

ADDIS ABABA UNIVERSITY
COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT
AFRICAN RAILWAY CENTER OF EXCELLENCE



**Experimental Investigation into the Lateral Resistance of a Sleeper
under Various Loading Rates**

A thesis submitted to the School of Graduate Studies of Addis Ababa Institute of Technology, Addis Ababa University, in partial fulfillment of the requirements for the degree of Master of Science in Railway Engineering (Civil Infrastructure)

By

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April, 2026

Addis Ababa, Ethiopia

Experimental Investigation into the Lateral Resistance of Sleeper under Various loading rates

APPROVAL

It is hereby certified that the thesis entitled “**Experimental Investigation into the Lateral Resistance of Sleepers under Various Loading Rates,**” submitted by Engda Sereke in partial fulfillment of the requirements for the degree of Master of Science in Railway Engineering (Civil Infrastructure), complies with the regulations of the University and meets the required standards of originality and academic excellence.

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Experimental Investigation into the Lateral Resistance of Sleeper under Various loading rates

Assertion

The thesis titled "Experimental Investigation into the Lateral Resistance of Sleeper under Various Loading Rates" is entirely original and has not been submitted to any university for evaluation. Any material sources that have been used as references have been acknowledged and properly cited.

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ABSTRACT

Railway sleepers are the primary structural elements that maintain the lateral stability of railroad tracks in a ballasted track system. Their interaction with ballast serves to maintain track alignment, prevent lateral movement, and ensure the track structure's strength to withstand both static and dynamic loads, all of which contributes to improved track performance and stability. The sleeper lateral resistance of a track through its interaction with ballast is significantly influenced by the loading rate variation in a ballasted track system. This research examines the effect of loading rate on the sleeper's lateral resistance in track performance and stability in ballasted track systems under experimental conditions. The single-tie push test method was used in this field investigation study to assess the sleeper's lateral resistance. Two loading rate tests (0.32kN/s and 0.92kN/s) have been conducted to determine the sleeper's lateral resistance and describe their lateral resistance behaviors. The results showed that the sleeper's lateral resistance increased by 14% under higher loading rates compared to lower loading rates. In addition, the lateral resistance of a sleeper under loading rate variation has three different characteristics: elastic, elastic-plastic, and plastic behaviors. The result shows that in the elastic zone, higher lateral stiffness was observed compared to other zones due to a strong frictional interaction between the sleeper and ballast particles to resist the lateral forces. In the plastic zone, the sleeper has low lateral resistance, slides easily and highly, and achieves minimal lateral stiffness, as the interaction between the surface sleeper and ballast particles is significantly diminished. Additionally, in this study the engagement of the ballast base, crib, and shoulder in the ballasted track system for maintaining the track's lateral stability was determined, and their contribution is 33.7%, 22.1%, and 45.2%, respectively. Accordingly, the ballast shoulder plays a primary role in maintaining the track's lateral stability by limiting the sleeper's lateral movement and ensuring the track's alignment.

Key words: Lateral resistance; loading rate; Railway sleeper; Ballast base; Ballast crib; Ballast shoulder; Single-tie push test

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CHAPTER ONE

1. INTRODUCTION

1.1 Background of the study

The railway system is currently a backbone of transportation in both developing and developed countries across the world due to several significant factors, such as affordability, speed, and reliability. It plays an essential role in transporting passengers and freight over long distances at an affordable price and with less traffic delay compared to other modes of transport. Moreover, this type of transportation is an environmentally friendly way to reduce the consequences of global pollution and increase the nation's sustainable development.

Generally, the two types of railway track structures now employed in the construction of modern track systems are ballasted and slab tracks, which are selected based on factors including cost, lifespan, and material availability [1]. Ballasted tracks are most widely used in new and existing track alignments throughout the world, which is more applicable to the new construction of railway infrastructures. In practice, ballasted tracks are constructed using high-quality materials and sufficient bearing capacity to withstand the track forces, which are made up of substructure and superstructure. The track superstructure, which is the upper portion of the railway track system and is composed of rail, fasteners, rail pads, and sleepers, has two primary functions: to maintain track stability and alignment and to ensure track performance.

The track function and stability of railway track structures are primarily governed by four key track resistance mechanisms: vertical, longitudinal, torsion, and lateral, which contribute to maintaining structural integrity. Longitudinal resistance is primarily governed by the stiffness of the rail and tie design, which is important to prevent rail expansion at high temperatures and to limit tensile formation at rail failure. Torsional resistance, which is provided by resistance components such as tie plates, anchors, and fasteners, plays an important role in maintaining track stability and stiffness; it stops the rail from rotating due to the track force. Lateral resistance is the primary resistance mechanism in railway track structures for improving lateral stability and is

balanced by the interaction between the ballast and sleeper, which prevents the sleeper from sliding laterally during train operation.

A critical component of ensuring track stability during the train operation and throughout its service life is track lateral resistance, which is primarily provided by the sleeper in both longitudinal and lateral directions. The sleeper's primary function is to keep the rail in place, maintain the track alignment, and resist the track movement by interlocking with ballast to ensure the track stability. Additionally, sleepers allow the ballast to withstand concentrated static and dynamic loads from the rails that are distributed over a larger area, reducing the stress at the sleeper/ballast interface to an acceptable level [1], [2].

The lateral resistances of the sleeper depend on the interaction between the sleeper and ballast, which is influenced by factors such as the ballast's type and quality, compaction, layer thickness, sleeper type and shape, and loading rate variation. The loading rate is one of the primary factors affecting the sleeper's lateral resistance. It represents the loading speed during train passages, and it has significant effects on the physical response of the sleeper-ballast interface.

Prior studies primarily focused on determining sleeper lateral resistance based on parameters, such as compaction, ballast quality, and other factors, and did not investigate the effects of loading rates on sleeper lateral resistance. Accordingly, this study investigates the effect of loading rates on the sleepers' lateral resistance in a ballasted track system.

1.2 Statement of the Problem

The railway sleeper is a primary track structure for ensuring the track's lateral stability that is situated on top of the ballast layer along the transverse direction of the track at a specified distance. Its primary function is to prevent the rails from moving laterally and to equally distribute the longitudinal, vertical, and lateral forces from the train throughout the larger surface of the ballast and subgrade.

However, comprehensive research findings and practical implementations have demonstrated that the lateral resistance of sleepers in a ballasted track system is influenced by several factors. Numerous experimental and numerical studies have shown that the lateral resistance of a sleeper

is affected by the ballast depth, shoulder length, ballast quality, ballast grading [1], [3], [4] and loading rate variation. The loading rate variations, one of the primary factors influencing the sleeper's lateral resistance, have a significant impact on the physical response of the sleeper-ballast interaction during train operation, ultimately affecting both performance and stability. Prior research has concentrated primarily on determining sleeper resistance based on various parameters, such as sleeper type, ballast quality, and other factors, and did not investigate the effect of loading rate on sleeper lateral resistance.

Hence, in this study, the effects of loading rate on the lateral resistance of sleepers in the ballasted track system are assessed through experimental field tests. The single-tie push test method was used in this field investigation to determine the sleeper's lateral resistance and assess the specific objectives of this study. This study also examined the role that the shoulder, crib, and ballast base played in the lateral resistance of the sleeper, which helps to restrict movement and maintain track stability.

1.3 Objectives

1.3.1 General objective

The main objective of this experimental study is to examine the effects of loading rates on the lateral resistance of sleepers in a ballasted track system and to assess the corresponding lateral resistance behaviors due to varying loading rates.

1.3.2 Specific objective

The specific objectives of this test investigation are outlined in the following key elements:

- To examine the effects of loading rates on the lateral resistance of sleepers in ballasted track systems, focus on track resistance performance and stability.
- To determine the maximum static lateral resistance of the sleeper under different loading rates.

- To determine the individual contributions of the ballast base, crib, and shoulder to the sleeper's lateral resistance and to identify the primary contributors that restrict the sleeper's movement in order to maintain track stability.

1.4 Significance of the study

Lateral resistance is a critical parameter that maintains the track's lateral stability, prevents the track buckling effect and misalignment, and significantly improves overall stability under high-speed train operation to ensure track safety. Studying the effects of loading rate on the lateral resistance of sleepers is significant for engineering practices, as it helps in selecting suitable material for construction tracks and optimizing the design to minimize the maintenance cost effectively. It also serves for the future as input data for properly considering the loading rate in the track design analysis in the track performance assessment. Understanding the contribution of the ballast layer component to the track's lateral resistance helps the railway engineer optimize the ballast geometry, prioritize ballast maintenance in high-resistance zones, and recommend reinforcement measures in the critical sections to maintain the track's stability.

1.5 Scope and limitations of the study

The scope of this test investigation is focused on examining the effect of loading rates on the lateral resistance of sleepers in ballasted track structures under static load conditions in track performance and stability. However, due to the shortage of investigation testing instruments, dynamic loading was not considered during this experimental field assessment for measuring the sleeper lateral resistance. Furthermore, the study evaluates the role that the ballast base, crib, and shoulder play in the sleeper's lateral resistance in the ballasted track system, which significantly restricts the sleeper movement and maintains the track's overall stability. Understanding the role that each ballast layer plays in the lateral resistance of the sleeper is useful; it enables railway engineers to give insight and knowledge to design the modern railway track system for ensuring the track's stability.

1.6 Research structure

The research structure of this study is classified into five chapters to simplify my work, and their outlines are summarized as follows:

Chapter One presents an outline of the research's background, objectives, problem statement, scope and limitations, and research structure.

Chapter Two presents a general review of the literature on earlier research that is relevant to the current study and has been divided into three main sections. Section one describes the overview of the track structure, ballasted track components and their functions, and the types of forces that frequently act on the track and affect its stability. Section two focuses on the fundamentals of track lateral resistance and discusses the effects of ballast geometry and components on the track's lateral resistance and long-term stability. The final section outlines various techniques for evaluating sleeper lateral resistance. It summarizes the recommended method for effectively measuring sleeper lateral resistance using the field investigation method to obtain more accurate results.

Chapter Three describes the properties of the testing materials, the method, and the testing procedure followed to conduct the experimental field test. It describes in detail the tested area, ballast bed geometry, ballast grading, sleeper characteristics and specifications, the measuring method of sleeper lateral resistance, and each testing procedure.

Chapter Four presents the effects of loading rate on the lateral resistance of sleepers, based on experimental field test results, and other specific objectives are also discussed. These include the evaluation of loading rate effects, sleeper resistance behaviors, and the contribution of individual ballast layers to the track's lateral stability.

Chapter Five summarizes the study's main findings and makes recommendations for further research to better understand the effect of loading rates in dynamic loading scenarios.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Overview of Track Structure

The track structure is a critical element of the railway system that ensures long-term serviceability by providing a stable, secure, and efficient guided train operation at different axle loads and speeds along the track alignment. To ensure effective operation and meet specified requirements, the track structure must be constructed with high-quality materials and strength to withstand the track forces and resist environmental effects [5].

The two types of railway track structures now employed in the construction of modern track systems are ballasted and slab tracks, which are selected based on factors including cost, lifespan, and material availability [1]. Ballasted tracks are most widely used in new and existing track alignments throughout the world, which is more applicable to the new construction of railway infrastructures. Slab tracks are currently employed in the construction of railway alignments to ensure long-term track stability and serviceability, particularly in transition zones such as bridges, the track turnout area, and low subgrade properties. This type of track is highly recommended for high-speed railway systems.

2.1.1 Ballasted Track

These types of track structures are currently among the most widely used in the world for both new and existing railway lines, primarily due to their simplicity to construct and low construction costs [5]. This type of track structure places the sleeper on top of a layer of compacted ballast; the primary function is transferring the train load from the rail into sub-ballast and finally subgrade [6].

According to B. Indraratna et al. [5] and [6], ballasted track is generally preferable to slab track due to its simplicity of design and construction, lower resource requirements, and less expensive installation. Although ballasted track has several benefits, it also has a number of drawbacks compared to slab track [1], as described below:

- Interruptions to traffic during maintenance
- The track substructure required a thicker and heavier foundation to construct a stronger bridge and viaduct.
- Reduced the hydraulic conductivity as a result of crushed ballast and water accumulation.
- Regular maintenance was required to maximize track stability, which led to a reduction in the interlock between the ballast particles and, as a result, an increase in ballast fouling.

2.1.2 Slab Track

The slab track system uses a concrete base rather than conventional ballast material to construct and support various track structure elements. In this type of track structure, sleepers are typically embedded in the concrete slab to support and align rail components, and rails are secured similarly to ballasted track systems [7]. The slab track was considered more preferable than the ballasted track [5] for the following reasons:

- Long service life without requiring maintenance and the potential for nearly complete replacement at the end of the life.
- Implementation of slab tracks reduced the maintenance project cost by 20–30%.
- Prevent the environmental emission problems due to removing the dust generation of the ballast.
- Minimized disruption of traffic

Although providing long-term track stability and minimizing maintenance costs, slab tracks have a number of drawbacks compared to ballasted tracks [1], [5] for the following reasons:

- Difficult to maintain the track structure damage because it is constructed under the rigid type of construction.
- Slab track construction is complex and time-consuming and requires more skilled engineers.
- Higher initial construction costs.
- Subgrade requires additional improvement and treatment.

2.2 Ballasted Track Components and Their Function

The permanent structural integrity of a ballasted rail system is composed of two layers: the superstructure layer and the substructure layer. The superstructure, which is the topmost component of the track surface, is primarily responsible for supporting and properly distributing the dynamic load to sub-structural elements. The substructure, or lower part of the track surface, is responsible for maintaining long-term track stability, distributing superstructure loads into the ground, and supporting and resisting superstructure force [7]. In a ballasted track system, the sleeper-ballast interaction is crucial for efficiently transferring load into the substructure, distributing static and dynamic loads appropriately, and enhancing the track's overall stability [7]. The components of a conventional ballasted track [1], [6] and its cross-sectional view [8] are illustrated in Figures 2.1 and 2.2.

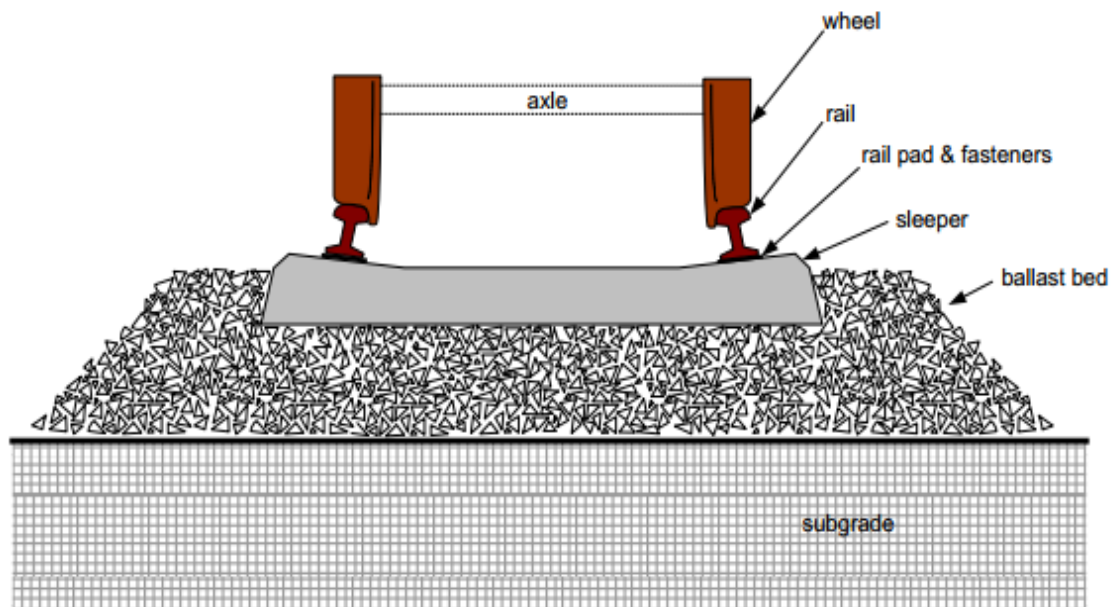


Figure 2.1: Conventional ballasted track elements [6]

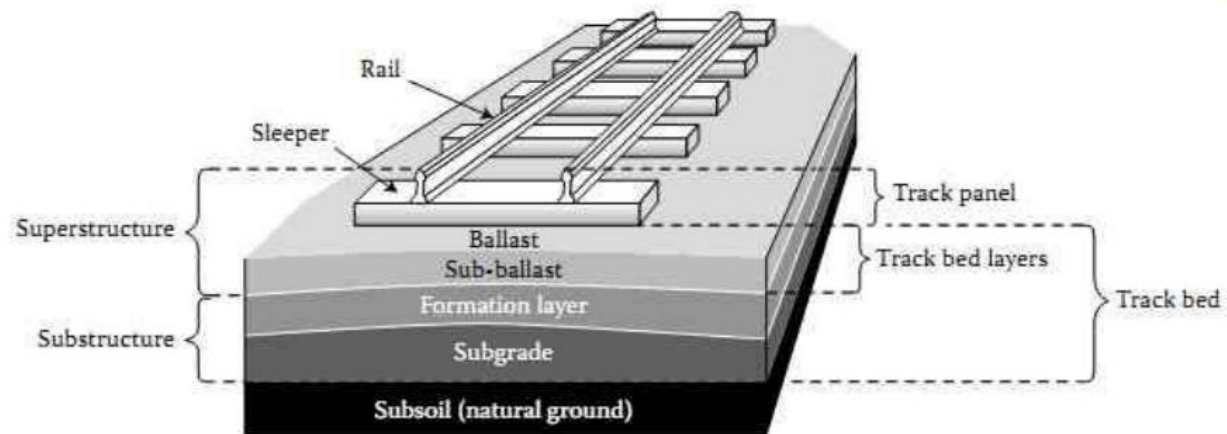


Figure 2.2: Ballasted track cross section and its components [8]

2.2.1 Track Superstructure Components and Functions

2.2.1.1 Rail

The rails are the first part of the track's superstructure, which is situated at the top of the sleeper and runs the entire length of the track to support and direct train movement [1].

Two methods are used to connect the rail sections: bolted joints and welding, which ensure the rail's long-term strength and serviceability for the track's proper structural functionality. The bolted joints, which are connected to the rails by drilled plates, may be the source of vibration and increased dynamic load, which could diminish passenger comfort and accelerate joint failure. This resulted in a decrease in rail stiffness and a decrease in track structural integrity, which increased ballast fouling and track settlement. Consequently, in order to reduce the aforementioned problem and maintain the track's long-term service for this type of joint, regular maintenance is required to enhance track stability [1], [9].

Continuous welded rail (CWR) is mostly used on passenger and heavy freight lines, and it is preferred because it reduces the rail maintenance cost, lessens the risk of substructure failure, and improves rail ride quality. However, continuous welded rail has certain drawbacks, such as the inability to repair defects in the rail section and the tendency to cause breakage due to temperature changes [1], [5], [9], [10].

2.2.1.2 Rail Fastener

Rail fasteners are essential for fixing the rail in the proper position on the sleepers to resist the track forces, preserve gauge distance, and maintain the track's lateral and longitudinal alignment [1], [5]. There are two ways to join the rail section and sleeper: using elastic or rigid fasteners. In elastic fastenings, rails are attached to sleepers with clips; in rigid fastenings, bolts or nails are utilized. Rail fastener systems consist of several essential components that help hold the rail to the sleeper properly and minimize longitudinal movement, ensuring a longer service life [1], [5].



Figure 2.3: Rail fasteners type, a) Rigid fasteners and b) Elastic fasteners [8]

Rail pads are installed between the top of the sleepers and the bottom of the rails to serve the following purposes: reduce the dynamic force influence on the sleeper, fix the rail's movement, and reduce the stress between them and the vertically stiff track [4], [8], [11].

2.2.1.3 Sleeper

Sleepers are the main superstructure component of a track, which are placed atop compacted ballast or embedded in a concrete slab and serve to level the rail alignment to ensure the track's long-term stability. The primary function of a sleeper is to transfer the concentrated static and dynamic load from the rails to the ballast, which is then distributed properly throughout the track's substructure to decrease tension in high-stress areas and ensure the track's stability [1], [2]. Apart from its primary function, the sleeper plays several other essential roles in the railway track system [1], [5], [8], [10] as described below:

- Maintain longitudinal and lateral stability of the track throughout the entire life.

- To keep the fastener in the correct location to prevent the rail's lateral movement and to maintain track gauge distance.
- Lowering noise and vibration on non-ballasted bridge decks due to high-stiffness material workability.

Sleepers are typically made of timber, concrete, and steel with different lengths and shapes depending on the railway track systems, as illustrated in Figure 2.4. Currently, the concrete sleepers are the more popular types and mostly usable around the world in the construction of modern railway track systems. These sleepers are rectangular in shape and constructed based on the gauge type, and it was recommended that they be between 2000mm and 2600 mm in length for a high-speed track system [9], [10]. However, the geometry and kind of sleeper employed vary depending on the track section, such as switches, turnouts, and transition zones, in order to maintain track stability [3].

In recent years, pre-stressed concrete sleepers have seen widespread adoption in various countries due to the advantages of mass production in precast yards and their cost-effectiveness. These sleepers are more durable for a long time, have higher strength, are heavier in weight, and are more rigid than other types, such as timber or steel sleepers [1], [2], [5].



A

B

C

Figure 2.4: The diagram identifies A as a timber sleeper, B as a steel sleeper, and C as a concrete sleeper [8]

2.2.2 Track Substructure Components and Functions

2.2.2.1 Ballast

Ballast, which is composed of crushed gravel or other materials, is placed on the sides and bottom of the sleepers to support the superstructure of components and maintain track stability. It is typically composed of granular materials with a size range of 20 to 65 mm. The primary function of ballast in a railway track system is to stabilize the track structure [11], which has been reported to have several critical roles [1], [5], [11] among the following:

- To evenly distribute the sleeper's load to a suitable stress level throughout the subgrade, improving track stability and distributing the load's intensity over the layer's underneath it.
- To withstand the forces that is provided to the sleepers in the vertical, lateral, and longitudinal directions in order to maintain their proper position.
- Fix and restrain the sleeper's movement along lateral, vertical, and longitudinal directions to allow sustainable train movement.
- Help to level track surface alignment and maintain the track's workability.

The determination of ballast material type is based on two primary criteria: the availability and quality of the rock and financial constraints. Nowadays, the most popular types of ballast materials that are recommended worldwide for building railway alignment for developing countries are quartzite, gneiss, granite, dolomite, and basalt [5].

Crushed stones are a stronger ballast material that fits and interlocks better, reducing the need for redundant track maintenance and preserving track stability. This kind of ballast material is graded into two different forms: 20/40mm for level crossings or other structures and 30/60mm for main lines. This type of ballast material has a higher bearing capacity than other types and maintains the track in a better position whether there is heavy traffic [4], [10].

Typically, railway track systems use a 300mm ballast depth because of the high quality of the subgrade foundation; however, to enhance the track's lateral confinement where there is the presence of a weak subgrade foundation, the ballast depth was increased up to 500mm.

2.2.2.2 Sub ballast

Sub ballast is a layer of the substructure located between the subgrade layer and the ballast, playing a role in increasing the subgrade's bearing capacity and providing additional support to the ballast to resist train-induced forces [5]. It is typically made up of a combination of sand, gravel, well-graded crushed stone, or board-graded stone [1], [8]. According to B. Indraratna [5], the sub-ballast layer is one of the essential substructure components that has been designed to serve multiple functions.

- To increase the ballast stiffness
- Reduce the flow of tiny (fine) particles into the ballast's substructure in order to minimize ballast fouling
- Improving track stability by minimizing the effect of water flowing upward into ballast

The sub-ballast layer is designed to be between 100 and 150mm thick to save construction costs and efficiently manage drainage to maintain total track stability. However, in order to minimize subgrade stress in high-speed track systems, sub-ballast layer thicknesses are increased by up to 300 mm depending on subgrade characteristics [3], [5].

2.2.2.3 Subgrade

The subgrade, a low-stress component of track construction that provides long-term stability throughout the railroad track's length, served as the foundation for the entire track structure. Its primary function in railway construction is to provide a strong foundation for the ballast and sub-ballast layers across the entire depth of influence [5], [7]. In addition, it is essential to control swelling, reduce consolidation settlement, and limit progressive settlement caused by repetitive train loads in order to maintain track stability [5].

To construct the subgrade, two types of ballast material are used: naturally occurring soil and ground (fill). When the track is built on soft soil, ground improvement techniques such as deep cement, lime grouting, and lime cement columns are typically required in order to maximize the subgrade strength [1], [7].

2.3 Overview of Track force

The type and number of loads that could be applied to the sleeper and ballast bed over their lifespan must be measured to assess and construct a more sustainable track structure for ensuring the track's long-term stability [1], [5], [8]. The two types of forces acting on the track structure are thermal and mechanical (also known as static and dynamic forces). The primary sources of the substructure's dynamic load are the uplift forces and train live forces, which include longitudinal, lateral, and vertical forces produced by the train's movement on the superstructure [5], [7], [8].

In the railway track system, dynamic stress on the rails is primarily generated by the uplift forces resulting from train movement. However, static loads result from the gravitational forces acted on by the train, which indicates the combined effect of locomotives, carriages, and other elements. This dynamic force frequently occurs on the tracks, which affects the resistance capacity of the rail, sleeper, ballast, and other components [5], [7].

The main cause of thermal stress in the rail is changes in temperature over time, specifically highly increased heat at midday. This stress results in a decrease in the track's longitudinal and lateral resistance, which causes the rail to expand or contract along the length [1], [5], [8].

2.3. 1 Types of Track forces

The track forces can be categorized into three groups based on the direction they are applied to the track structure: vertical, longitudinal, and lateral forces, as detailed below. These forces highly influence the serviceability of the track's superstructure components, such as sleepers, rails, and fasteners.

2.3.1.1 Vertical force

The vertical track force is primarily generated by the train weight during the train operation, acting perpendicularly to the rails, and resisted by the track structure element. There are two primary sources: vertical wheel force resulting from the train operation and uplift forces generated at the sleeper-ballast interface [1], [8].

The vertical wheel force is frequently produced during train operation and can be estimated by dividing the weight of the train by the number of wheels and adding the dynamic fluctuation while accounting for the stationary value [8]. When the vertical downward track force is applied to the top surface of the rail heads at the wheel contact point, the rail structure in the stressed area deflects downward and away from the stressed area, rising vertically on both sides [9], [12], as shown in Figure 2.5. It results from the structural elements of the track, such as the ballast, rails, and sleepers, being insufficient to adequately withstand the vertical uplift force and downward track forces generated by train operation. As a result, the sleeper and other super- and sub-structural track components deteriorated, and less resistance capacity was developed.

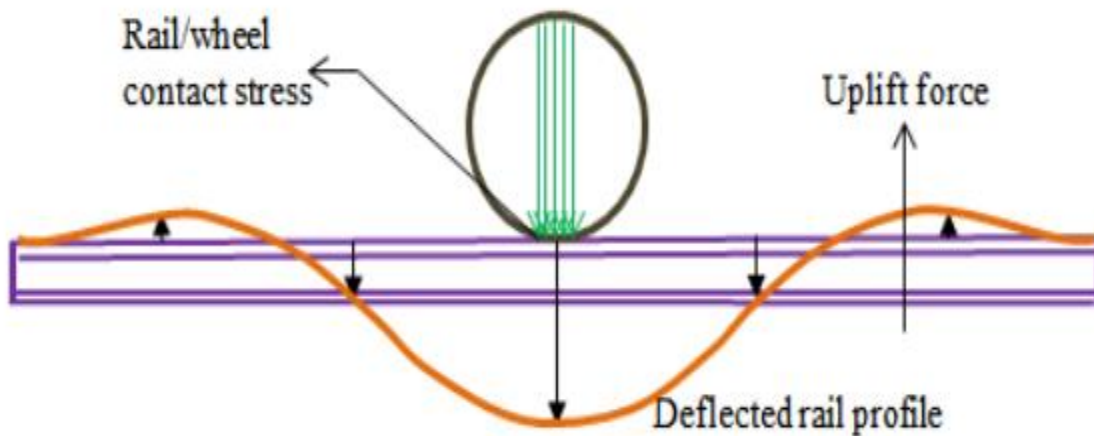


Figure 2.5: Graphical description of the development of uplift force [9]

According to Esveld [1], [5], the total vertical wheel load on the rail is the result of the combination of quasi-static stresses from the vehicle weight and dynamic loads from the train speed. The quasi-static forces, which are composed of the several significant structural components of the track forces that affect the lateral resistance route, are described as follows:

$$Q_{\text{total}} = Q_{\text{quasi-static}} + Q_{\text{dynamic}} \quad 2.1$$

$$Q_{\text{quasi-static}} = Q_{\text{static}} + Q_{\text{centrifugal}} + Q_{\text{wind}} \quad 2.2$$

Whereas, Q_{static} : Vertically applied load under static conditions

$Q_{\text{centrifugal}}$: Centrifugal force that occurs on the curved track during train movement.

Q_{wind} : Crosswind-induced vertical wheel force

Q_{dynamic} : Dynamic wheel load from sprung and un-sprung masses

As illustrated in Figure 2.6, the maximum vertical force at the limit equilibrium condition, when the centrifugal and wind forces act entirely on the outer rail [1], is equal to the sum of the static wheel and dynamic force effects developed by the train operation.

$$Q_{\text{centrifugal}} + Q_{\text{wind}} = G \frac{P_c h_d}{S} + H_w \frac{P_w}{S} \quad 2.3$$

$$h_d = \frac{Sv^2}{gR} - h \quad , \text{ super elevation deficiency} \quad 2.4$$

Whereas, G: Load applied by each axle, R: Track curve radius (m)

H_w : Force exerted by wind in lateral direction, h: super elevation indication),

V: The train variable speed (km/hr.)

S: Rail spacing width

g: Gravitational acceleration (9.81m/sec²)

P_c : The lateral distance from the rail center to the vehicle's center of mass (m)

P_w : The vertical distance of resultant wind force from center of rails (m)

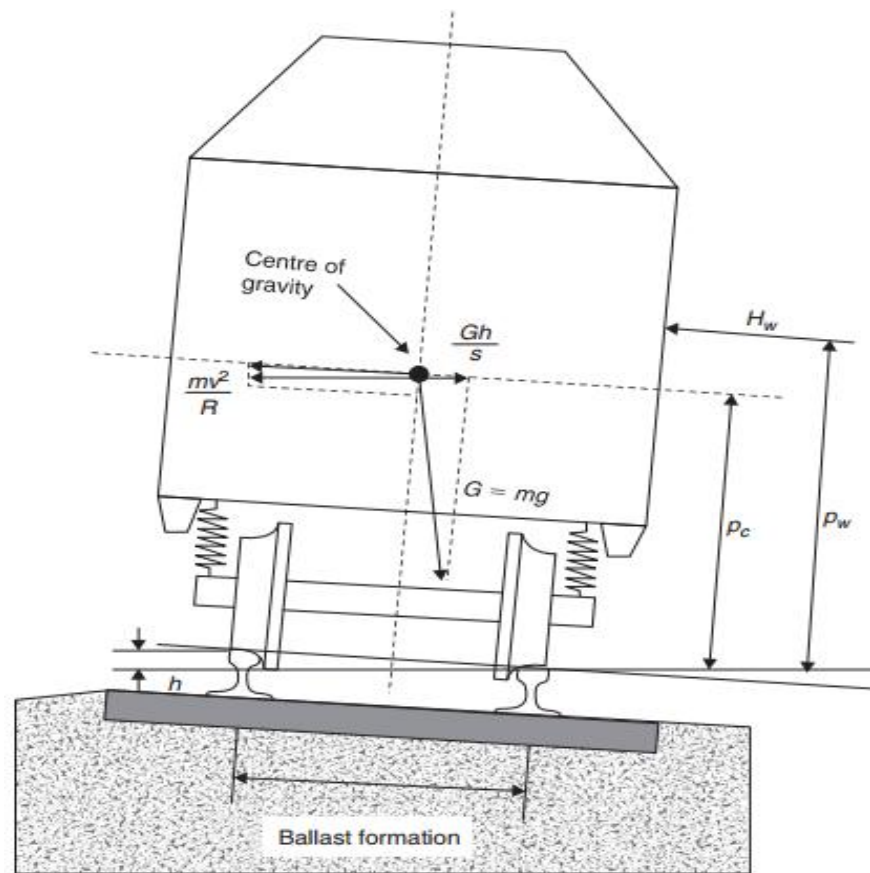


Figure 2.6: Graphical description of quasi-static forces acting on a vehicle along a curved railway track alignment [1], [5]

The dynamic wheel load, also known as Q dynamic, is the most unpredictable part of the wheel load because it fluctuates and is influenced by many different variables, such as the train speed and the surrounding environment. It is affected by several factors, such as the train speed variation, the track structural quality, and the physical properties of ballast and quality [5].

Selig and Waters measured the vertical wheel load on numerous US concrete sleepers, aiming to clarify the differences between static and dynamic wheel load distribution by conducting the experimental field investigation at straight track alignments. The investigation demonstrated that there is no significant variation in the load distribution between the two forces and that the highest difference between them is only two percent [7].

2.3.1.2 Longitudinal Forces

The longitudinal force significantly affects the structural stiffness of the rail, which acts on the longitudinal direction of the track alignment and frequently occurs in regions with high ambient temperatures. These forces primarily originate due to the braking force, rail wave action produced by the dynamic forces of the train, and the rail's thermal load effects [7].

In a study by Ignacio Villalba et al. [12], it was demonstrated that longitudinal forces significantly develop and increase within the track structure, contributing to the track misalignment and decreasing the resistance capacity of superstructure elements, especially rails and sleepers. These consequences lead to increased rail track buckling and decreased track longitudinal stability, as shown in Figure 2.7.

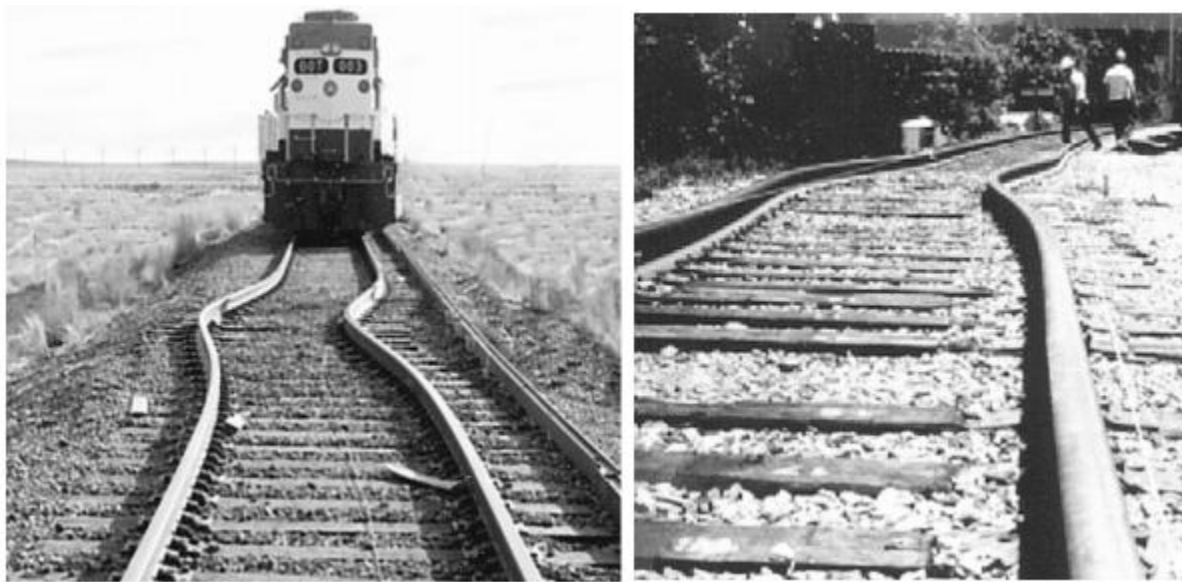


Figure 2.7: Rail misalignment and formation of lateral track buckling due to temperature variation [13], [14]

Track buckling occurs when the track's lateral resistance is low (because of the use of weak ballast material), and temperature variations result in highly developed thermal stress on the rail. There are two basic types of buckling in rail tracks: a sudden, rapid failure caused by environmental or load changes and gradual, progressive deformation over time [12], [15].

2.3.1.3 Lateral force

In track systems, lateral loads are more difficult to determine and understand due to changes in speed, track geometry, and track condition compared to the track's vertical loads. According to Buddhima, lateral forces in the railway track system can be divided into two primary sources: lateral wheel forces generated at the train wheel-rail interface and buckling reaction force resulting from temperature variations [1], [7].

Lateral wheel forces often arise from the interaction between the wheel and rail during train operation, and they are more dominant than the buckling reaction force due to their dynamic changes and frequent occurrence. Buckling reaction forces were primarily caused by high compressive stress that was developed on the rail as a result of the increased temperature effect. They also occur over an extended period of time as a result of the track structure's reduced serviceability and the low ballast compaction[1], [7].

Lateral wheel forces, which are the more dominant factor affecting the track structure's performance, are primarily resisted by the interaction of sleeper and ballast under the imposed loads on the top rail. In order to determine the lateral resistance of the track, the previous researcher conducted a number of experimental tests and numerical simulations under increased train speed in the standard track line.

For the first time, Prudhomme [16] carried out an experimental test to assess a wood tie track's "lateral strength" under a lateral load that was moving. Two tests have been performed to evaluate the wood tie track's lateral strength. In the first loading scenario, the lateral load increases after every ten passes, while the vertical load remains constant throughout the test investigation in order to measure the lateral resistance of a single-track line. In the second loading scenario, the vertical and lateral loads remained constant throughout the test investigation and during trial measurements. Based on the test results, two loading scenarios were important for defining the "critical" loads and conditions to describe the lateral strength of the wood sleeper.

As a result, Prudhomme introduced a fundamental mathematical formula by combining two loading test results to determine the lateral resistance of wood sleepers. This mathematical formula helps to evaluate the track's lateral strength under different track types and vertically applied axle

loads while accounting for variations in ballast quality and properties. This formula has been used over the years to determine allowable vehicle loads on track and, on occasion, to determine the maximum panel shift in ballasted track systems in order to optimize and ensure overall track stability. The developed formula for quantifying lateral strength is expressed as follows below:

$$L_P = 10 + \frac{V}{3} \quad 2.5$$

Whereas V is the per-axle weight in kN

This empirical formula represents the wood tie track's limiting track panel strength when the ballast quality is high. This equation does not incorporate significant parameters that affect track structure stability, such as rail curvature and thermal loads, and to solve this problem, a 0.85 safety factor was applied in the calculation. Currently, this equation is important for evaluating the track lateral resistance as a reference in the construction of new and modern railway track systems [16].

In order to assess the resistance of the new track panel and compare the lateral resistance of the old track with the Prudhomme limitations, French National Railways (SNCF) is currently conducting an experimental test on the TGV line in Paris, along the main track alignment. These tests are crucial for measuring the track's current lateral resistance, specifying a minimum lateral resistance for the track construction, and ensuring the track's long-term stability. The derailleur wagon was commonly utilized to apply the train weight's vertical load and then gradually apply the lateral load to measure the sleeper's lateral displacement, enabling an effective test of the track system's lateral resistance. During the test, the lateral load was applied with gradual increments up to the point of stabilizing lateral deflection, while the vertical load was applied at a constant level using a slow speed with three repeated tests using the same ballast properties. Throughout the investigation, the lateral displacement and vertical applied force were properly recorded, and the test calibration process was followed throughout each test [16].

According to the findings and recommendations of the French National Railways (SNCF) [17] study, the operational values and limitations of the concrete tie track are as follows:

- The maximum repeated lateral axle load exerted by the vehicles during the train operation throughout the service life of the track structure is equal to 85% of the Prudhomme value, which is expressed as $0.85(10+0.33V)$. The factor of 0.85 plays a significant role in evaluating how both thermal loads and the radius of curvature influence the lateral resistance of the track, aiding in understanding track stability under various conditions.
- Two methods can be used to calculate the lateral resistance of the concrete tie track to fully meet the minimum requirements for the track stability: $24+0.41V$ for tamped track and $38+0.63V$ for stabilized track.
- During track operations, lateral defects up to 8 mm (peak-to-peak) do not require maintenance when track forces are increased; however, significant track maintenance will be required if the defect is 12 mm or greater.

To sum up, the National Railway of France (SNCF) conducted a series of experimental tests along the main track alignment to determine and recommend the maximum lateral force on the track under high speeds exceeding 408 km/hour in a ballasted track system. The study concluded that the lateral resistance of the track does not exceed the Prudhomme limit values and is highly influenced by the ballast quality [16].

Therefore, the sleeper's lateral resistance, which enables it to withstand the net axle lateral load, is the primary factor that contributes to the track's overall lateral strength in a railway track system, ensuring the track's long-term stability [17].

2.4 Fundamentals of Track lateral resistance

Track lateral resistance refers to the track structure's ability to withstand the applied track force, which is mobilized by the rail stiffness, fastener resistance, and lateral interaction between the sleeper and ballast to ensure the track's stability [17]. In this instance, the sleeper's lateral resistance is the primary parameter that mobilizes and maintains the track's lateral stability.

The sleeper's lateral resistance is sustainable overall due to the combined effect of the ballast shoulder resistance at the sleeper's ends, the crib ballast resistance along the sleeper's sides, and the ballast base resistance underneath the sleeper [18]. Friction resistance develops from the interaction between the surface of the concrete sleeper and the ballast particles as they slide against each other during the train operation. The concrete sleeper and ballast layer overall interaction [18] is illustrated in Figure 2.8.

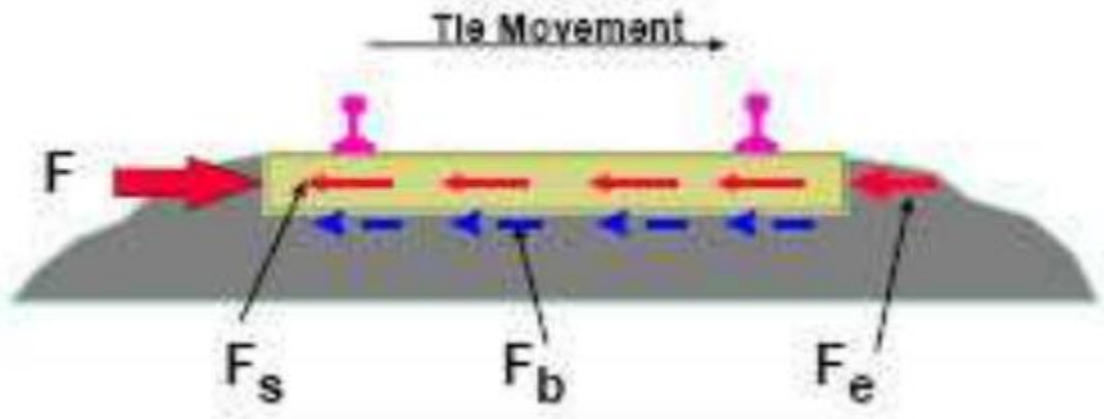


Figure 2.8: The Interaction between the Mono-block Concrete Sleeper and Ballast [18]

Therefore, the total lateral resistance of the entire track structure in a ballasted track system, which is developed by the ballast layer [20], can be calculated as follows:

$$F = F_s + F_b + F_e \quad 2.6$$

$$F_b = \mu_f Q \quad 2.7$$

$$F_{p \text{ dynamic}} = F_p - \mu_f Q \quad \text{for up lift force} \quad 2.8$$

$$= F_p + \mu_f Q_V(x) \quad \text{the track lateral resistance does not involve the uplift force}$$

Whereas

F : Lateral resistance of the track resulting from each ballast layer interface

F_s : The lateral restraining forces at the sleeper-side region interface.

F_e : Lateral restraining forces at the sleeper end region interface.

F_b : Lateral resistance constrained by the foundation layer interface

μ_f : Coefficient of frictional value resulting from surface roughness

F_p : Maximum lateral resistance of the sleeper before lateral failure occurs due to track forces

R_v : The vertical force distribution along the load transfer region interface.

Q : Vertical load is produced due to the weight of the sleeper by itself [11], [20].

Sleeper-ballast bed interface resistance is primarily governed by the lateral and vertical interaction between the bottom surface of the sleeper and the ballast bed particle, which is directly influenced by the frictional properties and physical characteristics of the ballast [3]. Its resistance depends on several factors, such as the ballast quality, the ballast frictional coefficient value, and the sleeper roughness quality.

Among the primary factors influencing the track's lateral resistance in a ballasted track system are the friction coefficient values between the ballast particles and sleeper, which are critical to maintaining the track's long-term stability. Fatemeh Khatibi et al. [19] carried out a numerical simulation (DEM) to evaluate the effect of the internal friction coefficient of the ballast on track lateral resistance. The study revealed that the numerical simulation result indicated a 10% increase in lateral resistance when the ballast friction coefficient was increased from 0.6 to 1.1 with the corresponding friction angles of 31 and 48 degrees. Commonly, the friction coefficient value is determined based on experimental investigation, and its value varies based on the ballast quality, which has a maximum range of 1.4 [18].

The lateral resistance of the track increased in proportion to the value of the friction coefficient between the ballast particles, which in turn significantly enhanced the frictional interaction

between the ballast particles and the sleeper. Additionally, it was also found that a decrease in the friction coefficient directly affected the ballast particle, causing a rise in ballast breakage and a decrease in lateral track instability [19]. The sleeper lateral resistance response with increasing the friction coefficient value [19] between ballast particles is graphically presented in Figure 2.9.

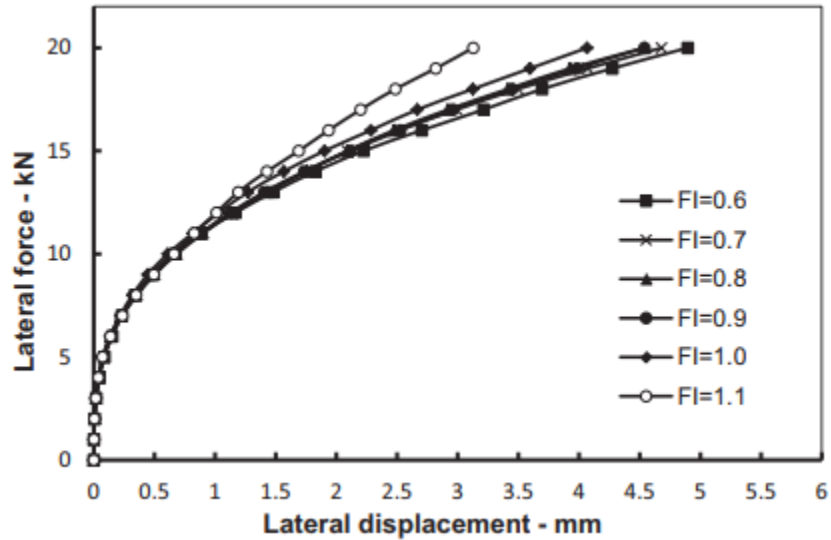


Figure 2.9: DEM simulation results illustrating force displacement curves corresponding to various parameter values [19]

The literature demonstrates that track lateral resistance is significantly influenced by both the friction coefficient value of the internal ballast particles and the friction between the ballast and sleeper in ballasted track systems [4], [21]. These primary parameters are affected by several factors, such as the types, size, and material quality of the sleeper being utilized.

To quantify these effects in different sleeper types, Jabbar Ali Zakeri et al. [15], [16], [20] established a numerical equation to estimate the friction coefficient in a ballasted track system. This equation is used to determine the effect of vertical load on the lateral resistance of wooden and concrete sleepers under varying frictional coefficients and is represented as follows:

$$\mu_{total} = \mu_2 + (\mu_1 - \mu_2)e^{-\beta R} \quad 2.9$$

Where as

μ : The cumulative friction index between two critical contact regions of the track section

μ_1 : The frictional index value under unloaded conditions

μ_2 : The frictional index value between the sleeper and ballast at vertical loads greater than 89kN

R: The track curve radius (m)

The values of μ_1 , μ_2 and β can be different, and it depends on the sleeper types and the value that is presented in Table 2.1.

Table 2.1: The friction coefficient value for the wood and concrete sleeper types

	μ_1	μ_2	β
Concrete tie	0.8	0.76	0.15
Wood tie	1.14	0.69	0.12

Therefore, it was concluded that the increase in the number of train passengers had a more significant effect on the concrete sleeper's corresponding friction coefficient between the ballast particles compared to the wood sleeper. However, with increased ballast consolidation, the ballast strength was increased proportionally, and the corresponding lateral resistance of the concrete and wood sleeper was enhanced and optimized, which significantly increased the track stability. Furthermore, they demonstrated that the passing vehicle has a greater influence on the track's lateral resistance, the contact between the sleeper and ballast, and the lower friction coefficients between the sleeper and ballast particles [20].

Another study revealed that as the axle load increased equally, the sleeper's lateral resistance and the rigidity of the ballast particle interaction increased significantly, increasing the sleeper's ability to withstand track movement and the ballast's resistance capacity [20]. As a result, when the axle loads increased, the sleeper bottom and sides were significantly more affected than the sleeper ends due to high frictional interaction between the vertical load and the sleeper's bottom stressed zone [14].

Jabbar Ali Zakeri et al. [20] conducted an experimental study to examine the effects of axle and vertical loads on the lateral resistance of track. The study found that the track's lateral resistance

and stiffness in high ballast quality increased significantly as the train's vertical load increased in the ballasted track system. The sleeper's lateral resistance-displacement curves and the corresponding vertical loading scenarios are presented graphically in Figure 2.10.

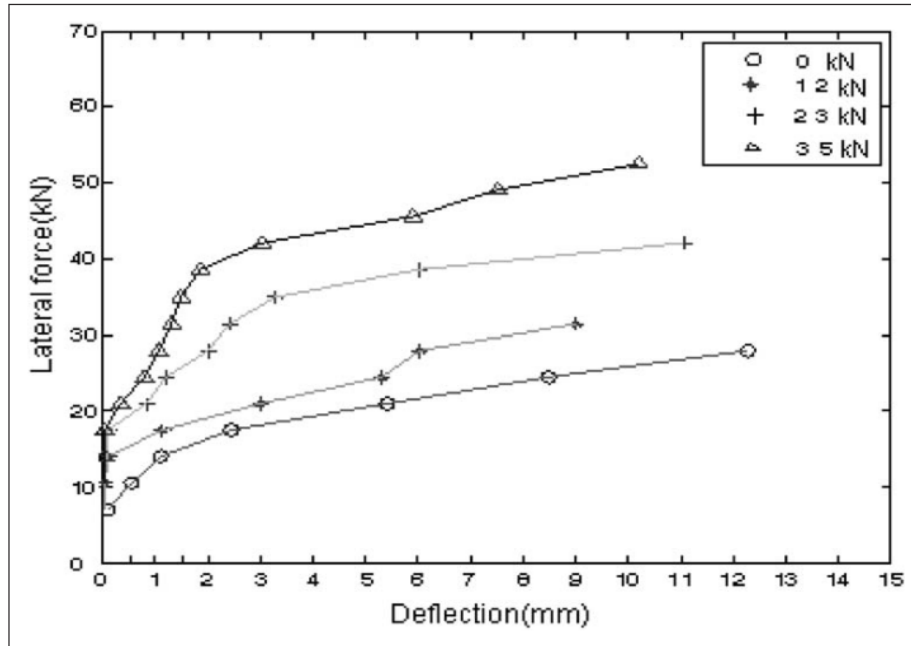


Figure 2.10: Lateral resistance-lateral displacement curves of the sleeper under four vertical loading scenarios [20]

In general [22], the resistance at the bottom of the sleeper is substantial, given the total frictional resistance of the sleeper and ballast, which is significantly influenced by the sleeper shape, the surface roughness, and the ballast compaction. Increased sleeper surface roughness, higher frictional interaction between the ballast particles, and high ballast compaction significantly improve sleeper-ballast interaction resistance and enhance the strength of the ballast to withstand track forces. This fractional resistance significantly increased the overall track stability and ensured the track's long-term serviceability.

Sleeper-crib ballast zone interface resistance: This resistance is developed by the interactions between the sleeper side and the crib ballast zone to restrain the sleeper's lateral movement and maintain the track's lateral stability. The interaction between sleeper and crib ballast is frequently determined by understanding the concept of soil hypothesis theory, which represents that the

ballast materials of the sleeper side are equivalent to active ballast pressure. This resistance depended on several critical factors, such as the height, quality, and compaction of the crib ballast, to allow it to withstand the track force and environmental effects [3].

The crib ballast's primary role is fixing and preventing sleeper displacement along the longitudinal direction to ensure the track's stability during the train operation. Its resistance depends on several critical factors, such as the ballast gradation types, ballast material type (crushed or other materials), tamping method used, and the track structural quality. At first, the ballast's lateral resistance was high as the sleeper's lateral movement increased due to the high contact between the sleeper and the ballast particles. After reaching peak resistance, lateral displacement increased; however, ballast or sleeper lateral resistance was constant due to a decrease in the interaction between the sleeper and ballast [18]. Therefore, based on Ali Zakeri's findings, the lateral resistance of the ballast is equivalent to 2 mm of sleeper displacement [18].

Sleeper- ballast shoulder interface resistance: This resistance is generated by the interaction between the sleeper end and the ballast shoulder, which restricts the sleeper's transverse movement and preserves the track's lateral stability. This interaction helps to prevent sleepers from laterally shifting under increased thermal loads and reduces the effect of track buckling by increasing the track's lateral stiffness while preserving its overall stability [3] .

In ballasted track construction, increasing the ballast shoulder width and the ballast depth are among the most practical and efficient ways to increase the track's lateral resistance while maintaining long-term stability [18]. A deeper ballast depth and a wider ballast shoulder allowed for stronger support from the sleeper's lateral shifting, which enhanced the sleeper's lateral resistance capacity and lateral load distribution. The result reduces temperature-induced track buckling and improves overall stability. A wider ballast shoulder reduces track geometry deterioration and maintenance expenses by providing the sleepers with stronger lateral support, which helps to maintain proper alignment of the track components. Aiming to reduce the track buckling effect and increase the track's overall stability, German and Russian railway companies have recommended a ballast shoulder width of 35 cm for both straight and curved track section [18], [13].

Moreover, in the interaction between the surface sleeper and crib ballast [22], the ballast shoulder material's primary function is to significantly restrict the sleeper's lateral movement with the aim of preserving the track's stability. Ballast shoulder resistance increased significantly as ballast compaction increased, and the well-designed ballast geometry ensured track stability. The ballast compaction substantially increased the ballast strength between the ballast particles by enhancing their interlocking and frictional interaction, which helped to increase the structural integrity. This interlocking of the ballast particles enhanced the sleeper's longitudinal and lateral resistance by properly restricting it to maintain the track's stability.

To further investigate the sleeper and ballast interactions, the earlier researchers developed a numerical technique to calculate the lateral resistance of sleepers under various circumstances. This mathematical formula, which is incorporated with many parameters, was developed by the Railway Technical Research Institute in Japan and can be explained as follows [16], [21]:

$$R_{\text{total}} = aW_{\text{sleeper}} + b\gamma_{\text{ballast}}S_{\text{end}} + c\gamma_{\text{ballast}}S_{\text{side}} \quad 2.10$$

Whereas the constant values of a, b, and c are determined through experimental testing, the values of these parameters in different sleeper materials are described in Table 2.2.

S_{side} : The sleeper side face's first moment relative to the top face

S_{end} : The sleeper end face's first moment relative to the top face

W: Rail tie weight

γ ; Density of ballast aggregate

R_{total} : The lateral resistance force developed by the concrete sleeper

Table 2.2: Experimentally determined coefficient values of each parameter [22]

Coefficient values for different parameters	a	b	c
Concrete sleeper and granite ballast [22]	0.76	29	1.9
Wood sleeper and granite ballast	0.76	28	1.4
Wood sleeper and gravel ballast [22]	0.7	28	1.2

Thus, this formula is important for evaluating sleeper lateral resistance under various conditions, such as ballast density, ballast quality, sleeper weight variations, and other critical factors that influence track stability in the railway system.

Furthermore, understanding the sleeper-ballast layer interaction is essential for assessing the sleeper's contribution to the overall track resistance in order to sustain the railway track system. The total track lateral resistance is directly proportional to the resistance of each track element, which includes the fasteners, sleeper-ballast interaction, and track rails. Accordingly, the overall lateral resistance of the railway track structure is predominantly influenced by the ballast, with a contribution of approximately 65%; the sleepers contribute about 25%, and the rails and fasteners contribute the remaining 10% [13], [19].

2.5. Effect of Ballast Geometry and Components on Track Lateral Resistance

Numerous experiments and numerical simulations were conducted to assess the effects of sleeper-ballast geometric parameters in order to optimize the ballast geometry and enhance the track lateral resistance.

Guoqing Jing et al. [18] conducted an experimental investigation to examine the effect of ballast shoulder width on a sleeper's lateral resistance. They found that as the length of the ballast shoulder increased from 200 to 500 mm, the track's lateral resistance increased by 5% and had a lower involvement. However, the study also concluded that beyond this range, further increasing the ballast shoulder had no significant effect on the sleeper's ability to withstand lateral movement for enhanced track stability [23]. Additionally, F. Khatibi et al. [24] found that increasing the width of the ballast shoulder has less of an effect on enhancing the sleeper's lateral resistance to increase track stability, which is similar to what was found in the Guoqing Jing et al. study [23].

In addition to [23], it has been demonstrated that increasing the crib ballast height by 0, 25, 50, or 100% has increased the lateral resistance, which is equal to 84%, 116%, and 137%, respectively, compared to having no crib ballast [23]. Therefore, the aforementioned researchers concluded that, in a ballasted track system, raising the crib ballast height is more effective for enhancing lateral resistance than increasing ballast shoulder width [23]. The track lateral resistance response and the crib ballast height increment effect are presented in Figure 2.11.

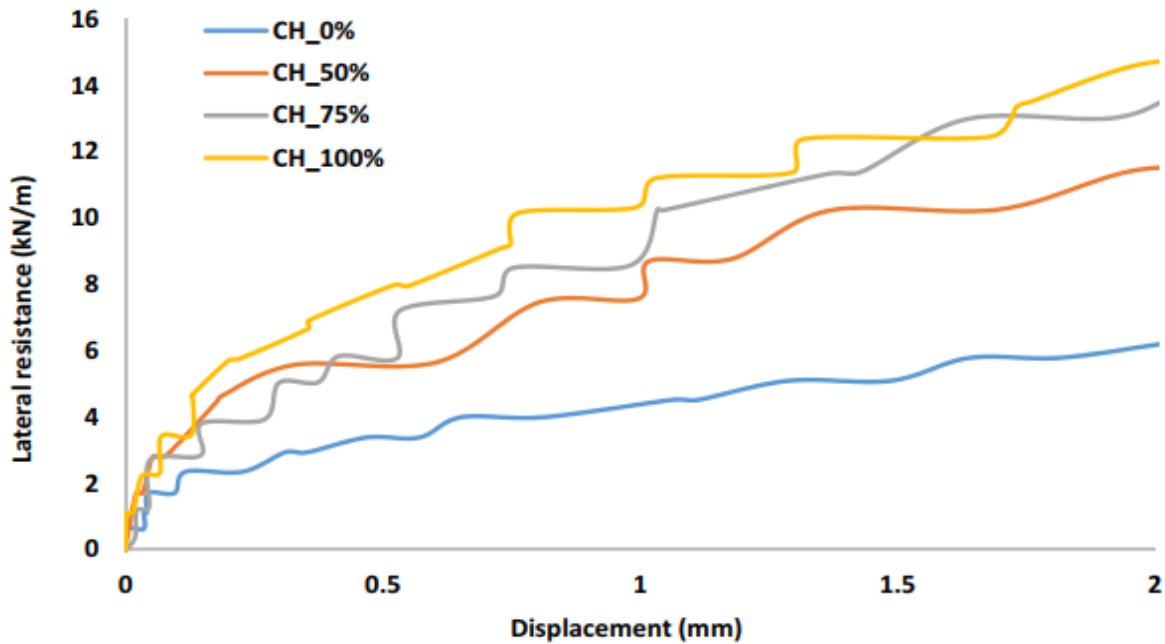


Figure 2.11: Force-displacement response curves of panels under varying crib ballast heights [23]

On the other hand, track lateral resistances have increased by 20%; rather than increasing the ballast shoulder width proportionally, the ballast shoulder height is raised from 0 to 150 mm [25]. Similarly, another study found that reducing the thickness of the ballast support zone from 30 to 20 cm significantly decreased the sleeper's lateral movement while increasing the lateral resistance by an average of 14.5%.

In a separate study [24], it was observed that as the ballast depth increases, both the buckling and safe temperatures decrease, thereby increasing track lateral resistance; however, the buckling temperature decreases more significantly than the safe temperature. They concluded that the ballast depth increments from 30 cm to 40 cm and 40 cm to 50 cm cause the buckling temperature to decrease by 5.04°C and 2.77°C, respectively [24]. The track buckling response and ballast depth increment effect are presented in Figure 2.12.

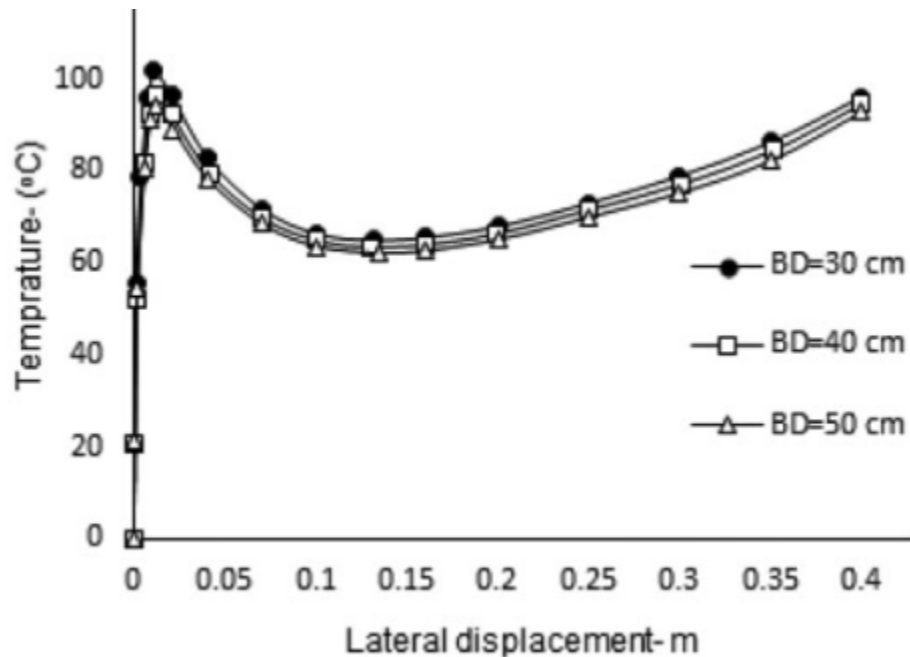


Figure 2.12: Track buckling response of tracks section with: Ballast depth (BD) =30, 40 and 50cm [24]

Furthermore, Guoqing Jing et al. [23] found that the strength of the ballast support zone has a significant impact on the track lateral resistance in ballasted track systems, which is critical for maintaining long-term track stability. The researchers reported that around 62% of the ladder sleeper's lateral resistance came from the ballast support zone of the crib, 29% from the shoulder, and 9% from the ballast bed to maintain the track stability.

On the other hand [26], another study reported that the base ballast, crib ballast, and shoulder ballast minimized the track buckling effect, and they contributed 50%, 25%, and 25% of the track lateral resistance, respectively, in dry ballast conditions. Both the track lateral pullout test and the single tie push test have been used to evaluate and determine each ballast support zone's static lateral resistance, with two test results that are equivalent.

Further investigation was conducted to evaluate the interaction between the shoulder, crib, and base of a concrete sleeper and the surrounding ballast layer, together with the pertinent features, under conditions of lateral impact force (dynamic loading) utilizing a pendulum loading test device [27], [28]. The experiment's findings showed that the base ballast, crib ballast, and shoulder ballast

zones contributed, on average, 48%, 23%, and 29% of the sleeper's total dynamic lateral resistance [28], respectively, with the ballast base contributing more. Additionally, they revealed that the relationship between the sleeper's dynamic lateral resistance and lateral displacement under impact load was linear at the beginning and changed into quadratic forms as the sleeper's lateral displacement increased [27].

Moreover, it was determined that the lateral impact force, which varies from 13 to 28kN, largely depends on the dynamic interaction between the sleeper and ballast and on the dynamic train conditions. The experimental study concluded that the sleeper ballast base has a high dynamic friction coefficient value compared to the sleeper side; its value ranges from 0.8 to 1.5, demonstrating that lateral resistance increases as the ballast friction coefficient value increases [19], [28]. However, there is less lateral resistance contribution generated by crib ballast because the sleeper side resistance dynamic friction coefficient value is expected to be between 0.5 and 0.6 [27], [28].

Finally, researchers concluded that, in ballasted track systems, the sleeper bottom surface's roughness more effectively enhanced the sleeper-ballast interaction and greatly enhanced the track's lateral resistance [9]. Modifying the sleeper's bottom surface from a smooth (Type II) to a rough (frictional) surface raised the lateral resistance of the sleeper by 67% [29]; providing a nail at the standard sleeper increased it by 54% [30], and adding a wing at the end and middle increased it by 98.5% [31].

2.6 Methods of Measuring the Sleeper's Lateral Resistance

Measuring the track's lateral resistance is essential for identifying the ballast quality that can support the track structure and for evaluating the sleeper's resistance capacity to ensure track stability in the railway track system. Different methods have been described by numerous researchers for measuring the lateral resistance of ballasted tracks. These measurement methods include the single tie push test (STPT), panel displacement, mechanical track displacement, derailment wagon, and continuous dynamic measurement with a dynamic track stabilizer and lateral panel loading test (LPLT) [18], [27], [32].

The single tie push test (STPT) is a widely used experimental method applied in both field and laboratory settings to accurately measure the lateral resistance offered by an individual sleeper within a railway track system. This test inquiry technique involved applying a lateral load to one side of the sleeper end using a hydraulic jack and measuring the sleeper's 2 mm lateral displacement using a lateral transducer on the other side. In this test method, to eliminate the influence of superstructure components such as rails and fasteners on the lateral resistance, four fasteners were released from the tested sleeper at two rail seat locations before the lateral force was applied [18], [32]. Based on the test results, a lateral force versus lateral displacement graph is developed to generate the lateral force-displacement curve, which indicates the sleeper's lateral resistance at 2mm lateral displacement equivalent values.

The panel displacement test method is a field experimental inquiry technique used to determine the lateral resistance of a track frame that works with a rigid frame that is 4–6 meters in length and has a solid foundation. In this test method, the track frame's lateral resistance is determined by the interaction between the sleeper and ballast when a lateral force is applied to the middle length of the tested track frame. The corresponding lateral displacement is then recorded using lateral transducers that have been prepared and installed on each tested sleeper. Therefore, in this test method, the distributed overall lateral resistance of each and every sleeper is equal to the lateral resistance of a single sleeper [18], [32].

Mechanical track displacement is one of the most accurate field research techniques and is essential for determining the track's lateral resistance during tamping maintenance as well as for measuring

the track's vertical lateral resistance. In this test method, two extra lifting cylinders and track lining adjustments were needed for the tamping machines to be able to correct the vertical elevation and lateral alignment during the tamping operation. It was also important to examine how the tamping operation affected the track's lateral resistance and the corresponding displacement, which were measured during the test investigation [18], [32].

Continuous dynamic measurement is currently a recommended method for assessing lateral track resistance in continuous alignment and sleeper-ballast interaction. That is carried out by moving the machines under test across the track to evaluate the track's strength and stability. In this test method, a dynamic track stabilizer machine was used to precisely measure the friction forces between the ballast and sleeper that result from the track's lateral displacement, as well as the lateral resistance generated by the force that machines provide to the track to maintain its stability [18], [32].

Therefore, for this test investigation, the single-tie push method was selected to measure the lateral resistance of the sleeper in the railway track system due to its simplicity and accessibility. The general description of this field investigation method is presented in detail in section 3.5, and its significance is also described.

CHAPTER THREE

3. MATERIALS AND TESTING PROCEDURE

3.1. Description of the Tested Area

This field test investigation was carried out on a sub-line at Indodi Railway Station, located southwest of Addis Ababa, along the Ethiopia-Djibouti railway line. The line was constructed by experienced Chinese railway construction companies, particularly the Civil Engineering & Construction Organization of China. This railway infrastructure project was funded in part by the Ethiopian and Djibouti governments, with the remaining 70% coming from a long-term loan from the Chinese government. The line is currently operated and maintained by specialized Chinese contractors working together with the Railway Corporation of Ethiopia. It is run by a standard gauge railway company, which was formed by the combined two government railway corporations, specifically Ethiopia and Djibouti [33].

The Ethiopia-Djibouti Railway Line was the first modern, cross-border, standard-gauge, electrified railway in Africa and was developed as part of Ethiopian railway infrastructure expansion under five-year development plans [39]. It was designed and built at a design speed of 80 and 120 km/h for freight and passengers, respectively, with compliance with Chinese electrified railway standards for National Railway Class II.

Currently, Indode Railway Station is one of the more prominent, workable railway stations on the Ethiopia-Djibouti railway line and serves as the Ethiopia-Djibouti Railway (EDR) maintenance center. It provides vital services such as loading and unloading imported products, resolving train defects, and offering temporary storage for containers and other commodities as a dry port service station. Map of Indode Railway Station and the tested sub-line track are presented in Figures 3.1 and 3.2, respectively.



Figure 3.1: Map of Indodi Railway Station



Figure 3.2: Tested sub- track line at Indode Railway station

3.2 Description of Materials

3.2.1 Ballast Bed Geometry

This line was constructed using a broken ballast layer composed of Class I crushed rock, with a specified 500 mm ballast thickness, 500 mm shoulder width, 150 mm shoulder height, and a 1:1.75 side slope, according to the Ethiopia-Djibouti railway line design and construction standards manual or as-built data. A broken ballast (crushed stone) material [20] has a high bearing capacity, which contributes to controlled gradation and uniform strength, efficient drainage properties, resistance to lateral loads, and improved track positioning, especially under heavy traffic. According to J. M. Sadeghi et al.[11], approximately 2500 metric tons of ballast were required per kilometer to construct a single-line track, indicating the extensive coverage of rail track material in a construction track system.

The track line was constructed with four distinct ballast zones: the crib, shoulder, top ballast, and bottom ballast, in order to provide optimal track alignment and sleeper restraint. The ballast shoulder and ballast crib help to limit the sleeper's movement in both longitudinal and lateral directions, thereby ensuring track stability during train operation [11]. The bottom ballast's primary role is to keep the concrete sleeper from moving downward and to resist the train's vertical force in order to maintain the track profile for assured long-term service. It is influenced by several factors, such as drainage characteristics, ballast depth, and ballast quality. The bottom ballast is more stressed than other parts under the train's vertical pressure and is in frequent contact with the bottom of the concrete sleeper to withstand the track forces.

As observed from the actual site, screw clamp rail fasteners and the ULC 54 rail type were used to secure the concrete sleeper on the track surface to align the rail's longitudinal and lateral profile to ensure track stability (Figure 3.3). As illustrated in the figure, the UIC 54 rail type and SKL rail fasteners are fixed to the concrete sleeper by rail fastener components in order to achieve maximum track stability. Figure 3.4 presents the rail fastener components, such as the tension clamp, abrasion plate, etc., and their functions as described below.



Figure 3.3: Concrete sleeper fixed using UIC 54 rail and SKL rail fasteners at the test site

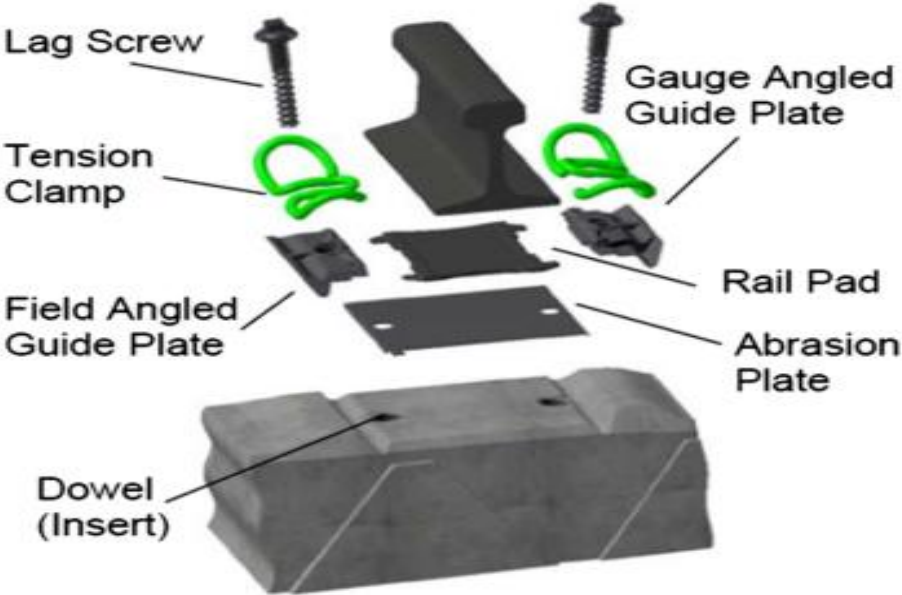


Figure 3.4: SKL rail fastener component [34]

The tension clamp's geometry is designed to minimize residual stress within the clamp following normal rail defection, hence enhancing the fastening system's capacity to sustain sufficient clamping force over an extended period. An angle guide plate was installed on both side rails, which reduces stress on the rail-seat area and encourages constant compression of the concrete sleeper over time, thus increasing the sleeper's resilience and durability. In contrast, abrasion plates

were installed on the bottom rail, which contribute to the reduction of structural damage or failure of the bottom rails by strengthening the rails and increasing the rail pad's lifespan to withstand track force and maintain track stability [34]. Furthermore, the angled guide plate provides properly laterally distributed rails by reducing the side-stressed zone.

In 2017, an experimental investigation was carried out by Donovan E. Holder [34] to investigate the global lateral load distribution over the superstructure using the Safelok I fastening system and the SKL-style fastening system. It was found that the Safelok I fastening method effectively distributed lateral forces through the embedded shoulder by attaching the rail side with an abrasion plate, which restricted the rail movement and ensured the track's long-term stability. SKL-style fasteners were found to effectively transmit the lateral forces from the rails broadly into an angled plate, in contrast to Safelok I fastening systems, which uniformly transfer the lateral pressures into the rail seat region to safeguard the track stability. Finally, it was discovered that more than 55% of the lateral tire pressure is transferred into the angled guidance plate when comparing the SKL-style fastening system to the Safelok I fastener system; this is allowed because the lateral load transfer is beyond the standard limit [40].

As observed at the tested site, UIC 54 rail is fixed on the mono-block concrete sleeper using SKL rail fasteners in the track surface, and the sleepers are embedded at uniform spacing along the ballast layer to ensure the track's stability. Figure 3.5 illustrates the actual measurement of the sleeper spacing distance, which is 600mm. The design manual, measurements, and observations from the tested site all point to a standard rail gauge of 1.435 meters at each position.



Figure 3.5: Sleeper placement with 600mm spacing as measured at the actual site

3.2.2 Ballast Grading

Ballast grading is a significant factor in determining the mechanical behaviors and the ballast performance, which directly affects the ballast drainage capacity, shear resistance, deformation, and both lateral and longitudinal resistance. In track construction, the ballast grading design is essential for minimizing lateral and vertical ballast settlement, maximizing shear strength, providing effective drainage characteristics, and ensuring the track's overall structural stability.

According to Yifei Sun et al. [35], comprehensive cyclic tri-axial tests were carried out under monotonic loading to evaluate the performance of various grading systems in order to determine the appropriate ballast grading for modern railway track systems. The test findings demonstrated that the uniformly graded ballast, which has a lower coefficient of uniformity ($C_u < 2$), significantly increased ballast deformation, lowered shear strength, and increased maintenance activity as compared to slightly broadly graded ballast ($C_u = 2-2.5$). Furthermore, as aggregate size and density were increased, the ballast's shear resistance capacity effectively increased to withstand repeated train loads and preserve track stability [35].

In related studies, Thom and Brown have shown that the granular aggregate in the ballast material has a high coefficient of uniformity, which leads to decreased drainage resistance, ballast shear stiffness, and track lateral stability. Therefore, the ballast should be designed with optimum gradation, be coarse, and be a free-draining medium to meet the drainage requirements for ensuring track stability. Furthermore, in order to prevent settlement, ensure high ballast strength, and effectively interlock the ballast particles to withstand track stress, the ballast should be designed as a broadly graded aggregate [5]. To provide track stability and meet overall functional requirements, ballast should be designed using the combination of uniform and broad grades of aggregates.

In summary, ballast grading is the most significant parameter in railway track development to ensure long-term track serviceability and minimize maintenance time [15]. They now employ crushed stone ballast material with well-graded aggregate in Ethiopian railway development since it meets their requirements.

In this test investigation, crushed stone was used as a ballast material whose particle size distribution meets Chinese Standard TBT2140 [36], [37] and is currently more usable for Ethiopian National Railway Lines, particularly the Ethiopia-Djibouti Railway Line. Figure 3.6 illustrates the particle size distribution of the crushed stone ballast, which is compatible with the Chinese Standards [36], [37].

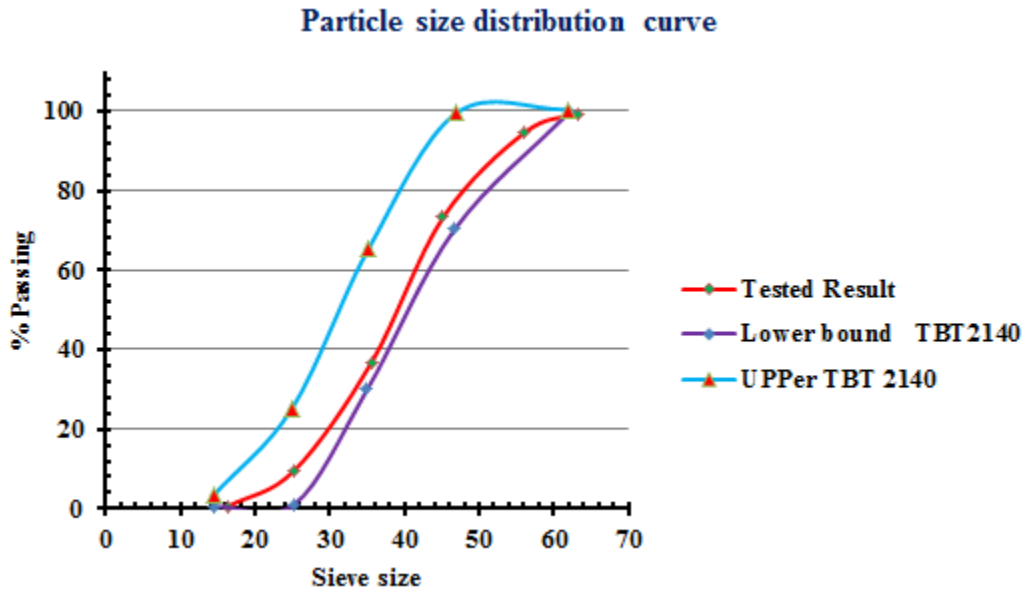


Figure 3.6: Particle size distribution curve of the crushed stone ballast [2], [36], [37]

3.3. Sleeper

The track lateral resistance depends on the types of sleeper material (wood, steel, and concrete sleepers) and the various components of the ballast layer (shoulder, crib, and base). According to Morteza Esmaili et al. [3], concrete sleepers have a more intense static and dynamic resistance and a higher level of interaction with ballast compared to steel and wood sleepers. As a result, concrete sleepers are currently more preferred for use in ballasted track train systems for both low-speed and high-speed tracks.

In this test investigation, Chinese Type II concrete sleepers, also known as B70 mono-block pre-stressed concrete sleepers, were utilized, and this type of sleeper is mostly used in the construction of modern railway systems. They were designed and manufactured by Railway Corporation of

China, Ltd. (CRC) and Civil Engineering & Construction Organization of China (CCECC), and they are presently in use on Ethiopia's National Railway Line (the Ethiopia-Djibouti Railway Line). It was manufactured in accordance with Chinese railway concrete sleeper specifications and high concrete grade quality. Precast concrete railway sleepers are designed and molded with a minimum of C40 to ensure structural performance and minimize maintenance needs. The concrete railway sleepers are manufactured to include steel wires, strands, and heat-treated steel reinforcement in the casting to provide durability and ensure long-term serviceability [38].

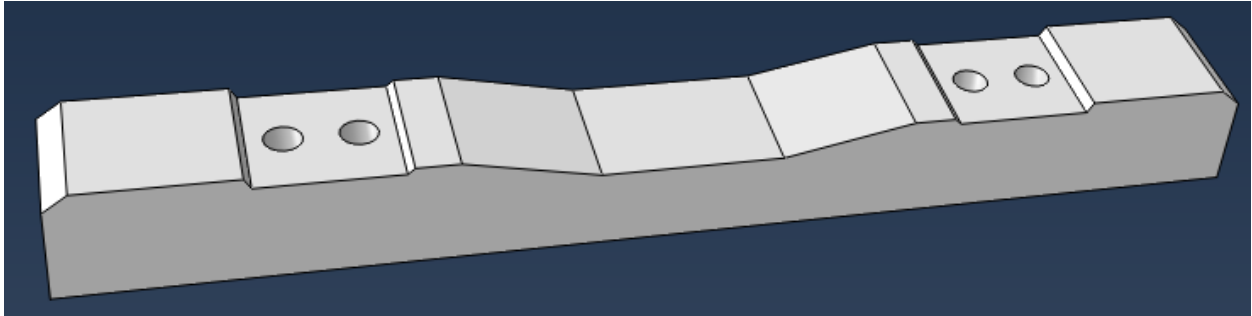
In recent years, many newly constructed conventional and high-speed railway lines have used Type-II prestressed concrete sleepers (B-70) in the construction of modern railway systems due to their superior performance. It was used for freight and passenger lines, with an axle load of 25 tons and speeds of 80 km/h and 120 km/h, respectively [39], to ensure safe train operation and withstand its loads. The material properties, service time, geometry dimensions, and other characteristics of the concrete sleeper are described in Table 3.1.

Table 3.1: Geometrical dimensions, service time, durability, and other characteristics of the test concrete sleeper [27], [39]

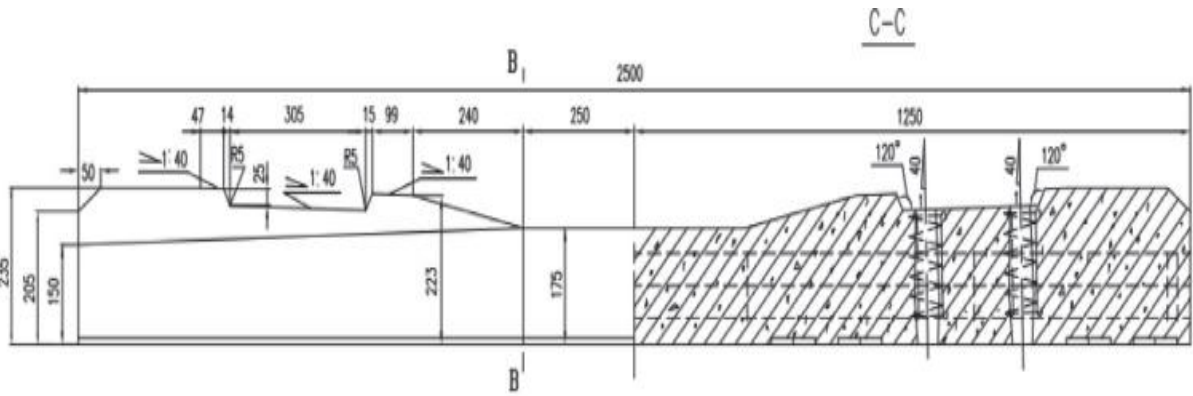
No	Properties	Sleeper type
		Concrete sleeper
1.	Material type	Concrete
2.	Mass(kg)	300
3.	Transversal length (m)	2.5
4.	Thickness (mm)	220
5	Gauge length (mm)	1435
6.	Density of materials (kg/m ³)	2440
7.	Modulus of elasticity (GPa)	36
8.	Durability	High
9.	Sleeper-ballast interaction characteristics	Very good
10.	Impact	Low
11.	Service life (in years)	50-60

As described in the China Concrete Sleeper Code Standards and literature, the Chinese Type II concrete sleepers are 2500, 300, and 220 mm in length, width, and height, respectively. The dimensions of the mono-block concrete sleepers are clearly described in Figure 3.7, and their values were obtained from literature [39] and direct measurements at Indodi Railway Station. Figure 3.7 illustrates the concrete sleeper's detailed dimensions at specified views and actual measurements at the Indodi railway station.

A)



B)



C)

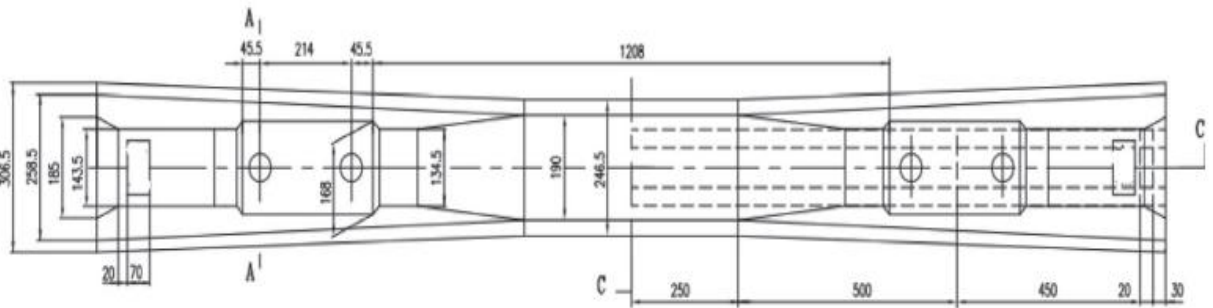




Figure 3.9: Chinese mono-block concrete sleeper (Type-II), detailed dimensional measurements at Indodi Railway Station

3.4. Lateral load Consideration

Lateral forces on the track are more difficult to analyze than other track forces, which are primarily transmitted by the sleeper and exerted in the track's transverse direction. These forces are generated from two sources. These consist of lateral wheel force produced by the interface between the wheel and rail and the buckling reaction force caused by the thermal effect [5], [7].

Lateral wheel forces are generated from the interaction between the wheel and rail as well as the lateral force exerted on the rail by the wheel flange. The sources of lateral wheel force are centrifugal forces in curves, the train's response to geometric deviations, and high-speed bogie instability, which results from hunting effects [1], [5].

The total horizontal lateral force applied by a train's wheels to its outer rails during movement is determined by the combination of the quasi-static force and dynamic forces [10] and is numerically expressed as follows:

$$Y_{\text{tot}} = Y_{\text{quasi static}} + Y_{\text{Dynamic}}$$

$$\text{Or } Y_{\text{tot}} = Y_{\text{flange}} + Y_{\text{centr}} + Y_{\text{wind}} + Y_{\text{dyn}} \quad [10] \quad 3.1$$

Whereas

Y_{flange} : Lateral force caused by wheel flange -rail interaction on the curve

Y_{centr} : Centrifugal lateral force

Y_{wind} : Lateral wind force

Y_{dyn} : Dynamic lateral forces due to the hunting effect

Assuming that the centrifugal and wind forces are concentrated on the outer rail, the maximum lateral load on the outer rail (Y_{max}) is equal to the total of the centrifugal and wind forces. This information is necessary to calculate the sleeper's lateral resistance [10] and is numerically expressed as follows:

$$Y_{\text{max}} = \frac{2Q_0 a_d}{g} + H_W + Y_{\text{dyn}} = \frac{2Q_0 \left(\frac{h_d g}{2b}\right)}{g} + H_w + Y_{\text{dyn}} \quad 3.2$$

$$Y_{\max} = \frac{Q_0 a_d}{b} + H_w + Y_{\text{dyn}} \quad 3.3$$

Where as

Q_0 : Train axle weight

H_w : Lateral wind force

h_d : Superelevation deficiency

Y_{dyn} : Dynamic lateral forces due to the hunting effect

b : Rail spacing width

g : Gravitational acceleration, (9.81m/s²)

The total horizontal force on the track under dynamic conditions is the result of multiplying the maximum static lateral (horizontal) force by the dynamic factor, which depends on the train wheel-rail interaction and train speed fluctuation [10]. It's numerically expressed as follows:

$$Y_{\max} = \text{DAF} \left(G \frac{h_d}{s} + H_w \right) \quad 3.4$$

DAF is dynamic amplification factor which depend on the train speed and track quality

The entire lateral force delivered to the outer rail track superstructure is resisted by the interaction of the ballast and sleeper as well as the horizontal rigidity of the track frames [10]. The track's lateral resistance is primarily generated by the interaction between the sleeper and ballast, which is restricted along the track's horizontal axis to optimize the track's stability. The acceptable value of the lateral resistance required by a loaded track to maintain stability was determined using the Prud'-homme formula [5], [10] which has been expressed as follows:

$$H \geq 10 + \frac{P}{3} \quad 3.5$$

Where as

H: Allowable lateral resistance of the track (kN)

P: Vertical load per axle (kN)

The empirical coefficient of value is 10 and $\frac{1}{3}$, which is determined by experimental testing, and its value varies depending on ballast quality, sleeper type, and maintenance condition (manual or modern tamping). The aforementioned standard empirical calculation is used nowadays to verify that the design track maintains lateral stability [10].

The lateral forces acting on the track are produced by the vertical wheel forces on the modern track system, which transfer about 45 percent of the train's vertical wheel load into the sleeper.

In this investigation, the standard axle load of mixed-use track was considered, and its value was 170kN, commonly used in the modern railway track system. According to the calculation defined by AREMA in engineering practices, the vertical wheel load is simply equal to one half of a standard axle load. Therefore, the lateral force that results from the vertical wheel load is equal to the vertical wheel load multiplied by the lateral-to-vertical load ratio, which varies depending on the type of track and ranges from 0.2 to 0.4.

3.5 Method of Measuring the Sleeper Lateral Resistance

Measuring the track's lateral resistance is essential for identifying the ballast quality that can support the track forces and for evaluating the sleeper's resistance capacity to ensure track stability in the railway track system. Different methods have been described by numerous researchers for measuring the lateral resistance of ballasted tracks. These measurement methods include the single tie push test (STPT), panel displacement, mechanical track displacement, derailment wagon, and continuous dynamic measurement with a dynamic track stabilizer and lateral panel loading test (LPLT) [18],[32].

Therefore, for this test investigation, the single-tie push method was selected to measure the lateral resistance of the sleeper in the railway track system due to its simplicity and accessibility. The single tie push test (STPT) is a widely used experimental method applied in both field and laboratory settings to accurately measure the lateral resistance offered by an individual sleeper within a railway track system. This test inquiry technique involved applying a lateral load to one side of the sleeper end using a hydraulic jack and measuring the sleeper's 2 mm lateral displacement using a lateral transducer on the other side. In this test method, to eliminate the

influence of superstructure components such as rails and fasteners on the lateral resistance, four fasteners were released from the tested sleeper at two rail seat locations before the lateral force was applied [18], [32].

When compared to other measurement techniques, the single-tie push test is the most effective and practical way to measure the lateral resistance of a single sleeper in the track strength and stability of a ballasted track system.

Furthermore, Zakeri [32] concluded that compared to track panel displacement experiments, the single-tie push test (STPT) has the following advantages: The test is simple to conduct in both the lab and the field, efficiently reducing cost and accurately measuring the lateral resistance of a single sleeper during the interaction between the sleeper and ballast.

Yohei Koike conducted an experimental study using a 1/5-size track model to assess the lateral resistance of various sleeper types in a ballasted rail system. As a result, the lateral load obtained from the single sleeper pullout testing was greater than the horizontal force obtained from the fifth sleeper's track panel pullout test [21]. Therefore, the single-tie push test is a more accurate method of measuring a sleeper's lateral resistance than the track panel approach without compromising the other track components. The test results for each of the two tested methods are presented in Figure 3.10.

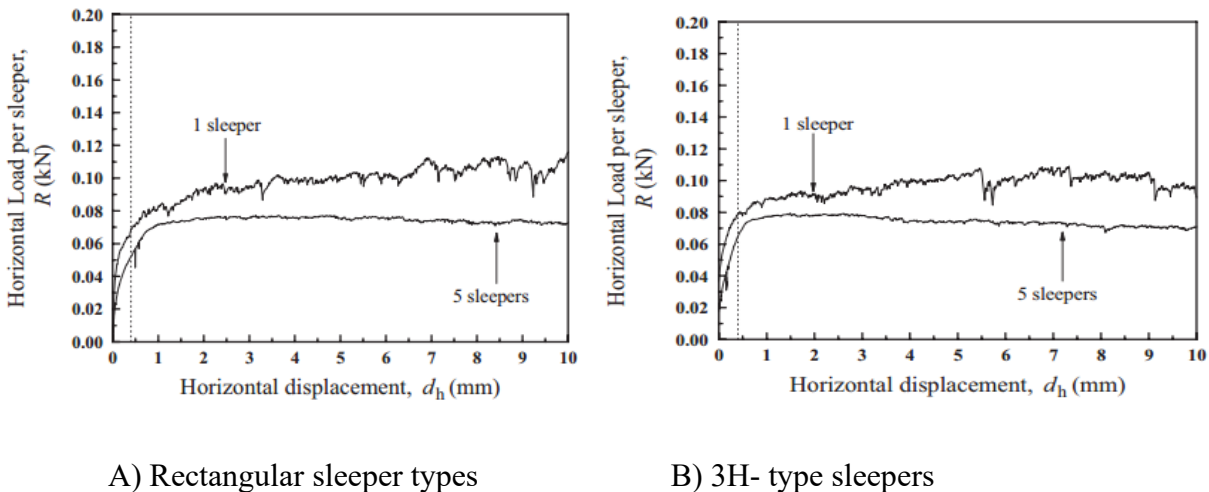


Fig 3.10: The lateral resistance per sleeper and displacement obtained from single sleeper pullout tests and track panel pullout tests [21]

3.6. Experimental Field Test Setup and Calibration Procedures

The single tie push test (STPT) has been used in this field investigation to investigate the lateral resistance of sleepers at different loading rates. Two loading rates (0.32kN/s and 0.92kN/s) were utilized to investigate how loading rates affected the lateral resistance of the sleepers. In order to conduct this test, lateral load was supplied to the first sleeper at a loading rate of 0.32kN/s up to peak lateral resistance and subsequently to the second sleeper at a loading rate of 0.92kN/s up to peak lateral resistance. It is essential to determine the lateral resistance of the sleeper at each loading rate and to compare the test results obtained with gradual loading to those obtained with quick loading.

To conduct the field test using the above-mentioned method, the following procedure was utilized to investigate the effect of loading rate on the lateral resistance of the sleeper.

Step 1: The tested sleepers' rail pads and fasteners were released properly.

As stated by M. Ciotlaus and G. Kollo (2018), the rail pad and fasteners were taken out of the tested sleeper in order to more accurately examine the sleeper's interaction with ballast and eliminate the effect of the track superstructure component. The test setup properly released the rail pad and fastener from the tested sleeper, as illustrated in Figure 3.11.



Figure 3.11: Released fastener and rail pad from the tested sleeper

Step 2: Proper installation of the car jack, load cell, and lateral support on the tested sleeper.

The car crick was held in place and fixed by lateral support, as illustrated in Figure 3.12; it was essential that the sleeper receive lateral force. A car jack was utilized in place of hydraulic jacks to apply lateral forces to a single sleeper to assess its lateral resistance. The lateral support material is made of concrete and prestressed concrete and measures 1 m in length, 30 cm in width, and 40 mm in depth. Another source of support is stock rail, which is stored on-site.

Once the sleeper end is fixed by a car jack, a load cell, and lateral support to prevent the car jack from shifting laterally throughout the test, as illustrated in Figure 3.12. The load cell is an essential device for recording the applied lateral forces on the tested sleeper, which was placed between the car crick support and the car crick.



Figure 3.12: Installation of lateral support, load cell, and car crick on one end of the tested sleeper

Step 3: Installation of the lateral transducer on the tested sleeper

The transducer was attached to the other side of the sleeper end using a rectangular steel section support, which helps to hold and support it, as illustrated in Figure 3.13. It was significant to record the sleeper's lateral displacement when the lateral force was applied. To secure and keep the rectangular steel section, two reinforcement bars are installed on the ballast. The reinforcement bars are then attached with two bolts. A rectangular section of steel is connected to the transducer using a bolt. The installation and test configuration of the transducer on the other side of the sleeper end are presented in Figure 3.13.



Figure 3.13: Installation of the transducer on the tested sleeper using support fixtures

Step 4: Install the transducer and load cell on the data logger

Two pieces of test equipment, the load cell and transducer, are connected to the data logger to record the lateral load and lateral displacement of the sleeper, respectively [18]. The data logger automatically records the imposed lateral force and the corresponding lateral movement of the sleeper during the test and then attaches the flash storage device to save the test results for evaluation. The test setup and installation of two pieces of equipment on the data logger are presented in Figure 3.14.



Figure 3.14: Installation and adjustments of the load and displacement reading setting on the data logger

Step 5. Lateral load applies

Finally, the tested sleeper was then pushed laterally along the track's transverse direction, using a car jack to produce lateral force and determine its lateral resistance. Based on the test setup and procedure, three tests at 0.32kN/s and three tests at 0.92kN/s were conducted on the sleeper with each of three consecutive sleepers to investigate the effect of loading rate on the sleeper's lateral resistance with the interaction of ballast. As stated by the Iran National Railway Code 301 [3], [29] and Ali Esmaili [46], the transverse resistance of a single sleeper, which is represented as the sleeper's 2 mm lateral displacement, correlates to the lateral forces to evaluate the track stability. The test setup and lateral load applied on the tested sleeper are illustrated in Figure 3.15.



Figure 3.15: Lateral load applied to the tested sleeper



Figure 3.16: Illustration of saving the output on a flash device

Each test in this investigation was conducted three times using identical ballast geometry and properties in order to further enhance test accuracy and get more accurate results throughout the study. Six (6) tests were carried out in the field, and the average of each test result was used for interpretation and discussion of the test result. After each test was finished, the sleeper was reattached to the rail using screw clamp rail fasteners on the real seat area, and then the ballast was returned and also compacted using a vibratory compactor, as illustrated in Figure 3.17. All test results are presented and described in sections 4.2 and 4.3.



Figure 3.17: Ballast returned, leveled, and sleeper connected to the rail using screw clamp lock fasteners

Additionally, to investigate and determine the contribution of the ballast layer component to the sleeper's lateral resistance, the single-tie push test was also carried out, as the test procedure states below, and three consecutive tests were conducted.

Test 1: The tested sleeper was interacted with in the ballast layer components.

Each component of the ballast layer in this test resists the sleeper's movement in the longitudinal, lateral, and vertical directions in order to enhance track resistance and achieve high lateral stiffness under all applied lateral forces. This test has a higher lateral resistance than the other two tests because of the significant friction resistance developed to withstand lateral forces as a result of the

sleeper's contact with each component of the ballast layer. On the other hand, each ballast layer helps in withstanding the lateral forces exerted on the sleeper with the aim of preserving the track system's stability and integrity. Therefore, the overall lateral resistance in this test is equal to the interaction of the sleeper with the ballast base, the ballast crib, and the ballast shoulder. Installing the testing equipment on the tested sleeper in the full ballast section is illustrated in Figure 3.18.

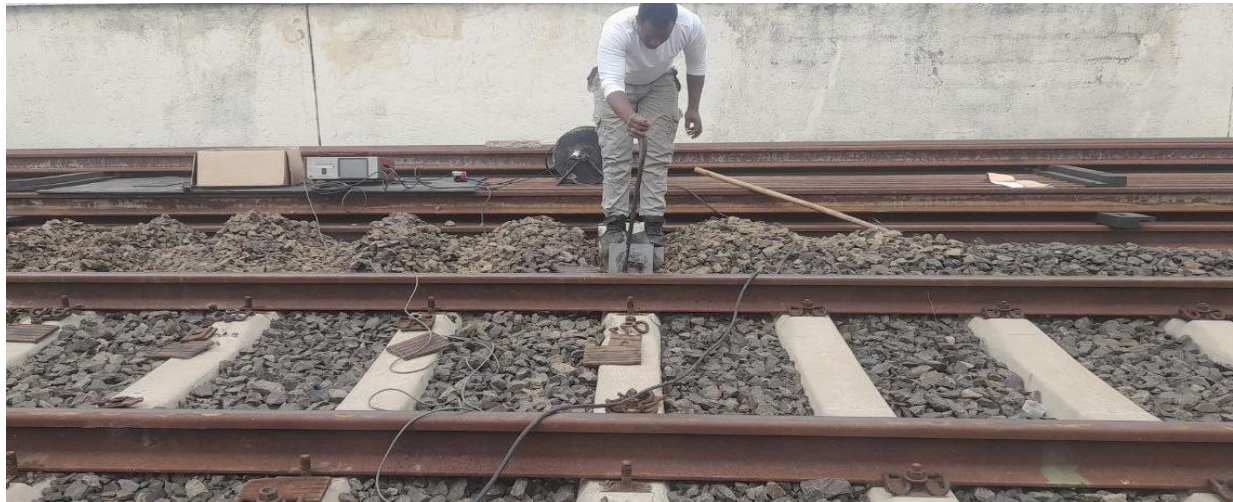


Figure 3.18: Installation of the test instrument and conduct of the test at full section

Test 2: The tested sleeper was interacted with only the base and crib ballast layer components.

On the other hand, in this test, the ballast shoulder was removed from the tested sleeper at one end. Only the ballast base underneath the sleeper bottom and the ballast crib along the sides of the sleeper were able to withstand the lateral forces that were applied to the sleeper during this test; the ballast shoulder did not contribute to this resistance. Therefore, the overall lateral resistance in this test is equal to the interaction between the sleeper base with the ballast base and the base crib along the sleeper sides. The installation of the testing device and the removal of the ballast shoulder from the tested sleeper are illustrated in Figure 3.19.



Figure 3.19: Ballast shoulder removed from the tested sleeper and installation of the test instrument

Test 3: The tested sleeper was interacted with only by the base ballast layer component.

On the other hand, in this test, the ballast crib along the sleeper sides and the ballast shoulder along the sleeper ends were removed from the tested sleeper. Only the ballast base underneath the sleeper bottom was able to resist the lateral forces imposed on the sleeper during this test; neither the ballast crib nor the ballast shoulder contributed to this resistance. Therefore, the overall lateral resistance in this test is equal to the interaction between the sleeper base and the ballast base. The

installation of the testing instrument and the removal of the ballast shoulder and crib ballast from the tested sleeper are illustrated in Figure 3.20.



Figure 3.20: Removing the crib and shoulder ballast from the tested sleeper and installation of the test instrument

Three (3) repeated tests were performed for each test condition in this test investigation with the intent to increase test accuracy and obtain average results. Nine (9) tests were carried out in the field, and the average of each test result was used for interpretation and discussion of the test result. All test results are presented and described in section 4.4.

Upon completion of all testing, the tested sleeper returns to its initial position with appropriate standards, fixed rail on sleeper by fasteners, ballast back and level, then compacted with the vibrator compactor shown in Figure 3.21.





Figure 3.21: Standardized the placement of the tested sleeper and surrounding ballast in the correct position

CHAPTER FOUR

4. TEST RESULTS AND DISCUSSION

This chapter presents the test results of the experimental field test and describes the research outcomes, and they are organized into specific sections to discuss the objective of the current study. The effects of loading rate on sleeper lateral resistance and its mechanical characteristics in ballasted track systems are experimentally assessed in sections 4.2 and 4.3. The single-tie push test method was used in this field investigation study to assess the sleeper's lateral resistance. Lastly, the engagement of each ballast zone to the sleeper's lateral resistance, which significantly restricts the sleeper's lateral movement and maintains the track's lateral stability, is presented in Section 4.4. These results are also compared to those of the previous researcher in order to provide more insight and verification.

4.1 Validation of the Study

Test verification is essential for assessing the accuracy and errors of the sleeper's lateral resistance in real-world scenarios and for comparing it with the previous output to ensure that the study outcome is accurate and reliable.

To validate the study's outcomes, the testing procedure, methodology, and analysis of the field test results were compared with and evaluated against results from previous studies. Fatemeh Khatibi et al. [48] verified the developed DEM simulation model under variations in ballast depth, width, and height by conducting an experimental field investigation using STPT to determine the track lateral resistance on the Tehran City Aprin Railway line. The field investigation by Fatemeh Khatibi et al. [48] was conducted on a ballasted track system with a ballast depth of 35 cm, sleeper spacing of 600 mm, and standard monoblock concrete sleepers (B70). To determine its resistance, three different field tests were conducted, and the study result has been presented in Figure 4.1. Accordingly, the results of the field investigation conducted by Fatemeh Khatibi et al. [48] are used in the study for verification purposes.

In this regard, the results reported by Fatemeh Khatibi et al. [48] are in good agreement with the present study and are therefore used as a reference for verification purposes and enhancing reliability.

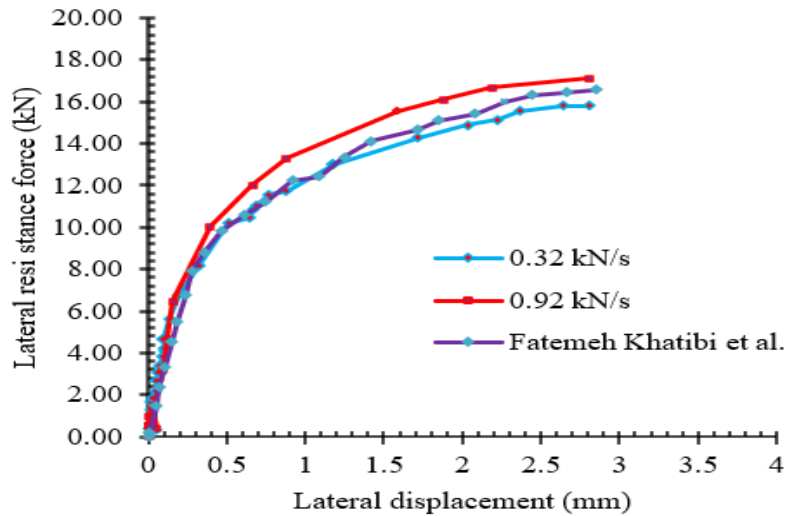


Figure 4.1: Illustration of the lateral force–displacement correlation from the current study and prior field test results.

As observed in the figure, the current field study and prior study test results show good graphical correlation. The results indicate a lateral displacement response with a 2 mm lateral resistance difference value at 7.6%. Therefore, a comparison between the current field results and those of Fatemeh Khatibi et al. shows good correlation, indicating that the current study provides accurate results.

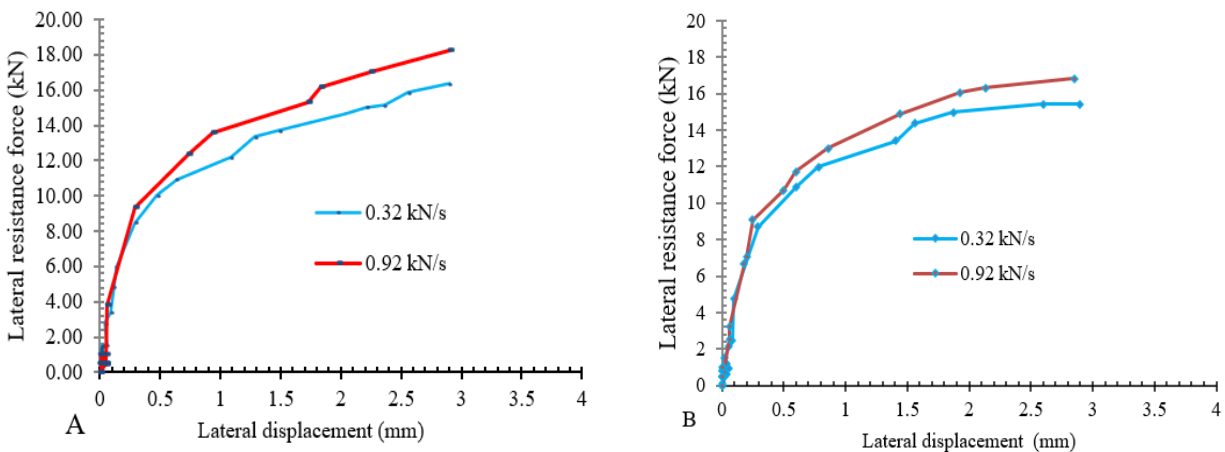
4.2. Effect of Loading Rate on the Lateral Resistance of Sleepers

Sleeper lateral resistance is the primary parameter that maintains the lateral stability of the track and is affected by several factors, such as loading rate, sleeper type and shape, ballast compaction, and ballast geometry. The ballast compaction substantially increased the ballast strength between the ballast particles by enhancing their interlocking and frictional interaction, which helped to increase the structural integrity. This interlocking of the ballast particles enhanced the sleeper's longitudinal and lateral resistance by properly restricting it to maintain the track's stability. Modifying the sleeper's bottom surface from a smooth (Type II) to a rough (frictional) surface

raised the lateral resistance of the sleeper by 67% [29]; providing a nail at the standard sleeper increased it by 54% [30], and adding a wing at the end and middle increased it by 98.5% [31]. Furthermore, increasing the side slope to 1:2, increasing the ballast shoulder height and width to 60 cm, and raising the ballast depth to 60 cm can significantly increase the sleeper's lateral resistance and ensure long-term track stability.

In the present study, the influence of loading rate (i.e., loading speed) on sleeper lateral resistance in a ballasted track system under static loading conditions was evaluated. As described in Section 3.6, an experimental field test was conducted to investigate this effect under 0.32kN/s and 0.92kN/s loading scenarios. A total of six tests were carried out under both the 0.32kN/s and 0.92kN/s loading conditions in the field, and the average test results were considered for analysis. Based on the test results for both the 0.32kN/s and 0.92kN/s loading conditions, force-displacement diagrams were made with the aim to compare the outcomes, as the sleeper's lateral resistance is commonly represented graphically. A graphic representation of the lateral resistance force and the sleeper's lateral displacement under conditions of both the 0.32kN/s and 0.92kN/s loading for each repeated test result is presented in Figure 4.2.

According to Iran's National Railway Code No. 301 and other related literature [18], [29], the standard reference for the sleeper's lateral resistance is 2 mm lateral displacement. This benchmark is important for comparing the sleeper's lateral resistance under two different loading scenarios.



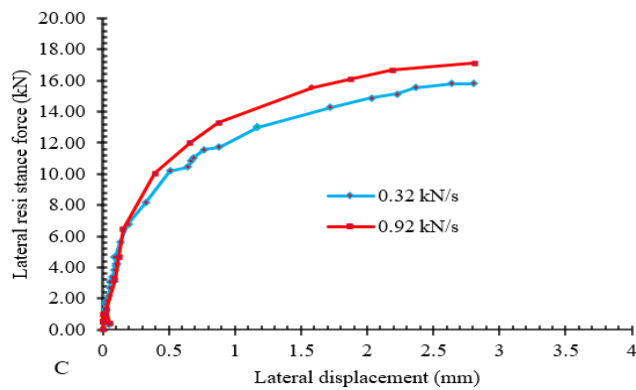


Figure 4.2: Lateral resistance force vs. lateral displacement of the sleeper for three repeated tests (a) Test 1, (b) Test 2, and (c) Test 3 under loading rates of 0.32kN/s and 0.92kN/s.

The test result showed that as loading speed increased, the sleeper's corresponding lateral resistance increased proportionally (Figure 4.2). As a result, the lateral resistance force of the sleeper under 0.32kN/s loading is 14.18kN, and under 0.92kN/s loading, it is 16.49kN. Accordingly, it can be concluded that the lateral resistance of the sleeper increased by 14% as the loading speed was increased. According to Qideng Sun et al. [47], higher loading speed increases the interaction between the ballast and sleeper particles, generating high frictional forces and allowing the ballast particles to interlock more quickly in order to withstand the applied track forces. In contrast, as the track was exposed to slow loading, the sleeper and ballast particles had less contact with one another and produced less friction force, while the ballast particles needed more time to rearrange. As the sleeper's contact with the ballast increased, the sleeper's lateral resistance correspondingly increased to enable it to withstand the track forces and maintain track stability [40].

Furthermore, to determine the relationship between the sleeper's lateral resistance and lateral displacement, as well as to calculate the lateral stiffness of the sleeper (slope) under two loading scenarios, curve-fitting analysis was considered. Consequently, the exponential and logarithmic trend lines were examined for analysis in order to evaluate the test result; however, the logarithmic trend line is a good fit for the data that was evaluated. Figure 4.3 presents the fitted data curves for the sleeper's lateral resistance and lateral displacement under two loading scenarios.

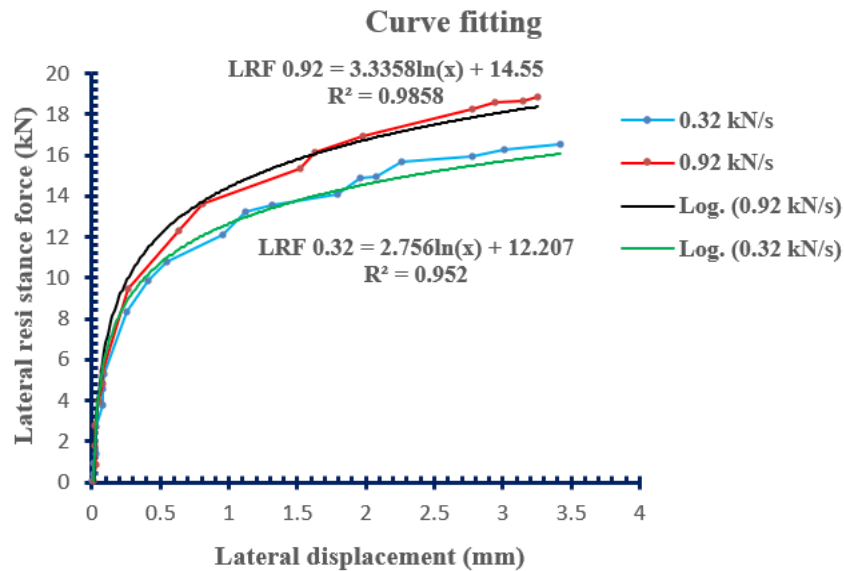


Figure 4.3: Fitted trend line of lateral resistance forces vs. lateral displacement of the sleeper

As observed in the figure, there is a nonlinear relationship between the sleeper's lateral resistance and lateral displacement under two loading situations. Additionally, results indicated that as loading speed increased, the lateral stiffness of the sleeper (i.e., the slope of the force-displacement curve) increased proportionally, as observed in the figure.

4.3. Effect of Loading Rates on Sleeper Lateral Resistance Behavior

The sleeper lateral resistance is a critical parameter that ensures the track's longitudinal and lateral stability when trains are operating on a ballasted track system. Its lateral resistance behaviors are affected by several factors, such as ballast compaction, ballast geometry, and, most importantly, loading rate variations.

In the current investigation, the lateral resistance behavior of sleepers in relation to loading rate variations was evaluated and discussed through experimental field tests conducted on a ballasted track system. To characterize its behavior under 0.32kN/s and 0.92kN/s loading conditions, two important parameters were considered: the sleeper's lateral stiffness and lateral resistance under applied lateral forces. Lateral stiffness [27] is represented by the slope of the linear relationship between two parameters (force and displacement) in the high stiffness zone of the linear profiles under the lateral interaction of the sleeper and ballast particles [27]. Similarly, lateral resistance of

the sleeper is represented by its displacement at 2 mm under applied lateral forces and the corresponding lateral force generated by the lateral interaction of the sleeper and the ballast particles. Its behavior under varying loading speeds is divided into three essential parameters, illustrated in the figure. This zone can have an elastic, elastic-plastic, or plastic zone, and their properties are described in detail below. The corresponding mechanical behaviors are described graphically, and their relationship is illustrated in Figure 4.4.

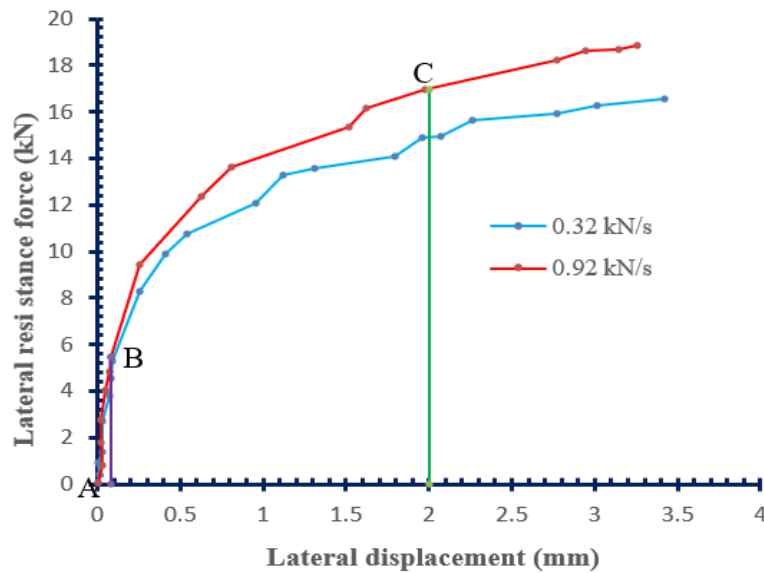


Figure 4.4: Sleeper lateral resistance behavior under 0.32kN/s and 0.92kN/s loading conditions

Elastic zone (Zone AB): In this zone, the graphic shows that the sleeper's lateral resistance force and lateral displacement have an approximately linear relationship with a steep slope. This steep slope indicates that the sleeper in this region is highly stiff, capable of withstanding the track forces. On the other hand, the sleeper in this zone effectively resists the imposed lateral force without lateral failure under both the 0.32kN/s and 0.92kN/s lateral conditions in order to maintain the track's lateral stability. It is a result of the sleeper and the ballast particle interacting strongly. Therefore, the slope of this linear relationship between two parameters is the high stiffness region in the linear profiles, which represents the lateral stiffness of the sleeper. Accordingly, the sleeper's static lateral stiffness is equal to 43.08kN/mm.

In contrast to other zones, this area has a high lateral stiffness, indicating a highly frictional reaction between the sleeper and ballast particles to withstand the track forces. A high frictional contact

between the sleeper and ballast particles decreases the sleeper's lateral movement, which in turn increases the sleeper's resistance to maintaining long-term track lateral stability. Accordingly, in this zone, the loading rate does not significantly affect the sleeper's lateral resistance and lateral stiffness because the test results of the two graphs coincide with each other.

Elastic-plastic zone (Zone BC): The relationship between the lateral resistance force and the sleeper's lateral movement in this zone is non-linear, as the graphic illustrates. The change from a linear to a nonlinear relationship indicates a decrease in track lateral stiffness. In this zone, the sleeper's lateral resistance peaked at point C, where it was able to withstand the track forces. This peak resistance value represents the lateral resistance force that the sleeper uses to keep the track stable. According to AREMA and Iran Railway Code No. 301 [11],[16], [29], this lateral resistance force is generally represented as the transverse resistance of a single sleeper [11]. Accordingly, the transverse resistance of the sleeper under 0.32kN/s and 0.92kN/s loading is equal to 14.18 and 16.49kN, and the corresponding lateral stiffness at 2 mm lateral displacement is 7.09 and 8.245kN/mm, respectively.

Thus, in this zone, the sleeper's lateral static stiffness decreased from 43.08 to 8.24kN/mm; as a result, the lateral stiffness was reduced by 80.87% in comparison to the elastic zone. The lateral stiffness of the sleeper was reduced in this zone compared to elastic zones, which indicated that there was decreased interaction between the ballast particles or between the sleeper and the ballast.

Therefore, in this zone, the loading rate affects both the sleeper's stiffness and lateral resistance, as the sleeper's lateral resistance varies under slow and rapid loading situations.

Plastic zone (after point C): The sleeper stops providing lateral resistance to withstand the imposed lateral forces and begins sliding freely laterally as a result of the track's decreased lateral stiffness and decreased interaction between the sleeper and ballast. This region has also shown high sleeper lateral displacement; as lateral forces rise, continuous (constant) lateral resistance will occur. The sleeper in this area has less lateral stiffness than in other zones because of its large lateral displacement, which limits lateral resistance. In contrast, there is very little or low interaction among the ballast granules and the sleeper in this region.

4.4. Evaluation of Ballast Support Zones and Their Contribution to Sleeper Lateral Resistance

The track's lateral resistance is sustainable overall due to the combined effect of the ballast shoulder resistance at the sleeper's ends, the crib ballast resistance along the sleeper's sides, and the ballast base resistance underneath the sleeper [18]. Particularly, the ballast base plays a significant role in restricting the sleeper's downward movement, the ballast crib resists the sleeper's longitudinal movement, and the ballast shoulder restrains the sleeper's lateral movement, all of which contribute to optimizing track stability. Therefore, studying the contribution of each ballast component to the lateral resistance of the sleeper is essential for identifying its individual role in restraining lateral sleeper movement during train operation.

Thus, in the present study, the contribution of each ballast support zone to the sleeper's lateral resistance was measured and quantified using experimental field tests carried out. To determine the individual effect and identify the maximum influence of each ballast layer on the lateral barrier of the single sleeper within the ballasted railway track system, three successive experimental field tests were performed. Test 1: The tested sleeper interacted with the ballast (base zone, crib zone, and shoulder zone); Test 2: The tested sleeper interacted with the ballast base and crib; Test 3: The sleeper test interacted with the ballast base only. Every test was conducted three times during this experimental field investigation with the intent to enhance result accuracy and obtain more precise data throughout the study. The test results of each test calibration are presented in Figure 4.5 and in Table 4.1.

As a result, the contribution of each individual component to the sleeper's lateral resistance was determined based on the track lateral resistance perspective. This perspective states that the force required to displace the sleeper laterally at a distance of 2 mm is equivalent to its resistance. Hence, a 2 mm lateral displacement of the sleeper is used as a reference to quantify the contribution and value of each individual component.

Therefore, the lateral resistance that came from the shoulder support zone contributed to the lateral resistance, which can be computed by deducting the combined effect of the track lateral resistance developed by the ballast base and crib support zone from the total effect of the entire track

geometry. In the same manner, the remaining lateral resistance contributed by the ballast base and ballast crib has been determined. This calculation is essential to quantify each individual resistance. Determination of each individual contribution to the track's lateral resistance is significant to cost-effective minimization; selecting the ballast materials and the ballast dimension to optimize track design ensures track stability.

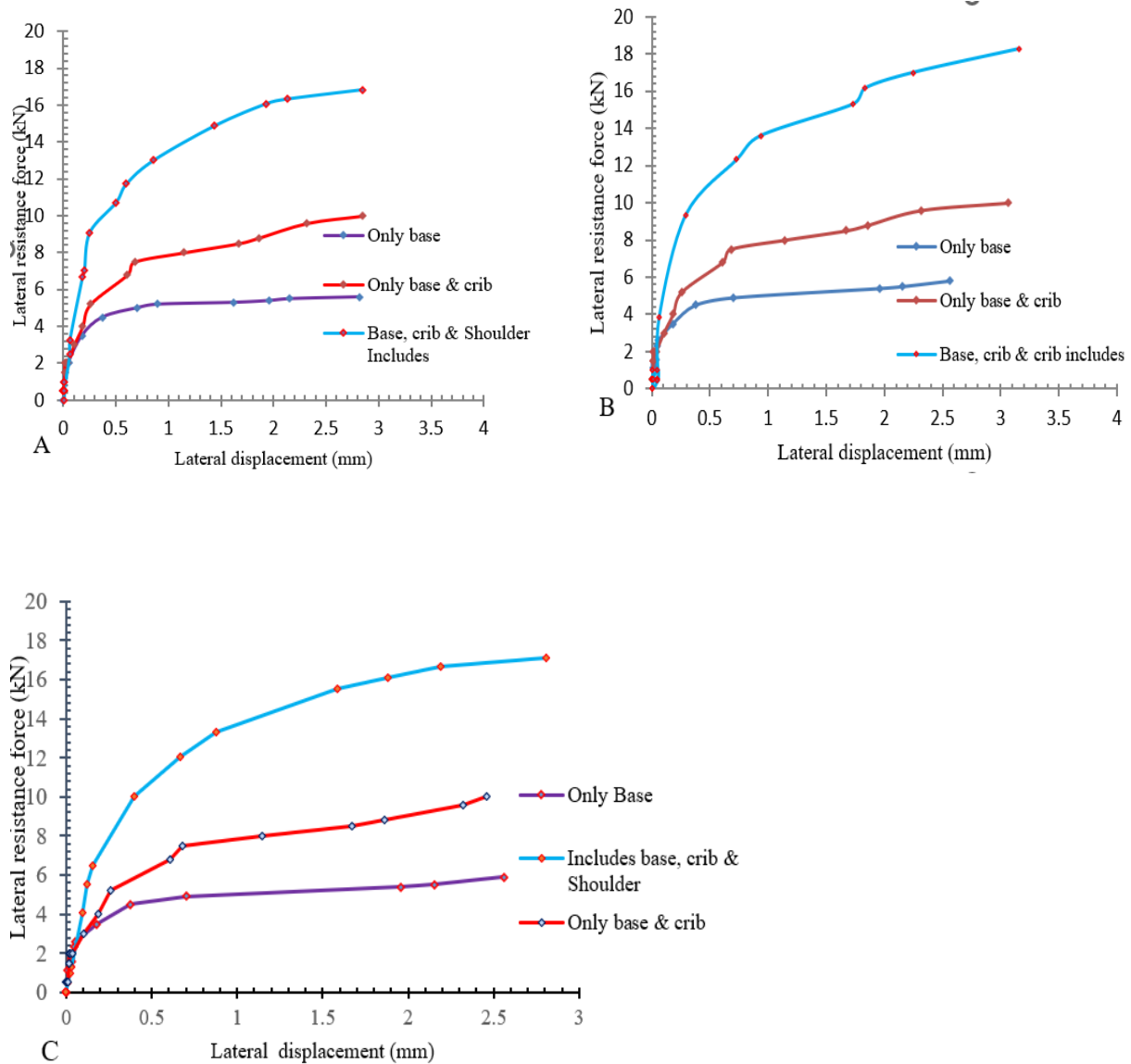


Figure 4.5: a) Test 1, b) Test 2, c) Test 3: Field test results of each test condition and lateral resistance force vs. lateral displacement

As observed from the test result, the ballast shoulder and the sleeper end interaction have high lateral resistance to resist the imposed lateral force on the sleeper during investigation in order to restrain the sleeper's lateral movement. As a result, a high level of interaction between the sleeper and the ballast shoulder support zone is important to reduce the likelihood of track buckling and maintain the track's overall stability. Thus, the high lateral resistance of the ballast shoulder helps to resist the track lateral shifting produced by the thermal load and train movement, thereby maintaining track lateral stability and minimizing the track buckling effect. The average contribution and static lateral resistance for each component of the ballast support zone are presented in Table 4.1.

Table 4.1: Average test result for each test condition and percentage contribution of each individual ballast layer component

Experimental Field Test Conditions	Field output for each test scenario (Average)kN	Ballast support zone components	Lateral resistance of each ballast support zone component (Average)kN	Percentage contribution value
S-Full ballast support zone inter.	16.49	Base ballast	5.42	32.7%
S-Crib-base interaction zone	9.04	Crib ballast	3.64	22.1%
S-Base interaction zone	5.42	Shoulder ballast	7.45	45.2%

The symbol S represents that sleeper.

Therefore, the contribution of the ballast support zone to the lateral resistance of the sleeper, which is described as 32.7% the ballast foundation, 22.1% the ballast crib, and 45.2% the ballast shoulder, effectively restrains the sleeper's lateral movement and properly aligns the track alignment to maintain the track's lateral stability. Among them, the ballast shoulder contributed approximately 45.2%, making it the primary ballast support zone responsible for restraining sleeper lateral displacement and maintaining track lateral stability. The ballast base and ballast crib are the second and third contributors to restraining the sleeper's lateral movement in the railway track system, thereby helping to maintain the track's lateral stability.

Therefore, the ballast shoulder is the primary lateral load distributor among the ballast components in the railway track system, playing a key role in maintaining the track's overall lateral stability. Finally, the calculated ballast contribution percentages, compared with previous studies, are presented in Table 4.2 and discussed in the following section.

Table 4.2: The Current Study Result and the Previous Researchers' Outcomes

Various researchers	Percentage contribution of each ballast zone component (%)			Evaluation method
	Base ballast	Crib ballast	Shoulder ballast	
Current study outcomes	32.7	22.1	45.2	Field investigation
International Union of Railways, 1976	33	33	33	Laboratory study
Saeed Mohammadzadeh [41]	26.4	24.6	49	Field investigation
Fatemeh Khatibi et al. [19]	26.1	24.3	49.6	Field investigation
Zakeri and Bakhtiary [3] , [42]	62	9	28	Laboratory investigation
AREMA, Volume1 2006	35-40	30-35	20-30	Laboratory investigation

As stated in Table 4.2, the percentage contribution of each ballast zone to the lateral resistance of the sleeper varies in various studies, as described in different researchers' results. The variations in each contribution are based on several factors, such as sleeper material (wood, steel, and concrete), sleeper shape, ballast compaction scenarios (loose or compacted), and ballast quality.

In this regard, Zakeri [3] conducted an experimental investigation using various sleeper types (wood, steel, and concrete) to determine the role of the ballast zone in providing lateral resistance to sleepers. According to Zakeri [3], the experimental study showed that the ballast base of the

concrete sleeper makes a relatively significant contribution (62%) to the track's ability to withstand high lateral forces while maintaining lateral stability. In contrast, the ballast crib only makes up 9% of the track's lateral stability or sleeper's lateral movement control in a ballasted track system [3].

On the other hand, the ballast support zone plays an equal role in restraining the sleeper's lateral movement to ensure the track's lateral stability, as presented by the International Union of Railways.

The study by Saeed Mohammadzadeh et al. [41] found that the contribution of each ballast support zone to maintaining the lateral stability of the track is influenced by compaction and varies depending on whether the ballast is loose or compacted. Saeed Mohammadzadeh et al. [41] stated that the ballast shoulder contributes higher percentages of compacted ballast in comparison to loose ballast, with 49% and 35%, respectively. As a result of increasing the ballast compaction grade, the ballast shoulder's contribution to preventing the sleeper's lateral movement has increased by 14%. However, the contributions of the base and ballast crib in compacted ballast conditions are lower than those in loose ballast circumstances, which are equal to 24.6 and 26.6%, respectively, in maintaining track stability. Each of them contributes 30.3% and 34.7% to the state of loose ballast, respectively. The researcher concluded that increasing ballast compaction during construction increases the overall contribution of each ballast zone to the lateral barrier of the sleeper.

Therefore, the current investigation of the contribution of the ballast base, ballast crib, and ballast shoulder to the lateral resistance of the sleeper in maintaining the track's lateral stability is closely associated with the study findings of Saeed Mohammadzadeh et al. [41].

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In this study, the effect of loading rate on the sleeper lateral resistance under static loading conditions in ballasted track structures has been examined by conducting an experimental field test using the single-tie push test method. Two loading tests (0.32kN/s and 0.92kN/s) were conducted to investigate the effect of load rate variation on the sleeper's lateral resistance in track performance and stability. The research result showed that as the loading rates increased, the sleeper's lateral resistance increased by 14%. Hence, the study result shows that as the loading speed increases, the lateral resistance of the sleeper also increases, and it is influenced by loading rate variation.

The lateral resistance of sleeper behavior under different loading rates has three different characteristics that have been divided into three parts; they are described as elastic, elastic-plastic, and plastic behavior. The result shows that in the elastic zone, higher lateral stiffness was observed compared to other zones due to a strong frictional interaction between the sleeper and ballast particles to resist the lateral forces. In the plastic zone, the sleeper has constant lateral resistance, slides easily and highly, and achieves minimal lateral stiffness, as the interaction between the sleeper and ballast particles is significantly diminished.

Additionally, this study assessed the contributions of the ballast base, crib, and shoulder in restricting the sleeper's movement in order to maintain track lateral stability. Their individual contributions are 32.7%, 22.1%, and 45.2%, respectively. Accordingly, in a ballasted track system, the ballast shoulders play a primary role in resisting lateral forces and maintaining the track's lateral stability by limiting the sleeper's movement.

5.2. Recommendations

According to the study finding, the lateral resistance of the sleeper is increased by the increased loading rate in the ballasted track system. It is therefore recommended that a higher loading rate be considered when performing track maintenance on modern ballasted track systems throughout the compaction period to achieve the optimal strength and ensure the track's long-term stability.

According to the study finding, in a ballasted track system, the ballast shoulder plays a primary role in limiting the sleeper's lateral movement and maintaining the track's lateral stability. It is recommended that track maintenance in the ballast shoulders be given more priority in ballasted track systems to ensure the track's lateral stability and reduce the effects of track buckling.

5.3. Further Study

The study results show that, in ballasted track systems with the identical ballast properties, loading rates significantly influence the lateral resistance of sleepers under static loading conditions. Therefore, further research should be conducted using both numerical and experimental methods to examine the effect of loading rate on sleepers' lateral resistance under cyclic loading in order to determine long-term performance.

Based on the field study result, the ballast shoulder plays a primary role in maintaining the track's lateral stability by restricting the sleeper's lateral movement. Therefore, further study should be conducted using both numerical and experimental methods to determine the ballast shoulder's long-term resistance performance under dynamic load conditions.

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Appendix

Lateral resistance vs Lateral displacement under two loading test result at 0.32kN/s and 0.93kN/s with three repeated test result

Test 1. Lateral resistance at 0.32kN/s and 0.92kN/s

Lateral Displacement (mm)	Lateral resistance (kN) loading rate at 0.32kN/s	Lateral Displacement (mm)	Lateral resistance (kN) loading rate at 0.92kN/s
0.005	0.5	0.005	0.5
0.005	0.5	0.005	0.5
0.025	0.5	0	0.5
0.004	0.7905	0.01	1
0.007	0.085	0.005	0
0.038	0.6375	0.005	0.5
0.037	1.1645	0.002	1
0.005	0.833	0	0.5
0.013	0.8925	0.005	0.5
0.009	0.5525	0	0
0.013	0.8925	0.005	0.5
0.054	0.952	0.06	2.5
0.023	1.53	0.06	3.23
0.052	2.125	0.18	6.6555
0.082	2.465	0.2	7.055
0.098	4.7345	0.25	9.095
0.293	8.687	0.5	10.71
0.604	10.897	0.6	11.73
0.782	11.968	0.86	13.005
1.41	13.413	1.44	14.875
1.558	14.365	1.93	16.065
1.87	14.977	2.13	16.32
2.6	15.4275	2.85	16.83
2.9	15.4275		

Test 2. Lateral resistance at 0.32kN/s and 0.92kN/s

Lateral Displacement (mm)	Lateral resistance (kN) loading rate at 0.32kN/s	Lateral Displacement (mm)	Lateral resistance (kN) loading rate at 0.92kN/s
0.05	0.35	0.051	0.10
0.01	0.43	0.005	0.50
0.015	0.44		
0.019	1.28	0.005	1.00
0.02	1.70		
0.03	1.87	0.003	0.50
0.05	2.21	0.026	1.00
0.055	2.72		
0.056	0.00	0.005	0.50
0.06	3.06		
0.075	3.40	0.005	0.50
0.09	3.83	0.055	0.43
0.09	3.83	0.03	1.28
0.095	3.83	0.095	3.23
		0.125	4.68
0.105	4.08	0.155	6.46
0.11	4.25	0.395	10.03
0.1	4.25	0.665	12.03
0.095	4.68	0.878	13.30
0.095	4.68	1.585	15.56
0.135	5.61	1.88	16.11
0.195	6.80	2.19	16.66
0.325	8.16	2.81	17.13
0.51	10.20		
0.645	10.46		
0.67	10.88		
0.69	11.05		
0.77	11.56		
0.88	11.73		
1.175	13.01		
1.72	14.28		
2.035	14.88		
2.225	15.13		
2.365	15.56		
2.64	15.81		
2.805	15.81		

Test 3. Lateral resistance at 0.32kN/s and 0.92kN/s

Lateral Displacement (mm)	Lateral resistance (kN) loading rate at 0.32kN/s	Lateral Displacement (mm)	Lateral resistance (kN) loading rate at 0.92kN/s
0.005	0.50	0.005	0.5
0.005	0.50	0.005	0.5
0.05	0.50		
0.007	0.85	0.001	1
0.008	0.19		
0.025	0.90	0.05	0.5
0.024	1.56	0.05	1
0.01	1.32	0	0.5
0.02	1.44	0.005	0.5
0.018	1.17		
0.02	1.44	0.005	0.5
0.057	1.56	0.05	0.5
0.045	2.79		
0.093	3.38	0.01	0.5
0.113	4.84	0.05	0.43
0.135	5.98	0.06	3.49
0.295	8.50	0.113	4.84
0.478	10.03	0.135	5.98
0.635	10.94	0.16	7.10
1.09	12.20	0.29	9.35
1.285	13.32	0.46	11.12
1.49	13.71	0.73	12.33
2.04	14.62	0.935	13.60
2.21	15.03	1.73	15.30
2.36	15.12	1.83	16.15
2.56	15.84	2.25	17.00
2.9	16.35	2.9	17.77

Three repeated test result for determination the contribution ballast layer component to lateral resistance of sleeper.

Test 1. Only ballast base, only ballas base and crib and Ballast base, crib and shoulder

Only ballast base		Only ballas base and crib		Ballast base, crib and shoulder	
Lateral displacement (mm)	Lateral resistance (kN)	Lateral displacement (mm)	Lateral resistance (kN)	Lateral displacement (mm)	Lateral resistance (kN)
0.01	0.5	0	0.5	0.005	0.5
0.01	1.15	0.005	0.5	0.005	0.5
0.025	1.3	0.01	0.5	0	0.5
0.035	1.54	0.015	2	0.001	1
0.049	2.3	0.015	1.5	0.005	0
0.055	2.6	0.015	1.5	0.05	0.5
0.18	3.5	0.025	2	0.05	1
0.375	4.5	0.04	2	0	0.5
0.7	4.9	0.04	2	0.005	0.5
1.96	5.4	0.105	3	0	0
2.155	5.5	0.185	4	0.005	0.5
2.56	5.8	0.26	5.2	0.05	0.5
		0.61	6.8	0	0.5
		0.68	7.5	0.01	0.5
		1.145	8	0.05	0.425
		1.67	8.5	0.06	3.825
		1.86	8.8	0.29	9.35
		2.32	9.6	0.73	12.325
		3.06	10	0.935	13.6
				1.73	15.3
				1.83	16.15
				2.25	17
				3.16	18.275

Test 2. Only ballast base, only ballas base and crib and Ballast base, crib and shoulder

Only ballast base		Only ballas base and crib		Ballast base, crib and shoulder	
Lateral displacement (mm)	Lateral resistance (kN)	Lateral displacement (mm)	Lateral resistance (kN)	Lateral displacement (mm)	Lateral resistance (kN)
0	0	0	0.5	0.005	0.5
0.005	1	0.005	0.5	0.005	0.5
0.05	2	0.01	0.5	0	0.5
0.18	3.5	0.015	2	0.01	1
0.375	4.5	0.015	1.5	0.005	0
0.7	5	0.015	1.5	0.005	0.5
0.9	5.2	0.025	2	0.002	1
1.62	5.3	0.04	2	0	0.5
1.96	5.4	0.04	2	0.005	0.5
2.155	5.5	0.105	3	0	0.5
2.82	5.6	0.185	4	0.005	0.5
		0.26	5.2	0.06	2.5
		0.61	6.8	0.06	3.23
		0.68	7.5	0.18	6.6555
		1.145	8	0.2	7.055
		1.67	8.5	0.25	9.095
		1.86	8.8	0.5	10.71
		2.32	9.6	0.6	11.73
		2.85	10	0.86	13.005
				1.44	14.875
				1.93	16.065
				2.13	16.32
				2.85	16.83

Test 3. Only ballast base, only ballas base and crib and Ballast base, crib and shoulder

Only ballast base		Only ballas base and crib		Ballast base, crib and shoulder	
Lateral displacement (mm)	Lateral resistance (kN)	Lateral displacement (mm)	Lateral resistance (kN)	Lateral displacement (mm)	Lateral resistance (kN)
0	0	0	0.5	0	0
0.01	0.5	0.005	0.5	0	0
0.01	1.15	0.01	0.5		
0.025	1.3	0.015	2	0.005	0.5
0.035	1.54	0.015	1.5		
0.049	2.3	0.015	1.5	0.003	0.5
0.055	2.6	0.025	2	0.026	1
0.18	3.5	0.04	2		
0.375	4.5	0.04	2	0	0
0.7	4.9	0.105	3		
1.96	5.4	0.185	4	0	0
2.155	5.5	0.26	5.2	0	0
2.56	5.9	0.61	6.8	0.03	1.275
		0.68	7.5	0.095	4.08
		1.145	8	0.125	5.525
		1.67	8.5	0.155	6.46
		1.86	8.8	0.395	10.03
		2.32	9.6	0.665	12.0275
		2.46	10	0.878	13.3025
				1.585	15.555
				1.88	16.1075
				2.19	16.66
				2.81	17.1275