and large amount of passenger as well as freight have brought a larger cumulative plastic deformation to the sub-grade soil.

The great amount of maintenance cost is inevitable if the sub grade status deteriorates. It is essential to characterize the long term deformation behavior of the railway sub grade soils of the upgrading speed railway induced by cyclic loading for maintenance and improvement to the existing railway lines (Hunt.G, 2005).The long term deformation with influencing factors including relative compaction of sub grade soils number of cyclic loading and the ratio of cyclic deviator stress over confining stress (Lekarp, 1998).

2.5.3. Geotechnical defects

Track stiffness experienced by train will vary along the track, Sometimes the stiffness variation maybe very large within short distance. This is happen due to the defects is one which affects the stiffness of the railway track. Geotechnical defects are such as poor initial compaction, consolidation and drainage of the sub-base below the free track. Geotechnical defects could cause differential settlement of the formation layer or the ballast or the sub-base leading to reduce stiffness which interims gives rise to higher dynamic impact loads and increased rates of ballast degradation and sub-base settlement (Selig, 1997).

The concept underlying all the proposed solution is to create a smooth variation in support stiffness along the track line. The dynamic track movements and long term settlements are governed mainly by the depth and behavior of the ballast with the contribution of the sub-soil or substructure.

2.6. Track support condition

Pita postulates the existence of an optimum vertical stiffness. The result of his experiments shows a great variation of stiffness below the sleeper in a transversal as well as in vertical direction. From this variation of stiffness, he explain that the greatly differing types of settlement of certain track sections by means of an FEM model of the ballast bed, where he assumes a random scattering of the modulus of elasticity according to statically experimental data. Local variation in stiffness is also the starting point of irregular ballast settlement according to other scientific paper.

The variation in ballast stiffness beneath one sleeper is generally stochastic. In some studies the sleepers are modeled as having stochastic support condition. Track stiffness is related to the amount of track vertical deflection. Therefore it could be expected that the characteristic of track support system greatly influence the magnitude of the track modulus.

Track modulus as proportion factors between rail vertical displacement and vertical contact pressure between rail bed and foundation beam. If one sleeper is totally unsupported (hanging the sleeper) the surrounding sleeper needs to carry a lighter load. This corresponding to a lighter of quasi static load from passing trains and an additional dynamic load due to the change in track stiffness caused by the hanging sleeper(Frohling, 1997)

Result in (Frohling, 1997), show that the effect of one hanging sleeper on the sleepers closest to it differs with the size of the gap between the sleeper and the ballast. When the gap is 1 mm the effect on the supported sleeper before the unsupported one is that the contact force toward the ballast is stretched out in time since that sleeper needs to increase. There's also a significant higher contact force between the rail and the wheel at the sleeper following the hanging one. This impact is caused by the imposed upward movement of the wheel when it has passed the deflection at the unsupported sleeper.

2.6.1. Ballast Support

Ballast is the selected material placed on top of the track sub grade to support the track structure. The ballast layer supports the track structure (the rail and sleepers) against vertical, lateral and longitudinal forces from the train to the Sleepers, to which the rails are fastened, are embedded in the ballast which is lightly compacted or tamped around the sleepers to keep the track precisely leveled and aligned. The Standard depth of ballast is 0.3 meters but it is packed to 0.5 meters around the sleeper ends to ensure lateral stability.

The ballast layer has several important functions:-It limits sleeper movement by resisting vertical, transverse and longitudinal forces from the train, It distributes the load from the sleepers to protect the sub grade from high stresses, thereby limiting permanent settlement of the track, It provides necessary resilience to absorb shock from dynamic loading, It facilitates maintenance surfacing and lining operations and It provides immediate water draining from the track structure.

According to Knothe (1998), the long-term behavior of the railroad track, including the ballast behavior and the damage mechanisms underlying the ballast settlement is discussed. Knothe states that there do not exist any generally accepted damage and settlement equations and hardly material equations for the ballast itself the ballast settlement is the function of a number of loading cycles and magnitude of the loading. Ballast must be capable of withstanding the loading from the train traffic a large number of loading cycles, vibrations of frequencies and intensities, repeated weathering and other factors that cause deterioration.

2.7. The Effect of track stiffness on track performance

In general understanding defines track stiffness as the elastic rail deflection that takes place under wheel loading. This generic track stiffness is a function of the structural properties of the Rail, Resilient pads in the track structure, Sleepers, Ballast, Sub-ballast and Sub-grade soil.

Fundamental analysis of track stiffness has typically been approached by means of the beam on elastic foundation (BOEF) approach. This analysis technique is known to be reasonably representative, but introduces the concept of the track modulus, i.e. the stiffness of the spring k per unit length of track.

Track stiffness: - Track stiffness is the elastic rail deflection that takes place under a wheel loading and the ratio of the load applied to the rail to vertical rail deflection.

Track modulus: - track modulus refers to the track, which is the stiffness of the spring “k” per unit length of track and a measure of the vertical stiffness of the track foundation. Track stiffness includes the bending stiffness of the rail, whereas track modulus is concerned only with the support condition below the rail. Both track modulus and track stiffness is related to the track performances.

Global track stiffness: - is a combination of stiffness’s of all different layers and components. The way local stiffness is combined determines the displacements of each layer. Forces and displacements will together with support conditions determine bending moments, as displacements will together with support conditions determine bending moments, as described in the following cases (Leposave Milosavjevic, 2012).

Ballast and sub-layers are influenced both by stiffness above and under themselves. A ballast layer resting on bedrock will experience large internal compression/expansion during a train passage as compared to a ballast layer resting on a soft clay layer.

A differential settlement in the ballast layer is more connected with compaction and variations in sleeper support. Two soil layers can have the same stiffness, but totally different ability for settlements. Yet, very soft layers, such as clay and peat, have generally close correlation between stiffness and settlements.

The track stiffness experienced by a train will vary along the track. Sometimes the stiffness variation may be very large within a short distance. Those are:-

- UN supported sleeper:-track stiffness is locally at that sleeper, very low.
- Insulated joints: - the bending stiffness of the rail has a discontinuity implying a discontinuity also of the track stiffness.
- Transition from an embankment to a bridge
- At switches both mass and stiffness change rapidly

Change track stiffness will induce changes in the wheel/rail contact force. This will intensify track degradation such as increased wear, fatigue, track settlement due to permanent deformation of the ballast and the substructure, and so on. As soon as the track geometry starts to deteriorate, the changes of the wheel/rail interaction forces will increase and the track deterioration rate increases. The determination process due to variation in track stiffness as follows.

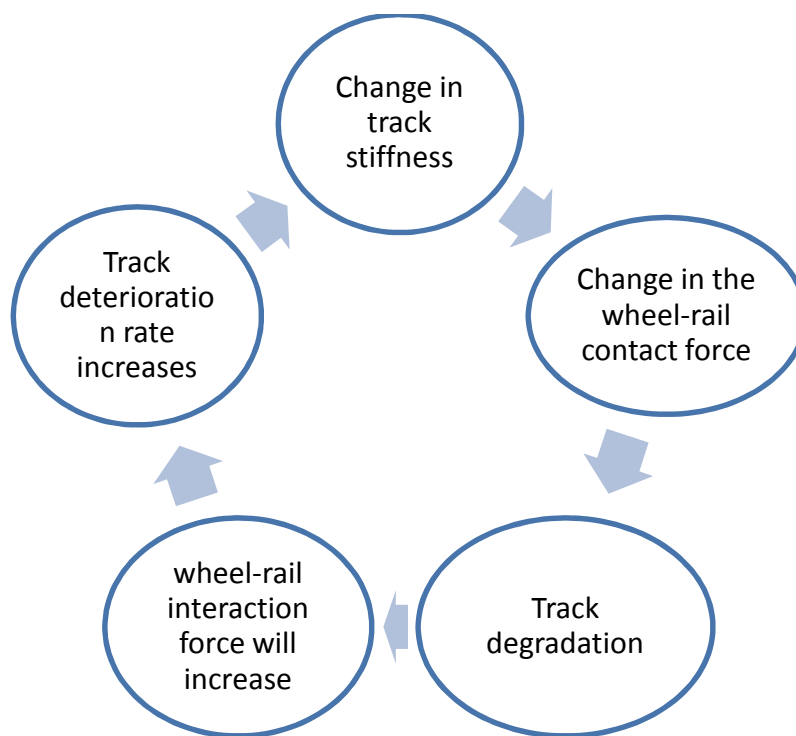


Figure 4 Track degradation determination process due to track stiffness variation

The rate of degradation of track components and the rate of track settlement will depend on the severity of the stiffness variation. As soon as the track geometry starts to deteriorate, the variation of the train/track interaction forces increase, and this speeds up the track degradation rate. Therefore, the influence of track stiffness irregularities on the development of track settlement and on the deterioration of track components and materials cannot be ignored.

2.7.1. Effect of track stiffness variation on Noise and vibration

Track stiffness requirements for noise and vibration may differ from those for track life cycle performance (Witt, 2008) for noise the stiffer the rail pads and the softer the ballast produces the lowest noise levels. However, the surface roughness of the railhead is significant for the amount of noise radiated by the wheel and rail. Thus any changes to the stiffness of the rail pad and the ballast increase the growth of railhead roughness is in the long term, likely to be important.

With ground born noise, ground born vibration and bridge noise, the response of the ground and building are significant. This means that the optimum stiffness for the rail pads and ballast will be specific to a site. However, the overall condition of the track has a significant influence in the amount of vibration and noise entering the ground. Therefore in the long term any influences that rail pad stiffness and ballast stiffness have on the track condition are likely to be significant (Allander H, 2004).

2.8. Track stiffness and maintenance

In order to determine the necessary maintenance actions for the substructure, its condition must be known. Usually most attention has been paid by the infrastructure managers to inspection techniques of the superstructure. Especially for the sub-ballast and the sub grade (subsoil) less consideration has been given although they have a substantial influence on the track maintenance costs.

The vertical stiffness of a railway track plays an important role when considering maintenance work, but it is also an important factor when looking at dissipated energy of a train. Optimal values of the vertical stiffness are proposed in (Lopez pita, 2004). Optimal values optimizing maintenance costs and the costs for dissipated energy of a train versus the vertical track stiffness. According to (Lopez pita, 2004), the optimum vertical track stiffness should be between 70 and 80 MN/mm.

2.8.1. Smoothing Track Stiffness Irregularities

In order to construct a transition zone with the desired variation of stiffness and geometry there are some possibilities (Zhang, 2010). Use of elastomeric products, such as rail pads, under sleeper pads (USP), and sub-ballast mats (SBM), Use of geo-grid (or geo-textile) reinforcement's, Use of Chemical treatment of sub-soil, Use of Management of the ground water and Use of fastenings with varying elasticity.

2.9. Model of track

The mass-spring system is a well-known and largely used mathematical model in the dynamics field. This system is the basis to model the ballasted railway track (figure 5). The structure is represented using discrete elements such as masses for the rail and sleeper, and spring-dashpot combinations for the rail pad and ballast bed.

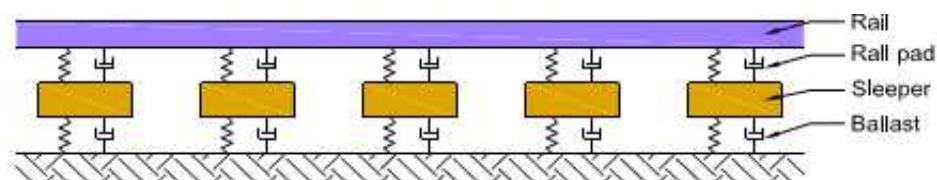


Figure 5 Dynamic models for ballast track

The vehicle moving over the track can also be modeled using a mass-spring system. The interaction of track with the vehicle is represented using the Hertzian-spring principle. The scope of the research limits the study to the response of the track only. Therefore, the effects and dynamic behavior of the vehicle is reduced to concentrated external forces applied on the track. The author refers the reader to for further information about the vehicle-track dynamic interaction.

2.9.1. Different track models reviewed

Through the years a lot of research has been carried out and a lot of different models have been formulated. In those models, the track geometry deterioration is mostly considered as a function of the number of loading cycles and/or a function of track stiffness variation. An overview of the track geometry deterioration models are directly or indirectly influenced by track stiffness. According to the exponential model, the factors of relative settlement, which is directly proportional to the interval between successive track maintenance, depends on the ballast pressure.

Ballast pressure, among other things is the function of track stiffness. Based on this model, it can be concluded that increasing the track stiffness adversely affects the settlement, and the deterioration of the vertical track geometry.

According to the German DSM Model, settlement of the track depends on the sleeper force. As the sleeper forces are lower in the section with lower track stiffness, according to this model, increased stiffness causes an increase in deterioration of vertical track geometry.

In the Satoh's model, the settlement depends on coefficient (βsh) that is directly proportional to the sleeper pressure and ballast acceleration. Sleeper pressure and ballast acceleration are both a function of the track stiffness and their values increase with increasing stiffness. Similar to this model, in the Houshino's and Sugiyamas model the vertical track geometry deterioration is directly proportional to structure factors J , which is influenced by sleeper pressure and ballast acceleration.

The French model of the vertical track geometry deterioration, the Guerin's one expresses the loading cycle. Increasing deflection leads to an increase in the intensity of settlement. Therefore, according to this model, the stiffness reduction causes in the increase in track settlement. It is similar to South Africa model, where the track settlement is directly proportional to the measured track stiffness.

Generally as a conclusion from different models review, too low stiffness value would cause track settlement, with a considerable stress increase in the rails. Too high value would increase dynamic load and thus acceleration track deterioration. The necessity to find the optimum track stiffness is obvious.

2.9.2. Continuously Supported Models: (BOEF)

Rail as a beam on elastic foundation may be modeled ordinary Euler-Bernoulli beam and Rayleigh-Timoshenko beam. *Winkler (1867)* used for modeling of the railway system, Euler-Bernoulli beam theory: an infinitely long rail beam resting on a uniform elastic foundation (Beam on Elastic foundation (BOEF) model).

The rail is modeled as a beam (with bending stiffness EI) which rests on a continuous elastic foundation. The elastic foundation represents all track components and is modeled by evenly distributed linear spring stiffness. The distribution force supporting the beam is then proportional to the beam deflection. Based on this model, the deflection and bending moment of the rail beam due to the moving load can be determined.

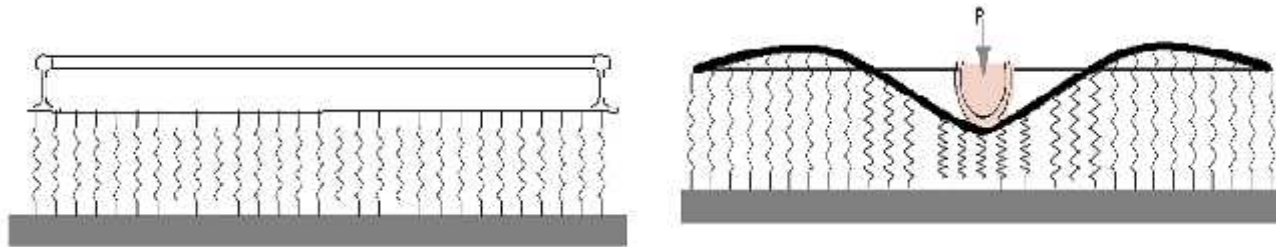


Figure 6 Beam on elastic foundation (unloaded and loaded)

The thick line indicates beam (rail deflection due to the wheel load “P”). This model may be used only for static loading of a track on soft support (i.e. a track with wooden sleepers). Dynamic effects cannot be analyzed using this model as it contains no mass.

2.9.3. Discretely Supported Models

Discretely support models are similar to the continuously support models but they consider the discrete spacing of sleepers; they often have multiple layer representing the rail pads, sleepers, ballast, sub-ballast and sub-grade.

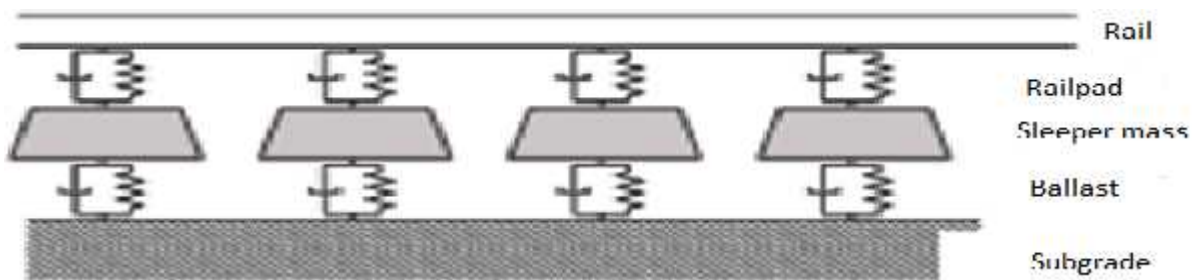


Figure 7 Rail as straight parallel beam supported by sleepers at equal distances

The ballast and sub-grade masses influence each other, in this model ballast mass use as spring and dashpot between the sleeper and sub-grade. Rail is modeled as a beam, the rail pads are modeled by spring-damper system, the sleepers are rigid masses, the ballast modeled by spring-damper systems and the sub-grade is modeled as rigid masses. By this model we can analysis the resonance vibration modes. These are embankment vibration, track-on-the-ballast vibration, rail-on-rail pad vibration, and pinned-pinned vibration of the rail.

2.10. Vertical Dynamic Stiffness and Settlement

A South African Study investigated settlement in relation to dynamic track stiffness. The settlement behavior was reproduced by the following equation (lichtberger, 2011)

$$\text{Equation 1 } EN = \frac{[K1 + K2 * (k2mi/k3)] * pdy}{pref} w * \log N,$$

This study proves the fact those irregular settlements which can be observed that along the track depends on the high degree of varying track stiffness. The higher track stiffness, the lower the settlement to be expected.

2.11. Relation between stiffness and track problems and maintenance

| parameter | problems | Maintenance/rehabilitation |
|--------------------------|--|---|
| Low track stiffness | Poor or weak subsoil or fouled ballast | Substructure design, stabilization soil |
| Variable track stiffness | Variable track support (stiffness modulus) | Matching real seat pads, substructure design ballast mats |
| Void sleeper | Fouled ballast, local settlement, poor fastener condition , poor ballast stiffness | Inspect fasteners, tamping stone blow, clean fouled ballast and replace |

Table 1 Relation between stiffness and track problems and maintenance

4.1. The optimal deflection of the sleeper

The vertical movement of sleeper under traffic depends on the sleeper spacing. The resistance of the rail to bending depending on the stiffness of the rail pads, the ballast bed and the subsoil properties. The large deflection leads to higher loads on the rail, if the deflection is small, it can increase the pressure on the ballast to unacceptable levels. The consequences can be the distraction of the ballast, which is called ‘white spot’ (lichtberger, 2011). The optimum ranges of deflection for good track stiffness is between 1.2mm and 1.5mm. Deflection above 1.5mm is too large. At a deflection below 1.2mm the support is too stiff.

CHAPTER THREE

Track modeling and analysis

3.1. Track modeling

The approach used to solve the problems of a theoretical determination of the track stiffness variation and its influence on full track condition is necessity in an idealization and simplification of the actual situation. The model representation of the track structure is that 2D system which considers the behavior of a longitudinal section. The model accounts for the behavior of each of the four major track structure components. Rails and sleepers stiffness are considered along with the stiffness properties of the ballast and sub grade.

The modeled track consists of the rail, rail pads, sleeper and ballast and sub grade. The total length of the model is 28 sleepers, whereas center to center distance between two sleepers is 0.6m.

The rail is modeled with an isotropic elastic material and has a beam cross section has an 'I'-profile. It has mass density of 7143 kg/m^3 . therefore the mass m of one meter of the rail is

$$\text{Equation 2 } M = \sum_{A=0}^I A_i + \rho = 60 \text{ kg/m}$$

This represents an UIC 60 rail, which is used in most newly built tracks in Europe nowadays. The young's modulus of the rail is $210,000 \text{ Mpa}$ and the poisons ratio is 0.3. The overall length of the rail is 23.62 m . The rail pads are modeled as the spring and dashpots which have the hyper elastic rubber property placed between the rail and the sleepers. In this model concrete sleepers are used. The height and width of the sleeper are 0.2 m and 0.265 m respectively.

Ballast can be considered as either a linear or non-linear material. When a railroad is recently constructed and has not been compacted, ballast always behaves non-linearly. in this case, the constitute equation for calculating the resilient modulus of granular-material is governed by the following two equations: (Embirson, 2001).

$$\text{Equation 3 } E = K_1 k_2$$

$$\text{Equation 4 } = 1 + 2 + 3 + z(1 + 2k_0)$$

Where, E is the resilient modulus; k_1 and K_2 are the coefficients; σ_1 , σ_2 and σ_3 are principal stresses; γ is the unit weight of materials and k_0 is lateral stress ratio.

Table 2 Material properties of models

| Material type | properties |
|---------------|---|
| Rail | Modeled as isotropic elastic material UIC 60 I-profile Mass Density=7143kg/m ³ Elastic modulus =210GPa Poisons ratio=0.3 Length=23.62m |
| Rail pad | Modelled as spring and dashpot Hyper elastic rubber material Placed between rail and sleeper |
| sleeper | Concrete sleeper |
| ballast | Either linear or non- linear material Elastic modulus =K ₁ K ₂ |
| Subgrade | Linear elastic material Poisons ratio =0.45 |

Sub grade is always considered to be a linearly elastic material. The bottom most layers are generally the bedrock which is considered to be incompressible with a Poisson's ratio of 0.45. Although these materials have an elastic response under very low levels of stress, they exhibit a plastic behavior under higher stresses, which occurs in our case. For this reason, elastic-plastic behavior was assumed (D.R. Ahlbeck, 1978). This assumption implies that reloading occurs in the same manner as unloading; therefore, the material experiences no hardening.

The most appropriate model to represent this phenomenon is the Drucker-Prager model (Xiaoyi, 2009), which is based on the hydrostatic stress. This model was applied to this study because it was used in several railway design studies. This model behavior may be introduced in ABQUS by implementing the cohesion C and the angle of internal friction (ϕ) and dilatancy (ψ) of each material.

3.2. Material Constitutive Models

The mechanical behavior of a railway structure is determined by the displacements, strains stresses and external loads. These variables are to each other by equilibrium equations and constitutive equations. The constitutive equations of the materials must represent the real response of material. The material parameter that used for the track modeling and analysis are shown in table below.

Table 3 Material parameters used for modeling

| Material | Property | Value | Remark |
|----------|---------------------|------------------------|---|
| Rail | Flexural stiffness | 128MN/m ² | Steel material |
| | Density | 7143 kg/m ³ | |
| | Mass | 60 kg/m | |
| | Modules elasticity | 210GPa | |
| | poisons ratio | 0.3 | |
| Rail pad | stiffness | 50-300 MN/m | Use 1.5e8,3.0e8 MN/m to analysis the effect of rail-pad stiffness variation |
| | damping coefficient | 50-75 KN/m | |
| sleeper | modulus elasticity | 30GPa | Pre-stressed concrete structure |
| | poisons ratio | 0.25 | |
| | density | 2500 kg/m ³ | |
| | length | 2.5m | |
| | height | 0.24m | |
| | width | 0.25m | |
| | spacing | 0.6m | |

| | | | |
|-----------|---------------------|--|---|
| ballast | modulus elasticity | 70-170(Mpa) | Use the stiffness of ballast, 60,150,250(MN/m) and the damping ratio, 50(KN.s/m) to analysis the effect of ballast stiffness variation. |
| | poisons ratio | 0.4 | |
| | density | 1900-2000(kg/m ³) | |
| | stiffness | 60-250(MN/m) | |
| | damping coefficient | 30-180(KN.s/m) | |
| | Drucker pragure | 50-250(KN/m), 30-180(KN.s/m) θ _f = 45 θ _d = 15 | |
| sub grade | modulus elasticity | 80Mp),200Mpa, 350MPa | Use the stiffness variation of subgrade,45,(MN/m) |
| | poisons ratio | 0.45 | |
| | density | 2000(kg/m ³) | |
| | stiffness | 45-120(MN/m) | |
| | Drucker-pragure | | |

Significant step in the analysis of railway track stiffness variation and understanding its consequences are described. In this paper analysis of track stiffness variation and its effects on the railway track performance are doing by mathematical methods and modeling the track.

In the analysis of the railway track stiffness variation, we have to consider support stiffness because for the variation of track stiffness and the support stiffness is the main one for track stiffness. In addition the track support performance must be considered and forecasting the track support failure time and the time of its maintenance.

Loads:- Due to the non-elastic nature of granular materials the strains of the structure depends on the load history. The loads of train were introduced as vertical load at the central point of the rail and represent tons per wheel transmitted by the train to the track. The vehicle static load differs from the actual load transmission due to dynamic forces that appear in the wheel-rail interface as a result of vertical movement. In this model the value of the increased dynamic load was calculated using Eisenmann’s formula

$$Equation\ 5\ Q_d = Q_e [1 + t * (1 + (v-60)/390)]$$

Where: - Q_d is dynamic load, Q_e is vehicle load, t is statistical security coefficient, is factor of the quality conditions of the track and v is speed of the vehicle.

In the calculation of dynamic load the statistical security coefficient (t) is 2, corresponding to the percentile of 95.9% and is 0.2, regarding the good conditions of the track (Xiaoyi, 2009).

3.3. Creating Finite Element Models

This chapter deals with modeling techniques that are used to analyze the railway track stiffness in the commercial software ABAQUS. A brief summary of the routines that have been used are presented.

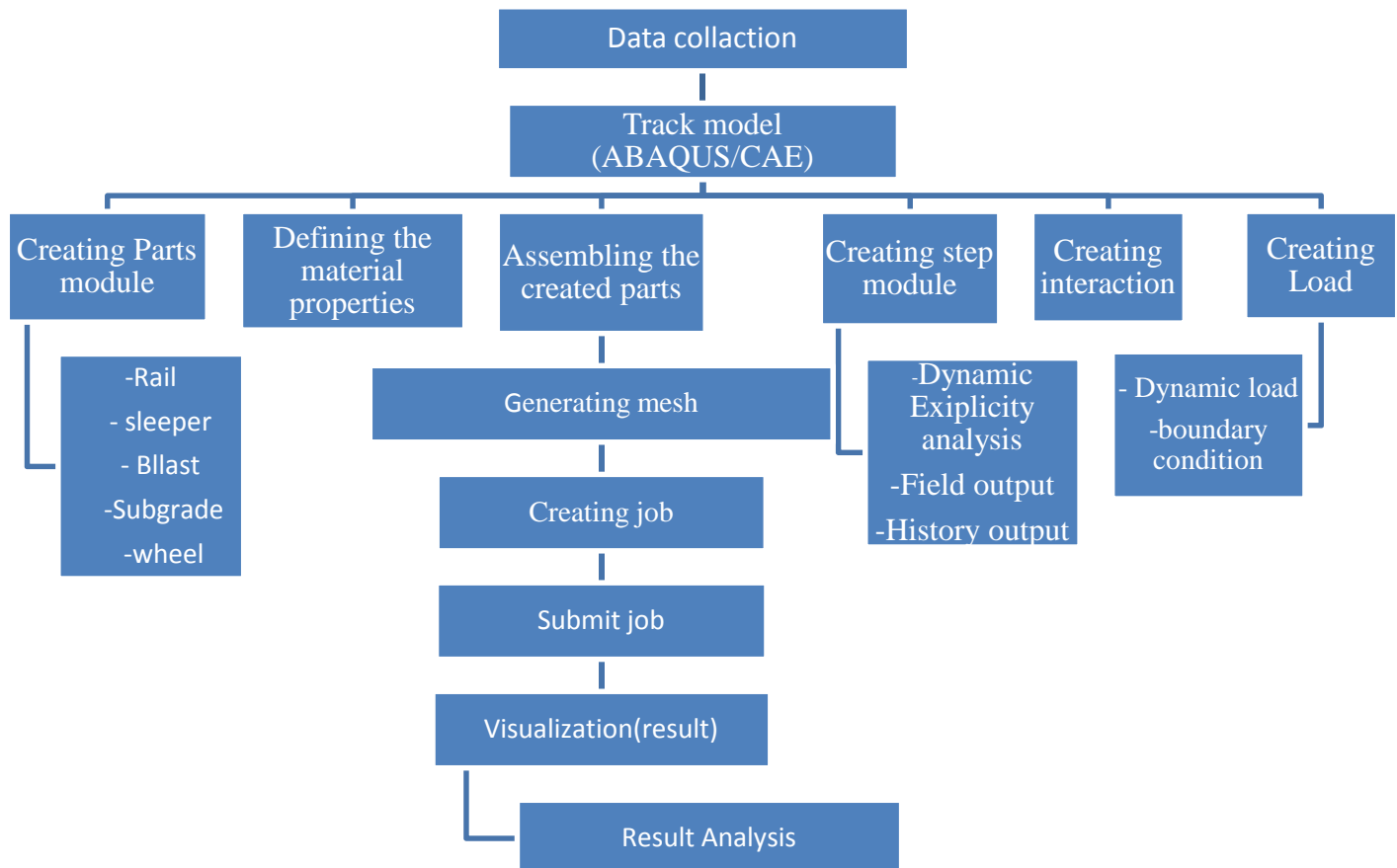
The finite element models were created in ABAQUS/CAE which includes the graphical user interface (GUI). This method of creating models is easier than coding an input file, especially when the models are large, as in the case with 3D models.

3.4. Modeling procedures in ABAQUS/CAE

The ABAQUS/CAE environment is divided into different modules, where each module defines a logical aspect of the modeling process, for instance, defining the geometry, defining the material properties, and generating a mesh.

The GUI interface generates an input file with all information of the model, to be submitted to the solver, using ABAQUS/Standard or ABAQUS/Explicit routines. The solver performs the analysis and sends the information back to ABAQUS/CAE evaluation of the results.

Figure 8 Flow Chart of track modeling and analysis



Elements: -Abaqus has an extensive element library to provide a powerful set of tools for solving many different problems. All elements used in ABAQUS are divided into different problems. All elements used in ABAQUS are divided into different categories depending on the modeling space. The element shapes available are beam elements, shell, elements and solid elements and the modeling space is divided into 3D and 2D planer space and axis metric space.

Beam elements:-beam elements have been used for the rails and sleeper modeling. A beam element is an element in which assumption are made so that the problems reduced to one dimension mathematically. The length of element must be large compared to its cross section there are two main types of beam elements formulation.

- Solid element:**-solid elements in two and three dimensions are available in ABQUS. The two-dimensional solid element allows modeling of plane and ax symmetric problems. In three dimensions the isoperimetric hexahedron element is the most common, but in some cases complex geometry may acquires tetrahedron elements. Those elements are generally only recommended to fill in awkward parts of mesh. ABAQUS provides both first-order elements are essentially constant strain elements while the second-order elements are capable of representing all possible linear strain fields.
- Rigid elements:**-for discretely supported track including ballast mass model, the ballast is modeled as rigid element since only it's mass is concerned. A rigid part represents a part that is so much stiffer than the rest of the model that its deformation can be considered negligible. Computational efficiency is the principal advantage of rigid parts over deformable parts.
- Spring and dashpot elements:**-spring and dashpot elements are widely used in this model. For instance, the rail pads between the rail and the sleeper, connectors for bounding adjacent ballasts in each direction, and the boundary conditions for constraining the sleepers.

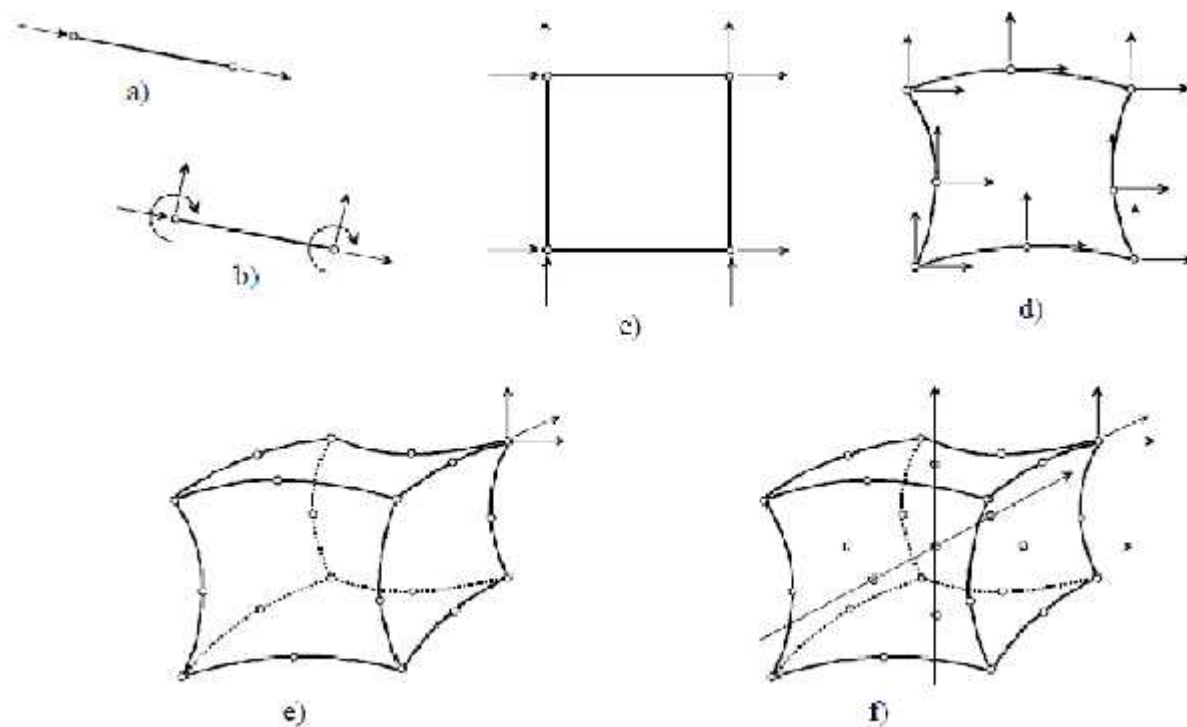


Figure 9 Different types of finite elements



Figure 10 Longitudinal section of discretely support tracks model

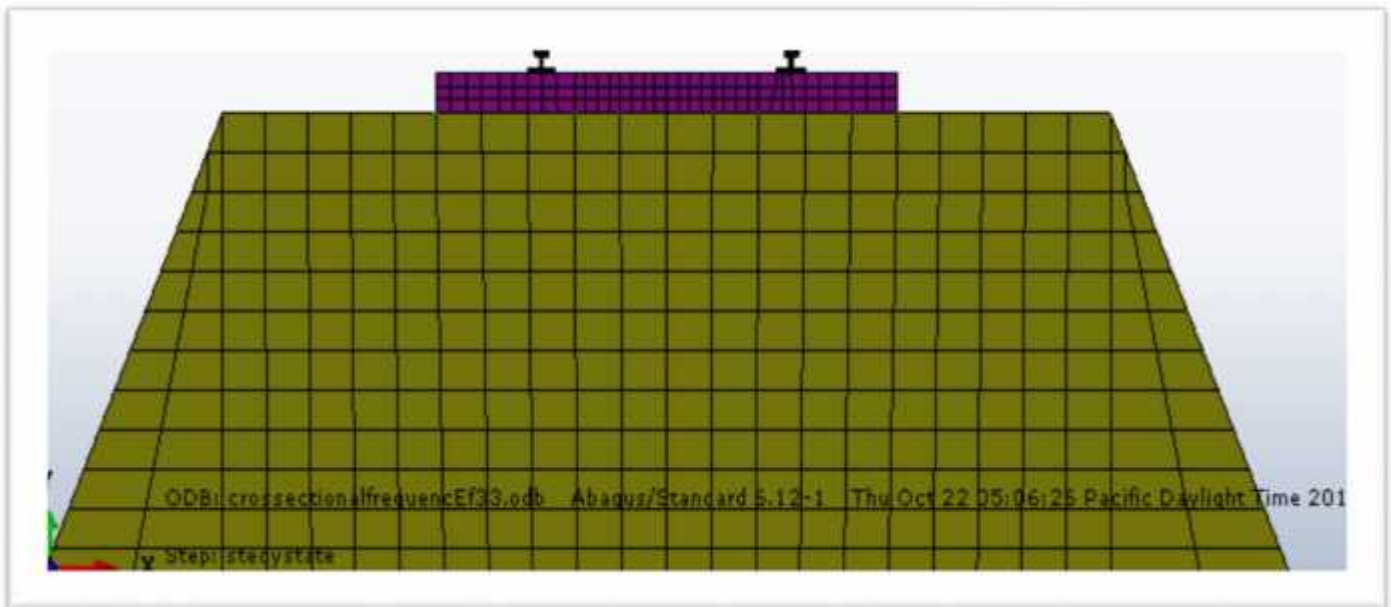


Figure 11 Cross-section model of track component

CHAPTER FOUR

Dynamic track stiffness analysis

4.1 Dynamic Implicit Analysis

The dynamic implicit analysis method is calculating the transient dynamic response of a structure. A direct-integration dynamic analysis in Abaqus/Standard must be used when nonlinear dynamic response is being studied. The general direction-integration method provided in Abaqus/Standard, called the Hilber-Hughes-Taylor operator, is an extension of the trapezoidal rule. The half-step residual is the equilibrium residual error halfway through a time increment, $t + \Delta t/2$ and once the solution at $t + \Delta t$ has been obtained, the accuracy of the solution can be accessed and the time step adjusted appropriately.

The principal advantage of the Hilber-Hughes-Taylor operator is that it is unconditionally stable for linear systems; there's no mathematical limit on the sizes of the time increment that can be used to integrate a linear system. This nonlinear equation solving process is expensive; and if the equations are very nonlinear, it may be difficult to obtain a solution. However, nonlinearities are usually more simply accounted for in dynamic situations than in static situations because the inertia terms provide mathematical stability to the system; thus, the method is successful in all but the most extreme cases.

The choice of the time increment depends on the type of analysis performed. In dynamic problems, a smaller time increment than the stable one might be used to get an accurate result depending on the variations in the structure. There are two ways of defining the time increment, automatic or fixed incrementation. The automatic incrementation scheme is provided for use with the general implicit dynamic integration method. The scheme uses a half-step residual control to ensure an accurate dynamic integration method.

4.2. Dynamic explicit analysis

The dynamic explicit procedure performs a large number of small time increments efficiently. An explicit central-difference time integration rule is used; each increment is relatively expensive (compared to the direct-integration dynamic analysis procedure available in Abaqus/standard) because there is no solution for a set of simultaneous equations.

The explicit central-difference operator satisfies the dynamic equilibrium equation at the beginning of the increment t , the acceleration calculated at time t are used to advance the velocity solution to time $t + \Delta t/2$ and the displacement solution to time $t + \Delta t$.

4.3. Steady-state Dynamic Analysis

One way to investigate the dynamic properties of a railway track is to load the track with a sinusoidal force. At frequencies up to about 1800HZ, this can be done by using hydraulic cylinders. If one wants to investigate the track response at higher frequencies, the track may be excited by an impact load.

In ABAQUS steady-state dynamic analysis provides the steady-state amplitude and phase of the response of a system due to harmonic excitation at a given frequency. Usually such analysis is done as a frequency sweep by applying the loading at a series of different frequencies and recording the response; in Abaqus/standard the direct- solution steady-state analysis the steady-state harmonic response is calculated directly in terms of the physical degrees of freedom of the model using the mass, damping, and stiffness matrices of the system.

4.4. General Static Analysis

The general static analysis can involves both linear and nonlinear effects and is performed to analysis static behavior such as deflection due to a static load. A criterion for the analysis to be possible is that is stable. The static use of time increment is not in a manner of dynamic steps but rather as a fraction of the applied load. The default time period is 1.0 units of time, representing 100% of the applied load.

The nonlinear effects are expected, such as large displacements, material nonlinearities, and boundary nonlinearities, contact or friction, command should be used. When dealing with unstable problems such as in buckling or collapse, the modified risk method can be used. It uses the load magnitude as an additional unknown, and solves simulations for loads and displacements.

4.5. Linear Eigen value Analysis

Linear Eigen value analysis is used to perform an Eigen value extraction to calculate the natural frequencies and corresponding mode shapes of the model. The analysis can be performed using subspace Eigen solver algorithm.

4.6. Analysis of Ballast Stiffness

As a bulk material ballast is relatively stiff and its stiffness depends on the degree of compaction and its material property (thickness of ballast, ballast coefficient, ballast bearing capacity and grain size of the ballast).(D.R. Ahlbeck, 1978), Assumed that the load transmitting from a sleeper to the ballast approximately coincides with the cone distribution. That is to say, the stresses of the ballast are uniformly distributed over the cone region.

The inclination of the cone is just the ballast stress pervasion angle corresponding to the poisson's ratio. Thus the effective acting regions of the ballast under each sleeper can be determined as shown in fig.12.

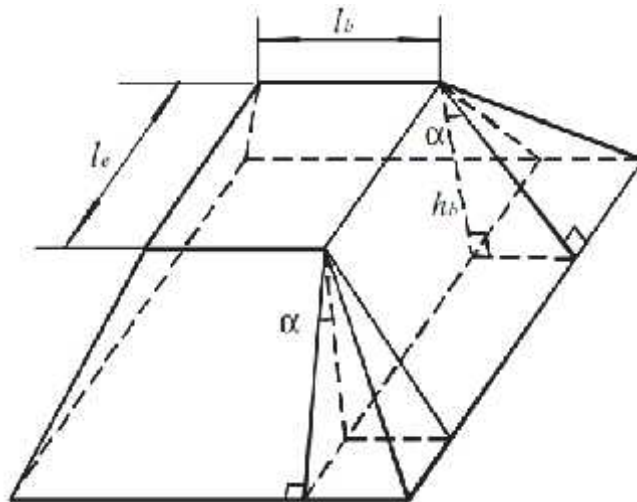


Figure 12 model of the ballast under one rail support point

The continuous granular ballast could be modeled as a series of separate vibrating masses when analyzing the track dynamics, by which the analytical process of the ballast vibration is greatly simplified.

According to the ballast model as shown in fig.12 the ballast mass under each sleeper support point could be evaluated as

$$\text{Equation 6 } M_b = \rho_b h_b [l_e l_b + (l_e + l_b) h_b \tan \alpha + \frac{4}{3} h_b^2 \tan^2 \alpha]$$

Where ρ_b is the density of the ballast, h_b is the depth of ballast, l_e is the effective supporting length of half sleeper, l_b is the width of sleeper underside, and α is the ballast stress distribution angle. The supporting stiffness of ballast mass can be determined as

$$\text{Equation 7 } K_b = \frac{2(l_e - l_b) \tan \alpha}{\ln \left[\frac{(l_e/l_b) * (l_b + 2h_b \tan \alpha)}{(l_e + 2h_b \tan \alpha)} \right]} E_b$$

Where: - E_b , is the elastic modulus of the ballast. Correspondingly, the sub grade stiffness under supporting point to the product of the cone underside area and the modulus of sub grade.

$$\text{Equation 8 } K_f = (l_e + 2h_b \tan \alpha)(l_b + 2h_b \tan \alpha) E_f$$

Where: - K_f is the K_{30} modulus of sub grade, which means the force acting on unit area that leads to unit deformation.

4.7. Influence of Ballast stiffness Variation

Ballast is a stone material, which plays an important role in varying the track layer stiffness. And have its own stiffness value. There is imperfection contact between ballast and sleeper at construction time due to compaction, ballast grain size and through the service life of track. This may happen under midpoint, end to end and at the same time mid-end point of one sleeper.

In practice, during operation and moving of the freight trains falling of small particles over the ballast layer causes an increase of stiffness in the layer of ballast. Also a gradual deterioration of ballast effect on size of ballast grade and forming powder due to friction exists between stones rubbing together, which affect the stiffness of ballast.

The finite element analysis model was conducted on the ballast stiffness variation and the output is as shown below.

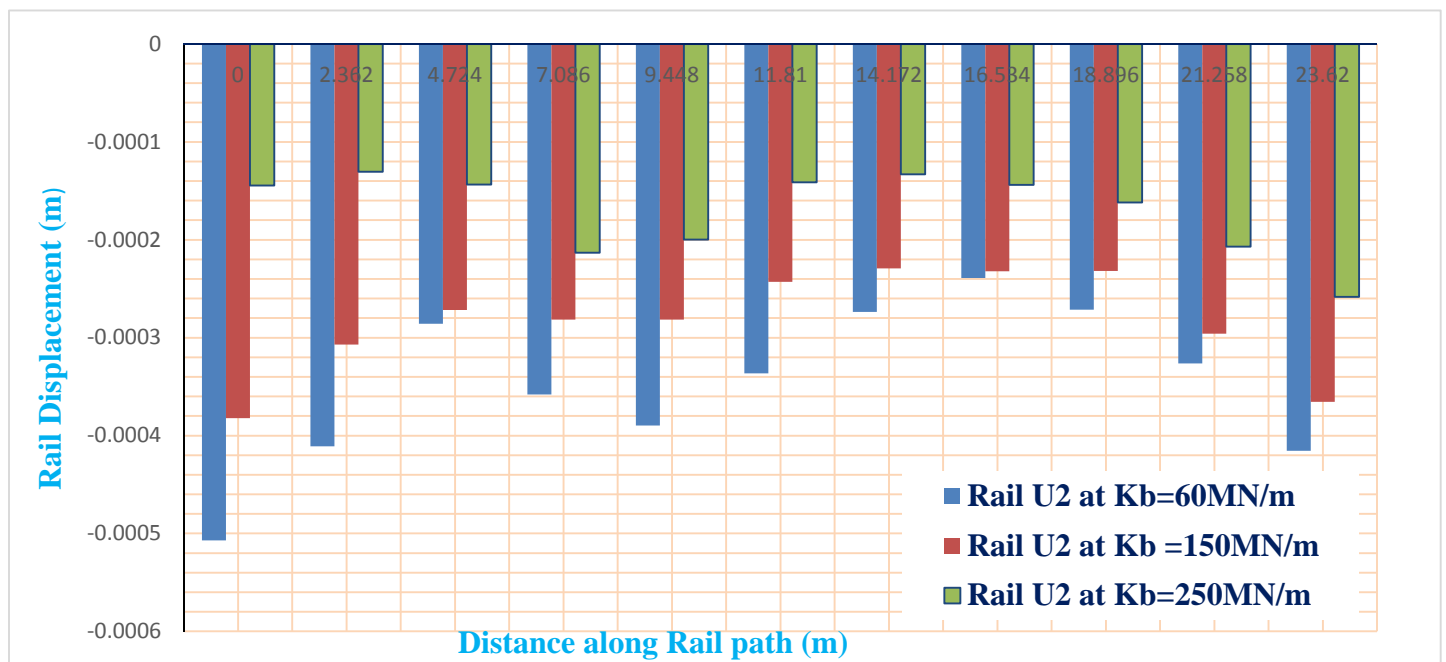


Figure 13 Vertical displacement of rail with ballast stiffness

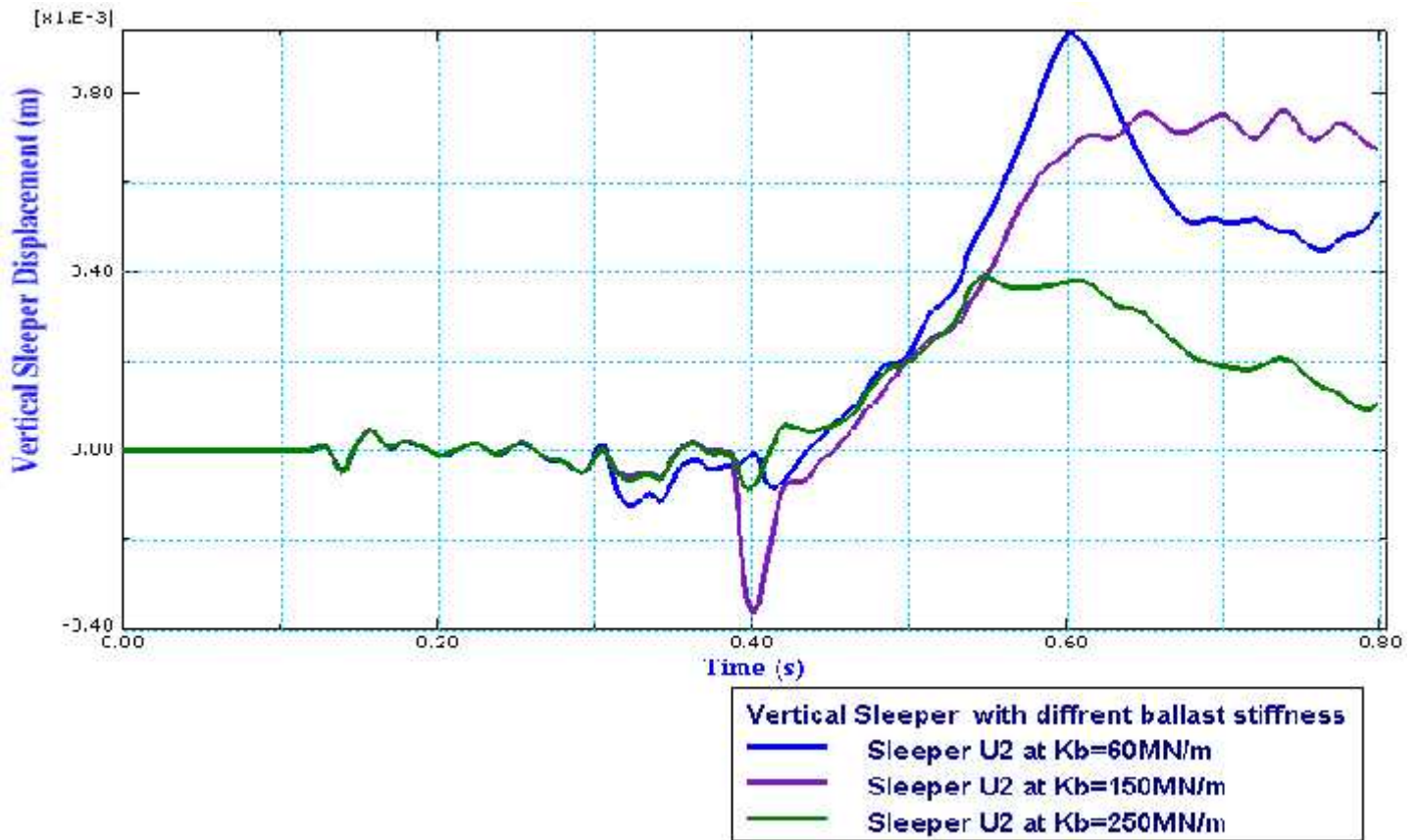


Figure 14 Vertical displacement of sleeper with different ballast stiffness

The effect of ballast stiffness considered in (Xia, 2008). He conducts sensitivity analysis on ballast stiffness by a sampled track-train interaction modeling. The result obtained from Finite element modeling (ABAQUS) is the same as the result of (Xia, 2008).

Increased ballast stiffness reduced Rail displacement at the mid span, on supports and also displacement of sleepers. Interaction forces between ballast-sleeper and sleeper-rail increased. Generally, the ballast stiffness was stochastic part of the track.

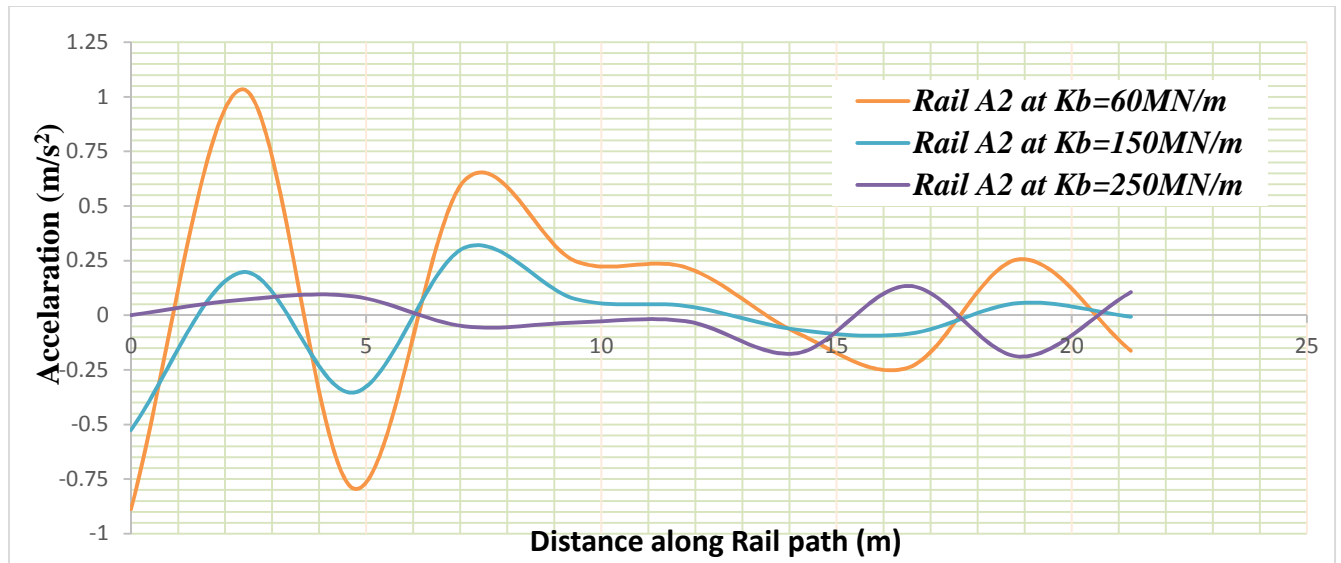


Figure 15 Vertical Acceleration of rail with different ballast stiffness

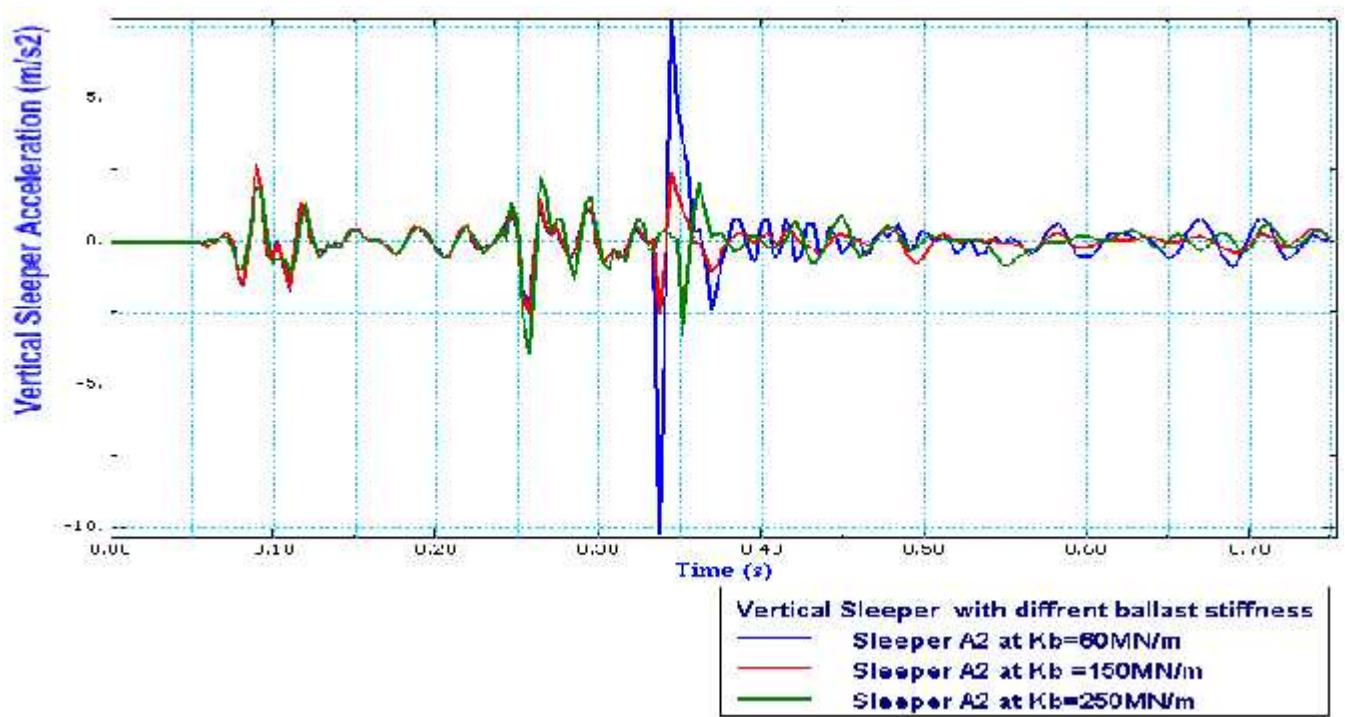


Figure 16 Vertical Acceleration of sleeper with ballast stiffness

Increasing ballast stiffness also reduces the rail and sleeper acceleration, velocity, sub grade strain rate. The biggest change is in vibration acceleration of ballast and rail stress increased. Rail tension and settlement decrease with increasing stiffness of the ballast bed. But on the other hand the force at the supporting point increases.

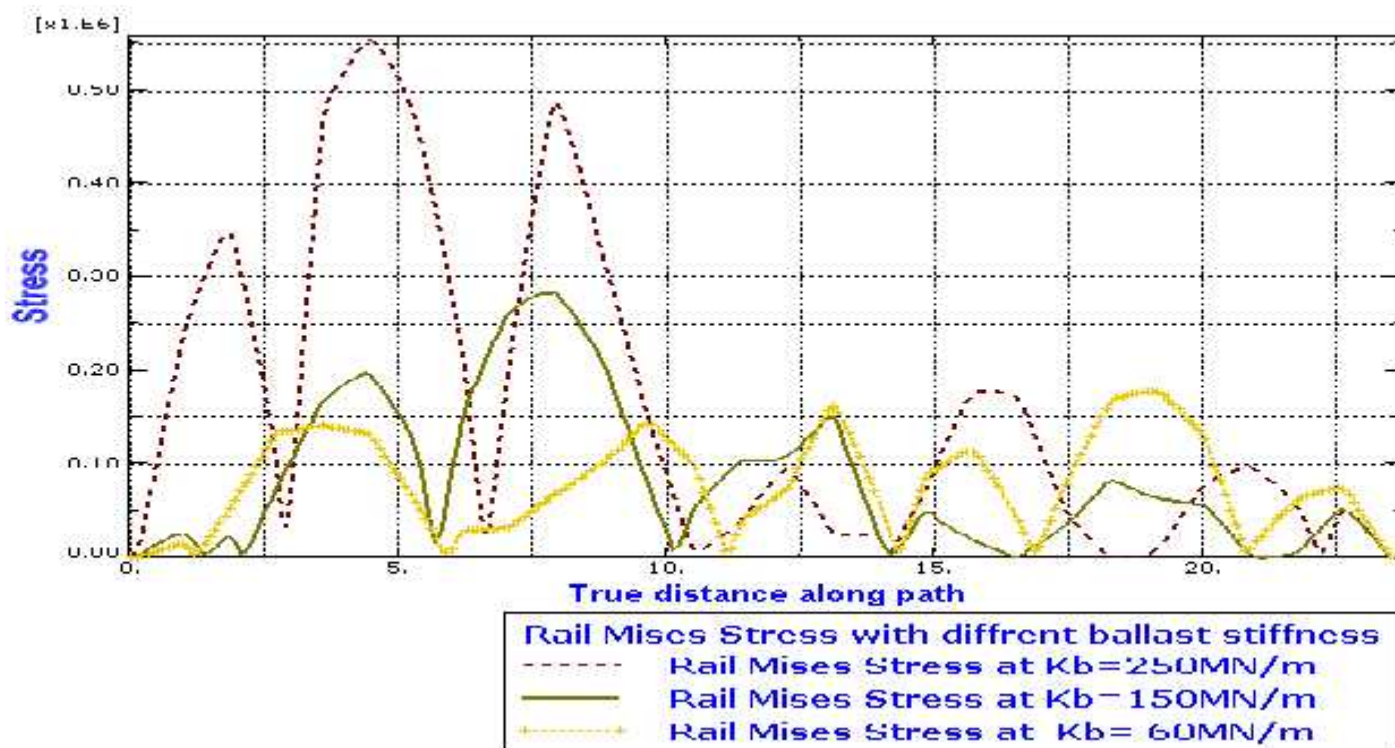


Figure 17 Rail Misses Stress under different ballast stiffness

4.8. Influence of Ballast Damping

The damping coefficient of ballast also plays an important function in the behavior of track vibration. As we know, the determination of such coefficient is practically very difficult. Increasing the ballast damping coefficients, the Rail displacements on both supports and at mid span approximately remained the same. The displacement of ballast layers rise. Rail vibration acceleration also roughly unchanged. Ballast vibration acceleration increase. Sleeper vibration acceleration was reduced. Contact forces of wheel and rail were decreased up to damping ratio of 80KN.s/m and after that remained unchanged. Interaction forces between sleeper and ballast also decrease.

Hence it seems that measuring and controlling the ballast layer’s vibration acceleration by using a stiffened ballast material could be beneficial in evaluating the ballast damping coefficient. If the damping behavior of the track material is poor we can improve by the additions of numerical damping to the material (Wood, 1980).

Equation 9 $C = tk$

The maximum numerical damping is obtained by the substitution of $\gamma = \sqrt{1/3}$. The strongest damping (super-damping) is obtained with $\gamma = -3$. It is recommended to use this value for the addition of numerical damping to the rail element; for all other elements we take $\gamma = -0.1$.

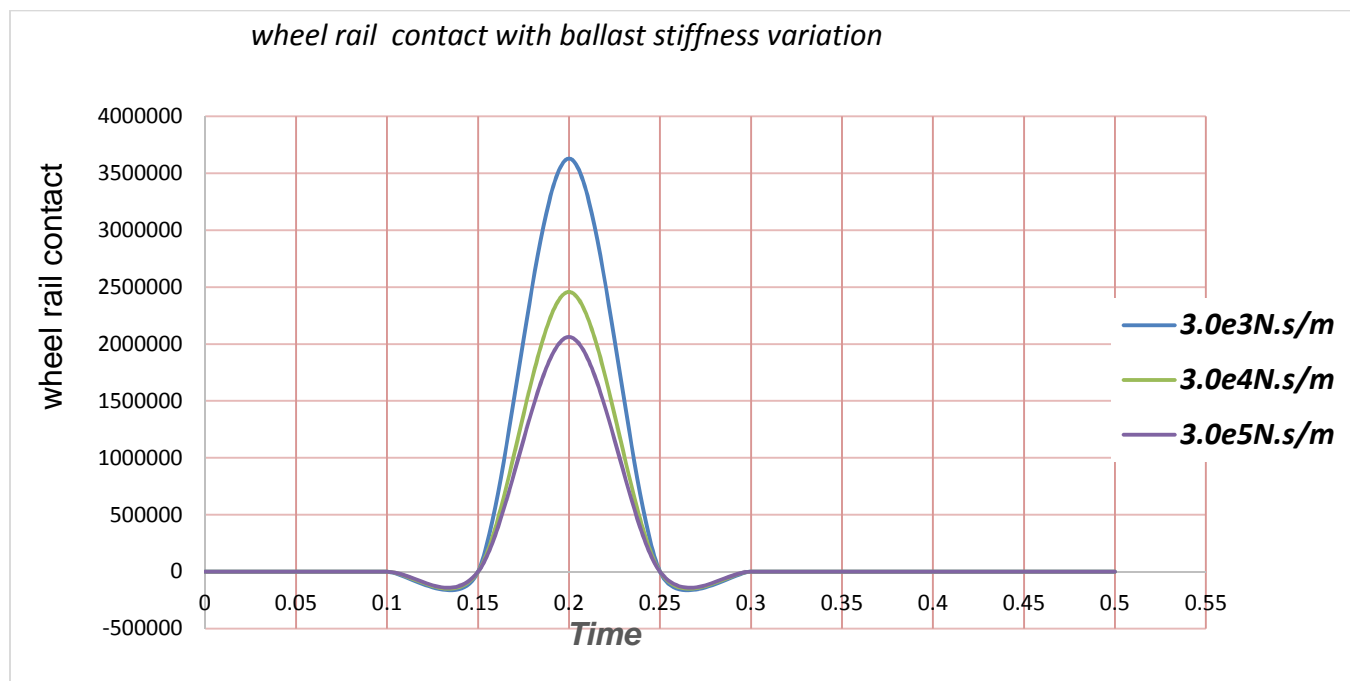
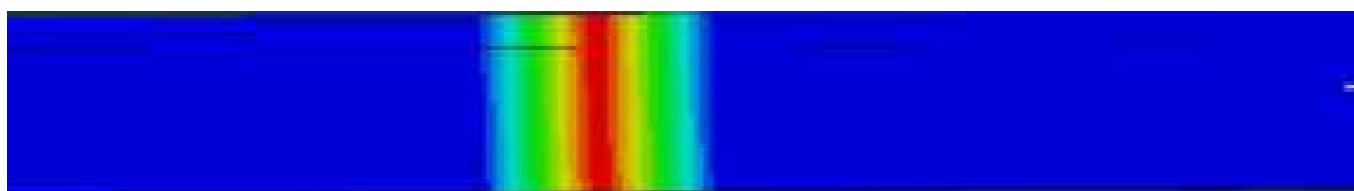


Figure 18 Wheel rail contact force with different ballast damping coefficient

4.8.1. Effect of ballast thickness

According to (Hameed, 2013) the ballast thickness affect the track stiffness.(Hameed, 2013) Use the Track 3.1 Programmed developed by US Army crops engineer to analysis the effect of ballast thickness on the track stiffness. He concludes that, Increased the ballast thickness increased the stiffness of the ballast and the track performance also increases. In this paper Modeling of the ballast track having different ballast thickness and analyzed the effect of ballast thickness by using FEM (ABAQUS) and the result that obtained from analysis almost the same to (Hameed, 2013).

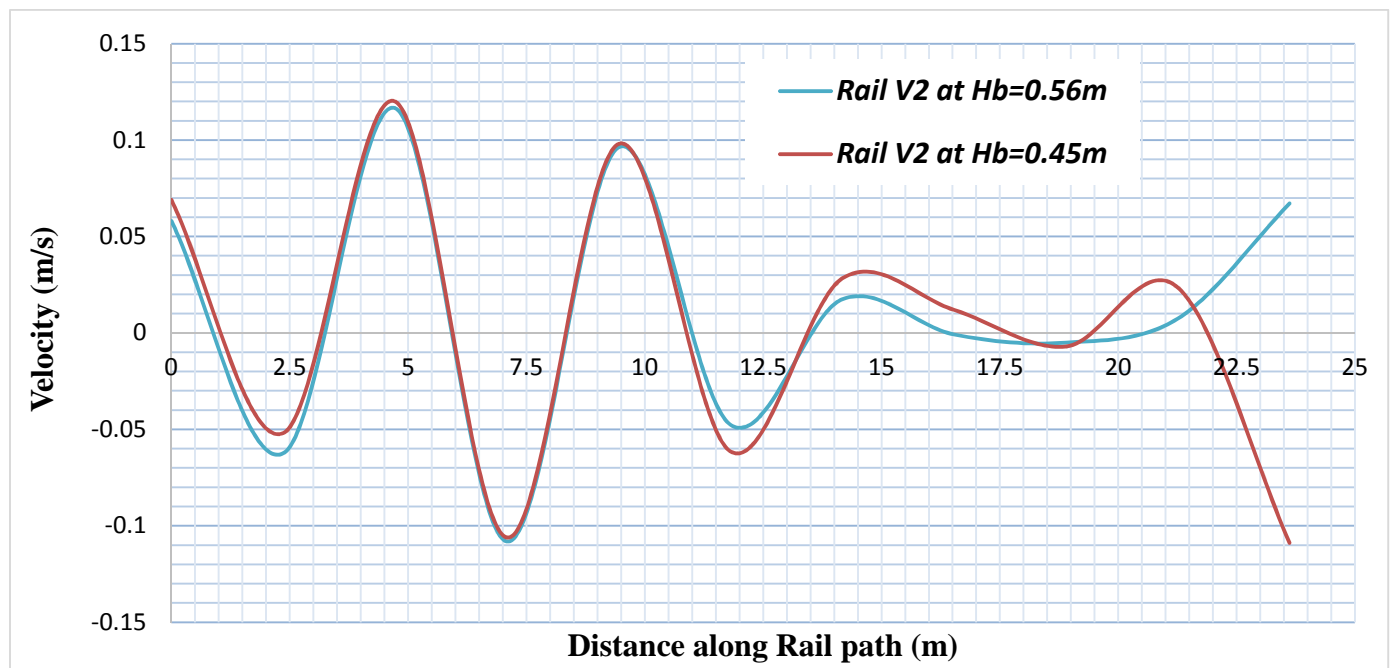


Figure 19 The Rail vertical velocity along the track length with different ballast thickness

As shown on Figure19, ballast thickness affects the vertical track velocity. Increased the ballast thickness reduced the rail vertical velocity. Because it's more stiffen and the bearing capacity increase.

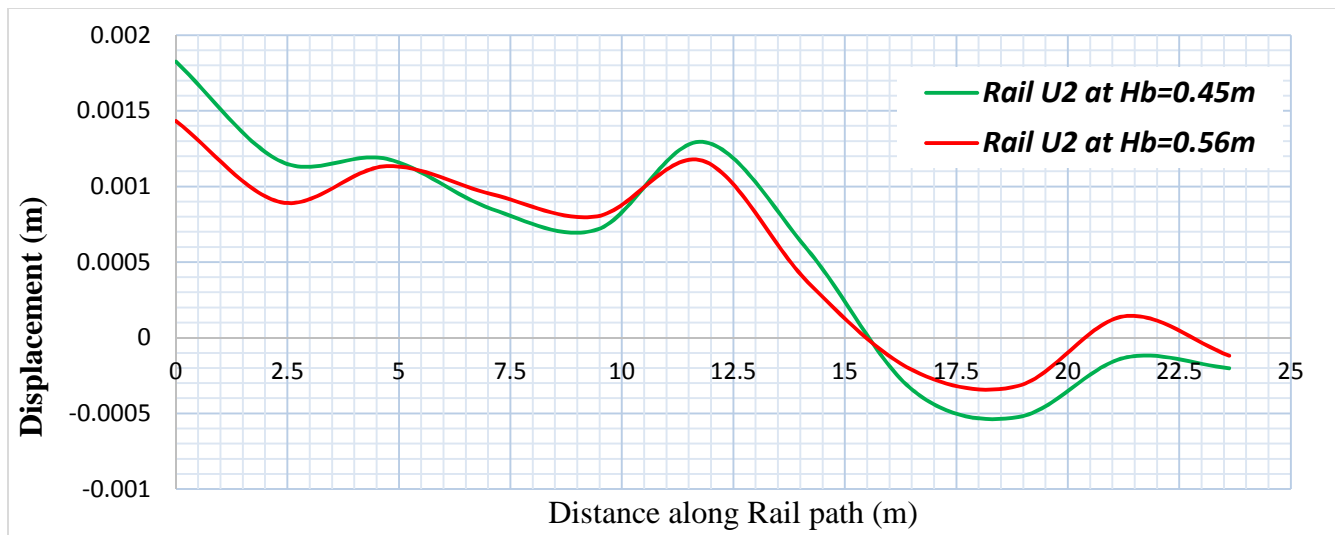


Figure 20 Rail Displacement with different ballast thickness

When we compare the result from different ballast thickness, increasing the ballast thickness from 0.45m to 0.56m increasing most of the region of the ballast stiffness and reduce the rail deflection and velocity.

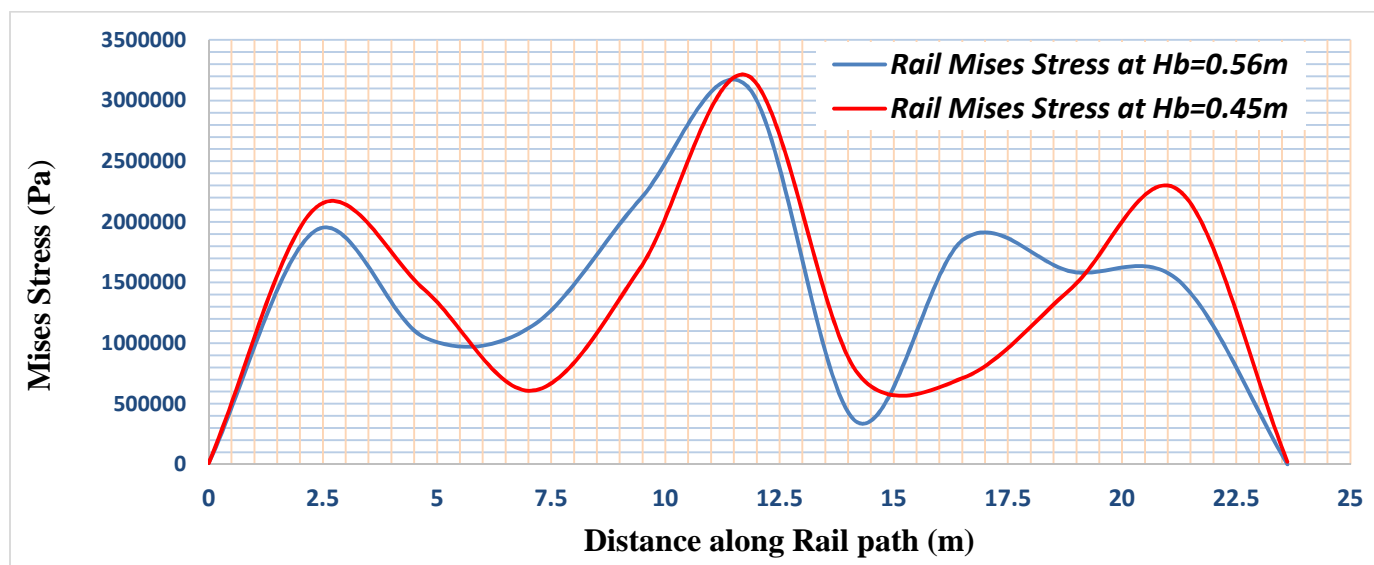


Figure 21 Rail Stress with different ballast thickness along the track length

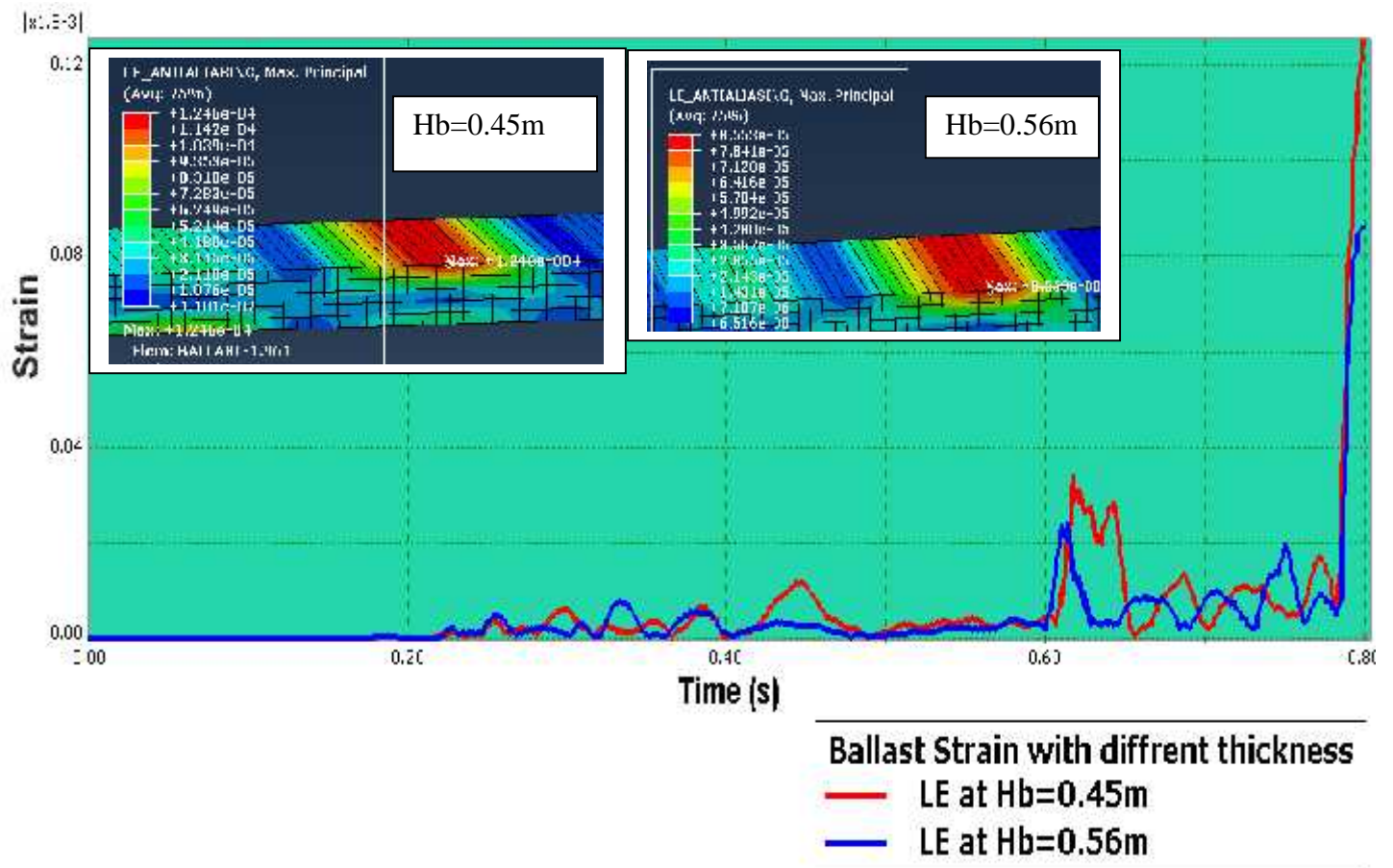


Figure 22 Max. Principal strain of ballast with different ballast thickness at nodes

According to (Hameed, 2013), The Rail tension and settlement decreases with increasing stiffness of the ballast bed but on the other hand the force at the supporting point increases.

The vertical ballast strains with 0.45m and 0.56m ballast depth clearly shows the strain pattern under the loaded sleeper follows the stress distribution pattern with the larger strain occurring beneath the rail seat. Increasing the ballast depth increase the logarithmic strain of the ballast bed became more stiffened and the strain and stress increases.

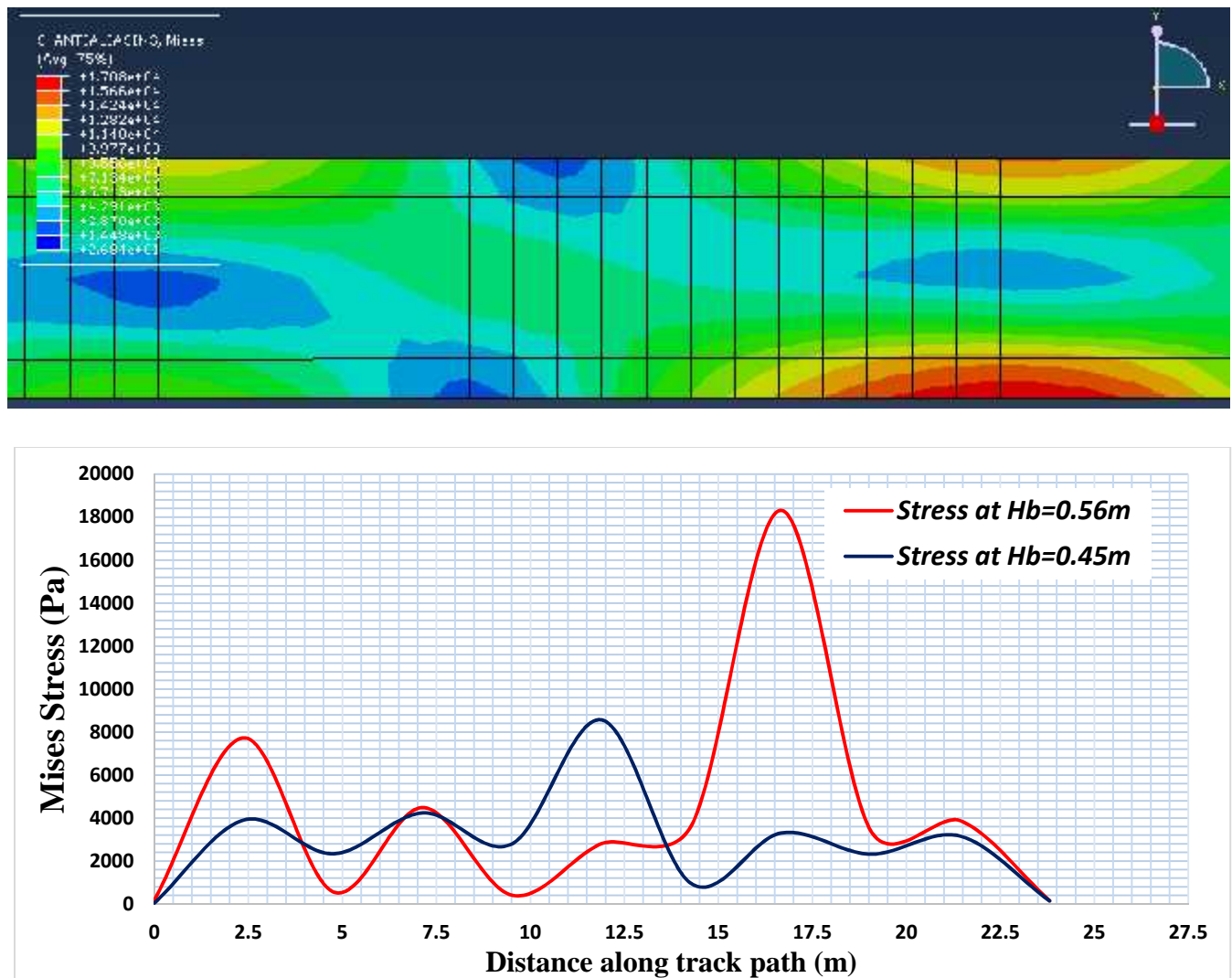


Figure 23 Ballast Mises Stress along the Track path with different ballast thickness

The Vertical Stress at the sleeper-ballast interface beneath the point of wheel load application was affected by different track parameters. Increases in ballast stress were also caused by an increase in ballast young’s modulus and ballast thickness and by a decreasing the sleeper young’s modulus and rail moments of inertia. Increasing the ballast depth and ballast young’s modulus, increase the ballast stiffness and increase the ballast interface stress.

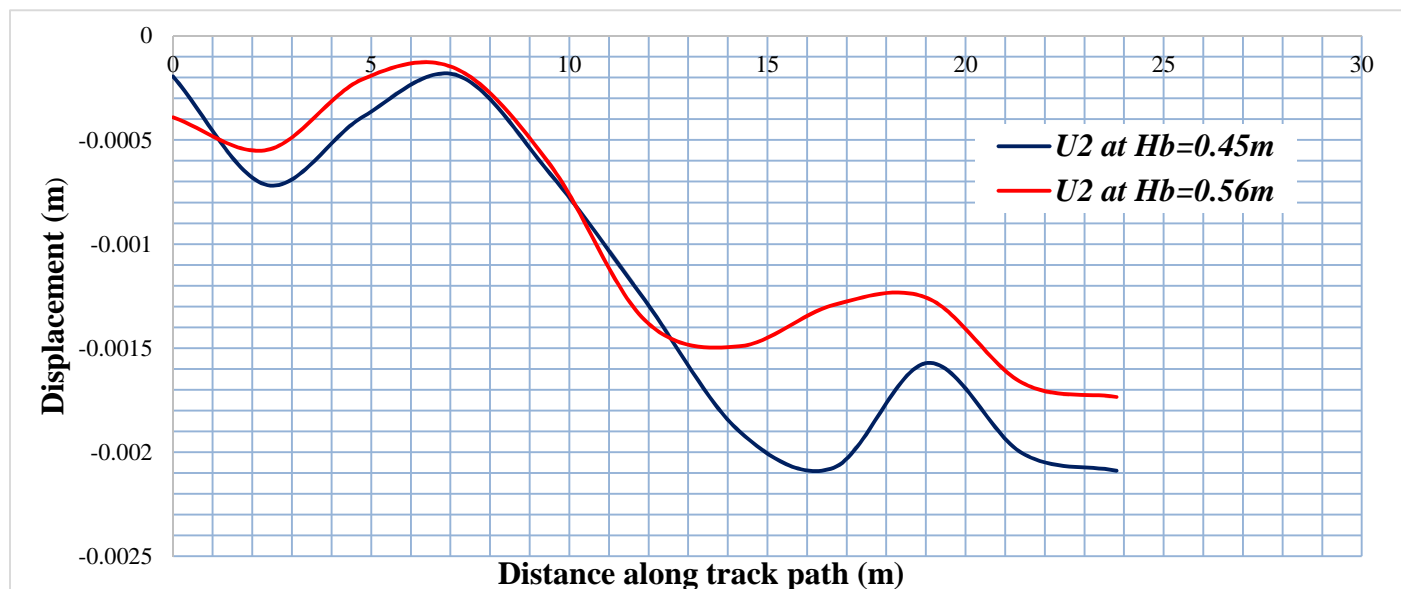


Figure 24 Vertical displacement of ballast with different ballast thickness.

Depending on the above results if the ballast thickness is 0.56m rather than 0.45m it is good for the track performance because 0.56m of ballast thickness more stiffened and reduce the deflection acceleration, velocity of rail and sleeper but the contact force between rail and sleeper, sleeper and ballast increases because of losing the damping property. This doesn't affect that much on the track. In this study the cost of the recommended and the designed thickness of ballast were considered for 1 km track length.

| | |
|---|--|
| Thickness of ballast for designed value | Unites |
| Ballast thickness (Hb) | 0.45m |
| Ballast volume (Vb) | $1000m \times 0.45m \times 3m = 1350m^3$ |
| Ballast stiffness (Kb) | 167.8MN/m |
| Cost for the designed ballast thickness | |
| 1m ³ of ballast | 21.5in dollar |
| 1350m ³ ballast | 29,025 in dollar |

| | |
|---------------------------------------|--|
| Recommended ballast thickness | Unites |
| Thickness of ballast (Hb) | 0.56m |
| Volume of ballast (Vb) | $1000m \times 3m \times 0.56m = 1680m^3$ |
| Ballast stiffness (Kb) | 167.8MN/m |
| Cost of recommended ballast thickness | |
| 1m ³ of ballast | 21.5 in dollar |
| 1680m ³ of ballast | 36,120 in dollar |

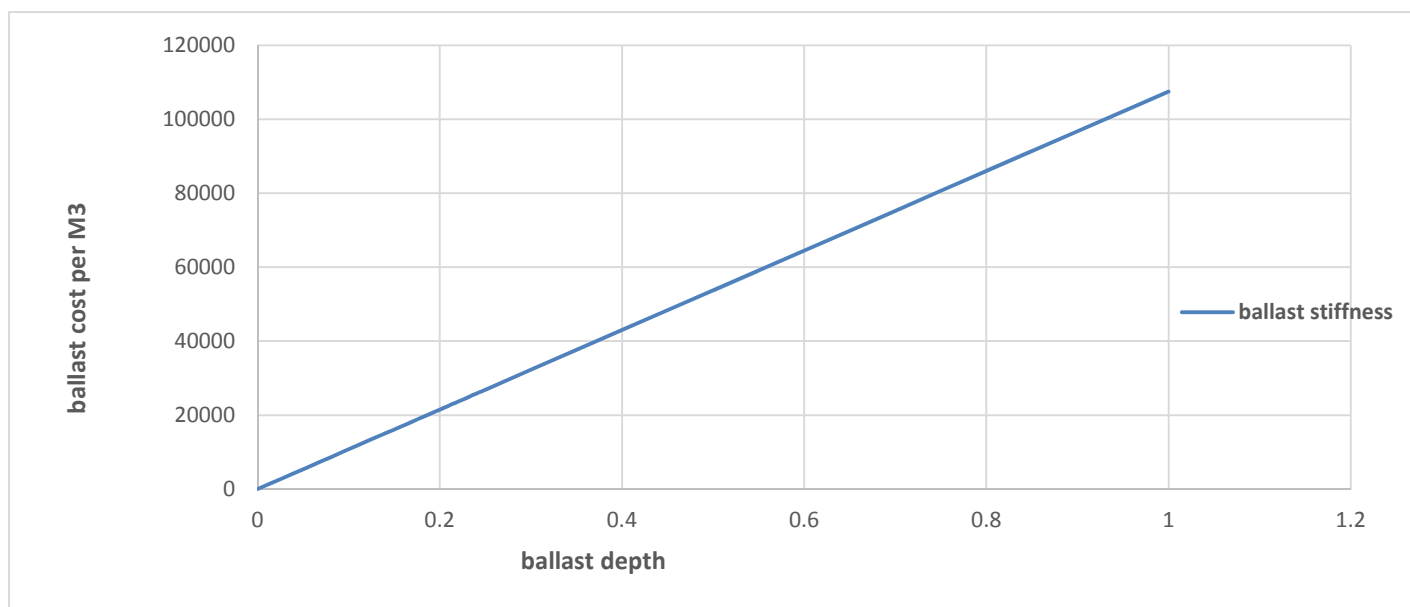


Figure 25 Ballast stiffness versus ballast cost

The above results shows that increased track component stiffness increase the cost of the material. Increasing the ballast depth, reducing sleeper spacing and sub grade strengthen to reduce the track displacement and strengthen the bearing capacity of the track component. The cost of the ballast linearly increases with increasing the ballast stiffness and ballast depth.

4.9. Effect of rail-pad stiffness

From a track dynamic point of view, Rail pads, which lie between rail and concrete sleepers, play an elastic role in the track structure. A soft rail pad permits a larger deflection of the rails when the track is loaded by the train. Hence the axle load from the train is distributed over more sleepers. The most commonly used physical model of a rail pad is the spring-damper system.

The spring can be assumed to be linear, and the damping is assumed to be proportional to the deformation rate of the rail pad. It may also be used to limit the stiffness of the railway track in order to reduce the dynamic effects resulted by the circulation of the trains. Since contact between rail and sleepers are rigid, this elastic rubber is necessary. Stiffness of rail pads also plays an important role.

As we increase the rail pad stiffness the sleeper and ballast displacement, acceleration and velocity also increase. But the rail displacement, acceleration and velocity decreases.

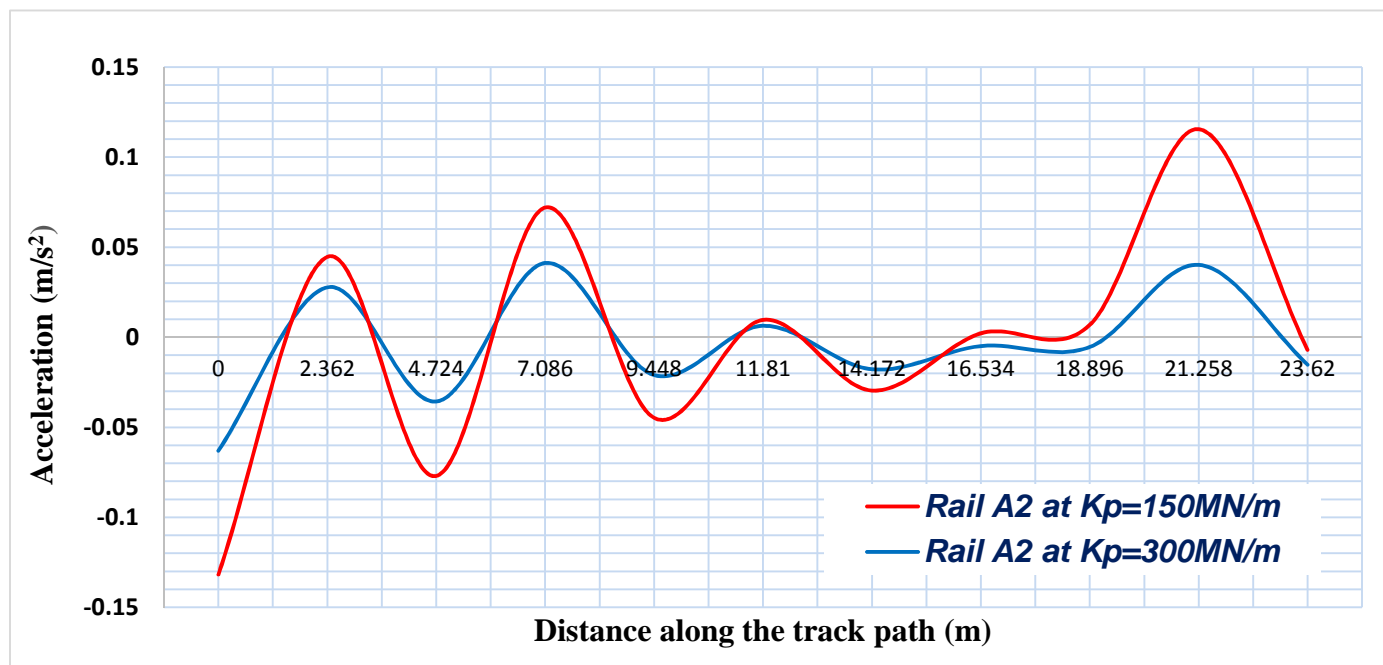


Figure 26 Vertical Acceleration of Rail along the track length with different rail pad stiffness

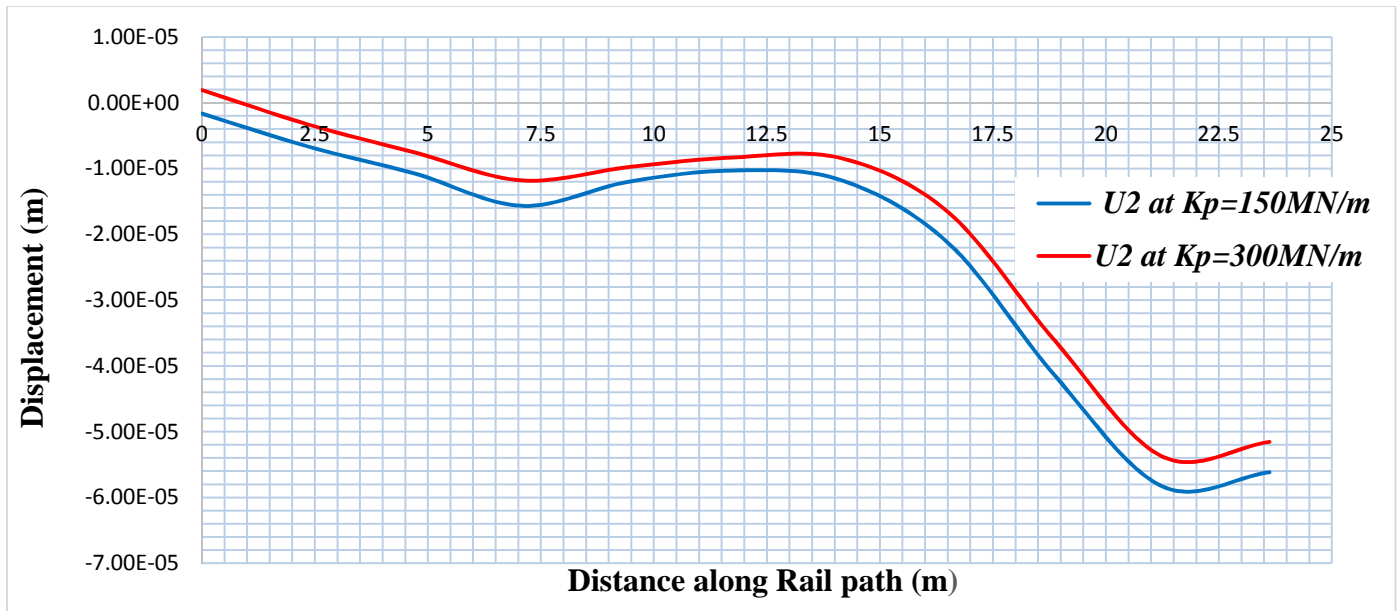


Figure 27 Vertical Displacement of Rail along the track length with different rail pad stiffness

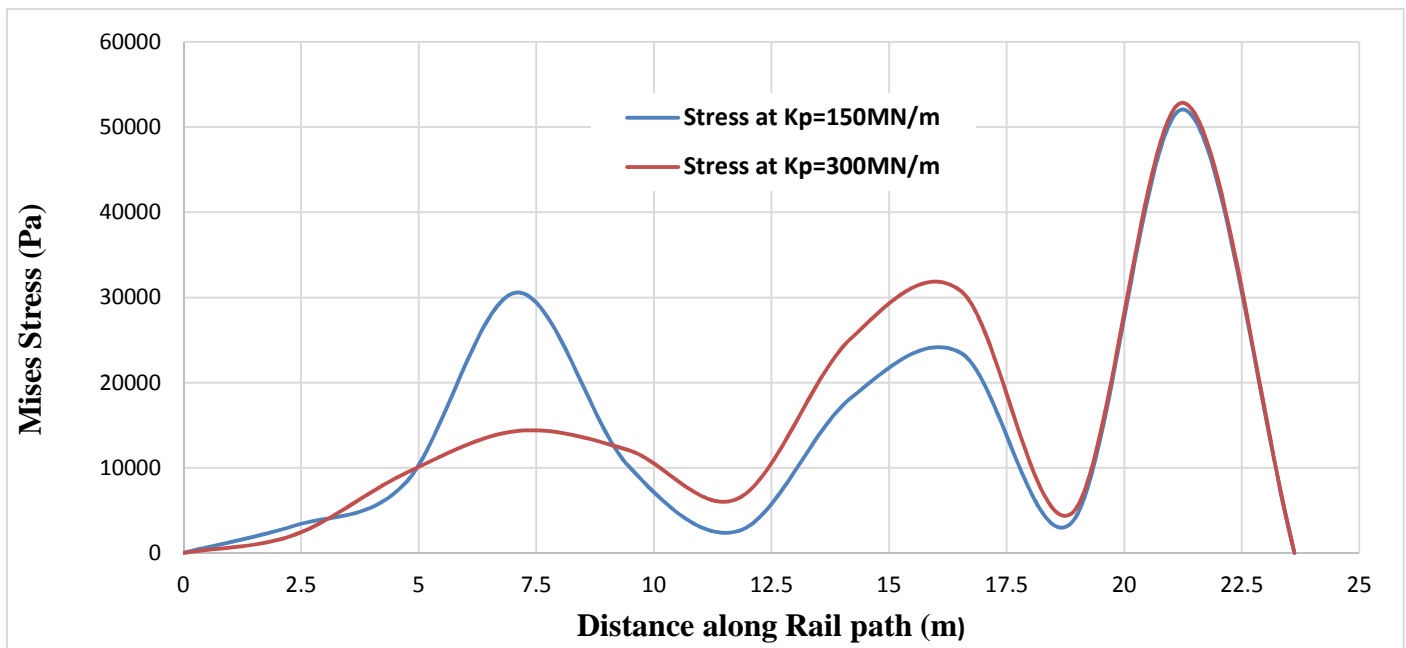


Figure 28 Mises Stress of Rail along track length with different rail pad stiffness

4.10. Train speed effect on track stiffness

In 1851 Willis wrote his essay on the effects produced by causing weights to travel over Elastic Bars”, demonstrating for the first time that, a load travelling through a beam caused larger deflection than the corresponding static loads. The train running with high speed induces high levels of vibration in the track and the surrounding area.

These vibrations can result in the deterioration of the track structure, causing derailment and ground failure in the worst cases.(KENNEY, 1954), was one of the first researchers who presented an analytical solution for beams on Kelvin foundations under moving loads. A critical velocity of the beam-foundation system defined as a speed at which dramatic increases in the beam displacement is observed has been presented by him.

$$V_{cr} = \sqrt[4]{4kEI/\rho^2}$$

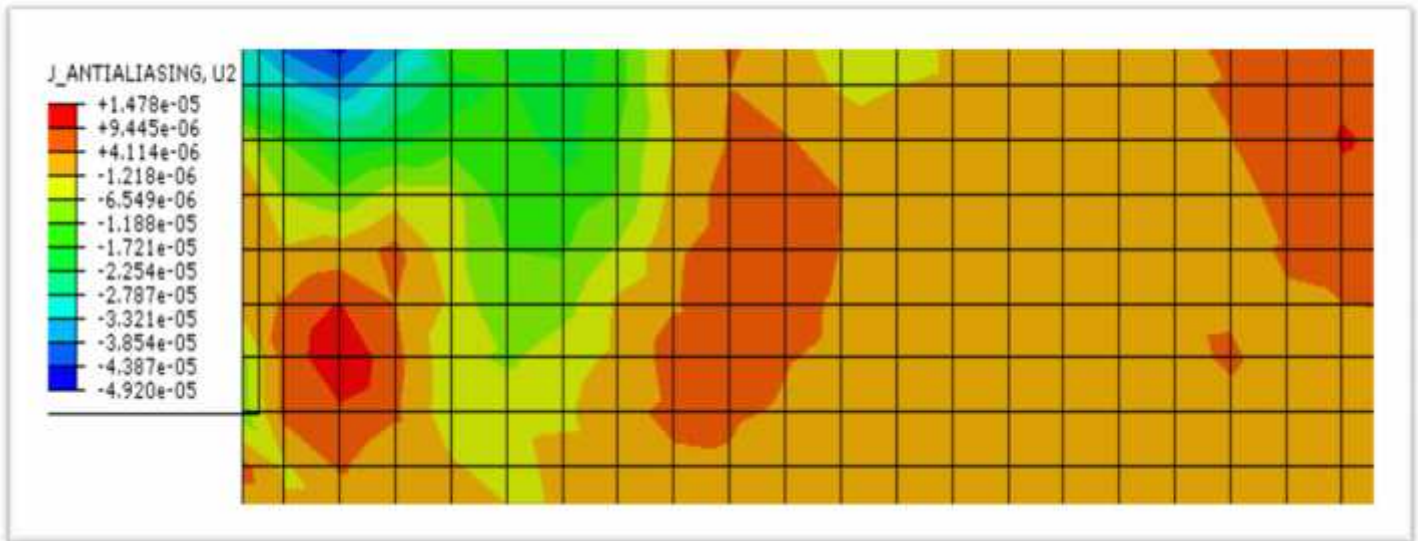
In which, k is the modulus of foundation stiffness (spring constant), E is the modulus of elasticity of the beam, I is the moment of inertia of the beam and ρ is the mass per unit length of the beam.

The ground wave will not be propagated until the train speed reaches the critical track velocity. Consequently no major structural or geometrical irregularities will be provided within the track to excite the train.

In this papers the effect of vehicle speed on the track stiffness is simulated by using finite element modeling (ABAQUS), displacement, acceleration and the bending stress are observed as shown figure 29.

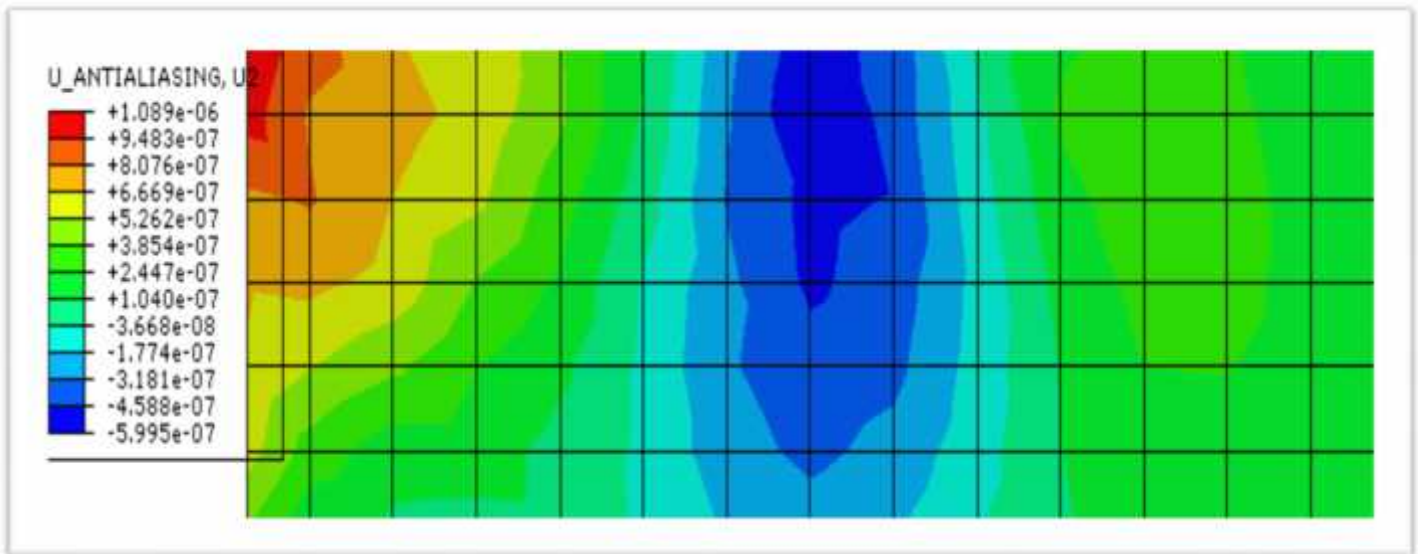
The result obtained at speed 33.33m/s revealed a typical dynamic response with wheel load. The response changed completely with the increasing speed. At 33.33m/s, the displacement amplitude, rail stress and ballast acceleration drastically increased.

$K_p = 143\text{MN/m}$, $K_f = 170\text{MN/m}$, $V = 33.33\text{m/s}$



(a)

$K_p = 143\text{MN/m}$, $K_f = 170\text{MN/m}$, $V = 11.11\text{m/s}$



(b)

Figure 29 The Vertical subgrade displacement with different track speed, (a) 33.33m/s (b) 11.11m/s

4.11.Effect of Sleeper spacing and Cross-section

Reducing the interval between sleepers spacing increases track stiffness. The track modulus is affected in a reasonable linear way for realistic range sleeper spacing values. The vertical stress and displacement at surface of the ballast layer increased with increasing the sleeper spacing.

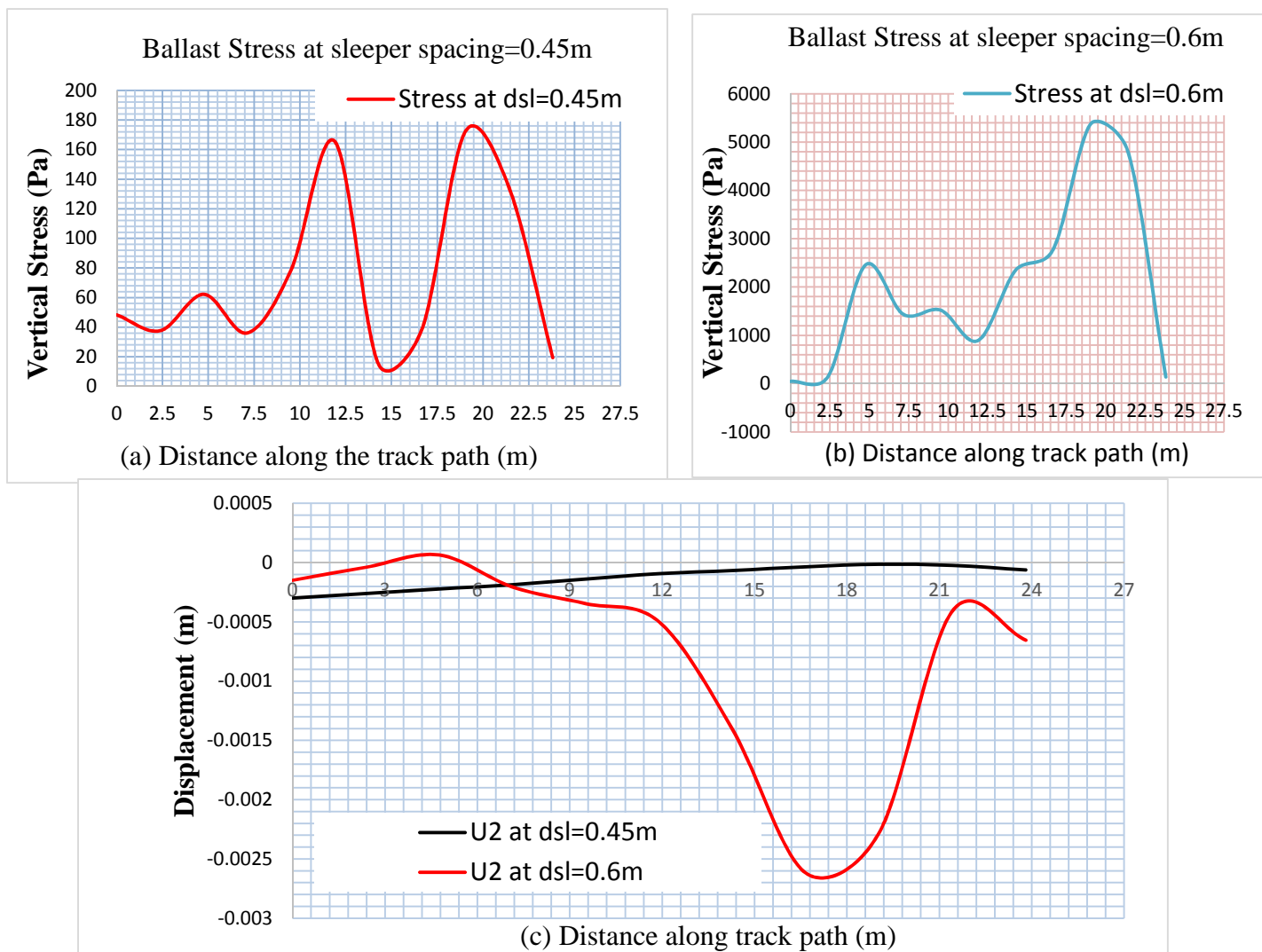


Figure 30 (a) ballast stress at 0.45m, (b) ballast stress at 0.6m, (c) rail displacement with different ballast thickness

The vertical stress at the top of the sub grade layer and the vertical stress at the surface of the ballast layer decreased with increased sleeper section.

4.12.Effect of Sub grade strength

This is typically the primary determinant of the overall track stiffness. The stiffness of the sub grade may depend on moisture content, climate and drainage. The sub grade may comprise layers of soil material having different bulk module and the track stiffness will be combination.

During the service life time the sub grade material became deformed and the track geometry degradation can occur. Excessive sub grade deformation frequently causes rapid track geometry degradation, especially when a sub grade is made up of clayey soils, and heavy axle loads. It is important to realize that an effective remedy for track geometry deviations may largely depend on the source of the deformation.

Increasing the bearing capacity of the sub grade soil and making the sub grade more stiffen, can reduce the stiffness variation of the track because of the sub grade deformation reduced.

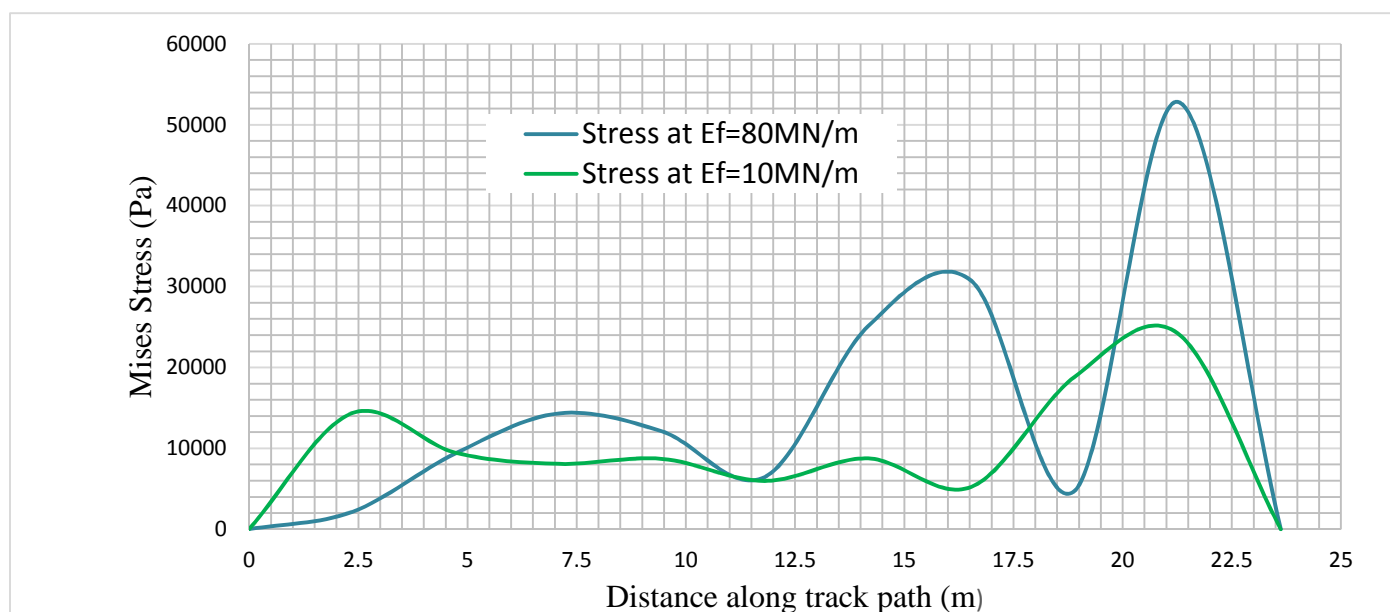


Figure 31 Rail Mises Stress with different sub grade modulus

The stresses at rail increased with increasing strength of sub grade due to increased sub grade stiffness due to less damping properties. The vertical stress at surface of the ballast layer increased with increased sub grade strength due strong in sub grade layer. The vertical stress at the top of the sub grade layer increased with increased sub grade strength and the bending stress of the rail decreased as well as the sleeper bending stresses decreased with increased sub grade strength.

Generally the response behavior of track components analyzed by finite element methods and the result obtained. The sub grade surface vertical stress beneath the wheel was affected by its material properties.

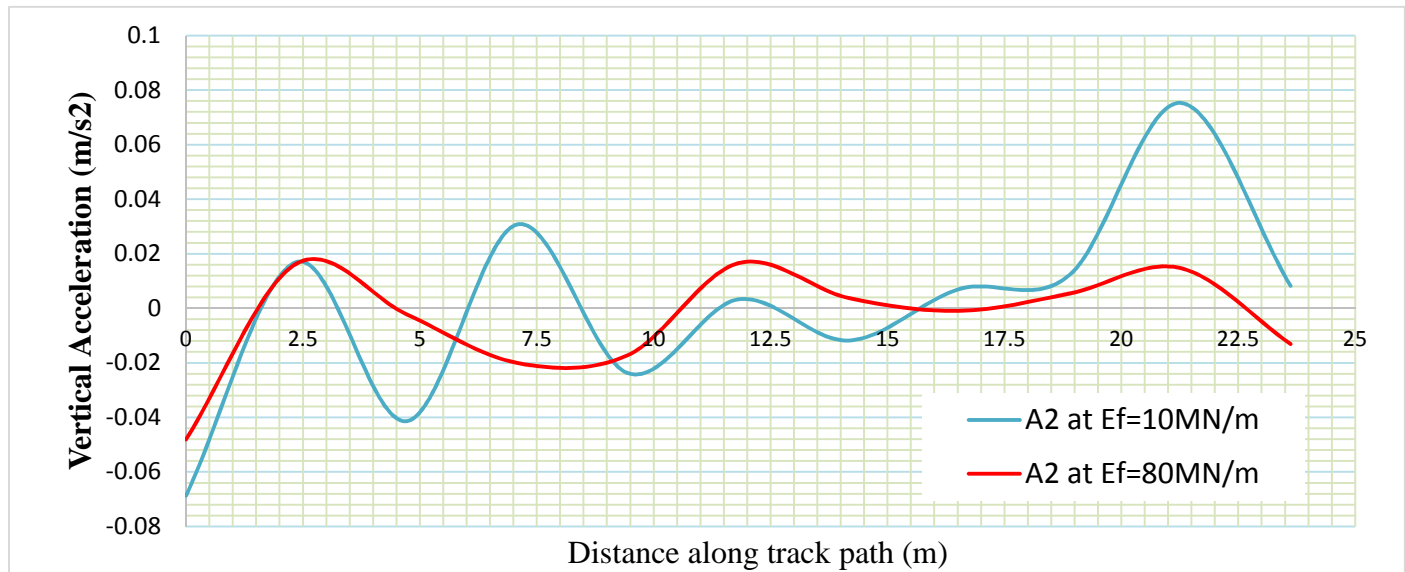


Figure 32 The Rail Vertical acceleration with different sub grade modulus

4.13. Linear Eigen value Analysis (Frequency domain analysis)

Linear Eigen value analysis is used to perform an Eigen value extraction to calculate the natural frequencies and corresponding mode shapes of the model. The analysis can be performed using loncoz Eigen solver algorithm.

4.13.1. Modes of Vibration

One way to investigate the dynamic properties of a railway track is to load the track with a sinusoidal force and then analyze the mode of vibration and the natural frequency of the track. As we discussed above the advantage of using an Eigen value analysis of the railway track in ABAQUS is that the whole structure can be analyzed and that global modes such as rail can be seen. When extracting the Eigen frequencies from the measured data, it is not clear what part of structure it belongs to. The following are some mode shapes of 2D track model and its natural frequency.

Table 4 Vertical Rail vibration mode shape with Natural frequency and mode number

| Mode Number | Natural frequency (Hz) | Rail Vibration mode shape |
|-------------|------------------------|---------------------------|
| 8 | 5.0188 | |
| 98 | 15.522 | |
| 148 | 18.272 | |
| 469 | 28.355 | |
| 982 | 62.502 | |
| 1009 | 262.63 | |
| 1041 | 752.98 | |
| 1059 | 957.74 | |
| 1063 | 962.53 | |

4.13.2. Resonance frequency

Several well damped resonances can be found in a track structure. **Figure33** Shows a typical track resonance vibration when rail is loaded with a sinusoidal varying force. According to (DAHLBERG., 2003), sometimes the resonance vibration may appear between 20-40Hz frequency range. This is a resonance when the track and a great deal of the track substructure vibrate and track resonance is usually obtained in the frequency range 50 to 300 Hz. This resonance is obtained when the track structure (Rail and sleeper) vibrate on ballast bed. Another resonance frequency can be found in the frequency range 200 to 600 Hz. This resonance is explained by the rail bouncing on the rail pads. This is almost similar to the result obtained from the finite element analysis shown in figure below.

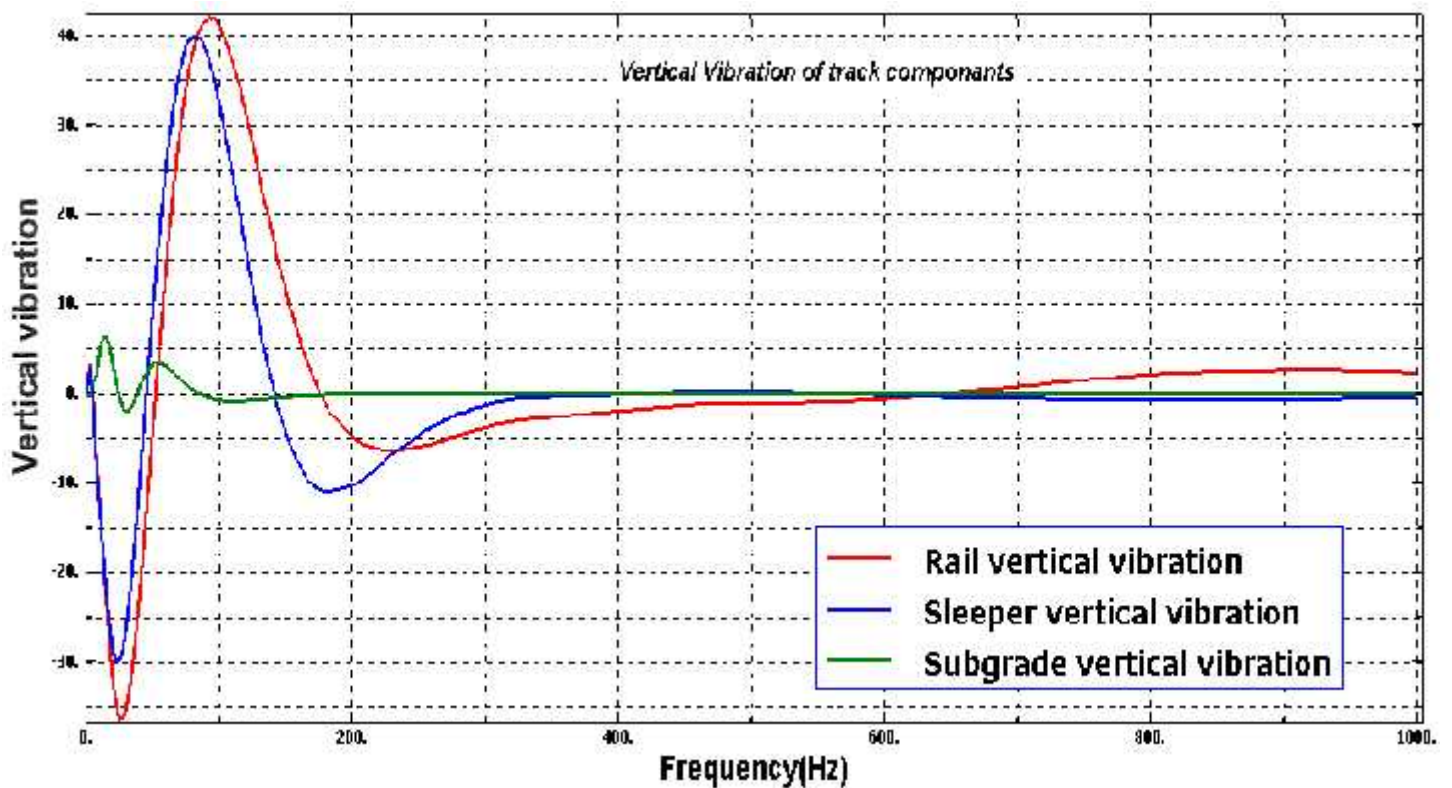


Figure 33 Vertical vibration of track components at different frequency

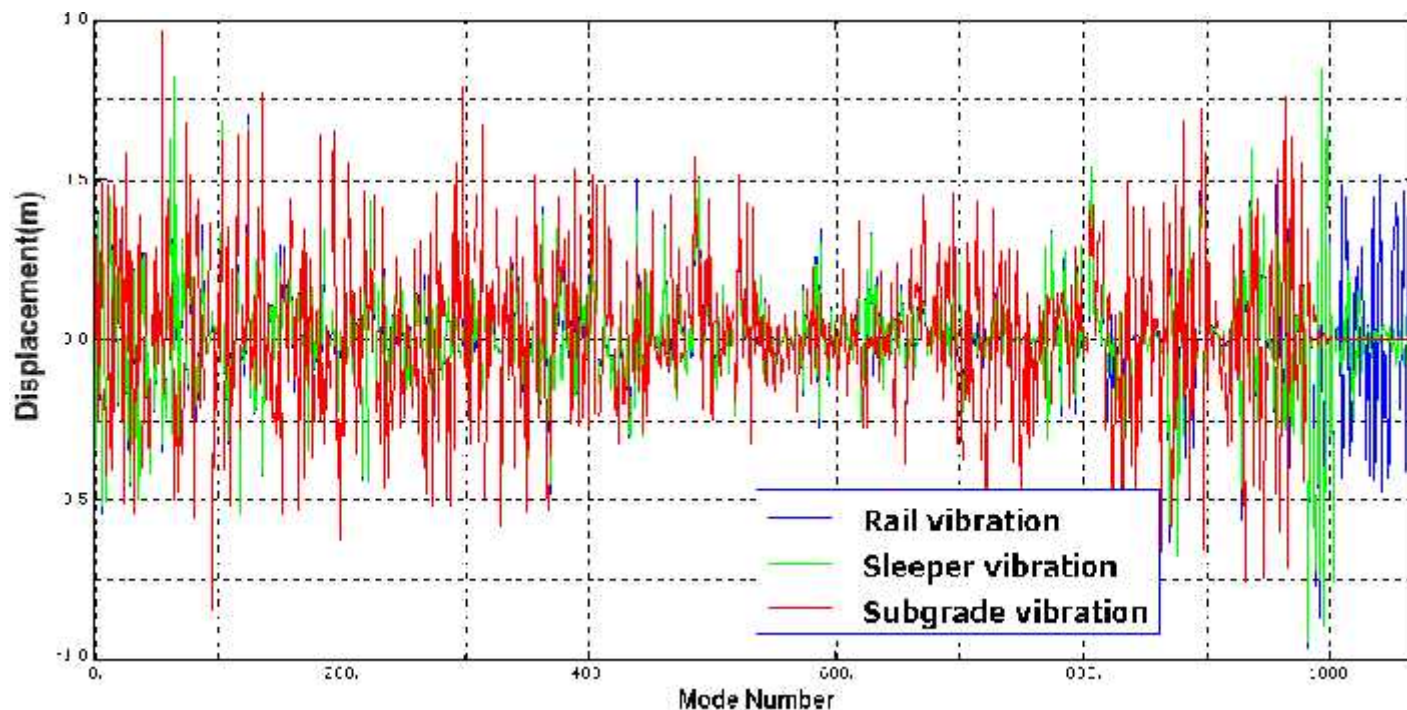


Figure 34 vertical vibration of track components versus frequency

As we see from the figure above, the sub grade vertical vibration dominates between 1-869 mode numbers and between 50.035Hz frequency ranges. Between mode numbers 870-1064(1024Hz) the vertical deflection of concrete sleeper dominate the vibration. After 1026 mode number (300Hz) the Rail vertical vibration dominates and the rail bouncing on the rail pads.

This condition explains the deflection vibration of rail tends to be damped after about 300Hz and in the low range frequencies both sub grade and sleeper vibrates by dominating each other up to 300Hz. Therefore we can identify three ranges of frequency that the tracks like to vibrate. The lower range of frequency (20-50.Hz), middle range frequency (50-300Hz) and higher range frequency (above 300Hz) are extracted from the analysis.

4.13.3. Effect of the rail pads stiffness

The dynamic effects of the rail pads stiffness on the track components have been studied in this section. Only spring and dampers in vertical direction were chosen to analysis. The rail pads have an important role in isolating high frequency vibration in the track structure. Its influence investigated in frequency domain methods by using the lower and upper frequency.

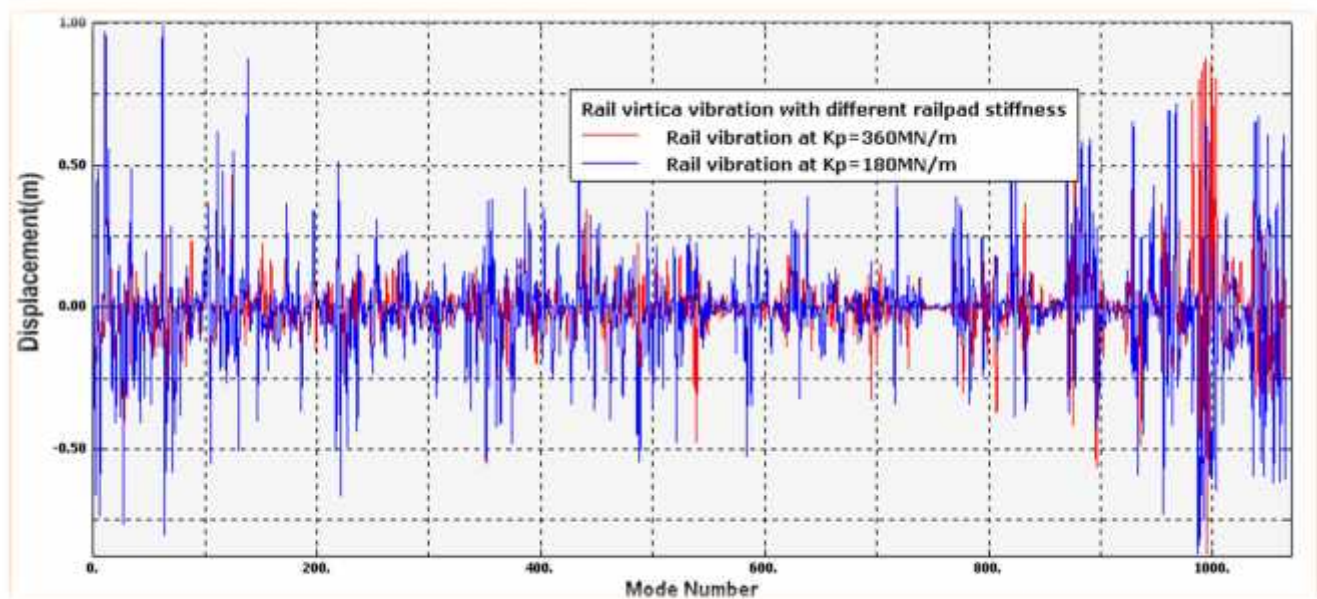


Figure 35 The Rail vertical vibration with different rail pad stiffness

As shown [fig.38](#), that at lower frequency the vertical vibration of rail are counteracted by less rail pad stiffness and at higher frequency the vertical vibration of rail are dominated by stiffen rail pad. It is found that simply increasing the constant stiffness of rail pad can lead small error in the Lowe frequency or high frequency domain.

4.14.Lateral Track cross-sectional analysis

Railway tracks must resist the lateral loads exerted by trains as a result of vehicle dynamic effects. In conventional ballasted railway track, lateral loads are transferred from the rails through the fastenings to the sleepers, and ballast. It is important to identify the mechanism of track lateral movement under dynamic wheel loads. In this section the vibration model analysis of lateral track cross-section and the vertical vibration of track analyzed.

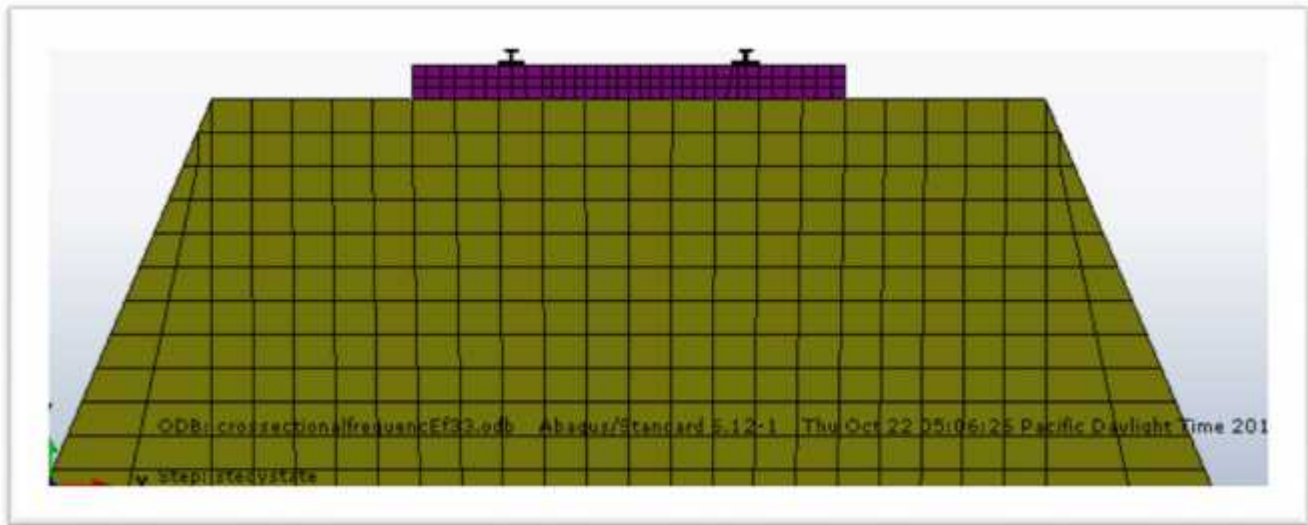


Figure 36 cross-sectional track model

Frequency domain analyses of track cross-section were shown in the figure below. From analysis, we can draw a conclusion that at lower frequency vibration are observed by secondary elastic media other than rail pads such as sub grades. From frequency ranges 20Hz-300Hz the vibration starts from Low frequency to and frequency abavo300Hz the vibration is transfer to the center of sub grade cross-section. Different sub grade vertical vibration at different mode numbers and frequency range are shown as figure 38.

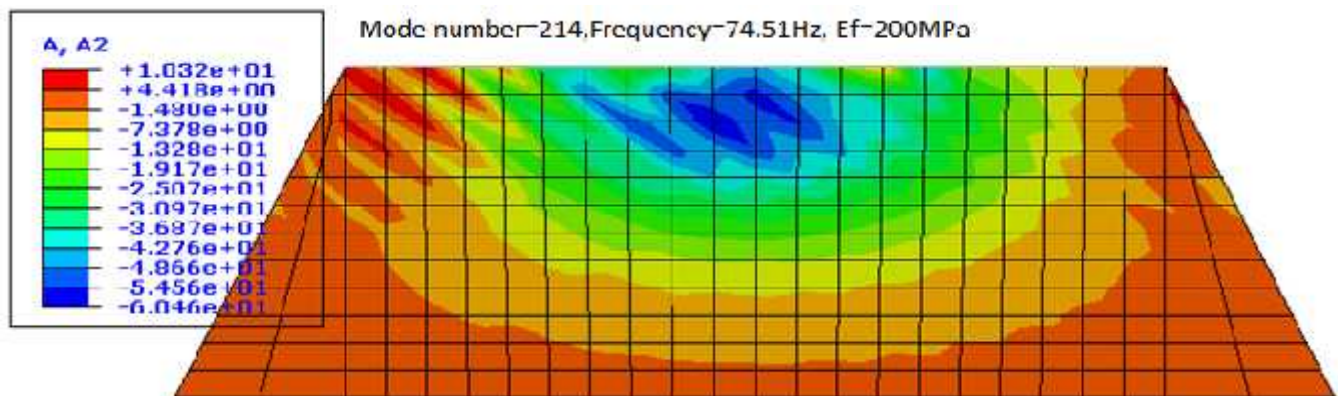


Figure 37 Vertical vibration of sub grade at different frequency at low frequency

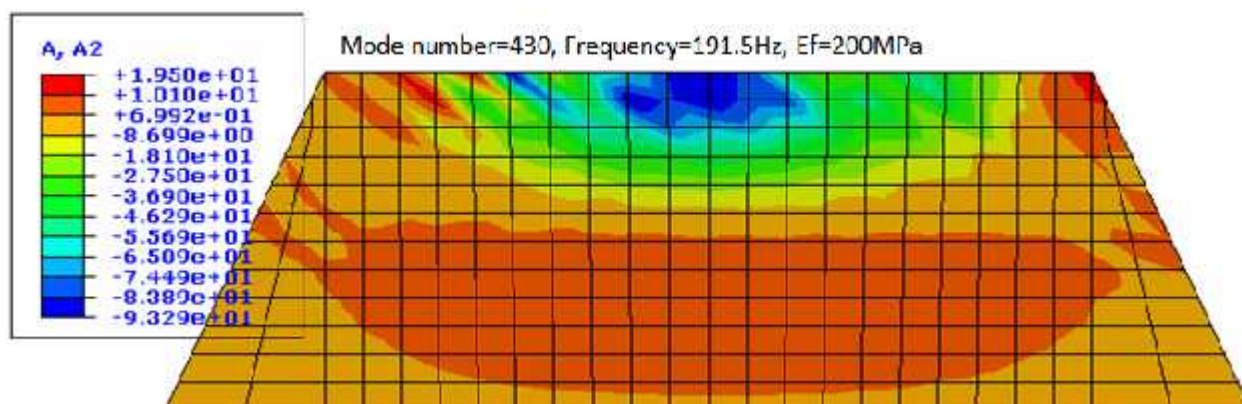


Figure 38 Vertical vibration of sub grade at different frequency at high frequency.

From the above graph we understand that, at low frequency the vertical vibration of sub grade cross-section dominated more at the side slope of the track and transfer to the center of sub grade cross-section at high frequency range. This shows that the side slope of the cross-section more affected by low frequency range. This happens up to the frequency range 300Hz. above this frequency range the super structure of the track starts to vibrate and more dominate.

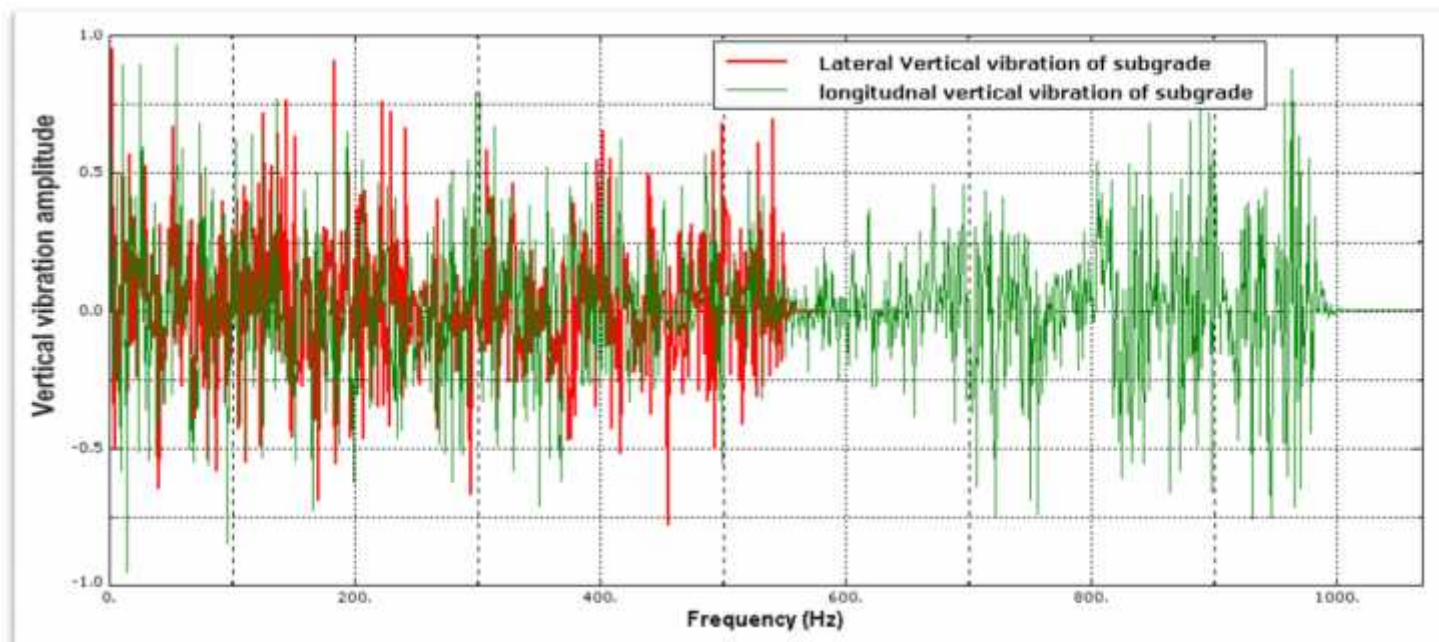


Figure 39 longitudinal vibration amplitude versus lateral cross-section vibration amplitude.

The result shown on the above figure that the vertical cross section vibration is compared to the longitudinal vibration, at the frequency ranges 20Hz – 500Hz the lateral vibration is dominated. After frequency range 500Hz the longitudinal track vibration increased and dominated. This shows even the track substructure vibrate at low frequency, the track substructure vibration at high frequency also obtained from the analysis.

4.14.1. Effect of sub grade modulus of elasticity

The roadbed or sub grade modulus is crucial factors for the performances of the granular layers. Track-bed evaluation also has been carried out for the effect of sub grade modulus. Three different sub grade modulus were evaluated in this section. The modulus 80Mpa, 200Mpa, and 250Mpa, which represent the quality of the sub grade from low to high. The result obtained as shown in figure 38.

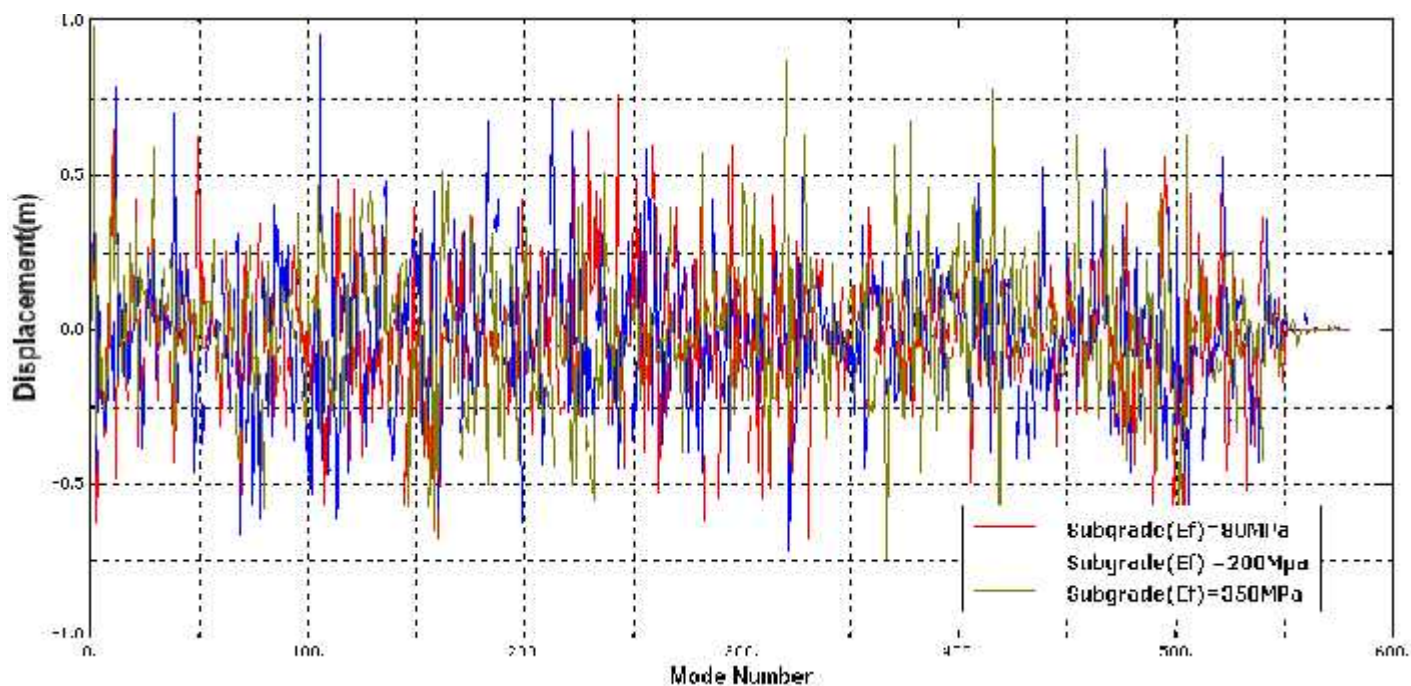


Figure 40 Vertical displacement of sub grade at different sub grade elastic modulus

As shown above figure, as frequency increase from 20Hz to 100Hz the sub grade vertical vibration dominate for high modulus material. This generally indicates that high stiffness sub grade material have a good damping properties for low vibration modes, however as the frequency increase the rail pad stiffness is responsible to damp the vibration.

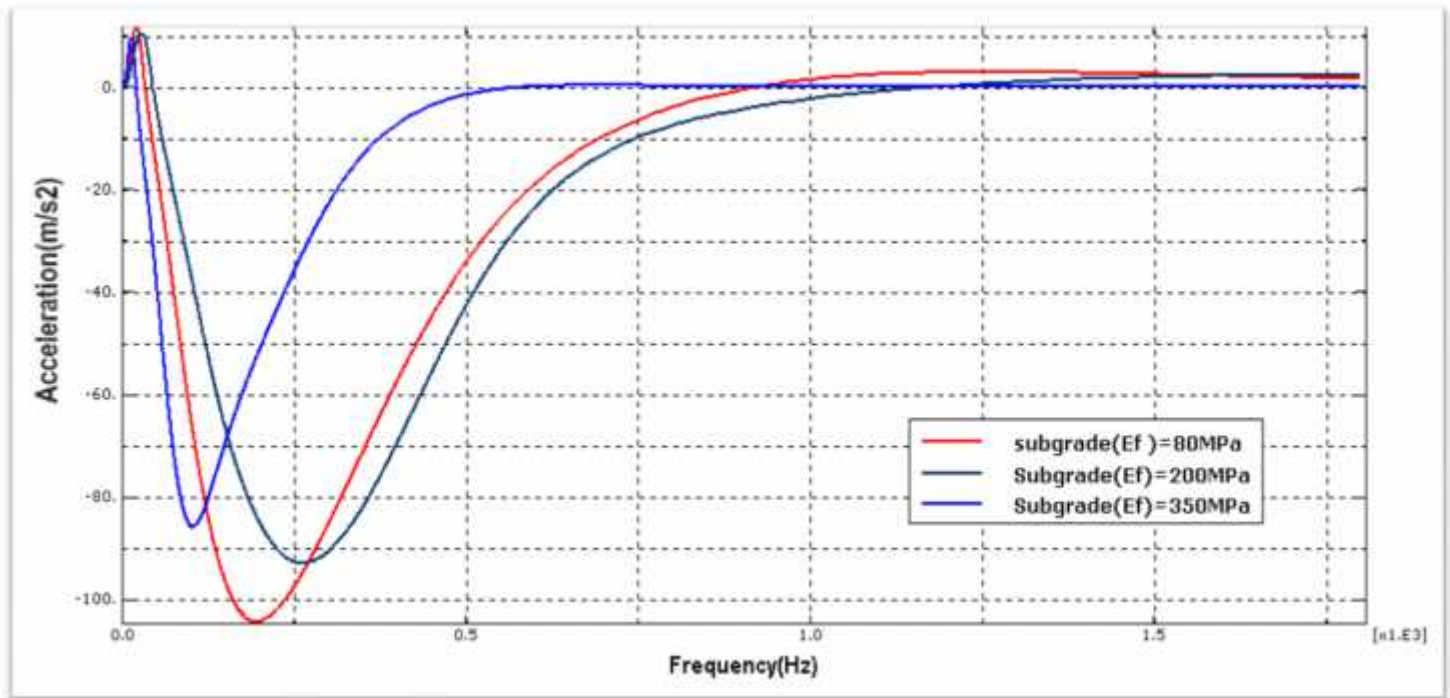


Figure 41 Sub grade acceleration at different subgrade modulus value

The lateral cross-section of sub grade acceleration at different sub grade modulus is extracted from the finite element frequency domain model. The result shows that as the sub grade modulus of elasticity increased the sub grade less accelerate low frequency ranges the more accelerated one is the lowest modulus of elasticity or which is not more stiffened. As the frequency and sub grade modulus of elasticity increased the rate of vibration decreased. The sub grade elastic material vibrates at lower frequency ranges. This shows that as we apply the sinusoidal load the rate of vibration starts from substructure parts at low frequency.

CHAPTER FIVE

5. Conclusions and Recommendation

5.1. Conclusions

In this paper for a better understanding of the Railway track stiffness variation consequences and influences on the track responses were investigated. The Modeling analysis of track stiffness variation depends on the track component stiffness variation and the Results for each track component stiffness variations. Interactive forces, track component displacements, Velocities and acceleration were presented.

Track stiffness is the function of the structural properties of the rails, rail pads, sleepers, ballast, and Sub-ballast and sub grade soil. Furthermore sleeper spacing influences the track stiffness. Using the software ABAQUS found that, decrease in sleeper spacing and increases in ballast young's modulus, ballast depth, sub grade young's modulus and rail moment of inertia increases the track stiffness at all. In general, relatively high track stiffness is beneficial as it provides sufficient track resistance to applied loads and results in decreased track deflection, which reduces track deterioration. On the other hand, very high track stiffness leads to increased dynamic forces in the wheel rail interfaces as well as on the sleepers and ballast which can cause wear and fatigue of track components.

The frequency domain analysis of track stiffness has been done in this paper. We conclude that the track vibration first starts at substructure at low frequency range and became dominated by super structure at higher frequency range.

The following Results were obtained

- The vertical stress at surface of the ballast layer increased with increased ballast thickness, sleeper spacing and sub grade strength.
- The bending stress at rail increased with decreased ballast thickness and reduced with increased sub grade strength (modulus of elasticity/CBR value) due to increase in sub grade stiffness.
- The vertical stress at the top of the sub grade layer decreased with increased ballast thickness but increased with increased sub grade strength and sleeper spacing.
- The sleeper bending stress and acceleration increased with increased sleeper spacing, decrease ballast stiffness but decreased with increased sub grade strength.
- The sleeper reaction force increased with increased ballast thickness, sleeper spacing and sub grade strength due to increased ability of sub grade layer to resist.
- Increasing the ballast stiffness reduces rail and sleeper displacements, acceleration, and velocities. But increases Rail stress, Rail-Sleeper and sleeper-ballast interactive forces.

- Reducing the rail pad stiffness reduces Wheel-Rail and Rail-Sleeper interactive force, but increases rail displacement, acceleration and velocity.
- It is observed that the magnitude of Wheel-Rail contact force mainly depends on the ballast stiffness, Sleeper spacing and rail stiffness.
- Abrupt change of the track stiffness has significant influence on the rail vertical acceleration, vertical displacement and the wheel rail interaction force.

5.2. Recommendation

Depending on the result obtained from track stiffness analysis, we recommend that, modifying the track component stiffness by using Under-sleeper pads, grouting substructures, Strengthen the ballast and subgrade material (modulus of elasticity). Reducing the sleeper spacing and increase ballast thickness considerably reduce the stiffness variation. Smoothing of the track stiffness distribution and using the track component stiffness to the optimum considerably reduce the variations of the wheel-rail contact force and rail displacement, acceleration

5.3. Area of future work

For construction of new railways, the track stiffness appears to be a very important parameter in determining the life cycle performance of the track. Building a new line to meet a prescribed track stiffness value appears to be reasonably straightforward and there is not a large premium on the cost of construction. Considering of track stiffness variation and its influences therefore seems to be quit justified for this application. For management existing lines there appears to be strong evidence that sub-optimal track bed stiffness and track stiffness variation is common. The primary potential benefit of work in this topic area does appear to be in the area of analysis of track component stiffness variation consequences and its influences on track structure.

The most evident for future research activity are therefore listed below

- The role of soil moisture on track stiffness (and track substructure behavior generally) is considered to be important, along with the associate subject of drainage. The influence therefore should be quantified better.
- The life cycle cost relationships that are employed to establish the influence of track stiffness need to be developed for new construction track line. These comprise relationship between traffic and track parameters and forces, between forces and damage, between damage and stiffness variation, between stiffness and cost or risk

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APPENDIX: 1

Analysis of track stiffness variation and its influences

Time domain Track modelling input data

Processing part, instance, and assembly information

End processing part, instance, and assembly information

Options being processed

```
*heading
*node
*element, type=cps4r
*Nset, nset="assembly_subgrade-1_subgrade section"
*Nset, nset=assembly_subgrade-1_set-1
*Nset, nset=assembly_subgrade-1_set-5
*Elset, elset="assembly_subgrade-1_subgrade section"
*Elset, elset=assembly_subgrade-1_set-1
*elset, elset=assembly_subgrade-1_set-5
*node
*element, type=cps4r
*nset, nset="assembly_sleeper-1_sleeper section"
*elset, elset="assembly_sleeper-1_sleeper section"
*node
*element, type=r2d2
*node
*element, type=b21
*nset, nset=assembly_rail-1_set-6
*nset, nset=assembly_rail-1_set-8
*elset, elset=assembly_rail-1_set-6
*elset, elset=assembly_rail-1_set-8
```

```
*node
*element, type=mass
*element, type=rotary
*element, type=spring
*element, type=dashpot
*rigid body, refnode=assembly__pickedset306, elset=assembly_b_set-113
*material, name="rail steel"
*density      *elastic      *material, name="sleeper concrete"
*density      *elastic      *material, name="subgrade material"
*density      *Drucker prager*Drucker prager -hardening
*elastic      *dashpot, elset=assembly_r-s1-dashpot
*dashpot, elset=assembly_r-s2-dashpot
*mass, elset=assembly_set-123_inertia-1_mass_
*rotary inertia, elset=assembly_set-123_inertia-1_roti_
*rigid body, refnode=assembly__pickedset306, elset=assembly_b_set-113
*friction
*friction
*element output, directions=yes
*element output, directions=yes
*rigid body, refnode=assembly__pickedset306, elset=assembly_b_set-113
*amplitude, name=amp-1
*output, field, filter=antialiasing, number interval=200
*output, history, filter=antialiasing
*output, field, filter=antialiasing, number interval=200
*output, history, filter=antialiasing
*step, name=contact
*step, name=load
*step, name=contact
Contact establishment for ballast
*dynamic, explicit, scale factor=0.1
*boundary, type=velocity
*output, field, filter=antialiasing, number interval=200
*surface interaction, name=sleeper-rail
*friction
*surface interaction, name="subgrade -sleeper"
*friction
*surface interaction, name=wheel-rail
*surface behavior, pressure-over closure=linear
*boundary
```

```
*step, name=contact
*dynamic, explicit, scale factor=0.1
*boundary, type=velocity
*contact pair, interaction=sleeper-rail, mechanical constraint=penalty, cpset=r-s30
*end step
*step, name=load
*dynamic, explicit, scale factor=0.1
*boundary, type=velocity
*load
*end step
```

Problem size

| | |
|---|------|
| Number of elements is | 1220 |
| Number of nodes is | 1888 |
| Number of nodes defined by the user | 1398 |
| Number of internal nodes generated by the program | 490 |
| Total number of variables in the model | 3158 |

(Degrees of freedom plus max no. of any Lagrange multiplier Variables. Include *print, solve=yes to get the actual number.)

End of user input processing

Job time summary

| | |
|-----------------------|-----------|
| User time (sec) | = 0.30000 |
| System time (sec) | = 0.10000 |
| Total CPU time (sec) | = 0.40000 |
| Wall clock time (sec) | = 0 |

APPENDAX 2

Frequency domain track modeling data file

Abaqus 6.12-1 date 19-oct-2015 time 06:25:38

For use by under license from Dassault systems or its subsidiary.

Frequency domain analysis of track stiffness variation

Step 1 increment 1 step time 0.00

Step 1 calculation of eigenvalues

For natural frequencies

The loncoz Eigen solver is used for this analysis

Abaqus will compute uncoupled

Structural and acoustic modes

All Eigen values in the specified range will be extracted

Highest frequency of interest 50.000

Maximum number of steps within run 35

Block size for loncoz procedure 7

The eigenvectors are scaled so that

The largest displacement entry in each vector

Is unity

This is a linear perturbation step.

All loads are defined as change in load to the reference state

Extrapolation will not be used

Characteristic element length 0.232

Details regarding actual solution wave front requested

Detailed output of diagnostics to database requested

Print of increment number, time, etc., to the message file every 1 increment

Equations are being reordered to minimize wave front

Collecting model constraint information for over constraint checks

Collecting step constraint information for over constraint checks

Check point start of solver

Computer precision used by Abaqus 2.22045e-016

Convergence criterion for loncoz runs 1.81899e-012

Number of equations 2690

***warning: only 2576 Eigen modes will be extracted because there are no more

Unrestrained degrees of freedom

Number of unrestrained degrees of freedom 2576

Heuristic scale for the first nonzero Eigen values (problem scale) 1.79351e-002

Initial shift value 0.00000e+000

Number of cups used by direct solver 1
Number of negative Eigen values 0
Number of positive Eigen values 2690
Number of negative Eigen values not associated with Lagrange multipliers 0
Number of negative Eigen values associated with Lagrange multipliers 0
Computational interval for the initial loncoz run
Eigen values needed to the right of shift value 2576
Eigen values needed to the left of shift value 0
Right boundary of the computational interval 9.88935e+004
Left boundary of the computational interval -3.95574e+037
Loncoz run terminated. Number of steps: 21
Termination based on the cost-per-Eigen value criterion
Number of accepted Eigen values 37
Accepted Eigen values

3.08374e+002 3.51170e+002 4.29432e+002 6.15359e+002 7.94916e+002 7.95255e+002

9.70207e+002 9.94414e+002 1.06261e+003 1.08067e+003 1.10092e+003 1.12220e+003

1.21721e+003 1.21944e+003 1.34302e+003 1.52085e+003 1.52488e+003 1.74371e+003

1.83465e+003 2.03471e+003 2.12997e+003 2.13203e+003 2.17801e+003 2.36203e+003

2.56178e+003 2.57131e+003 2.63394e+003 2.76673e+003 2.87028e+003 2.89789e+003

3.05275e+003 3.10814e+003 3.30824e+003 3.41137e+003 3.48067e+003 3.59017e+003

3.74277e+003

Analysis summary:

Total of 16512 increments
0 cutbacks in automatic incrementation
0 iterations including contact iterations if present
509 passes through the equation solver of which
29 involve matrix decomposition, including
0 decomposition(s) of the mass matrix
1 reordering of equations to minimize wave front
0 additional residual evaluations for line searches
0 additional operator evaluations for line searches
67 warning messages during user input processing
1 warning messages during analysis
0 analysis warnings are numerical problem messages
0 analysis warnings are negative Eigen value messages
0 error messages

Job time summary

User time (sec) = 19634.
System time (sec) = 613.40
Total CPU time (sec) = 20248.
Wall clock time (sec) = 38322

The analysis has been completed!!!

