ADDIS ABABA UNIVESITY

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Characterizing the Influence of Ballast Flying

A Thesis Submitted to the school of graduate studies of Addis Ababa University in partial fulfillment for the degree of Master of Science in Civil Engineering under Railway Engineering.

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Abstract

Ballast flying is understood as cause of track deterioration in many countries over where high train speed is operated. The deformation and degradation behavior of ballast under static and dynamic load cause the ballast to fly early from under the track. In this thesis, the railway ballast particle force equilibrium is analyzed through basic mechanics and mathematical formula and a discrete element model is set up to discover the factors and influences. Ballast flying is correlated with ballast shape and mass, especially the ballast shape mass ratio corresponding to operation speed. Ballast interlock ability governs the ballast flying possibility and severity. Ballast flying possibility increase with ballast bed acceleration. The performance of ballasted track depend not only on its design, but also the way and quality of maintenance ,ballast needed to analyze the shape and mass of ballast material used to reduce the flying of ballast under track.

This thesis investigated the effect and influence of ballast flying using a Discrete Element Modeling (DEM) approach. Results show that ballast flying particle is correlated with ballast shape and mass, aggregate gradation and ballast interlock ability. From DEM output it can be conclude that finer and non-uniformly graded aggregate are easily fly under railway track during operation and ballast with high angular shape resulted in the highest shear resistance or high stability. Acyclic loading analysis was conducted for angular particles relatively low confining pressure for analysis of particle fragmentation the generated assembly of angular particles undergoing fragmentation at various load cycle. from the simulation observe that though the mechanical load increase the fragmentation of railway ballast increases and finally leads to ballast displacement which lead to ballast flying.

As the applied normal force increased, the shear force also increased primarily influenced by the shape effects of aggregate angularity and surface texture. Yet, a rough surfaced rounded particle had shear strength higher than that of a smooth-surfaced angular particle. The fact that rounded gravel particles have less aggregate interlock compared to crushed angular aggregate to transfer shear force can be explained by the bilinear contact force paths for the rolling and climbing up of the rounded particles. Angularity and cubical particles have high resistance to the vertical displacement under traffic loading because the inter particle force high when compared with the spherical and rounded/circular particles.

Key words: Ballast flying characterization, discrete element modeling, ballast interlock ability, ballast mass

Acknowledgement

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Finally, I would like to thank Ethiopian railway cooperation for the support and allowing accessing data for this thesis work.

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Notation

A	wind loads effective area of ballast particle
a	ballast acceleration
a_t	ballast particle vertical acceleration
C	the consequence from the event of ballast flying
D	the maximum aggregate size;
d	the aggregate size being considered
E	Young's Modulus
F_i	ballast particle interlock force
F_w	High speed train resulted wind force acted on the ballast effective surface and
F_a	force corresponding ballast acceleration due to bed vibrations
G	gravity force
h_b	the depth of the ballast
k_n	normal stiffness
K_s	shear stiffness
l_e	the effective supporting length of half sleeper
l_b	the width of sleeper under side
m	mass of ballast particle
M_b	ballast mass
Mg	gravity by mass
n	around 0.5 for maximum density according to Fuller and Thompson (1907
p	the percentage finer than the size;
p_b	ballast density
P_d	the probability that a ballast particle will displace from its rest position,

$P_{\mathrm{fb/d}}$	the conditional probability that a ballast particle will fly given the displacement
V	Poisson’s Ratio
μ	Coefficient of friction
α	the ballast stress distribution angle
η	Structural Damping Parameters

Acronyms

AALRT	Addis Ababa Light Rail Transit
AREMA	American Railway Engineering and Maintenance of Way Association
DEM	Discrete Element Method
ERC	Ethiopian Railway Cooperation
HSR	High Speed Railway
HMA	Hot Mix Asphalt
FHWA	Federal Highway Agency

CHAPTER 1 : INTRODUCTION

1.1 Introduction

Railway is a means of transportation guided by rails giving access to trains to move passenger or freight from one place to another. It has different components bringing the structure functional. These are rails, fastening systems sleepers or ties, ballast, fill material and the sub grade. The different parts of railway structure can be categorized as super structure (rail, fastening systems and sub grade). Ballast is the main structure part of the rail road which distributes the train loads to the underlying supporting structure without failure. Ballast can be constructed from different material sources like, Basalt, Granite, Slag and Gravel. The mechanical and chemical composition of the construction materials affects the performance of ballast structure. (Dr.P.Anbazhangan, 2013).

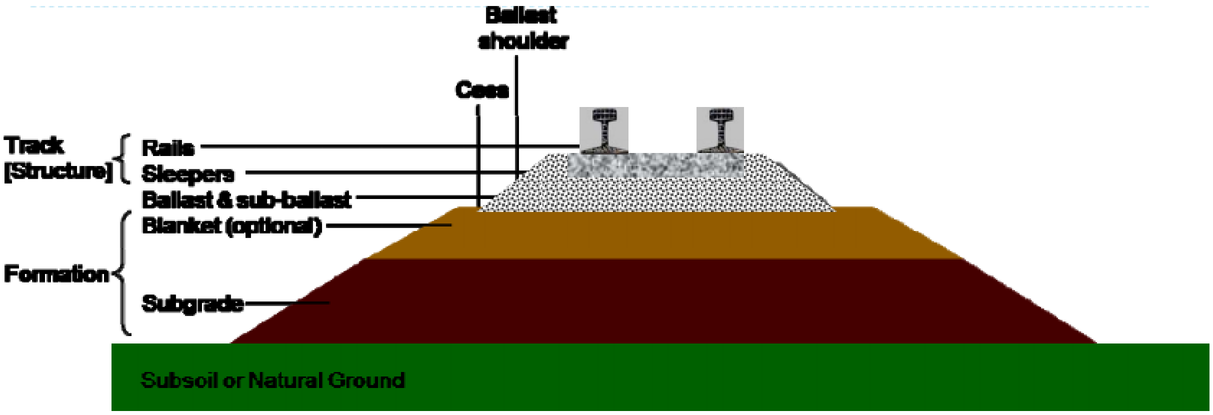


Figure 1.1 Railway track structure (Dr.P.Anbazhangan, 2013)

Railway ballast generally consists of an assemblage of irregularly shaped, large angular and hard ballast particles which transmit an impact load through multi contact loading condition that exists in the boundary layers separating individual ballast. During a train's passage at high speed, each ballast particle receives a dynamic load at low frequency (up to several tons) because of axle load passage. Each ballast particle also receives an impact load at high frequency excited by the rolling contract mechanism between a wheel and rail through a sleeper bottom. The frequency passage of train on tracks loosens and deforms the ballast and supporting bed. Therefore, the ballast requires periodic maintenance work that entails high maintenance costs. (AREMA, 2007).

The train running over the track causes stresses in from different directions (Vertical, lateral and longitudinal) to the ballast through the wheel-rail-sleeper combining the static and dynamic loads. There are different empirical methods developed to determine the different loads that can be exerted. The total vertical load is computed as a function of static and dynamic load, centrifugal and wind loads.

Railway ballast is a layer consisting of angular aggregates between10-63mm in size placed underneath the slope track. Ballast tracks are popular due to many advantages including, economy, higher load bearing capacity and good drainage. The need to maintain continuously edge over other means of transportation has increased the pressure on the railway industry to improve its efficiency and decrease maintenance and infrastructure costs. The performance of ballasted track depends not only on its design, but also on the way and quality of maintenance. Ballast needed to analyses the shape and mass of ballast material used to reduce the flying ballast material uses to reduce the flying of the ballast under track. Therefore railway infrastructure companies are interested in good quality ballast material with low maintenance cost and tamping (AREMA, 2007).

The flying ballast particle is correlated with ballast shape and mass, especially the ballast shape mass ratio corresponding to operation speed. Ballast interlock ability governs the ballast flying possibility and severity. The performance and in-track life of aggregate as rail way ballast has been determined to be primarily dependent upon the rate of material break down under mechanical loading.

Studying the effects of ballast particle size distribution and confining pressure on ballast shear strength settlement and degradation, based on static and dynamic loading of the train, shape (angularity), mass proportion and geotechnical property of the ballast material to determine the factor that determine ballast flying under Railway track.

This study focused on the analysis of the influence of ballast flying from under track bed or analyses factors that determine segregation of ballast material under track bed through Discrete Element Method (DEM) computation try to set the counter measure to reduce ballast flying.

Railway ballast is a layer consisting of angular aggregates between 10mm and 63mm in size placed underneath the track slope. Ballast track are popular due to many advantages, including economy, higher load bearing capacity and good drainage. The need to maintain competitive edge over other means of transportation has increased the pressure on the rail way industry to improve its efficiency and decrease maintenance and infrastructure costs.

The performance of ballasted track depend not only on its design, but also the way and quality of maintenance ,ballast needed to analyze the shape and mass of ballast material used to reduce the flying of ballast under track. Therefore railway infrastructure companies are interested in good quality ballast material with maintenance costs and tamping.

The previous study results show that ballast flying particle is correlated with ballast shape and mass, especially the ballast shape mass ratio corresponding to operation speed. Ballast interlock ability governs the ballast flying possibility and severity. The performance and in-track life of aggregate as railroad ballast has been determined to be primarily dependent upon the rate of material breakdown under mechanical loading.

This study focused on the analyses effect of ballast particle size distribution and confining pressure on ballast shear strength, settlement and degradation, based on static and dynamic load of the train, shape (angularity), mass proportion and geotechnical property of the ballast material.

1.2 Problem Statement

A large portion of a railroad company's annual budget to sustain the railway track system goes into maintenance and renewal of track ballast.

Problems investigated by this work are railroad track rail head damage and ballast settlement usually associated with the ballast component of track that require remedial action and routine maintenance. During track operation, fine particles can accumulate with ballast voids due to, breaking of sharp angular projection (corners) infiltration of fines from the surface and pumping of soft saturated sub grade. Ballast flying makes the granular mass effectively less angular and decreases its shear strength. Flying also impedes drainage in the track. The routine replacement of flying ballast creates serious concerns for the environmental protection authorities, in addition to light disposal costs.

Generally, during track operation, the repeating cyclic load of train causes ballast emigration from under track; that segregation of ballast material increasing maintenance cost and track deterioration. This research focuses on analyzing the influence of ballast flying and set out possible countermeasures on ballast railway track.

Many factors may characterize the influence ballast to fly under rail way track, like:-

- Aggregate shape properties including aggregate angularity and surface texture.
- Tie-aggregate contact interface.
- Ballast compaction level and
- Aerodynamic of high-speed train.

Among these factors, aggregate type and shape properties have been known to directly affect the compaction of ballast, lateral stability, settlement, and the long term performance of the railroad track.

1.3 Research Objectives

In this study, a computational simulation model for the particulate nature of ballast referred to as the "Discrete Element Method (DEM)" will be introduced. The main objective of this study, characterizing the influence of ballast flying will be investigated. Specific objectives to be accomplished are listed as below:

1) To analyze the characterizing the influence of ballast flying under railway track using discrete element Method.
2) To determine the causes of ballast flying.
3) To identify the factors that affects the railway ballast flying.

1.4 Significance of the Study

This study will be important for Ethiopian railway cooperation to implement selection of ballast material, reducing maintenance cost of rail way ballast and the environmental protection authority reducing the production of ballast cycle for maintenance and disposing cost.

The research study aims at contributing at the development of a "Ballast DEM computation" that will help engineers better understand the behavior and performance of ballast through realistic modeling of the effects of aggregate shape and size distribution on lateral stability, ballast flying settlement, and the dynamic interactions under loading.

1.5 Structure of the thesis

The outline of this thesis is Chapter one deals with introduces the needs of the research on assessing and discovering Railway ballast flying mechanism (analysis of the influence of ballast flying and reviewing its countermeasures) due to high speed train dynamic responses, Chapter two review the literature and explores characterizes flying ballast particle mechanism, Chapter three deals with mathematical modeling of the railway ballast flying using Discrete Element Method (DEM) and deals with analysis of the effect of ballast flying on the rail track and determine the cause of rail way ballast flying (using DEM computation), finally Chapter four highlights the main conclusions of the present thesis and points out direction for future research.

1.5.1 Ballasted bed sample

Ballasted samples were taken from various parts of both networks of Addis Ababa LRT (North south and East-west), primarily from beds subjected to long term traffic. Laboratory analysis of the samples were conducted in order to determine the extent of gradation and especially the quality of the resulting fine as well as related variation with the aggregates typically used on the bed.

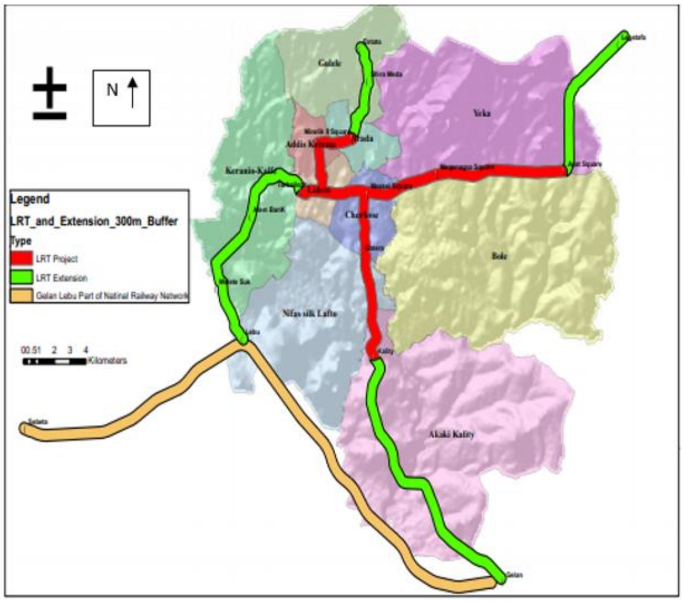


Figure 1.2 AALRT section where ballast samples were taken

(adapted from ERC)

CHAPTER 2 LITERATURE REVIEW

2.1 Introductions

The ballast flying phenomena requires at least two stages of particle movements, which are involved with train dynamic response both from lateral wind and sleeper interaction. Based on the direct reason, the ballast flying problem influence factor includes: sleeper dynamic force induced by train load and lateral wind by train (G.Q. Jing1, G.X. Liu1, J. Lin1, J. Martinez2 and C.T. Yin3, 2014).The deformation of fresh and recycled ballast varies non-linearly with the number of load cycles which cause flying of the ballast under track. A number of serious track problems include fouling pumping, sub grade failure and excessive ballast break down (B.indraratan, 2006). According to (N.Tennakoon1, B. Indraratn and S. Nimbaker (2014) Around 76% of ballast flying originates from the fracture and abrasion of ballast particles, 3%, from sub grade intrusions, and 21% from sleeper wear (N.Tennakoon1, 2014)

As the ballast has a major influence on the durability and quality of the track, several requirements have to be fulfilled for rock aggregates to be used as rail-way ballast. Track bed strength and drainage are important factors for the quality of the track. As the track is heavily loaded by high traffic volume and dynamic loading of the trains with the high speed, it is exposed to dynamic and static stresses. Higher quality of the rock ballast results in longer tamping intervals and lower costs for the railway company (Kasa, 2013).To provide a more reliable indication of in-track performance of ballast materials, improved laboratory tests are needed which duplicate the loading conditions and which test the appropriate ballast material properties. The Abrasion test is presently being evaluated by the railroad research community to determine if it provides a reliable and relevant measure of ballast material quality (M.Chrismer, 2010).

2.2 Track components and functions

Track component rails are longitudinal steel members to direct train wheels; the only parts of the track component that come into direct contact with the train. Therefore, the rails transfer concentrated wheel loads to the supporting sleepers. The rails must be stiff enough to carry the wheel loads with minimum deflection between sleeper supports. The vertical and lateral profile of the rails must be coupled with the profile of the wheels, as any defect on the rail or wheel surface might cause a significant magnitude of dynamic load which is detrimental to the railway track structure. Rail sections may be connected by bolted joints or welding, and these joints may lead to large impact loads from trains that affect the track components below (AREMA, 2007).

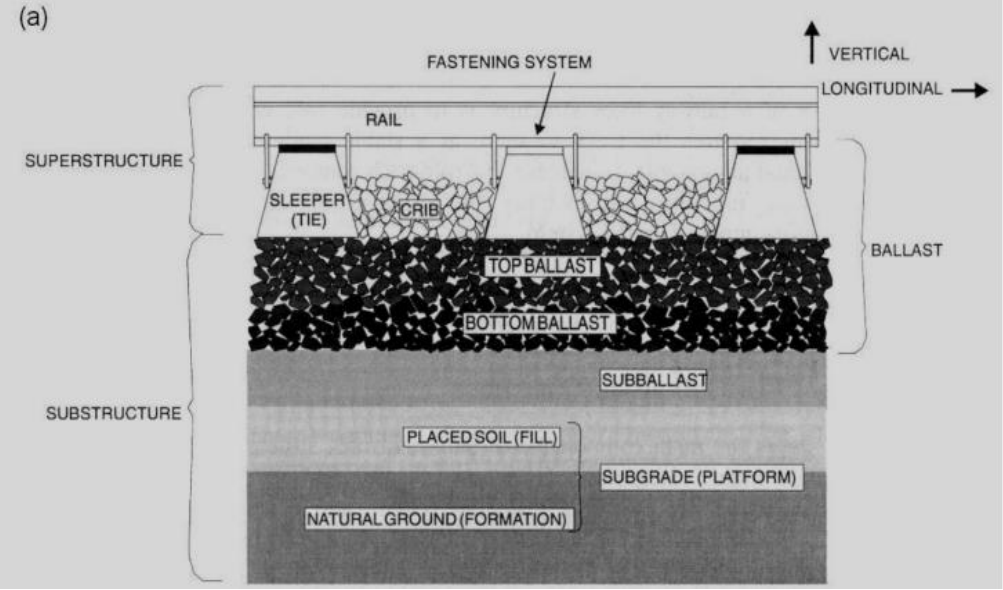


Figure 2.1 Superstructure and substructure components of a railway line, lateral view

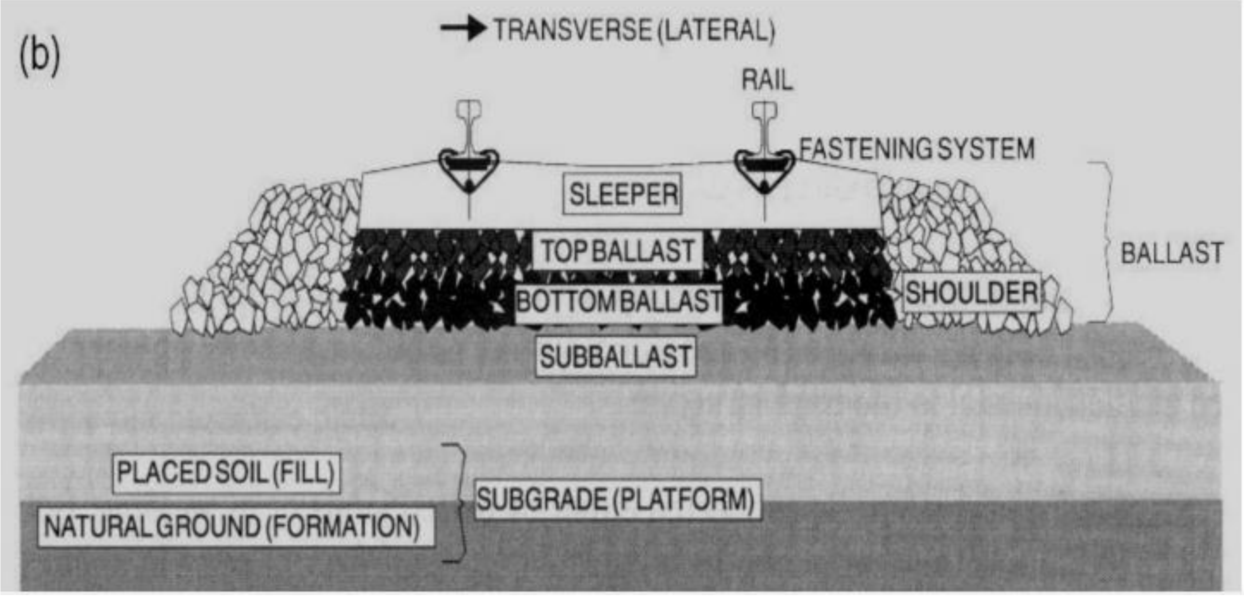


Figure 2.2 Superstructure and substructure components of a railway line, longitudinal view

2.2.1 Track Components

Rails are longitudinal steel members to direct train wheels; the only parts of the track component that come in direct contact with the train. Therefore, the rails transfer concentrated wheel loads to the supporting sleepers. The rails must be stiff enough to carry the wheel loads with minimum deflection between sleeper supports. The vertical and lateral profile of the rails must be coupled with the profile of the wheels, as any defect on the rail or wheel surface might cause a significant magnitude of dynamic load which is detrimental to the railway track structure. Rail sections may be connected by bolted joints or welding, and these joints may lead to large impact loads from trains that affect the track components below. The fastening system is used to hold the rails onto the sleepers, to ensure fixing of the rails. Depending on the type of the sleeper and geometry of the rail, various kinds of fastening systems are utilized. In some situations, rail pads are used on top of the sleepers to absorb the energy generated by the traffic movements.

The main functions of sleepers are to provide a solid, even and flat platform for the rails, and support the rail fastening system. They are laid on the top of a compacted ballast layer. Sleepers receive the rail loads and distribute them over a wider ballast area to decrease the stress to an acceptable level. In addition, the sleepers can be used to resist lateral, longitudinal as well as vertical rail movement through anchorage of the superstructure into the ballast. Sleepers can be made of wood, concrete or steel. Currently, timber and concrete sleepers are the most common types of sleepers, which are used worldwide. Steel sleepers are expensive so this type is only used in special situations (Kasa, 2013).

Railway ballast can be defined as granular coarse aggregate. Traditionally, angular, crushed hard stones and rocks, uniformly graded, free of dust and dirt and not prone to cementing action have been considered good ballast materials. Ballast is a granular material with high bearing capacity that is placed above sub-ballast or subgrade to act as a platform, to support the track superstructure. Its main function is to spread the high loads of passing axles to the subgrade. In doing this, there are high stresses transmitted through the ballast. Moreover, ballast provides a certain amount of resiliency as well as energy absorption for the railway track. The source of ballast varies between different areas, depending on the quality and availability of the material. Ballast index characteristics include particle size, shape, gradation, surface roughness, particle density, bulk density, strength, durability, hardness, toughness, resistance to attrition and weathering (G.Q.Sing, 2012).

2.2.2 Ballast Material

Ballast is the main structural part of rail road where the sleeper or ties are laid. Its main function is to transfer the loads coming from the super structure to sub grade without failure and providing good drainage to the track. There are Different types of material used for ballast construction like limestone, basalt, granite, slap and gravel or crushed rock (AREMA, 2007).

All these function are fulfilled when the following parameters are properly selected: Thickness of ballast layer; cross-selection of railway track including the sub-grade profile with gradients and track superstructure; quality of crushed rock aggregates and their compaction level (AREMA, 2007).

2.2.3 Requirements for the aggregates of rail ballast

The top width of the ballast bed influences the restraint of horizontal displacement of the sleepers. The higher the width of the ballast bed shoulder the larger the restraint. The ballast bed shoulder shall be 35-45 cm wide on average. So an aggregate with the following property is traditionally considered to be best ballast material (AREMA, 2007).

- ✓ resistant to environmental factors
- ✓ high compressive strength and high impact resistance
- ✓ angular crushed
- ✓ hard stones and rock
- ✓ uniformly graded
- ✓ free of dust, dirt and resistance to cementing action
- ✓ No admixtures which prevent air circulation and water filtration.
- ✓ No crushed rock elements with sharp ends (sides).

2.2.4 Ballast function

According to AREMA even though there is many more function of the ballast structure, the following are the most important ones, (AREMA, 2007).

1. To maximally uniformly distribute loads transferred from the wheels to the sleepers and substructure.
2. To ensure track stiffness by simultaneously reducing dynamic loads.
3. Act as resiliency and energy absorbed for the track structure.
4. To ensure good water and air filtration in order to increase a service life of sleeper and to preserve the strength of the railway track substructure.
5. Pressure reducing ballast structure to allowable stress for the underlying structure just below the sleeper.
6. Tamping will rearrange ballast particle while adjusting track geometry. This eases and speeds up the maintenance operation.

2.2.5 Ballast structure

Ballast is an important constituent of conventional track structure. Its importance has grown with the increasing axle loads and train speeds. Various types of material such as aggregate of rocks and boulder, natural gravel, shingle and sand etc. are used according to the requirement, availability and cost to make ballast (JS.Mundery, 2006).

The shape of the ballast shall be cubic and /or angular. This would be automatically achieved if the parent rock material is non-stratified and has good compressive strength (Mundery, 2005) . One of the important functions of the ballast is to distribute the load coming to the sleeper safely onto formation. The pressure on the sleeper through the body of the ballast for coarse, rough, dry and clean ballast, this angle is about 45^0, but becomes smaller for moist and dirty ballast. This brings out distinctly the advantage of clean ballast cushion and reducing the information pressure. To obtain uniform distribution of the wheel loads upon the formation, it is advantageous to have the longest and the broadest sleeper possible. The quality of the ballast should be to provide the widest possible angle pressure spread, and deep enough to distribute the oncoming loads to the maximum area at the level of the formation (JS.Mundery, 2006).

The performance and in track life of aggregate as rail road has been determined to be primarily dependent upon the rate of material break down under mechanical loading (M.Chrismer, 2010).

The coarse ballast breakage is a result of particle fraction and breaking off chips and corners under impact loading and is a measure of ballast material toughness. These impact leads are caused by imperfection in wheels and track, and are in abundance in the rail road’s environment. The generation of finer material is due to attrition or abrasion from particle to particle contract under repeated load and is a measure of ballast material hardness to accurately predict the amount or rate of breakdown (M.Chrismer, 2010).

2.2.6 Ballast Flying Mechanism and Analysis

Factors affecting ballast strength and stability include: ballast aggregate gradation, aggregate shape properties, and loading characters.

The ballast flying phenomenal requires at least two stages or condition, ballast particles and particle movements. When the train moves with high speed, loosely packed ballast gets detached from ballast formation and starts moving from its position (flying of ballast), which might be due to combined aerodynamic and ground vibration effects.

Ballast flying is correlated with ballast shape and mass especially the ballast mass ratio. The ballast interlock ability governs the ballast flying possibility and severity. The ballast shape, mass, gradation and interlock ability parameters should be further measured and analyzed.

2.2.7 Ballast flying and projection phenomena

For train operated on ballasted track at speed higher than or equal to 250 km/hr., ballast pick up caused by the aerodynamic effect of the train on the track bed may be observed, and may present a risk in the vicinity of the track (William, 2013)

2.2.8 Ballast flying Mechanism (Phenomena)

Ballast flying has been considered as a problem in train aerodynamic with increasing the maximum speed. And this phenomenon seriously threats the safety of train operation on the ballasted track (G.Q. Jing1, G.X. Liu1, J. Lin1, J. Martinez2 and C.T. Yin3, 2014). Ballast flying problems obsess the ballasted high speed railways; its microscopic Mechanics is less of discovered. The

Microscopic ballast flying model is used for ballast bed geometry and ballast shops optimization, and guides the ballast flying countering Methods. Results show that ballast flying particle is correlated with ballast shape and mass; especially the ballast shape mass ratio corresponds to operation speed. Ballast interlock ability governs the ballast flying possibility and severity (G.Q.Sing, 2012). Ballast flying possibility increases with ballast bed acceleration. Influence factors of ballast flying have been characterized by ballast particles acceleration and ballast shape mass ration. There possibly exists a critical value for the ballast surface mass ratio under certain high speed train operation, which is use full for ballast shape control (G.Q.Sing, 2012).

During passage of a high speed train ballast particles become detached from the ballasts bed. This phenomena is called ballast flying and causes rail defects which require grinding to repair, it is mechanical, aerodynamic or a combination of the two. Geotechnical effects (ground acceleration) alone are insufficient to cause ballast flying: the cause probably a combination of aerodynamic and ballast acceleration effect. (William Powrie and Jeffrey Priest, 2011).

The Ballast flying phenomena requires at least two stage conditions, an initial suspension or displacement of ballast flying particle and subsequent movements on the rail head or wheels, which involves with train dynamic and ballast particle individually (G.Q.Jing and L.G Xiooling sun, 2012). Ballast flying results a lot of problems, which leads to pollution of the Environment and the ballast flying phenomena from ,high speed railway cause a form of rail head damage, known as “ballast pitting”, which has become more apparent recently. It is hypothesized that this form of damage is due to small particle of ballast being crushed between the rail head and the wheels of rail vehicles (G.Q.Jing and L.G Xiooling sun, 2012). Most of the ballast research develops around experiments or macroscopic theoretically analysis but less on ballast flying Microscopic mechanism (G.Q.Jing and L.G Xiooling sun, 2012).

Railway ballast flying leads to rough track and uneven ride caused by excessive dynamic ballast loading and other track substructure problems Proper selection of ballast aggregate type, gradation, angularity and surface texture properties and proper construction and compaction in the field primary influence ballast layer recoverable(elastic) and permanent(inelastic) deformation trends under repeated train loading (Huang, 2009).Recent laboratory and field research studies have shown that frequency of loading or load pulse duration are result of trafficking speed might be settlement unbound aggregate layers leads to ballast flying and fouling (Huang, 2009).

2.2.9 Risk of ballast flying analysis

The phenomenon of ballast flying may be characterized by both the mechanistic and probabilistic design (Francesco Bedini Jacobini, Erol Tutumluer, Mohd Rapik Saat, 2013).

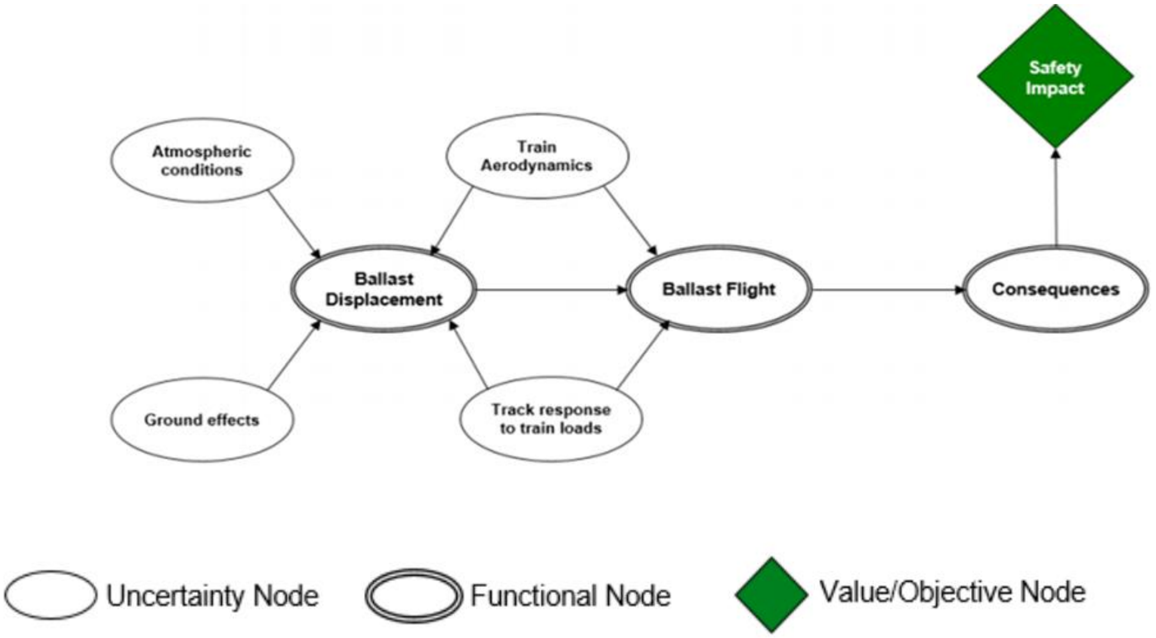


Figure 2.3 Preliminary risk influence diagram for flying ballast

The probabilistic occurrence of a ballast flying event is modeled as a combination of two sub-events: the displacement of ballast particles and the ballast flight given the displacement. The ballast displacement is affected by the atmospheric conditions and ground conditions, while atmospheric, track, ground and aerodynamic forces contribute to the likelihood of ballast flight given a ballast displacement.

2.3 Factors Determining Railway Ballast Flying

2.3.1 Introduction

When the train moves with high speed, loosely packed ballast gets detached from ballast formation and starts moving from its position(flying of ballast),which might be due to combination of ground vibration and aerodynamic forces of the moving train. Ballast flying is also correlated with ballast shape and mass ratio. The ballast interlock ability governs the ballast flying and severity. (G.Q Jing1, Y.D Zhou1, Jian Lin1, J. Zhang2*, 2012).

2.3.2 The concept of risk

To define the risk of flying ballast, Rf_b is through the following relationship used: (Francesco Bedini Jacobini, Erol Tutumluer, Mohd Rapik Saat, 2013).

$$f = P_d \times P_{fb/d} \times C$$

Where,

P_d is the probability that a ballast particle will displace from its rest position,

$P_{fb/d}$ is the conditional probability that a ballast particle will fly given the displacement, and

C is the consequence from the event of flying ballast.

To be able to estimate the probabilities described above, there is a need to understand the conditions at which flying of ballast may occur. In the following sections, the major factors are presented and discussed in detail (Francesco Bedini Jacobini, Erol Tutumluer, Mohd Rapik Saat, 2013).

2.3.3 Aerodynamic effects

With the high speed railway development, several problems are presented, such as ballast flying, track stiffness variation on transition and ballast bed instability. The high speed train produce powerfully airflow can cause ballast flying away to hit the track and train causing significant damages.

Aerodynamic load must counteract gravity and reaction exerted by the ballast bed over the specific particle. This indicates that the aerodynamic force and dynamic load of train induced by high-speed trains are high enough to move the ballasts on the track. The trains produce powerful airflows that increase the ballast flying occurrence.

When a train runs at high speed, a strong turbulent airflow is induced beneath the train because of the boundary layer on the train surface as well as the perturbation by irregular shapes of train such as protruding bogies and cavity of inter- car (G.Q Jing1, Y.D Zhou1, Jian Lin1, J. Zhang2*, 2012).

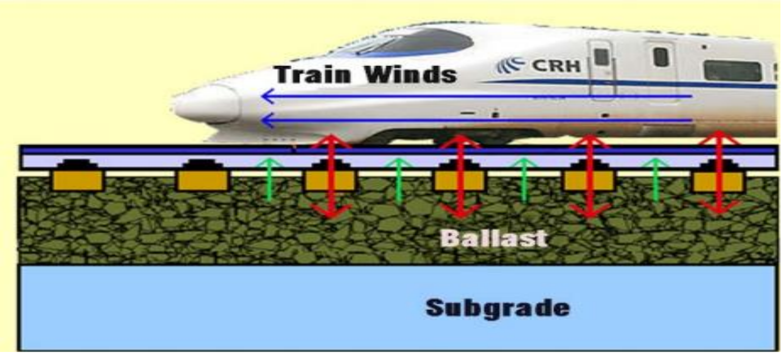


Figure 2.4 Ballast aerodynamic and dynamic Effects.

When a high speed train overpasses a critical speed it produces a wind speed close to the track large enough to start the motion of the ballast elements, eventually leading to the rolling of the stones and, if they get enough energy, they can jump and then initiate a siltation-like chain reaction.

Aerodynamics is one of the most important aspects studied related to train operations (Quinnetal.2010). The key aerodynamic factor is speed, since the aerodynamic force is proportional to the square of the speed of the train. Discussion with several HSR operators worldwide suggests that ballast flight have appeared too accumulated at speeds above 260km/hr. (161.4 mph). Other factors to take into account in this first risk factor are aspects related to the train design. A different nose configuration of the front of the train might be the key difference in experiencing ballast flying. One factor that is considered important by HSR operation when attempting to characterize flying ballast is the length of the train. Studies performed in Spain as well as in Italy suggested that the length of the train plays a major role in the initial displacement of particle (Agretti, 2012, and Lazaro, 2011). It was noted that ballast flying was more likely to occur with a double-composition train – two separate transit units coupled to make up a longer train. This is due to the buildup of vortices underneath the car body of the train. While the length of a single composition train (8 cars) does not generate an aerodynamic pressure sufficiently high to displace the ballast particle, a 16-car composition is more prone to generate the phenomenon. This has been observed in Spain (Lazaro & Gonzalez, 2011) and Italy (Agretti, 2012).In addition, wheel set design directly relates to the transit configuration. The important aspect to consider here is the design of the flange of the wheel. If a ballast particle is set into motion due to some of the factors described previously, the particle could then hit the tip of the flange, thus causing the projection of the particle.

While the speed of 260 km/h may be considered as a threshold value above which ballast flying may occur, there are other environments that may lead to the occurrence at lower speeds such as in tunnel which itself imposes a boundary to the air flow generated by the train. It was noted that in tunnels where posted speed limits were around 140 km/h (87 mph), the sign posts appeared to have significant damage from objects hitting the signs at high speeds, in additional consideration related to speed is the effect of passing trains. There have been instances (FRA Accident Database, 2003) where a ballast stone was blown up when two trains travelling at speeds below 160km/h (100mph). In summary, speed is probably the most important factor to contribute to ballast flying and it has been reported by HSR operators that ballast flight occurrences are seriously limiting the ability of these operators to raise the speed on their lines. Lazaro et al. (2011) have performed a full scale experimental test to validate a risk model based on the speed of the train. It was noted that the likelihood of ballast being displaced from its "at rest" position would dramatically increase as the speed of the train went above 260 km/h (161.5 mph). Similar results were found in field studies performed in Italy (Diana, 2012; Rocchi, 2013).

2.3.4 Ballast Gradations

Gradation is one of the most influential aggregate characteristics in determining how aggregates will perform in a constructed structural layer. Railroad ballast is often designed using uniformly graded material to mainly satisfy the drainage requirement. However, uniformly graded aggregates may tend to be structurally less stable due to larger air voids and possibly yield more settlement than continuously or densely graded materials. A good ballast design needs to consider both void space and structural stability.

A specified ballast gradation must provide the following two key objectives:

- Ballast must have high shear strength to provide increased stability and minimum track deformation. This can be achieved by specifying broadly-graded (well graded) ballast.

For the purpose of this study ballast material were collected from AALRT ballasted track for investigation of gradation test, flakiness and elongation and abrasion test to measure out the influence of this parameter on ballast flying. The gradation of a ballast is a primary consideration for the in track performance of ballast material. The gradation must provide a means to develop the density requirement for ballast section and provide void space to allow proper run off ground water. Ballast should be graded uniformly from lower limit to provide proper density, uniform support, elasticity, interlock ability and to reduce deformation of the ballast section from repeated track loadings.

AREMA (2.10.4) states that Ballast for concrete tie installations must be limited to crushed granites, trap rocks or quartzite. A very important consideration is the selection of the proper gradation of the ballast material for concrete ties. The early concrete tie installations were placed on ballast materials graded to the AREMA No. 4 (1½ inches- ¾ inch), resulting in good in track performance. Therefore, Crushed stone ballast bed in accordance with AREMA No. 4 grading requirements will be used (show below under Figure 2.6) Minimum depth of ballast for single track ballast is 300 cm. The AREMA (2.4.5) manual provides recommended values of ballast gradation size as shown in the table 2.1 below:

Table 2.1 Recommended Ballast Gradations (AREMA, 2007)

Size No. (See Note 1)	Nominal Size Square Opening	Percent Passing									
		3″	2 ½ ″	2″	1 1/2″	1″	¾″	½″	d″	No.4	No. 8
24	2 ½ ″ - ¾ ″	100	90-100		25-60		0-10	0-5	-	-	-
25	2 ½ ″ - d″	100	80-100	60-85	50-70	25-50	-	5-20	0-10	0-3	-
3	2″ - 1″	-	100	95-100	35-70	0-15	-	0-5	-	-	-
4A	2″ - ¾ ″	-	100	90-100	60-90	20-55	0-10	-	0-3	-	-
4	1 ½ ″ - ¾ ″	-	-	100	90-100	90-100	0-15	-	0-5	-	-
5	1″ - d″	-	-	-	100	95-100	40-75	15-35	0-15	0-5	-
57	1″ - No. 4	-	-	-	100	95-100	-	25-60	-	0-10	0-5
Note 1: Gradation Numbers 24, 25, 3, 4A and 4 are main line ballast materials. Gradation Numbers 5 and 57 are yard ballast materials.											

2.3.4.1 Maximum Density and Characteristic Gradation Curves

It is usually assumed that the “preferred” gradation is one that produces the maximum density which creates more particle-to-particle contact and thus increases the structural stability. For railroad ballast, maximizing the density will obviously minimize the function of drainage. Nevertheless, maximum density gradation still provides a datum to start with.

A widely used equation to describe a maximum density gradation was developed by Fuller and Thompson (1907) which, sometimes, is also referred to as Talbot Equation. The basic equation is:

$$P= (d/D)^{n}$$

Where:

"P" is the percentage finer than the size;
"D" is the aggregate size being considered;
"D" is the maximum aggregate size;
"N" is around 0.5 for maximum density according to Fuller and Thompson (1907).

In the early 1960s, the FHWA introduced the standard gradation chart used in the HMA industry today. This graph uses n = 0.45 and is convenient for determining the maximum density line and adjusting gradation (Roberts et al., 1996). This graph is slightly different from other gradation charts because it uses the sieve size raised to the nth power (usually 0.45) as the x-axis units. Thus, the maximum density line appears as a straight line from zero to the maximum aggregate size for the mixture being considered (solid line in Figure 2.6).

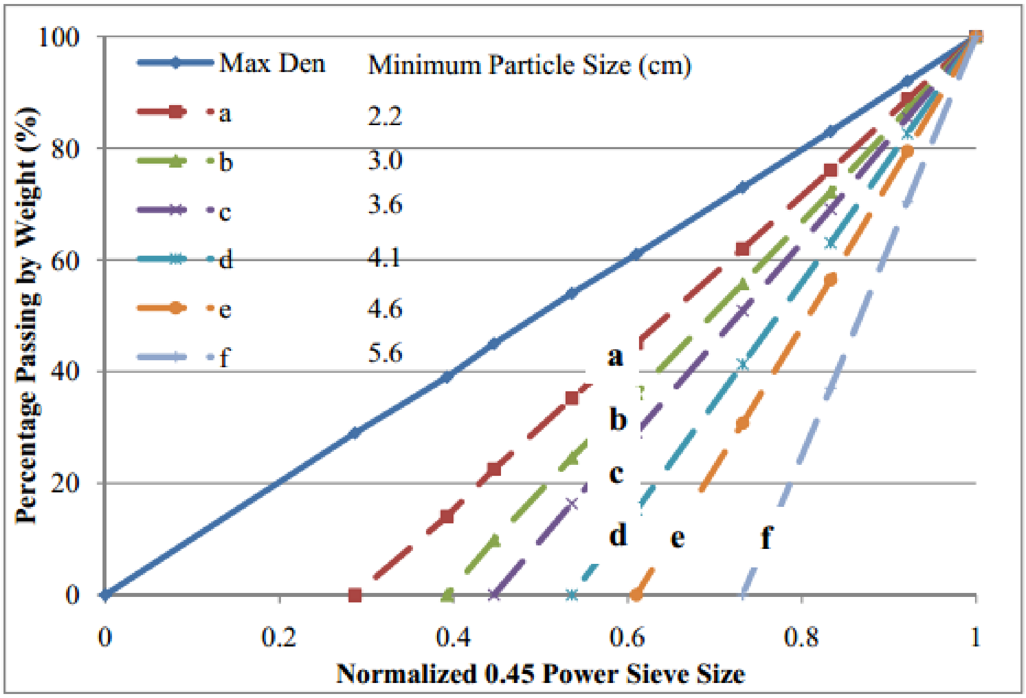


Figure 2.5 Normalized 0.45 Power Gradation Test (Source: AREMA, 2000)

The diagonal solid line in the above Figure is the normalized gradation commonly considered as the gradation that produces the maximum density. From this maximum density line, one can calculate the weight percentage corresponding to any particles size, thus prepare a particle size distribution with maximum density and stability.

2.3.4.2 Commonly used ballast gradations

Although ballast is normally treated as uniformly graded material, there are different gradations for ballast around the world. Figure below shows typical ballast gradations used in Australia (china and Queensland), in France, and in the US (the AREMA No. 24, No. 3, and No. 4 gradations).

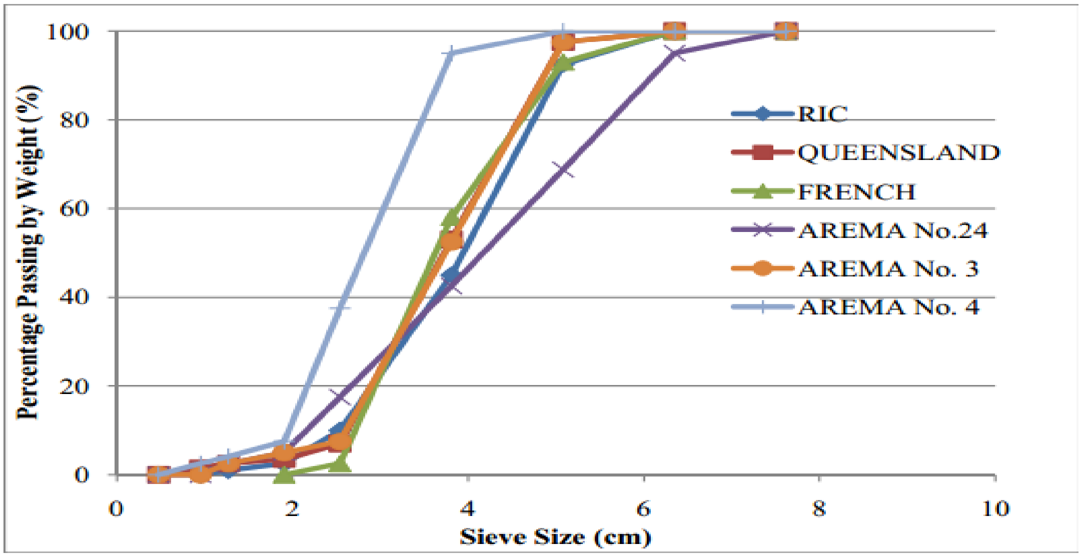


Figure 2.6 Common ballast gradation (Source: AREMA, 2000)

For Ethiopian railway construction at present the china gradation standard has begun adapted and the size of railway ballast particles is set according to the size of sieve meshes representing the following values:

- 16 mm – minimum value and 63 mm (it can be also 50) – maximum value.

Table 2.2 Ballast stone gradation test standard used for Ethiopia national and AALRT ballast construction track adapted from china [from AALRT laboratory]

Test item		Standard code	Test result	
			Side length of the sieve opening(mm)	Mass of aggregate passing the sieve (100%)
Particle size grading	**16mm**	0~5	**16mm**	0
	25mm	5~15	**25mm**	4
	35.5	25~40	**35.5**	24
	45mm	55~75	**45mm**	61
	56mm	92~97	**56mm**	94
	63mm	97~100	**63mm**	100

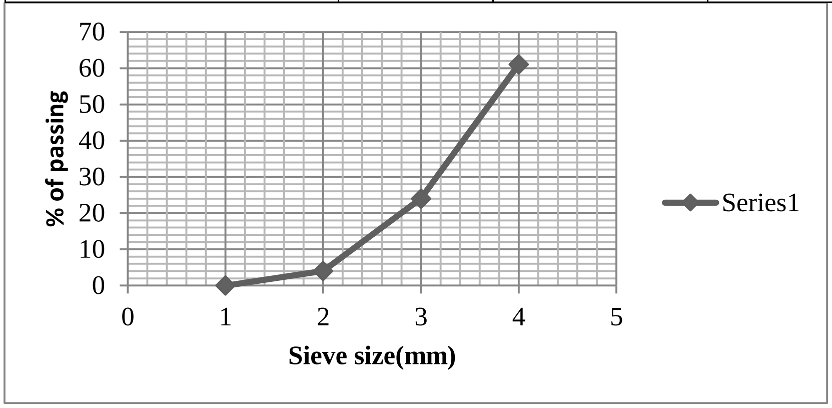
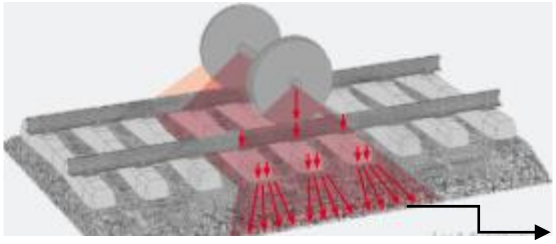


Figure 2.7 China Standard Gradation for Ballast (adapted from china railway manual)

2.3.5 Ballast bed vibration

Ballast flying is influenced by the ballast bed acceleration, with the ballast bed increasing, the ballast flying possibility and severity increases. Hence, the ballast bed acceleration and vibration reduction and optimization methods are used to reduce or terminate the ballast flying phenomena. The vibration of the railway is the key factor to cause track geometry change and increase of track maintenance cost. The effect of friction and impact of ballast induces a counteracting motion of adjacent ballast blocks, so that the vibration level of one ballast block will be attenuated by the adjacent blocks. If the shearing effect is not considered, this attenuating effect is absent. Thus the ballast mass can vibrate more freely and its vibration level will be overestimated. On the other hand if higher shear stiffness and shear damping of the ballast are adopted, it implies that the stronger attenuating effect between neighboring ballast blocks is considered, which result in less ballast vibration. It can be conclude that the ballast shearing parameters have great influence on the dynamic behavior of tracks and strongly depend on the structure and the material of the ballast (Aikawa, 2013).

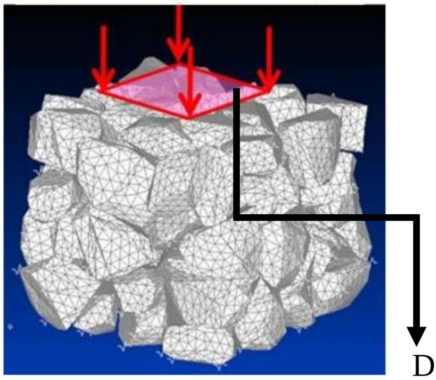


Conical Load distribution on railway ballast

Figure: 2.8 Load distribution on railway ballast

2.3.6 Ballast mass and shape

Ballast particle shape and ballast bed quality not only influence the resistance ability and stability, but also the ballast flying characteristics. Ballast aggregate are uniformly graded and angular in shape. The particle packing degree, which is governed by ballast gradation, influence the ballast performance since it determine, the distribution of aggregate particles within the ballast structure and hence the interaction of aggregates in distribution of applied stresses



Distribution of applied stresses on ballast aggregate

Figure. 2.9 Dynamic load from sleeper on ballast (Aikawa, 2013)

2.3.7 Track response

Several research studies have explored the behavioral response of ballast subjected to the dynamic load of the train (Luo, Yin, & Hua, 1996). It was noted that under certain loading conditions, the particles at the surface of the track would become weightless, meaning that the reacting forces applied to the particle would be large enough to overcome any gravity forces. Closely related to the transit design are the effects of the bogies. The distances between wheels sets and between bogies can change the load input frequency to the track, thus causing different responses of the track. Several models are available to characterize the response of the track structure due to the exciting loads imparted by the train. Models are accurate in predicting the behavior of track as a whole, but little information was found in attempting to explain the initiating mechanism of ballast displacements.

2.3.8 Ground condition

It is important to consider the response of the sub-ballast and subgrade to loadings coming from the train as well as loadings produced by natural events, such as mild seismicity. Small magnitude earthquakes, while not felt directly by humans, can on the other hand produce an input ground motion to the ballast layer, thus causing some vibratory effects. The vibrations may not be visible, in other words, the ballast particle may not move. Still, the ballast particles lying on the top layer of the ballast crib could become sensitive to the input ground motions sparked by the minor earthquake. Earthquakes of magnitude 3 or less normally do not cause a slowdown of operations, since there is not enough energy released to cause any damage to the track structure itself. A second factor of risk related to the ground conditions can be found in the different response of the sub-ballast layer. A hot mix asphalt layer presents a different dynamic response to that of an unbound aggregate or other stabilized material. Furthermore, one has to consider the areas of track transitions such as from an embankment to a viaduct/tunnel or a bridge approach. Transitions of the track substructure have an effect in terms of the differential settlement and change in the stiffness, thus a different type of response.

2.3.9 Atmospheric conditions

While it may not be considered relevant to the study of ballast particles in motion, atmospheric events might play a role in setting the right conditions for a particle to be picked up by a passing train. While several previous research studies discuss the effect of crosswinds on the body of the train, it is important to take into account the effect of those same crosswinds on the ballast structure (Baker, 2013). High winds blowing on the track could alter the arrangement of the particles laying on the surface of the tracked. This effect is particularly important with respect to smaller ballast particles present in the ballast for the reasons described previously.

High speed lines have been built under several operating environments. Extreme conditions can also cause foreign objects such as ice falling off the train to lead to ballast motions. The French Railroad Agency SNCF has conducted some experimental modeling to simulate the falling of ice from a moving train. As the train travels in cold and freezing climates, ice can buildup in the covering region of the wheel set (Saussine, G., Allain, E., Paradot, N., & Gaillot, V., 2011)When a train, for example, goes through a tunnel and experiences a temperature change, the ice may start melting, thus falling off the train.

2.4 Causes of Ballast Flying on Railway Track

During passage of a high speed train, ballast particles become detached from the ballast bed. A particle on the rail which is crushed by a train causes rail defects which are difficult to repair and Causes damage to under carriages and exposed equipment on trains unless protection is provided and it also cause track settlements and deterioration. On railroad, particularly high-speed main lines, keeping ballast off ties is important because the section created by passing train can cause the ballast to fly around, potential damaging equipment (train body) and rail head damage. the ballast flying cause the following effect.

- Rail defects
- Train body damage
- Track settlement
- Track deterioration
- track lateral instability

2.5 Counter Measures for Railway Ballast Flying

To prevent the ballast flying phenomena the corresponding engineering method or possible measures are proposed and recommended as follows.

2.5.1 Increase the surface ballast interlock ability

The ballast flying can be reduced or eliminated with ballast particle interlock ability between ballast particles, especially the surface layer ballast particle. Several methods can be used to improve the ballast particle interlock force such as:-

The ballast compaction (tamping) is practical method; such as ballast bed well compacted, squeezed and pressed. China high speed railway ballast bed standards require ballast density not less than 1.75g/cm3 to assure ballast compaction as well as the interlock. The ballast surface roughness or texture; is considered to increase the ballast particle interlock or friction (Erol Tutumluer , Hai Huang,Youssef Hashash and Jamshid, 2006).

Increase the ballast particle interlock force using binding bitumen between ballast particles; which substantially increase the interlock force.

2.5.2 Reduction of ballast bed vibration

Ballast flying is influenced by the ballast bed acceleration, with the ballast bed acceleration increase; the ballast flying possibility and severity improve. Hence, the ballast bed acceleration and vibration reduction and optimization methods are used to reduce or terminate the ballast flying phenomena.

From the design or operation stages, we could alter the sleeper type, distance, fastener, rail or sleeper pad, ballast mat, ballast depth and density and so on. For example, increase the sleeper mass, increase the rail pad elasticity, ballast mat application reduce the sleeper and ballast vibration. There is a unique condition should be noted, during ballast spreading or tamping, the ballast particles are easily fell on to the sleeper surface. In the cases, sleeper vibration is 10-20 times of ballast bed, far bigger than the gravity g, so based on the ballast flying possibility is relatively higher than normal ballast bed case. Furthermore, the ballast vibration distribution affect the results, for example, the surface ballast particles along or adjacent to the sleeper, with fierce vibrations and less interlock restrict, which are easily flying off the surface than the normal sections. A case in point is that the ballast particles falls onto the sleeper will result in ballast vibration far more bigger than ballast along the sleeper, the latter normally bigger than ballast in the crib, it is possible to take correspond measures for counteracting.

2.5.3 Application of asphalt in railway construction to reduce bed vibration of ballast

The properties of bitumen and asphalt offer good opportunities to apply this type of material in railway track construction. This has been proven in various applications, both for heavy loaded tracks and for high-speed tracks. The use of asphalt in railway construction provides a positive contribution to the bearing capacity of the structure. It improves both the stability and the durability of the structure, which contributes to the reduction in the need for maintenance. In addition, the use of asphalt also helps to reduce vibration and noise (Association, 2003).

The mechanical properties of the asphalt layer will lead to a reduction in the vibrations and noise produced by passing trains. The use of modified asphalt (polymer modified bitumen, rubber crumb) can further improve the vibration dampening effect of the sub-ballast (Erol Tutumluer , Hai Huang,Youssef Hashash and Jamshid, 2006).

2.5.4 Track stability using ballast bonding method

Stabilization of ballast bed using ballast bonding is a method that bonds ballast stones at their edges and contact points. To accomplish the expected bonding of ballast stone, beside the correctly used bonding procedure, the following conditions have to be met (Prof.stjepan lakusic,Maja Ahac and Ivo Haladin, 2010).

- properly construction of the subgrade
- mud free and well compacted ballast bed and
- proper track geometry

Two basic methods of ballast stabilization of ballast bed using bonding. Those are surface and structural bonding. The difference lies in the thickness of the stabilized layer.

a) Surface bonding: the purpose of surface bonding is to prevent movement of ballast stone in the surface area of the ballast bed. The goal is not increase its mechanical bearing properties. The main reasons for such a solution are:

- Prevention of lifting the smaller ballast stone by high speed trains.
- Easier surface maintenance of ballast bed.
- Lateral stabilization of ballast bed for the purpose of reconstruction works.

b) Structural bonding: The main purpose of structural bonding is to enhance the mechanical properties of the ballast bed, namely, to include the adhesive in load transfer. Structural bonding is used for:-

- used as transitional areas between the classical ballasted track and rigid track way(like bridge, tunnel and level crossings
- Tight curves with small radius to prevent lateral displacement of track.
- Improvement of track bearing capacity.

CHAPTER 3 CHARACTERIZATION OF RAIL WAY BALLAST FLYING

3.1 Introduction

The ballast flying phenomena requires at least two stages or conditions, an initial suspension or displacement of ballast particle and a subsequent movement onto the rail head or wheels, which is involved with train dynamic and ballast particle individually. The ballast particles flying problems caused reasons and influence factor include: sleeper dynamic force induced by train load, ballast material property, and together with lateral winds by train.

3.2 Modeling of Ballast Flying

Continuum based method such as Finite Element Method (FEM) used for track analysis can hardly simulate the behavior of a particulate assembly such as the ballast layer to properly address problem related to track flying, lateral stability, and settlement. In a ballast layer, individual aggregate particles move independently and interact only at contact points. Such discrete nature of the medium results in a complex behavior of the granular assembly, which is very difficult to model by continuum theory used in the FEM .In addition, dilation, inter-particle sliding and nonlinear stress dependent behavior of granular materials with typical anisotropic stiffness and deformation properties under vertically induced load application are almost impossible to be adequately modeled using the continuum approach.

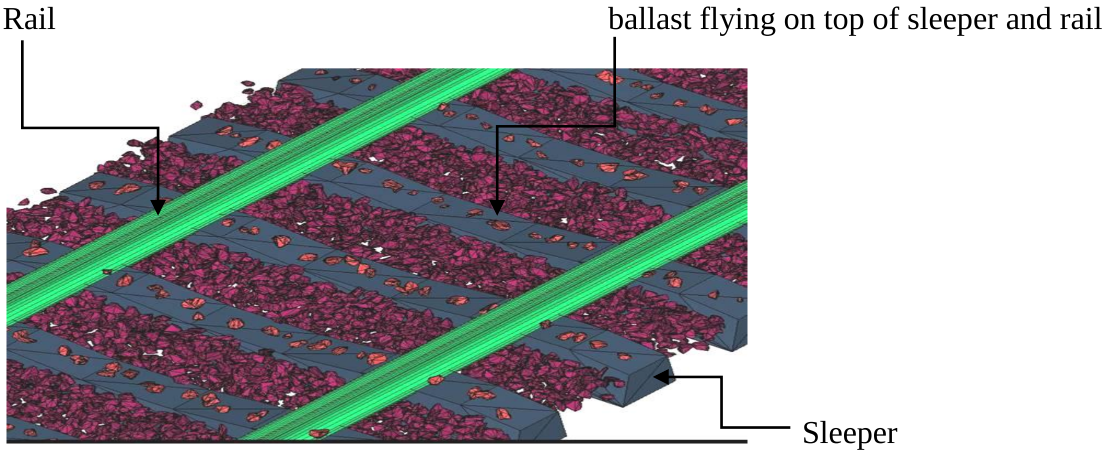


Figure 3.1 Track model created by DEM computation

Ballast and sub ballast are typically modeled as load distributing materials. Ballast material particularly deflects in highly nonlinear manner under load due to voids at the sleeper ballast inters face and ballast itself. Despite this ballast beds are often modeled as discrete or distributed linear spring and viscous dampers in the vertical direction. The mass properties of ballast bed are also important; however the amount of mass that should be incorporated in dynamic load is difficult to estimate. Another possible model represent the ballast and subgrade together as an elastic or viscos - elastic half space which consider the fact that track is supported over the number of sleeper rather than single sleeper.

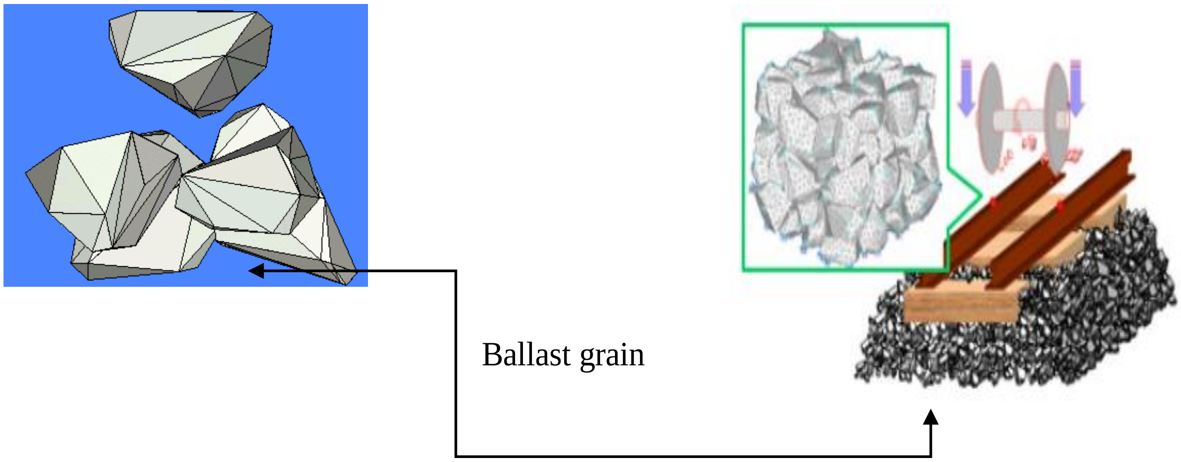


Figure 3.2 Ballast grain modeling (DEM)

3.3 **Analysis of Rail Way Ballast Flying**

Ballast piece abrasion, breakage and movement are major influences in ballast degradation, which are related to impact loads originating at the interface between rails and the wheels of passing trains. Each of these influences induces two different types of motion within the ballast layer. One is displacement in the low-frequency domain due to rigid-body motion, which is characterized by the low-frequency bounce mode determined from body weight and ballast elasticity (originally caused by deflection motion occurring when a heavy axle passes over the rail). The other is elastic vibration in the high-frequency domain, which is generated by elastic wave propagation inside ballast solids (originally caused by impulse waves generated from the mechanism of rolling contact between wheels and rails).As ballast flying indication needs the ballast material factor and flying conditions. From ballast flying source, it is related with single particle, but also railway ballast bed structure, such as gradation and geometry shape.

3.3.1 Mathematical Modeling of Railway Ballast Flying

The ballast particle is vertically analyzed and characterized by the equation:-

M_g, F_i, F_w, F_a

Where,

Mg= is gravity by mass

F_i =is ballast particle interlock force

F_w= High speed train resulted wind force acted on the ballast effective surface and

F_a= is force corresponding ballast acceleration due to bed vibrations

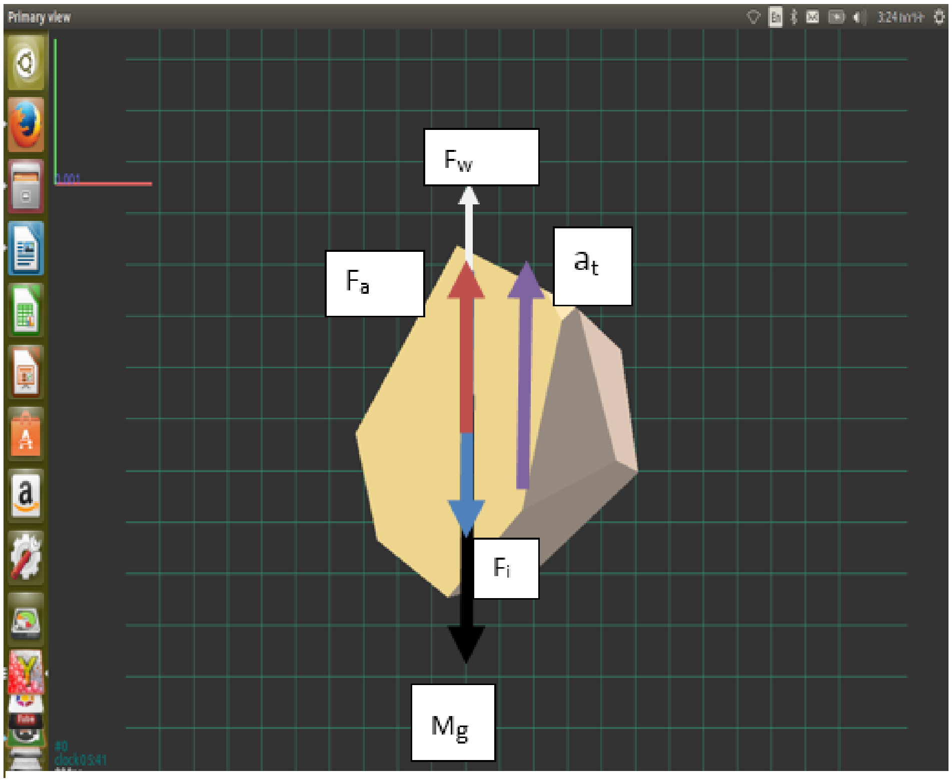


Figure 3.3 Ballast mechanics modeling by YADE

Based on the Alembert principle, the equation for ballast particle balance is (G.Q Jing1, Y.D Zhou1, Jian Lin1, J. Zhang2*, 2012).

$F_w + F_a = m_g + m_a + f_i$ ……………………..….. *(1)*

For engineering safety consideration, the ballast particle interlock force F_i assumed to be zero the then the formula (1) above can be simplified as:

$F_w + F_a = m_g + m_a + f_i$

$m_{at} = F_w - m_g + F_a$

$m_{at} = F_w - m_g + m_a = F_w - m\,(g - a)$ ……………….. *(2)*

Where a is ballast particle vertical acceleration caused by sleeper induced dynamic responses. Based on aerodynamic s, the ballast particle force can be calculated by:

$Fw = \int_0^A \int_{V1}^{V2} f(A) f(V)\, dA dV$……………………….. *(3)*

Where;

A =is wind loads effective area of ballast particle,

V1 & V2=are the points where the ballast particle interaction beginning and ending of wind speed. Due to wind speed calculation complexity, take wind pressure α, and then the above calculation became:

$Fw = \alpha \int_0^A f(A) f(V)\, dA dV$……………………….. *(4)*

Then inserting the equation (4) into (2)

$m_{at} = \alpha \int_0^A f(A)\, dA (x + a)^n = \sum_{k=0}^{n} \binom{n}{k} x^k a^{n-k} - m(g - a)$……………………….. *(5)*

$a_t = \frac{\alpha \int_0^A f(A)\, dA}{m} - (g - a)$……………………….. *(6)*

From equation (6), the part to evaluate the ballast shape are divided by the mass

$a_t = \alpha \int_0^A \mathrm{f(A)dA} / m$……………………….. *(7)*

3.3.1.1 Illustration

Table 3.1 Ballast parameter value for mathematical analyses (adapted from AALRT laboratory)

Parameter	**Value**
Ballast mass(g)	50,100,150,200,150
Gravity(m/s2)	9.18
Ballast particle vertical acceleration(m/s2)	0,4,8,12,14.16
Train speed (km/h))	60,120,300,350,
Wind load (KN)	20

Using;

$$\mathrm{a}_t = \frac{\alpha \int_0^{\mathrm{A}} \mathrm{f(A)dA}}{\mathrm{m}} - (g - a)$$

Where;

A = is wind loads effective area of ballast particle

m = mass of ballast particle

g = gravity force

a = ballast acceleration

a_t =ballast particle vertical acceleration

$a_t = \frac{\alpha \int_0^{20} f(20)dA)}{50} - (9.81 - 0) = \frac{0.5*20}{50}$ - *(9.81-0) =1.962* *where* $\alpha = 0.5$

$a_t = \frac{\alpha \int_0^{20} f(20)dA)}{50} - (9.81 - 4) = \frac{0.5*20}{50}$ - *(9.81-4) =1.162*

$a_t = \frac{\alpha \int_0^{20} f(20)dA)}{50} - (9.81 - 8) = \frac{0.5*20}{50}$ - *(9.81-8) =0.362*

$a_t = \frac{\alpha \int_0^{20} f(20)dA)}{50} - (9.81 - 12) = \frac{0.5*20}{50}$ - *(9.81-12) = -0.438*

$a_t = \frac{\alpha \int_0^{20} f(20)dA)}{50} - (9.81 - 14) = \frac{0.5*20}{50}$ - *(9.81-14) = -0.838*

$a_t = \frac{\alpha \int_0^{20} f(20)dA)}{50} - (9.81 - 16) = \frac{0.5*20}{50}$ - *(9.81-16)= -1.238*

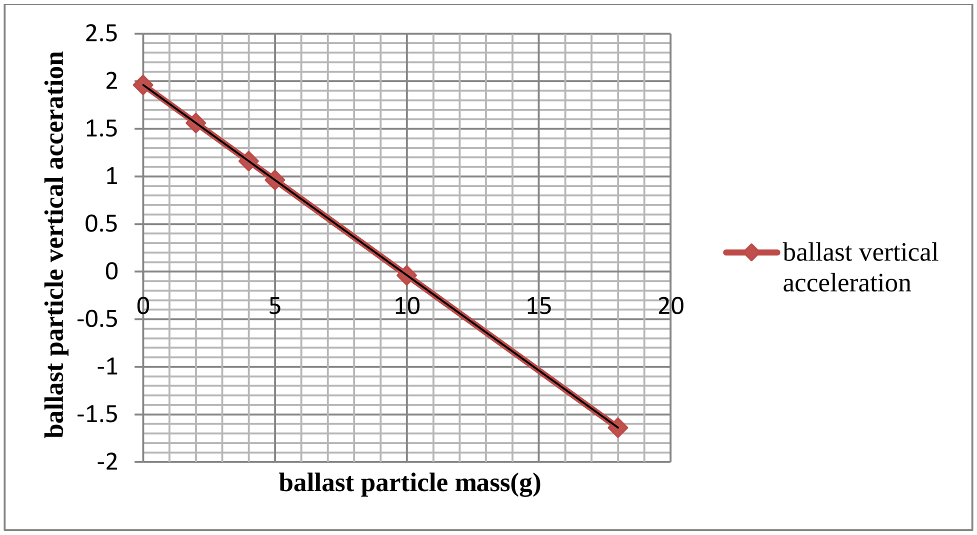


Figure 3.4 Mathematical analyses of ballast flying

The a_t indicator reflects the particular ballast particle state of balance. For example, under certain train speed, the dynamic response of ballast bed acceleration induced by the sleeper, if the $a_t < 0$ for the certain surface ballast particles, then illustrate the ballast particles are stable and free of ballast flying; if $a_t=0$ proves to belong to the critical state of stability, the corresponded train speed is the critical speed (simultaneously, the critical wind speed); and if the $a_t>0$ which results in the possibility of ballast flying phenomena accordingly. Furthermore, the left side of)(g–a) is a constant value for ballast particles under certain train and track conditions, which are train dynamic response interactions with track structure, can be measured and analyzed, for example, by the acceleration apparatus added on the surface ballast layers., which governs ballast stability balance state, included the wind load effective area, the ballast particle mass, all these factors influenced by ballast shape, ballast density, ballast size etc. furthermore, they have relationship with ballast compaction, ballast bed geometry and ballast gradation.

The wind load, effective area, the ballast particle mass, all these factors influenced by ballast shape, ballast density, ballast size etc. furthermore, they have relationship with ballast compaction, ballast bed geometry and ballast gradation. Especially Equation (7), under the constant valueα, the value has direct influence to determine the ballast particles stability, and this value can be defined as ballast flying shape mass ratio, it clearly demonstrates that different high speed train corresponds to determined value of shape mass ratio.

Equation (6) could be explained by the form Equation (8), where the volume of can be calculated with the integral of surface area multiplied with the thickness of the ballast, or flatness.

$$a_t = \frac{\alpha f(A)}{\int_{Z1}^{Z2} A(Z)dZ} - (g - a)\,Z \text{ ....} \quad (8)$$

It could be roughly taken that the A (Z) and f (A) are equal to some extent, with which

$$a_t = \frac{\alpha}{p\int_{Z1}^{Z2} dZ} - (g - a) \text{ ....} \quad (9)$$

Where (g − a) (is determined and known values when the train speed and ballast bed vibration constant depend on ballast particle position, density, shape etc.

3.3.2 Modeling ballast flying using discrete element method (DEM)

The Discrete Element software (DEM) is a discontinuous approach and a powerful numerical tool for computing the motion of a large number of particles such as granular material. The DEM was first introduced by Cundall (1971) for the analysis of rock mechanics problems and then applied to soils by Cundall and Strack (1979). Different from traditional continuum computational method, in DEM each element is separated and can have independent movement. All particles are assumed rigid bodies and the interaction only happens at contacts or interfaces between these bodies. Behavior at the contacts uses a soft-contact approach and rigid particles are allowed to overlap one another at contact points. According to the force-displacement law, the overlap in every contact will generate an interaction force between particles. A set of contact forces acting on the particle and the external stresses (like gravity) will cause the motion of particles which is calculated by the Newton’s second law. The motion of particles consequently change the contact situation and results in the changes of contact forces between particles, which continually bring about new motion of particles

DEM was used in modeling of ballast interaction using the computer code **PFC$^{\mathbf{3D}}$**developed by ITASCA CONSULTING group. The objective of this computational work was to gain an understanding of the micro-mechanics of ballast interaction which complemented experimental work.

These methods are able to analyze multiple interacting bodies undergoing large dynamic movements. By modeling the individual particles and computing their motion, the overall behavior of the granular assembly, which may include unrecoverable deformations, dilation, post-peak behavior, and anisotropy, is modeled implicitly. Interaction of granular materials or rock masses can be modeled accurately and realistically using DEM, since any discontinuous detail can be included in the analysis. The DEM is believed to be one of the most promising tools to simulate ballast behavior. This paper also uses DEM modeling to show flying of ballast on railway track.

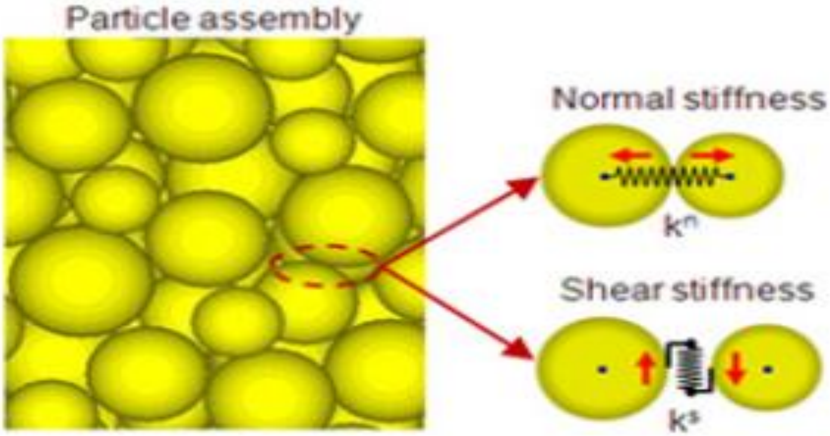


Figure 3.5 DEM particle assembly and example of mechanical contact point

The Discrete Element Method (DEM) is also a numerical method used to compute the stresses and displacements in a volume containing a large number of particles such as grains of sand. The granular material is modeled as an assembly of rigid particles and the interaction between each particle is explicitly considered. The particle shapes and geometries are specified by the user. Spheres or ellipsoids are commonly used. The contact dynamic approach is suitable to simulate very dynamic processes without new calibration of numerical parameters (restitution coefficient or friction).

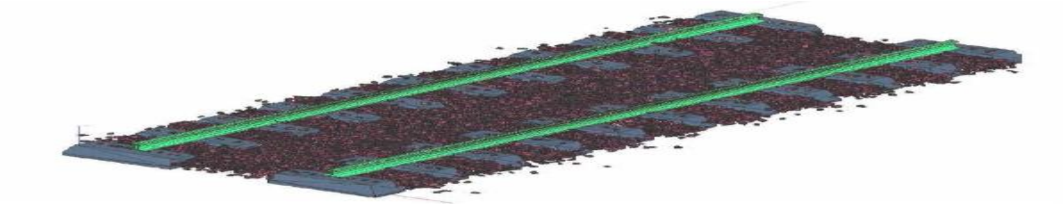


Figure 3.6 DEM Particle assembly and example railway track model

3.3.2.1 Basic DEM and Collision Theory

When two moving objects collide; an impulsive force results which alters the velocity of one or both of the objects. The moving objects have momentum energy as well as potential energy due to their elevation.

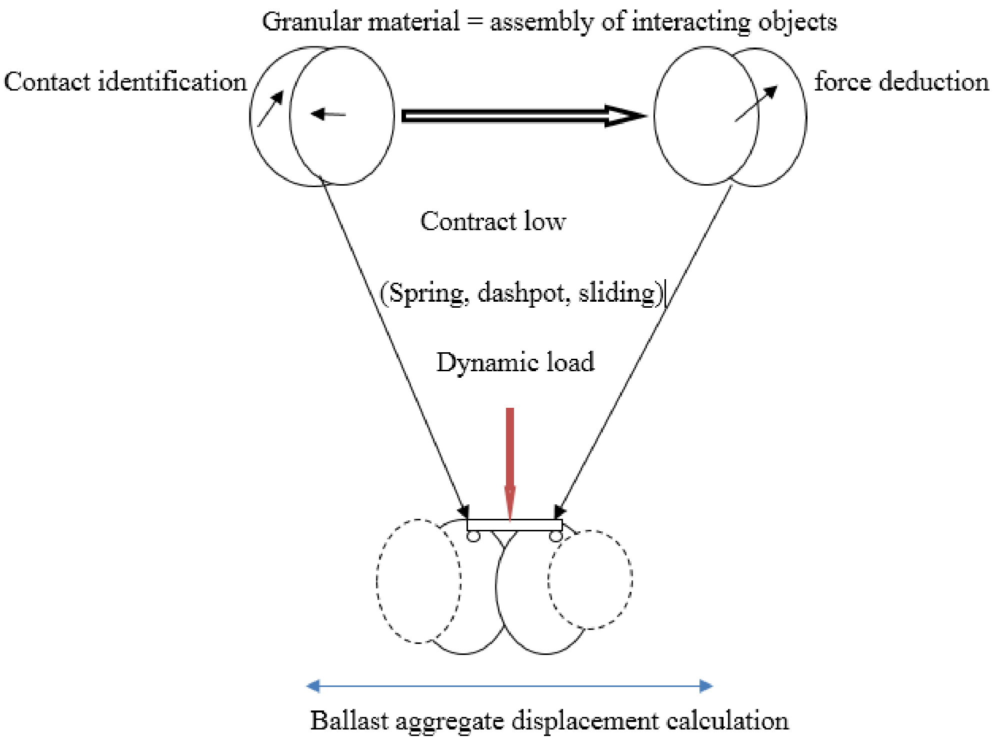


Figure 3.7 DEM collision Theory (ITASCA CONSULTING, 2013)

In order to simplify the calculation process, discrete element method usually uses the following assumptions:

(1) All particles are considered as rigid bodies and the geometry of particles will not change under the extrusion force between particles. The deformation of particle system is the summation of deformations in contact points of all particles;

(2) The contacts between particles happen at a tiny small area, i.e. contact at point;

(3) The contact behavior of particles is soft contact which allows some overlap in the contact points between rigid particles. The value of the overlap in each contact can be determined by force

displacement law. Compared with the size of particles, the overlap between particles is small and it is also much smaller than the translation and rotation of particles;

(4) The interaction only happens at contacts between particles and the time step should be small enough to make sure that each particle only has force effect on its contacted particles and will not affect other particles.

(5) The values of speed and acceleration are constant in each specific time step and single rigid particle motion is predicted by Newton's second law of motion.

(6) Time step chosen is so small that, during a single time step, disturbances cannot propagate from any particle further than its immediate neighbors. Then, at all times, the forces acting on any particle are determined exclusively by its interaction with the particles with which it is in contact.

Railroad ballast layers are actually particulate media where individual aggregate particles are surrounded by other particles in contact with air voids in between. When ballast is strained due to rail buckle and train wheels, motion takes place that may involve one or all of the following modes:

- Inter-particle slippage,
- Particle rotation, particle separation, and
- Even fracture at particle contacts

An incremental force law is applied from F = ma or a = F/m

The magnitude of the force acting on the particle depends on the normal stiffness used as well as the size of the time step. If increase the time step d_t, need to reduce the normal stiffness K_N in order to replicate the movement of the particles realistically. Also, as the diameter of the particles changes, the mass of the particle changes in proportion to the radius cubed. It is this force which prevents the particles from overlapping as it forces them apart.

So, the movement of the particles depends on

- Mass of particle which depends on diameter and density
- Normal stiffness K_N
- Size of time step d_o

For any given particle density, diameter and time step, the normal stiffness K_N has to be adjusted to give realistic results.

Using the DEM ballast model, individual effects of aggregate particle size distributions and shape properties on railroad ballast strength, lateral stability, and settlement potential were studied. From the DEM simulation results, it was found that aggregate particle size distribution and shape have significant impact on ballast performances. Ballast with broader size distribution was shown to yield less settlement potential than ballast with more uniformly graded aggregates. Also, ballast with angular aggregate particles were found from the DEM simulations to have higher strength as well as better lateral stability than ballast with rounded aggregate particles due to better stone on stone contact and aggregate interlock

In a typical DEM simulation, the following sequence is run repeatedly:

- reset forces on bodies from previous step
- approximate collision detection (pass 1)
- detect exact collisions of bodies, update interactions as necessary
- solve interactions, applying forces on bodies
- Apply other external conditions (gravity, for instance).
- change position of bodies based on forces, by integrating motion equations

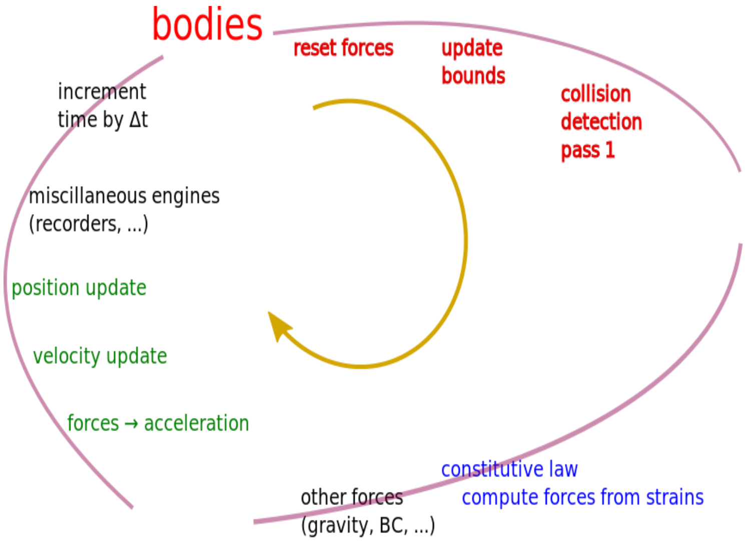


Figure 3.8 Typical DEM simulation loop; (ITASCA CONSULTING, 2013)

The interaction forces between two particles are represented by damped spring in the normal direction and spring in series with frictional slider in the tangential (shear) direction.

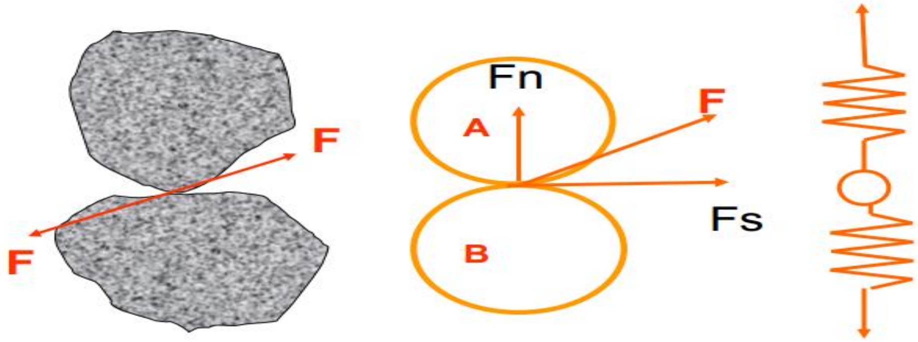


Figure 3.9 Damped Spring; Models railway ballast load distribution (Erol Tutumluer,Hai Huang,Youssef Hashash and Jamshid Ghaboussi, 2010)

Basic DEM interaction defines two stiffness and normal stiffness K_N and shear (tangent) stiffness K_S. It is desirable that K_N be related to friction and Young's modulus of the particles' material, while *KS* is typically determined as a given fraction of computed K_N. The K_S/K_N. ratio determines macroscopic Poisson's ratio of the arrangement which can be shown by dimensional analysis. Elastic continuum has two parameters (E andν) and basic DEM model also has two parameters with the same dimensions K_N andK_S/K_N. Therefore, macroscopic Poisson's ratio is therefore determined solely by K_S/K_N and macroscopic Young's modulus is then proportional to K_N and affected byK_S/K_N.

$$KS = \frac{Ks[A]Ks[B]}{Ks[A] + Ks[B]}$$

$$Kn = \frac{Kn[A]Kn[B]}{Kn[A] + Kn[B]}$$

Where, K_N = normal stiffness

K_S = shear stiffness

The acceleration forces individual of each particle is computed by the net force caused by interaction among neighboring particles. Having found the acceleration, the particle velocity and displacement are computed for each step using explicitly integration Newton Law of Motion.

Limitation of discrete element method

- Can only use spherical particle to model ballast aggregates us default.
- Particle rotation becomes dominant in contact between particles due to the spherical shape.
- Calculation time is relatively long.

3.3.2.2 Using PFC^{3D} for simulation of ballast flying

PFC^{3D} is chosen as an example to explain the major model parameters used in DEM which are:

(1) Element shape, size, and gradation; and

(2) Parameters describing contact between two elements. Element shape, size, and gradation

As shown figure 3.10 contacts between two elements in PFC^{3D} consists of three parts:-

(1) Normal spring which control the relationship between normal contact and the relative displacement perpendicular to the common plane.
(2) Shear spring which controls the relationship between incremental shear contact force and the movement parallel to the common plane and
(3) The surface friction angle which acts as a frictional slider and supplies friction angle between two elements in contact.

Two types of bonds are typically used in PFC^{3D} the contact bond and the parallel bond. In the contact bond model, elastic spring with constant normal and shear stiffness's, k_n and k_s, act at the contact points between particles, thus allowing only forces to be transmitted. In the parallel bond model, the moment induced by particle rotation is resisted by a set of elastic springs uniformly distributed over a finite-sized section lying on the contact plane and centered at the contact point is shown in Figure 3.10.

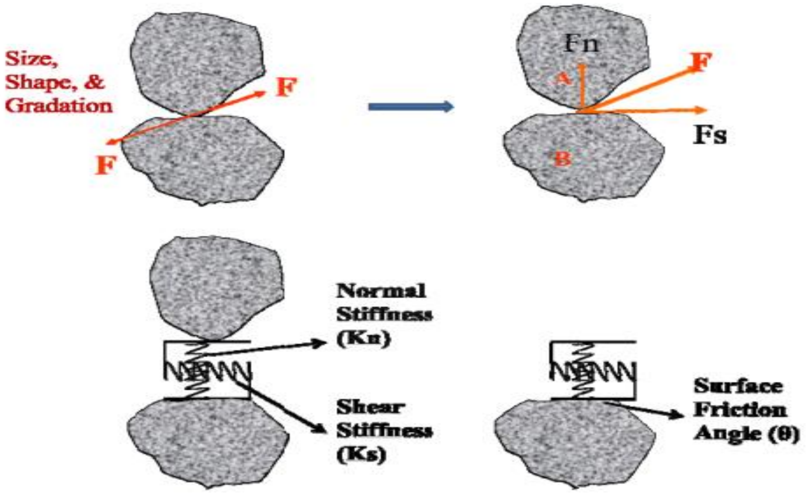


Figure 3.10 Major DEM Model Parameters

1. The effect of ballast gradation to ballast flying

A. Numerical Model

Sieve analysis is a technique commonly used to measure the gradation in particle size of a granular material. The test usually consists of shaking aggregate in nested sieves with progressively smaller mesh sizes. Table 3.2 presents the result of a sieve analysis applied to a crushed sample of ballast taken from AALRT site. The mass percentage of material within each size range is shown in

Figure 3.16.

Trial-1

Table 3.2 Ballast aggregate sieve analysis result of test for DEM input in accordance (with china standard)

Fraction[mm]	Mass%(-)of Passing
16	0
25	4
35.5	24
45	61
56	94
63	100

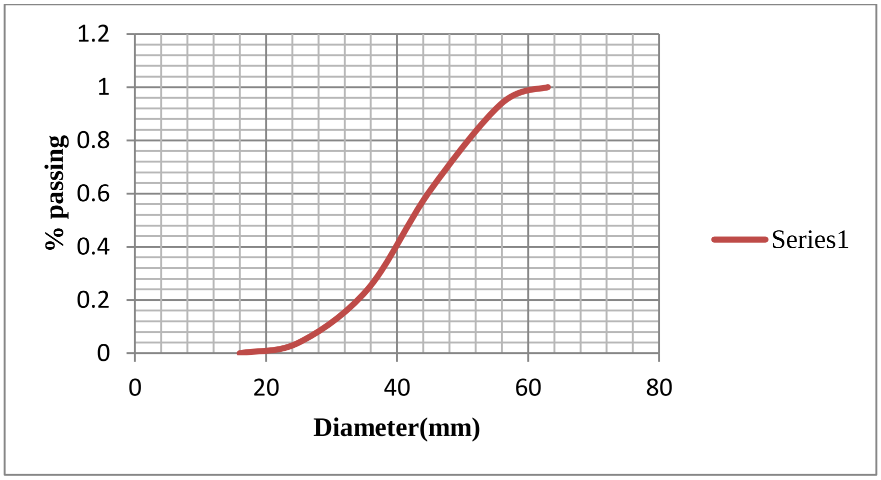


Figure 3.11 Ballast aggregate gradation plotted in laboratory (experimental)

Trial-2

Table 3.3 Ballast aggregate sieve analysis result of test for Dem input (with AREMA standard)

Fraction[mm]	Mass%(-)of Passing
16	0
25	0
35.5	45
45	75
56	96
63	100

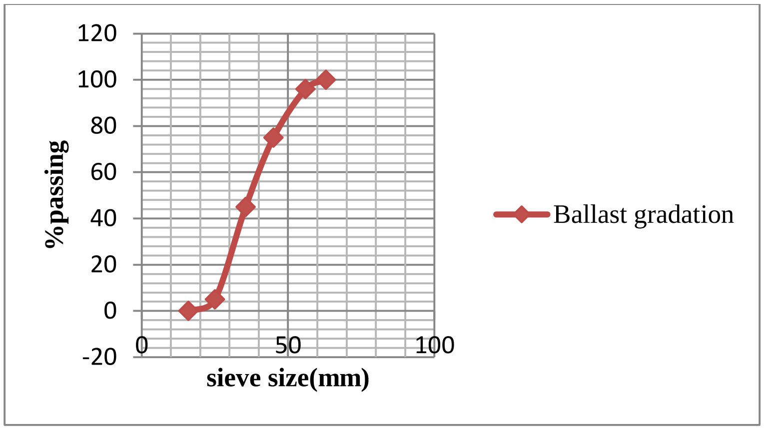


Figure 3.12 Ballast aggregate gradation plotted in laboratory (experimental)

Trial-3 (AREMA)

Table 3.4 aggregate sieve analysis result of test for DEM input (with AREMA standard)

Ballast sieve analysis results.

Fraction [mm]	Mass % [-]
0 – 30	8.3
30 – 40	8.3
40 – 50	9.4
50 – 60	8.5
60 – 75	14.8
75 – 100	20.0
100 – 120	19.5
120 – 150	8.8
150 – 180	2.1
180 – 250	0.3

In this study, the ballast gradation samples were generated (see Figure 3.16 below) and tested in accordance to the following DEM test procedure:

- Generate aggregate particles as discrete elements (K_N = 20MN/m; K_S = 10MN/m; $\theta = 31^0$) with the same angularity (AI=570, F&E Ratio = 1:1) and surface texture properties and drop them in layers, using a gravity constant of 9.8 m/s^2 (Huang, 2009).

B. Procedure for DEM input for ballast gradation

From table 4.3 of sieve analysis results is use as the basis to plot the size distribution of the sample that has been generated as code for DEM.

Table 3.5 Micro mechanical parameters of ballast adapted for DEM simulation gradation

parameters	**Ballast**
Particle density(Kg/m^3)	1500
Coefficient of friction(μ)	0.8
Contact normal stiffness(K_N)	0.52*10^8
Contact shear stiffness(K_S)	0.52*10^8
Contact normal stiffness of the wall particle k_n-wall(N/m)	1*10^8
Shear stiffness of wall of wall-particle, K_S-wall(N/m)	1*10^8

Trial-1

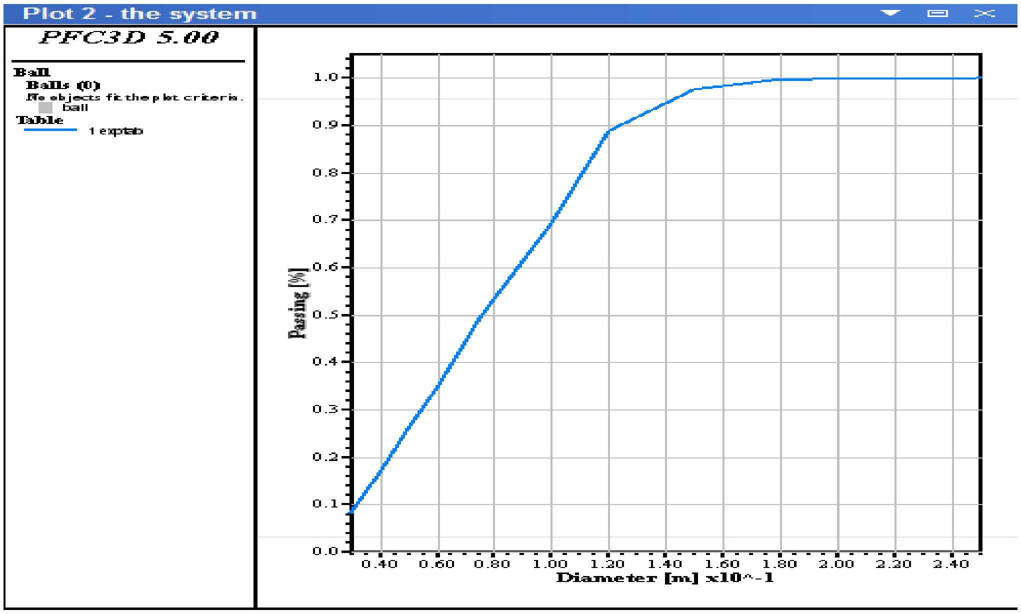


Figure 3.13 Ballast Gradations Plotted by PFC3D

Trial-2

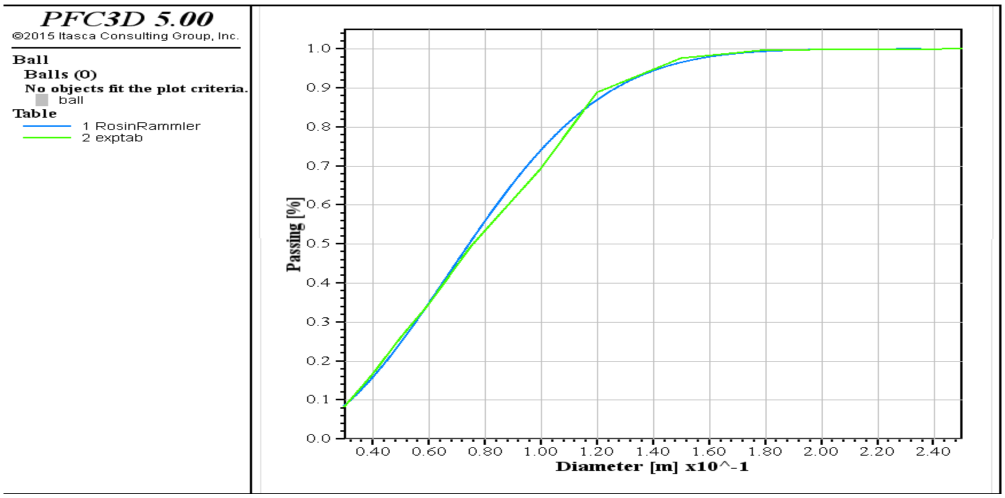


Figure 3.14 Ballast Gradations Plotted by PFC3D (experimental and Rosin rammer)

Trial-1

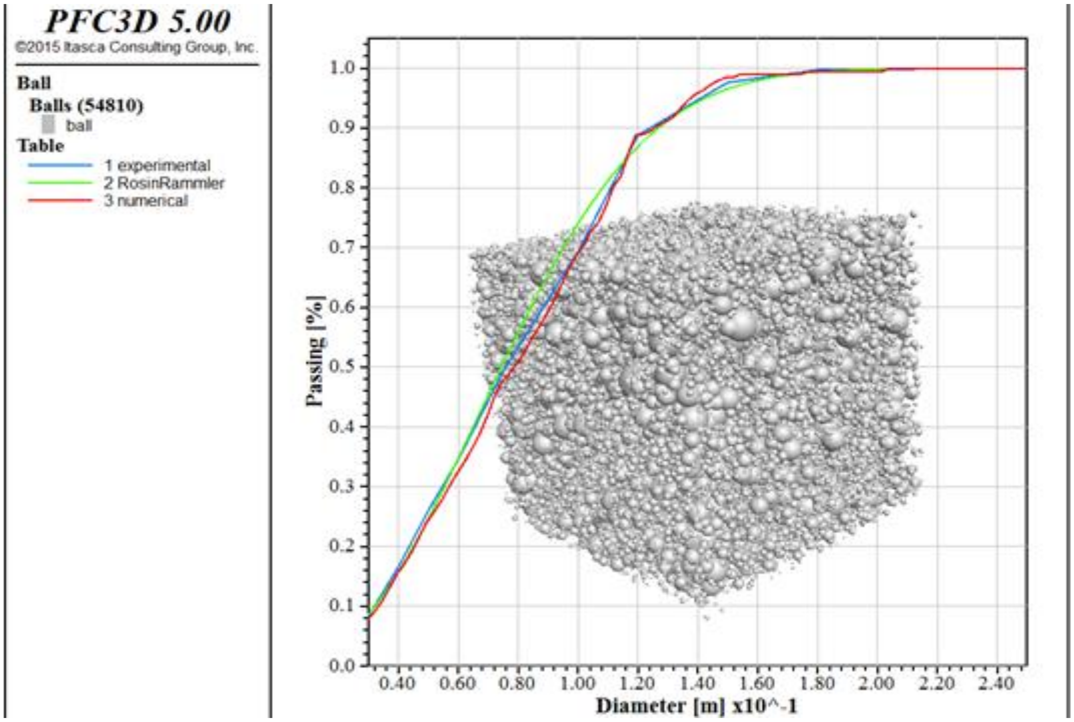


Figure 3.15 Numerical and Experimental Ballast Gradations Plotted by PFC3D.

A direct comparison with the Rosin-Rammler curve is possible for the comparison. We demonstrates that the ballast distribute command is capable of reproducing sieve analysis results. Note that the Rosin-Rammler curve has been artificially built on the base of the raw data coming from the sieve analysis. The numerical result would be closer to this curve if a higher number of bins were employed in the ballast distribute command.

Trial-2

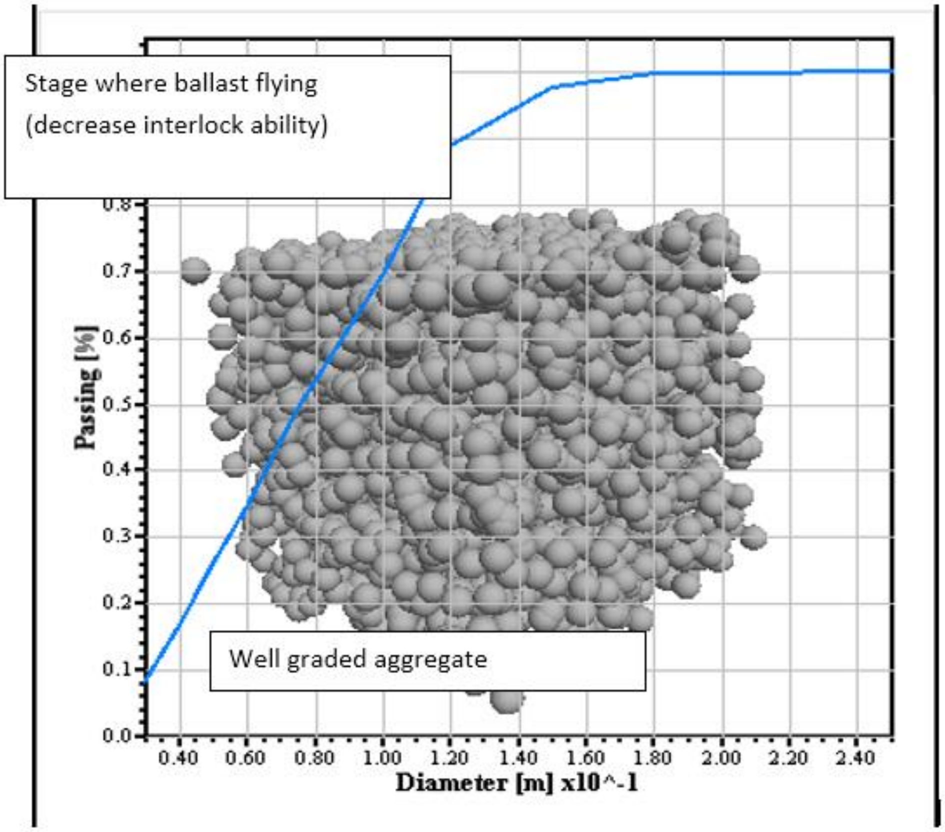


Figure 3.16 DEM Particle gradation result (using PFC3D)

C. Results and Discussion

Under this analysis the influence of gradation on ballast flying is investigated using the particle shape generation DEM method and the ballast DEM model. Mechanical behavior of ballast layers with different aggregate gradation, including those AREMA and china railway manual for gradation standard are used.

An investigation on the air voids content of ballast characteristic gradation curves revealed that more uniformly graded aggregate assemblies generally had larger air voids but higher tendencies to produce permanent deformation under repeated train loading. Although large voids are desirable for better drainage, having particles as small as 3.6 cm can still maintain large voids for drainage and provide better stability and improved resistance to permanent deformation accumulation, i.e. decreased settlement. The ballast Gradation is one that produces the maximum density which creates more particle-to-particle contact and hence increases the structural stability.

In view of the DEM study findings, it was concluded that AREMA No.24 gradation would yield the least amount of ballast flying among all the existing gradations.

According to the DEM methodology, there is also a room to further engineer current specifications, including AREMA No. 24 gradation, by optimizing the ballast aggregate sizes for a minimum allowable particle size of 3.5 cm. This would accommodate large enough air voids for drainage and also minimize the overall ballast flying early under railway track potential of the ballast layer. By adjusting the percentages of aggregates at different sizes, ballast gradations can be optimized at the microstructure level for large void space and adequate structural performance.

2. Effect of ground vibration (Ballast bed vibration)

The characteristics of dynamic loads acting on the ballast layer were examined based on the measured dynamic response during train operation at high speed. Regular discrete element (DE) analysis reveals the phenomenon of force transformation between ballast pieces due to changes in the center of gravity of each piece in a rigid body and the occurrence of sedimentary intrusion among pieces.

Considering the results of ballast behavior monitoring on existing ballasted track, the rigid-body motion and frictional sliding motion of ballast pieces alone do not fully explain the phenomenon of impact load transfer in the inner part of ballast, especially in regard to the high-frequency behavior of ballast pieces. Accordingly, to clarify propagation phenomena related to impact loads in a ballast layer, it is necessary to evaluate the characteristics of elastic deformation behavior related to angularities near contact points between ballast pieces, and to clarify the elastic wave propagation characteristics observed inside each ballast piece.

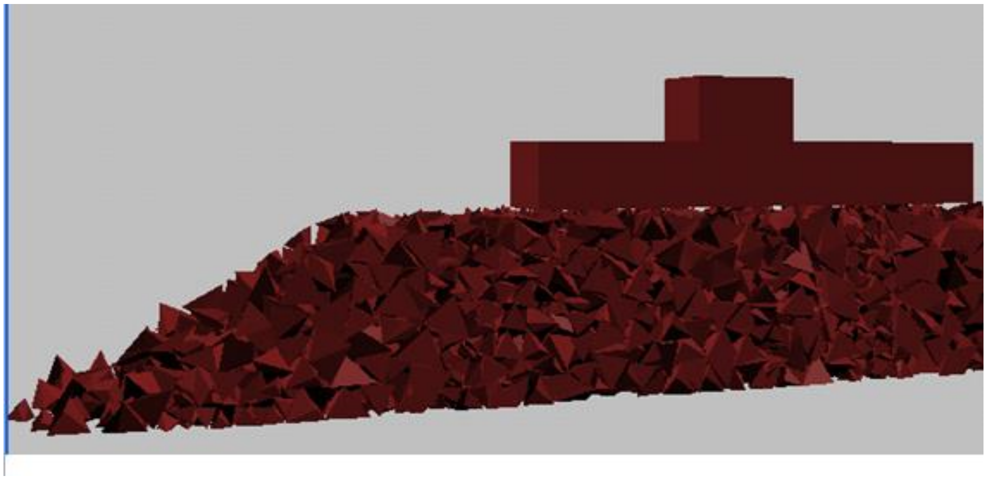


Figure 3.17 Ballast during maintenance (tamping) at initial stage.

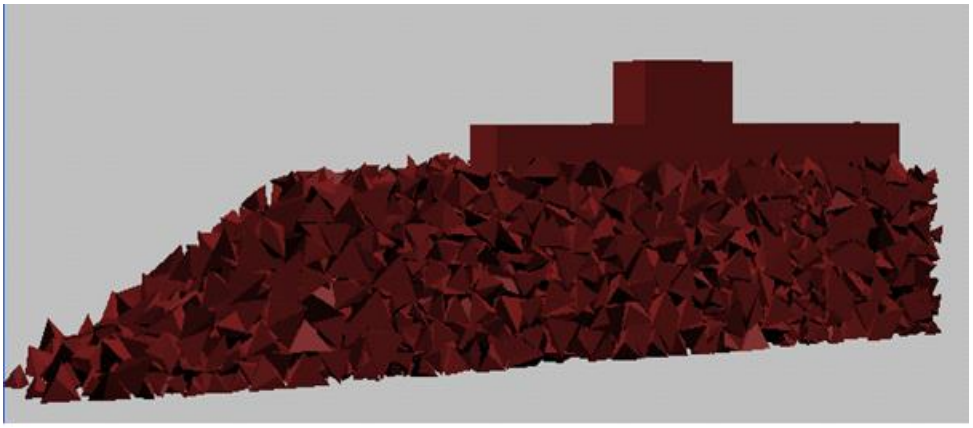


Figure 3.18 Ballast displacements during maintenance (tamping)

The load transmitted from sleeper to the ballast approximately coincides with the cone distribution. That is to say, the stresses of the ballast are uniformly distributed over cone region and zero outside of the cone. (W.M. zhai,K.Y Wang,J.H,Li).Therefore the continuous granular ballast could be modeled as a series of separated vibrating masses when analyzing the track dynamic, by which the analytical process of ballast vibration is greatly simplified.

The vibrating mass of ballast under sleeper support point could be evaluated as:

$M_b = Ph_b\ (l_e l_b + (l_e + l_b)\ h_b tg + 4/3 h_b \alpha + tg\alpha$………………………………… (1)

Where:

M_b= ballast mass

p_b= is ballast density

h_b= is the depth of the ballast

l_e= is the effective supporting length of half sleeper

lb= is the width of sleeper under side and

α= is the ballast stress distribution angle

Table 3.6 Parameters used for DEM simulation of railway ballast by PFC^{3D} (Huang, 2009)

Parameters used	**values**
Particle density(Kg/m3)	1500
Radius of particle (m)	$16*10^{-3}$-$1.8*10^{-3}$
Inter particle and wall friction(rad)	0.25
Particle normal & shear contact stiffness(N/m)	$3*10^{8}$
Side wall stiffness(N/m)	$3*10^{7}$
Top & bottom wall stiffness(N/m)	$3*10^{8}$
Parallel bond radius multiplier	0.5
Parallel bond normal and shear stiffness(N/m)	$6*10^{10}$
Parallel bond normal and shear strength(N/m)	$5*10^{6}$
Acceleration due to gravity(m/s)	9.81
Dynamic Load + static load (K_N)	125+177.6915=302.6915

A. Procedure for DEM input for ground vibration (Ballast bed vibration)

Table 3.6 of Parameters used for DEM simulation of railway ballast by PFC^{3D} and command developed are input in PFC^{3D} for the modeling. The shape of ballast which is irregularly shape and assumed as spherical particle for the analysis. Two different thickness of ballast sample are taken for the analysis after the ballast particle is created. The dynamic load applied was for both samples.

Ballast Sample – 1 (Red)	Ballast Sample – 2 (Blue)
Thickness(m) = 0.35	Thickness(m) = 0.22

Step 1: At initial stage

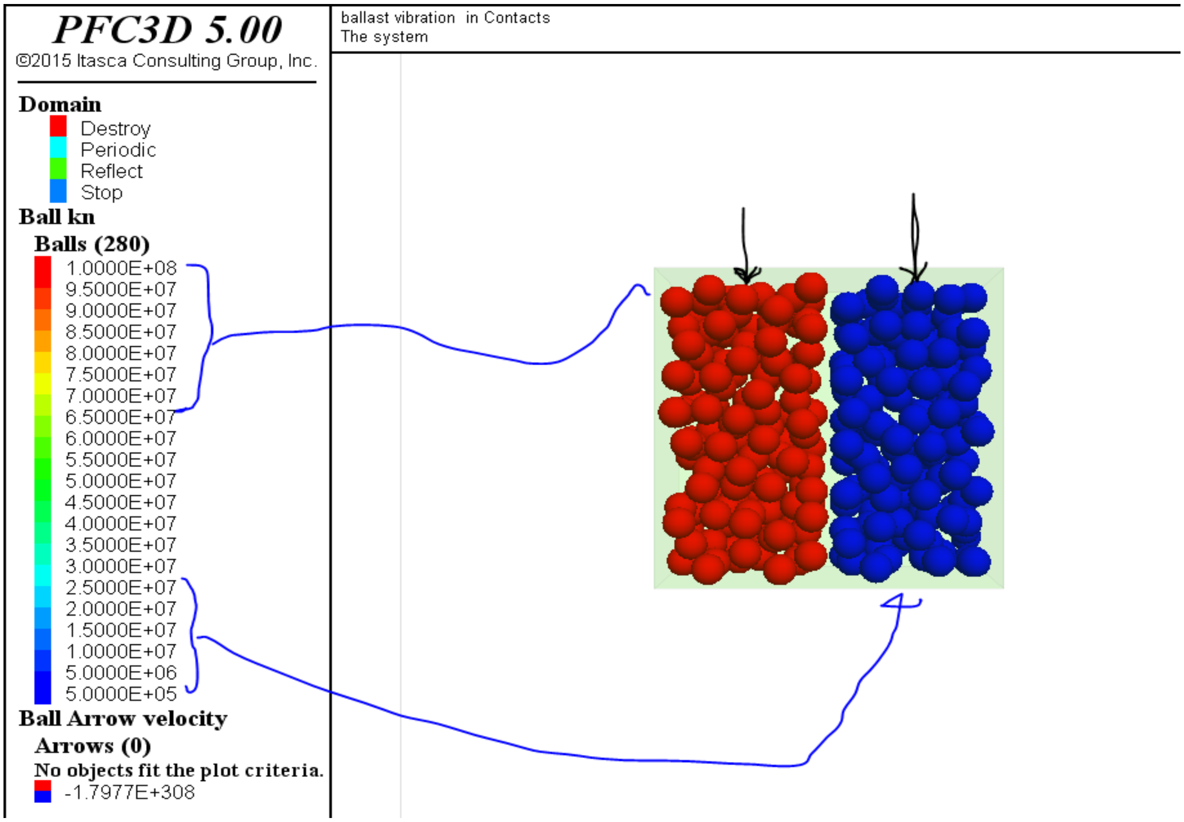


Figure 3.19 DEM modeling ballast bed vibrations

Step 2: After load applied

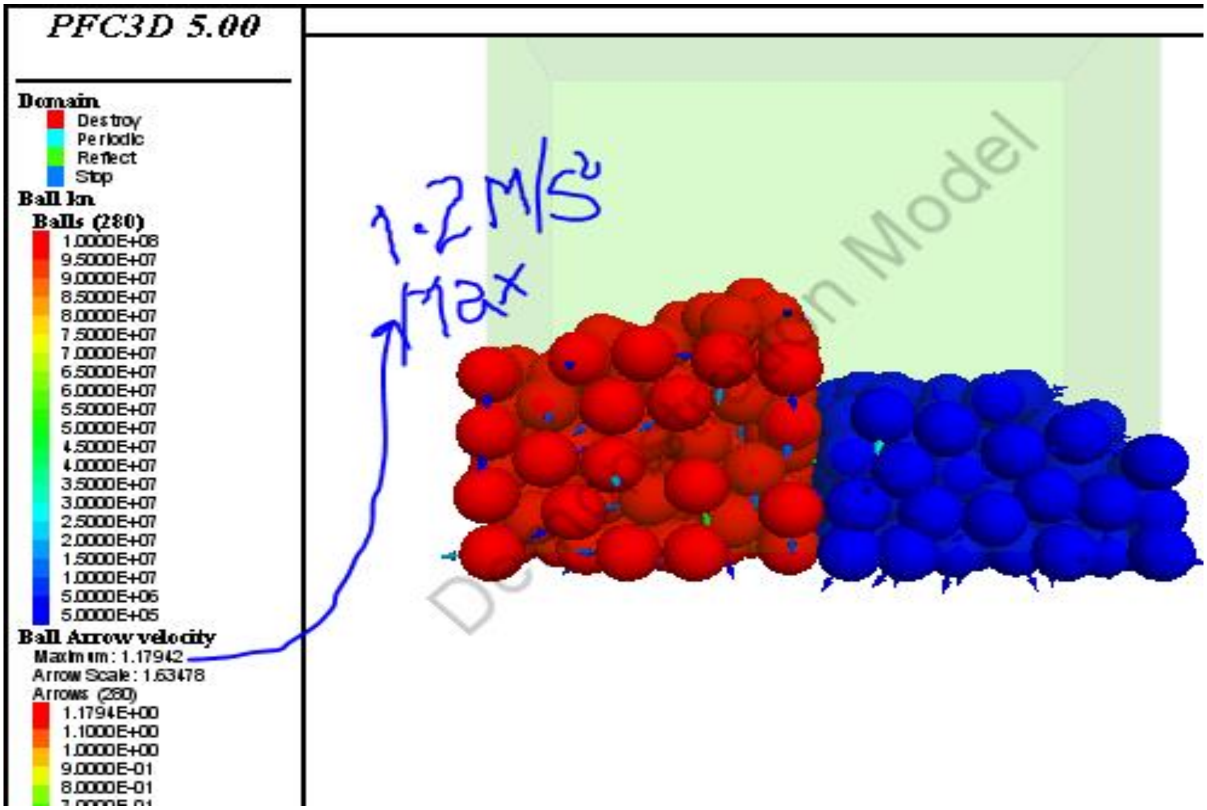


Figure 3.20 DEM result of ballast vibration during loading

During loading sleeper rotates about low rail end and moves towards the high rail end. Due to shape of sleeper ballast falls vertical during loading and is pushed up (down slope) during unloading.

Step 3: Out put

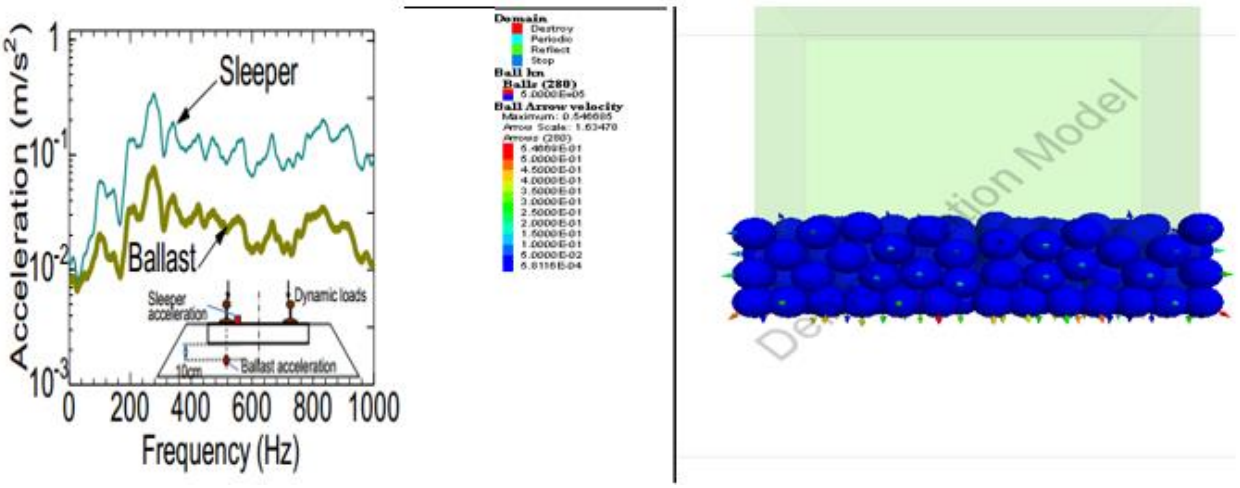


Figure 3.21 Sleeper and ballast displacement response during ground vibration

B. Result and discussion

Ballast flying is influenced by the ballast bed acceleration. With increasing the ballast bed acceleration; the ballast flying possibility and severity improves. Hence, the ballast bed acceleration and vibration reduction and optimization methods are used to reduce or terminate the ballast flying phenomena. From the design or operation stages, could alter the sleeper type, distance, fastener, rail or sleeper pad, ballast mat, ballast depth and density and so on. For example, as increase the sleeper mass, increase the rail pad elasticity and ballast mat application reduce the sleeper and ballast vibration.

The results of such investigation highlight the movement of ballast pieces due to the rigid-body motion and frictional sliding motion that occur between them. Regular DEM analysis requires that a significant degree of rigid-body displacement should occur in each ballast piece. However, as may be apparent from the measurement results, ballast displacement generated by the high frequency components of impact force in the ballast layer is less than that observed in DE analysis in several figures, and that generated by high frequency components of impact force added to the ballast layer is much less.

3. Influence of Ballast Shape

Fragmentation analysis can be very useful when investigating the fundamentals of damage in bonded-particle models.

DEM approach is used to investigate the gradation effect on ballast performance. It is conclude that AREMA No 24 gradation provides the best settlement and displacement resistance among all existing mainline ballast gradations. In the current AREMA ballast specification, beside aggregate size distribution, there is also aggregate shape requirement. Angular and cubical ballast aggregates with crushed faces are preferred. Using digital image technology, aggregate shape properties such as angularity and surface texture can be better quantified. With the image aided particle shape generation DEM method and using the "Ballast DEM Model", aggregate shape effects on ballast performances can thus be quantified and better understood (Erol Tutumluer , Hai Huang,Youssef Hashash and Jamshid, 2006).

The DEM approach with user defined arbitrary element shapes offer a new perspective to study aggregate shape effects on assembly performance. Shape of the ballast aggregate is one of the most important factors to affect ballast strength, workability, and stability. However, compared to particle gradation and air voids, the influences of aggregate shape properties on aggregate assembly strength, stability, and deformation characteristics have received less attention and have not been thoroughly investigated by means of quantifying individually the effects of aggregate morphological properties (Huang, 2009). A description of each particle shape properties index is given in the following paragraphs.

Table 3.7 Physical properties of ballast (Huang, 2009)

Item	**Ballast**
Density p	1500 kg/m3
Young's Modulus E	30 GPa
Poisson's Ratio V	0.45
Structural Damping Parameters η	0.01

A. Procedure for DEM modeling

In this modeling particle shape generation method for DEM to better capture the shape effect of aggregate particle on the railroad ballast displacement and ballast flying. The DEM model parameters are adapted based on previous research studies (Erol Tutumluer,Hai Huang,Youssef Hashash and Jamshid Ghaboussi, 2010) by conducting DEM shear box simulation using different combination model parameters.

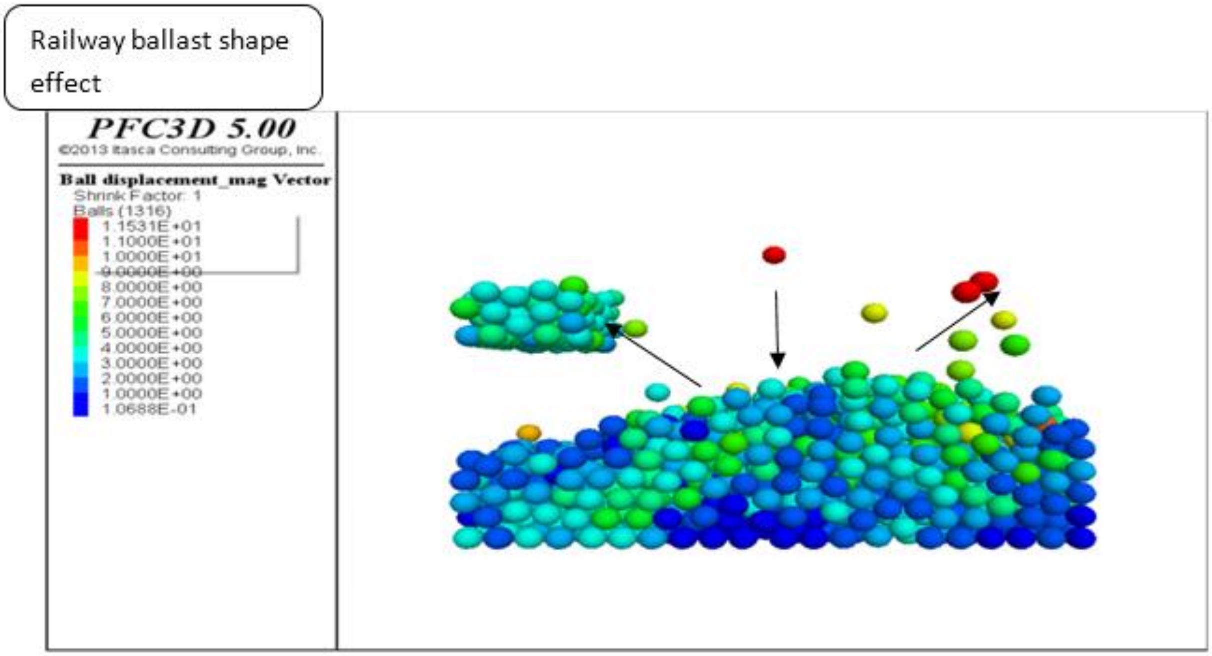


Figure 3.22 -DEM aggregate shape effects.

Ballast particle shape and ballast bed quality not only influence the resistance ability and stability, but also the ballast flying characteristics. DEM simulations show that the flat and elongated particles were not allowed to break although in reality they tend to easily break and degrade under heavy wheel loading. When flat & elongated aggregates are loaded they are very susceptible to breaking and will degrade rapidly.

Flat and Elongated Ratio

The flatness and elongation ratio is the of an aggregate particles maximum to minimum dimensions. Angularity is the count of sharp corners and fractured or crashed sides. Flat and elongated particles have a general tendency to break during construction and under traffic loads, therefore, cubical and angular particles are commonly preferred.

Surface Texture

Surface texture usually determines the surface friction property which plays an important role in aggregate interlock providing the strength through inter-particular friction.

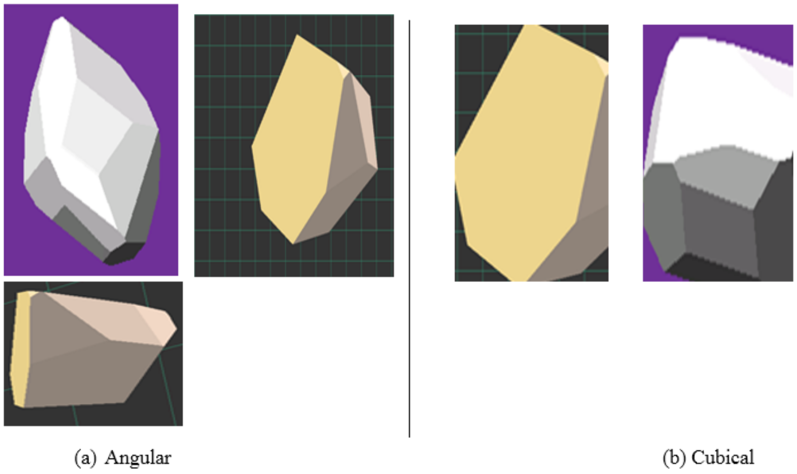
4. Particle Shape Characterization (DEM simulation)

Particle Shape Modeling

Particle shape is one of the most important factors, which influence ballast characteristics. In DEM simulation it is well verified that the shape and size is of great importance for particle interlock ability and rotation characteristics

A. Procedure for DEM modeling

Initially, randomly shaped polyhedrons were generated at random positions in a cylinder of magnified depth 5mm with no overlapping. This was done by sequential placing of trial polyhedrons that were rejected each time when any conflict with previously placed particles appeared. The polyhedrons then fall freely under 5 times magnified gravitational acceleration and friction angle 0.5 radians. Both gravity and friction changes were done to increase compaction of the assembly. After reaching low unbalanced forces,


(a) Angular

(b) Cubical

Figure 3.23: Views of the Generated YEDE- DEM Particle Shape

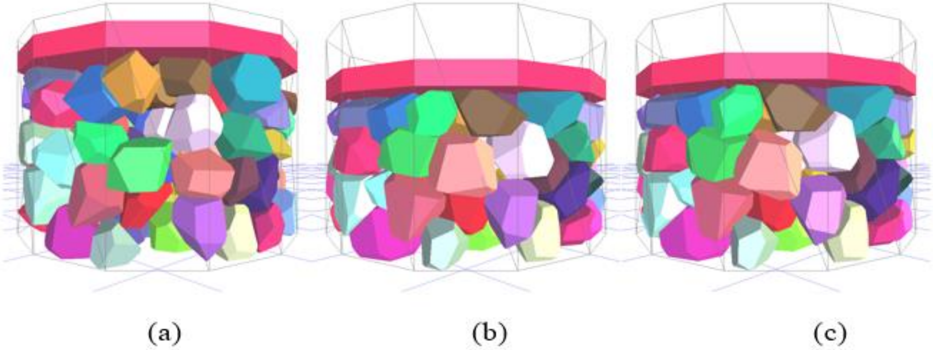


Figure 3.24: Snapshots of ballast particles during YADE-DEM simulation: a) at the beginning of loading; b) at the maximum load; c) after releasing all the load.

The assembly is subsequently subjected to loading conditions such as isotropic confinement or shear.

B. Result and Analysis

i. Angular particles

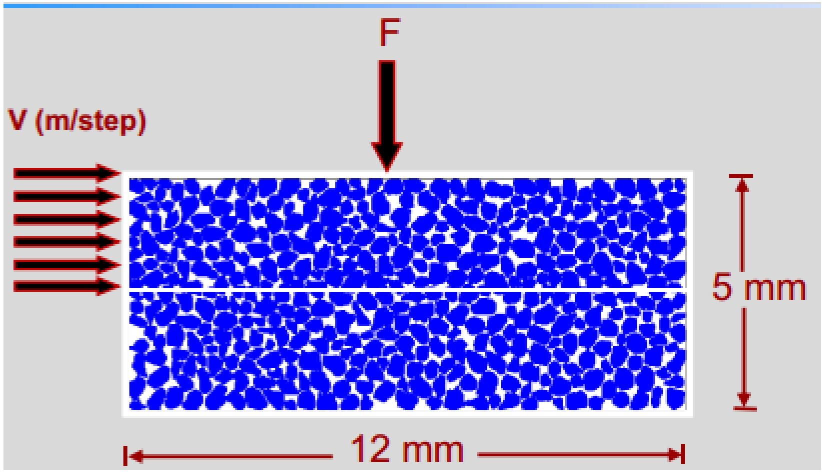


Figure 3.25: Angular and cubical Equivalent of 2-D Particles

Figure3.25: Vertical displacements vs. displacement under different normal stress (Angular particles)

As the applied normal force increased, the shear force also increased primarily influenced by the shape effects of aggregate angularity and surface texture. Yet, a rough surfaced rounded particle had shear strength higher than that of a smooth-surfaced angular particle. The fact that rounded gravel particles have less aggregate interlock compared to crushed angular aggregate to transfer shear force can be explained by the bilinear contact force paths for the rolling and climbing up of the rounded particles.

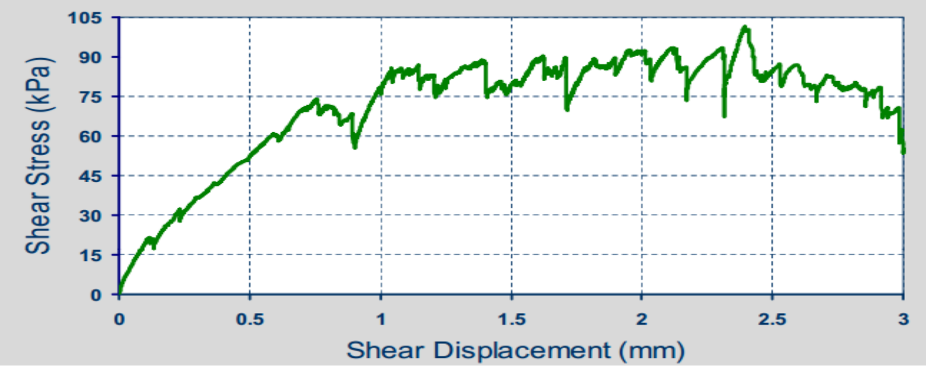


Figure 3.26 shear force vs. displacement under different normal stress (Angular particles)

- Angularity and particles interlocking resulted in more shearing resistance in ballast aggregate when compared to rounded material.

- Angularity and cubical particles have high resistance to the vertical displacement under traffic loading because the inter particle force high when compared with the spherical and rounded/circular particles.
- Ballast with angular aggregate (with high AI) resulted in the highest shear resistance or lateral stability.

ii. Circular and spherical particles

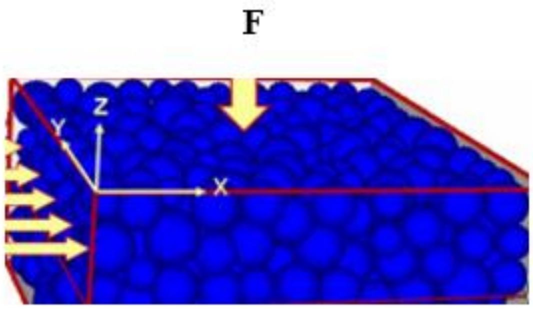


Figure 3.27: Circular and spherical Equivalent of 3-D Particles by PFC3D

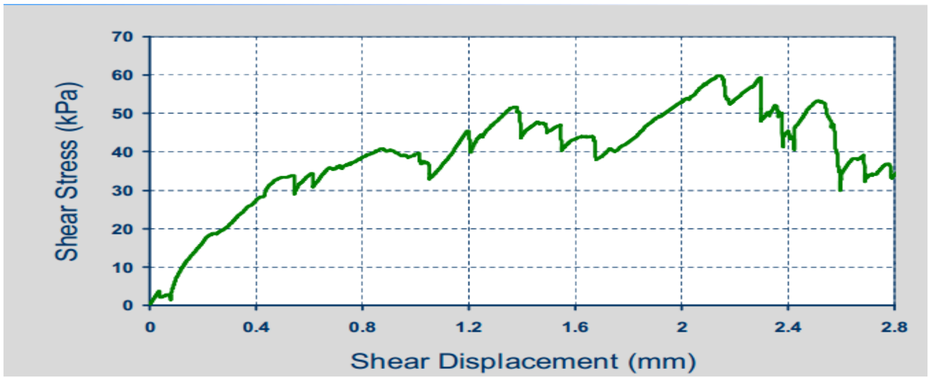


Figure 3.24 shear force vs. displacement under different normal stress (Circular and spherical particles

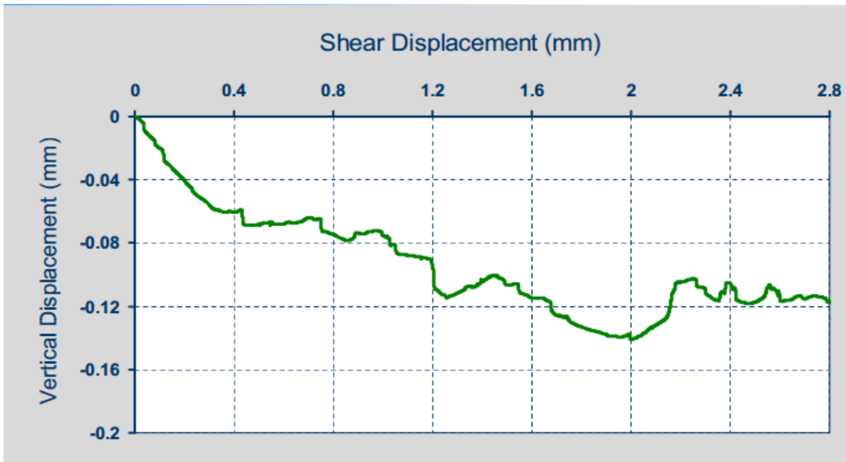


Figure 3.24 shear force vs. displacement under different normal stress (Circular and spherical particles)

The results of the DEM simulations further verified the mechanism of this superior interlock by angular particles through their higher coordination numbers and greater number of particle contacts. Higher number of contacts would provide better load distribution through increased density and particle packing and therefore lower wheel load stresses and particle-to-particle contact stress concentrations under wheel loading to eventually reduce ballast degradation and breakdown. The ballast DEM simulations have proved to be a powerful tool to study and optimize ballast gradations.

For the same gradations, high-angularity particles resulted in larger coordination numbers and thus created a greater number of contacts. This finding is in line with their expected superior shear strength and permanent deformation characteristics over those of rounded particles.

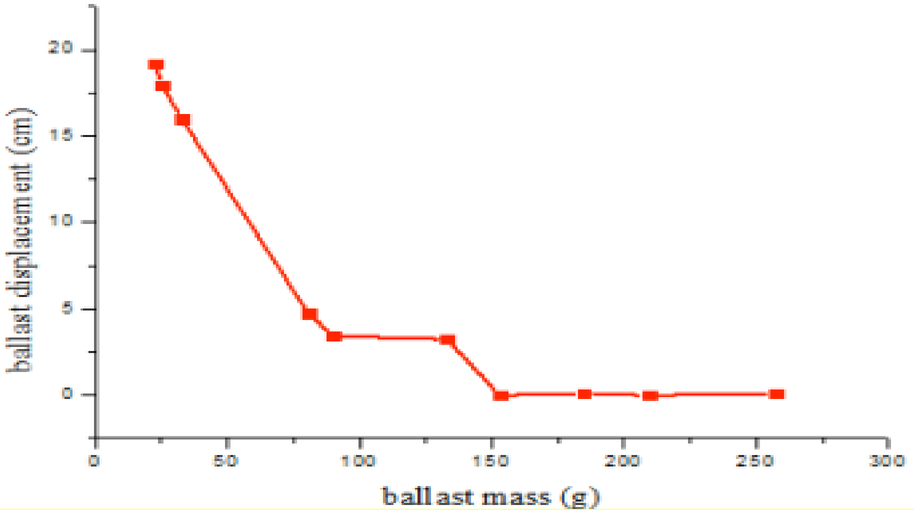


Figure 3.23 Displacement of ballast mass with respect to mass

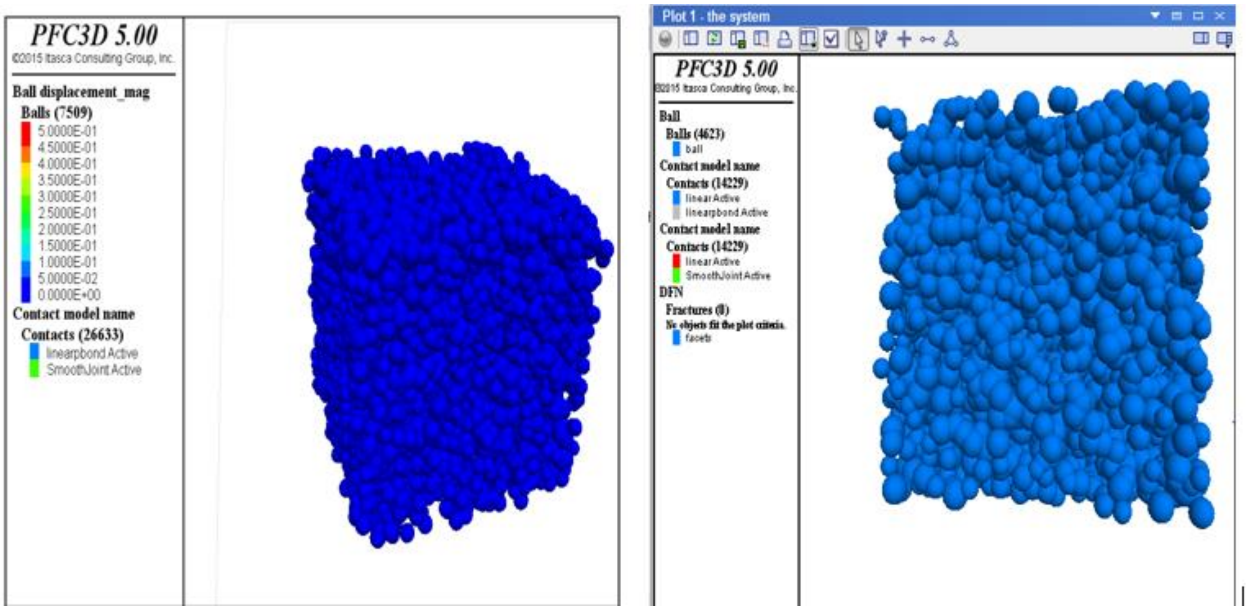


Figure 3.24: DEM Aggregate shape effects influencing ballast flying with dynamic contact load
Results and Discussion

The general view regarding the effect of aggregate types is that crushed aggregate with its angular shape compared to rounded aggregate has higher resilient modulus with a better load capability. And have high ability to interlocking to each other particle.

The displacement of ballast has inverse relation with the ballast mass in general. Ballast particle displacement is inversely proportional to its mass as the mass of ballast Increases the vertical gravitational force also increases.

5. Fragmentation of railway ballast

Fragmentation analysis can be very use full when investigating the fundamentals of damage in bonded-particle models. Fragmentation of ballast results change in particle size distribution during cycling dynamic load of train and tamping process during maintenance. This results in the breakdown of ballast particle from original size to medium or to fine particles. The breakage of large particles may produce only few medium sized particles or many fines. This thesis to modeling the movement of ballast particle from original position easily during high speed train operated on the track and cause ballast flying.

A. Procedure for DEM input for Fragmentation

Simple bonded ballast particle is generated, and then brought to failure under repeated dynamic load of train. The purpose of this modeling is to illustrate how railway ballast fragmentation may cause ballast flying.

A PFC^{3D} bonded assembly is first generated using an approach similar to the one detailed in the "Effect of ground vibration (Ballast bed vibration)". The initial state before compression is shown inFigure 3.26. In this view, the contacts are colored by the value of the property state (a value of 3 means that parallel bonds are installed) and translated for convenience. The particle shape assumed to be spherical in shape.

Table 3.8 Input parameters for ballast fragmentation analysis

Particle density(Kg/m^3)	1500
Radius of particle (m)	$16*10^{-3}$-$1.8*10^{-3}$
Inter particle and wall friction	0.25
Particle normal & shear contact stiffness(N/m)	$3*10^8$
Side wall stiffness(N/m)	$3*10^7$
Top & bottom wall stiffness(N/m)	$3*10^8$

Parallel bond radius multiplier	0.5
Parallel bond normal and shear stiffness(N/m)	$6*10^{10}$
Parallel bond normal and shear strength(N/m)	$5*10^{6}$
Acceleration due to gravity(m/s)	9.81
Dynamic load of train(KN)	20
Damping	0.5
Porosity	0.3
Load	2500N

B. *Modeling*

The fragmentation modes determine the way in which the grains break once the failure criterion is satisfied. In this model the original grain split into two segments or more.

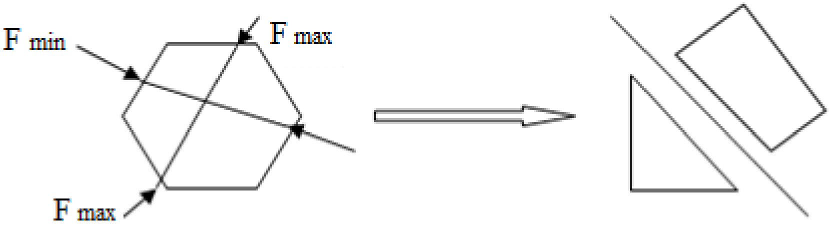


Figure 3.25: schematic representation of the fragmentation model

The numerical simulations are performed with a set of rigid grains of spherical shapes which come from digitalization of railway ballast grains. The sample presented in figure 3.26 below contains nearly 5000 particles which respect the ballast size distribution, 25/50 mm. The density is fixed to 1500 kg/m3. The particles are initially placed in a rectangular box (L=2 m, l =1.4 m, H=0.6 m) and deposited under gravity. The coefficient of friction is fixed to 0.5 between the particles and 0 for the wall. The restitution coefficient is set to zero since consider a dense sample of grains.

Impose a harmonic horizontal force on the ballast samples (50kPa) and a vertical velocity on the 8 m/s of 1 m/s. below; focus on the ballast behavior under the sleeper and the fragmentation process for different phases of loading cycle.

Step-1: Modeling-ballast particles.

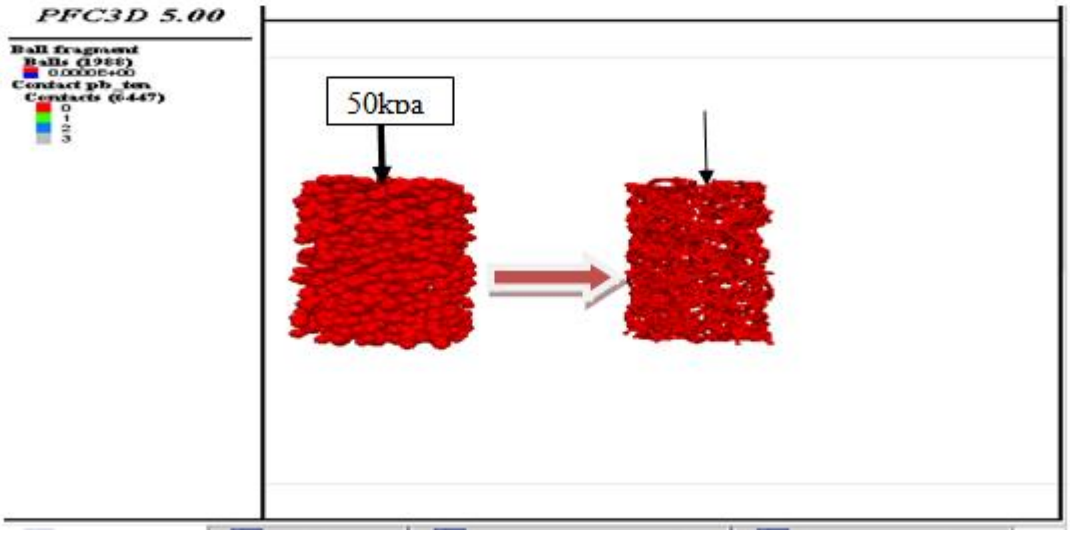


Figure 3.26 DEM model of Aggregate for fragmentation analyses

Step-2: Applying load

A simple bonded assembly is generated, and then brought to failure under uniaxial, unconfined compression. To perform uniaxial compression, the assembly is confined between top and bottom wall platens (which are assigned equal and opposite velocities along the *z*-direction), and the model is cycled to a target age limit. The magnitude of the forces exerted by the specimen on the platens is monitored via two histories as a measure of the compressive stress applied to the specimen.

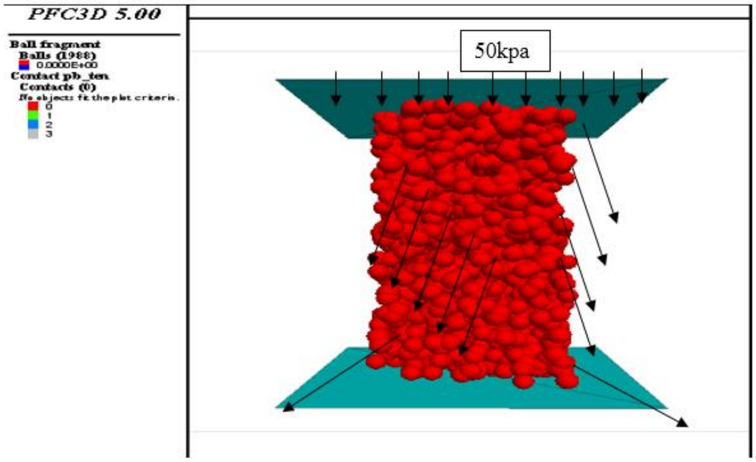


Figure 3.27 DEM model Aggregate Fragmentation

The compression is performed three times with different settings.

- **CASE 0** corresponds to a regular run.
- For **CASE 1**, the fragment logic is activated and the ball result command is used to save partial state information every 0.1 [time-unit] during the course of the simulation.
- For **CASE 2,** in addition to the use of the fragment logic and the ball result command, a FISH function is registered with the linear parallel bond break callback event, which monitors bond breakage events and creates fractures using the Discrete Fracture Network logic to store their location, size, and orientation. Additionally, the fragments are computed only if a bond breakage event occurred, and ball result states are stored only if the number of fragments in the system changed. The FISH functions used to set up this crack-tracking environment are implemented in "fracture.p3fis".

Step-3: Out put

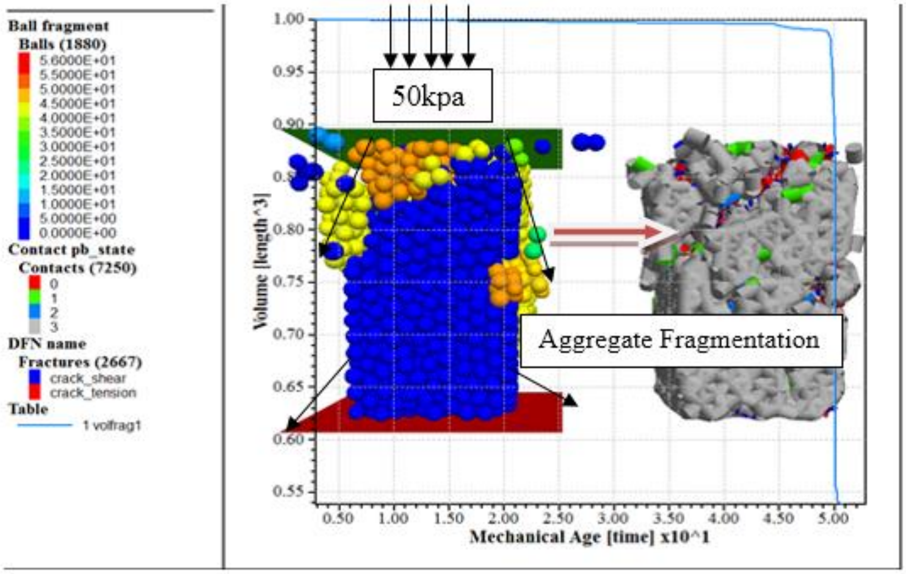


Figure 3.28: DEM model Aggregate Fragmentation

All three cases produce the same results. The final state for CASE 2 is shown in Figure3.28, where contacts and fractures are translated to the right-hand side for convenience. A combination of tensile and shear failures occurred in selected bonded contacts and resulted in the macroscopic failure of the specimen. Forces applied on the platens are identical in magnitude, as shown in Figure 3.29, and demonstrate the brittleness of the specimen.

C. *Results and Discussion*

A combination of tensile and shear failures occurred in selected bonded ballast particle contacts and resulted in the macroscopic failure of the specimen. Forces applied on the platens are identical in magnitude, as shown in Figure 3.28 and Figure 3.29 show that force-mechanical age curves obtained from simulation. From the curves we observed that the magnitude of the peak force and fragmentation. At the first accuracy of particles fragmentation increases with the repeating loading and reach maximum fragmentation of particles and to ballast particle breakage.

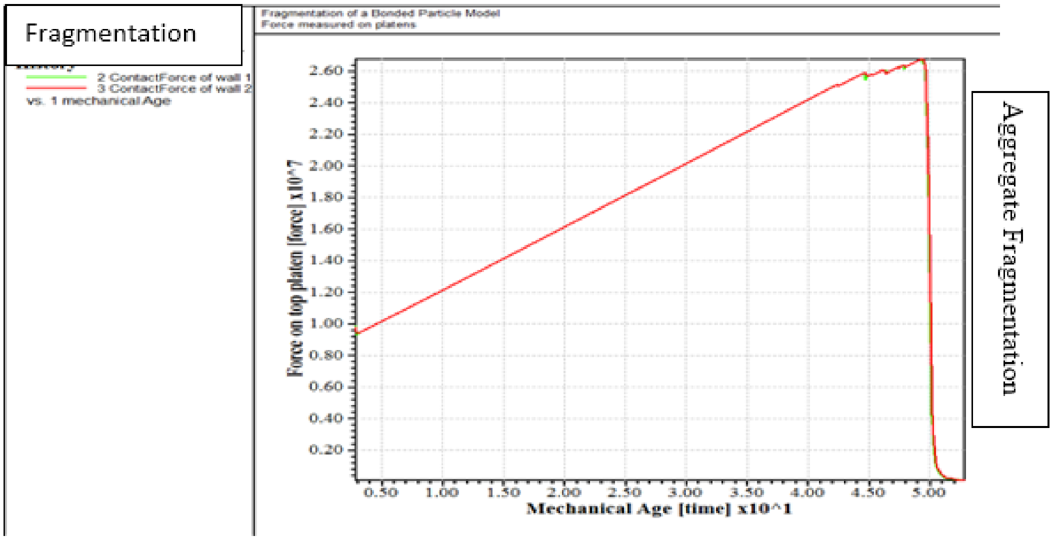


Figure 3.29: DEM model Aggregate Fragmentation with dynamic contact load though mechanical age

Figure 3.30 below Shows the evolution of the volume of the largest fragment (which consists of the whole assembly at the initial state) relative to its initial value, monitored during the course of the simulation.

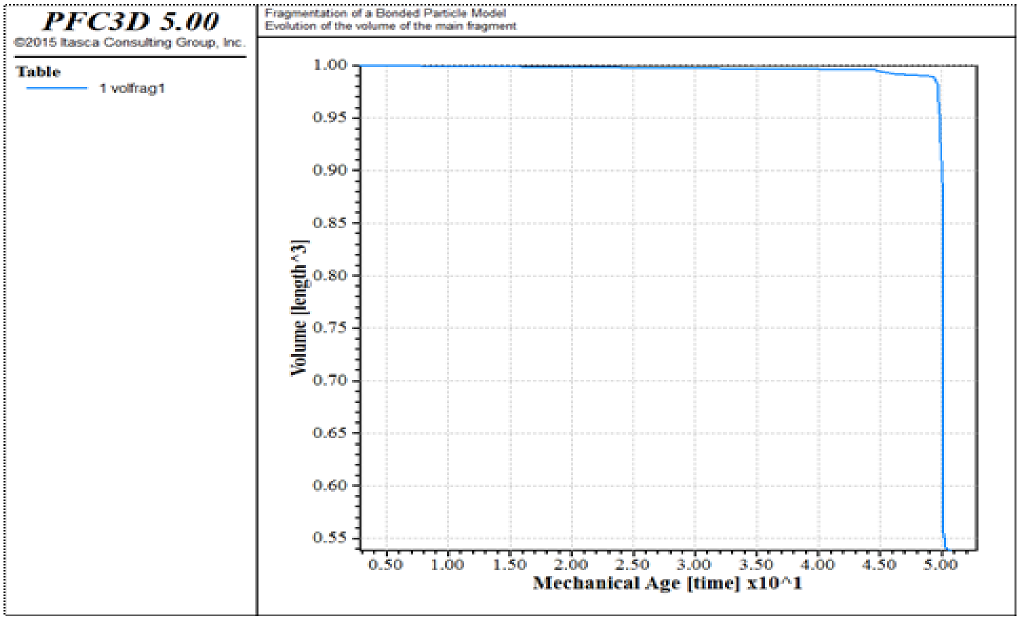


Figure 3.30 Evolution of the largest fragment volume relative to its initial value

Acyclic loading analysis was conducted for angular particles relatively low confining pressure were used (10, 30,50kPa) in view of rail track condition. The generated assembly of angular particles undergoing fragmentation is shown in Figure 3.28 above with few snapshots at various load cycle. The gradual deformation of the assembly indicates that the level of fragmentations of ballast caused by cyclic loading. Large deformation is due to damage caused by ballast breakage and rearrangement. The feature of this DEM analysis is that it is possible to quantity the influence of ballast fragmentation on the ballast flying through mechanical edge of the ballasted track. Fragmentation of rail ballast effect on the railway track:

- Change the particle size distribution.
- Decrease the shear strength of the ballast particle and
- The cause soiled fracture
- Yielding surface

Table 3.9 Ballast properties used for simulation for traffic loading

Item	Ballast
Density p	1500 kg/m3
Young's Modulus E	30 GPa
Poisson's Ratio V	0.45
Structural Damping Parameters η	0.01

Generally from the simulation we observe that though the mathematical load increase the fragmentation of railway ballast increases and finally leads to ballast displacement which lead to ballast flying.

6. Response of ballast aggregate to actual traffic loading

Ballast piece abrasion, breakage and movement are major influences in ballast degradation and ballast flying which is related to impact loads originating at the interface between rails and the wheels of passing trains. Each of these influences induces two different types of motion within the ballast layer. One is displacement in the low-frequency domain due to rigid-body motion, which is characterized by the low-frequency bounce mode determined from body weight and ballast elasticity (originally caused by deflection motion occurring when a heavy axle passes over the rail). The other is elastic vibration in the high-frequency domain, which is generated by elastic wave propagation inside ballast solids (originally caused by impulse waves generated from the mechanism of rolling contact between wheels and rails).

The ballast physical properties used in this study, including density, Young's modulus, Poisson's ratio. Young's modulus and Poisson's ratio were derived from previously published Poisson's ratio and. Structural damping parameters. General ballast structure values were adopted for the structural damping coefficient.

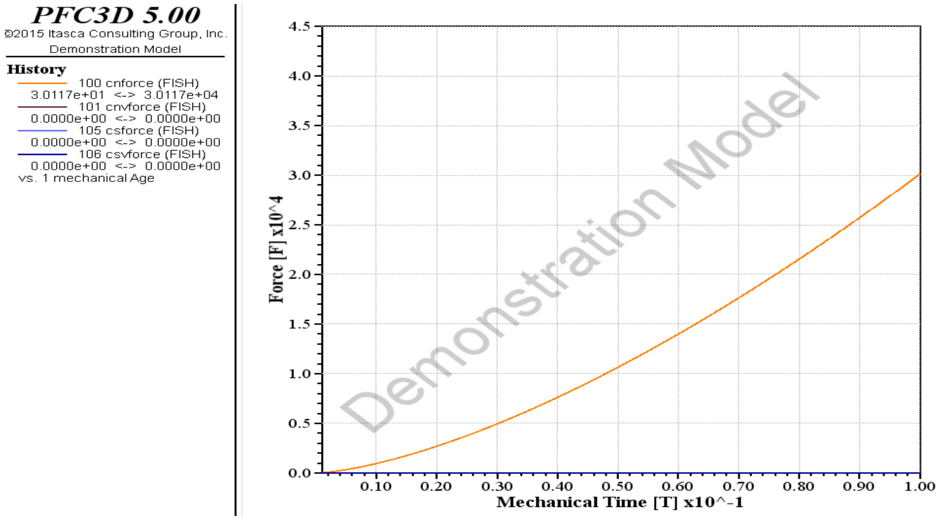


Figure 3.31 Influencing ballast flying with dynamic contact load

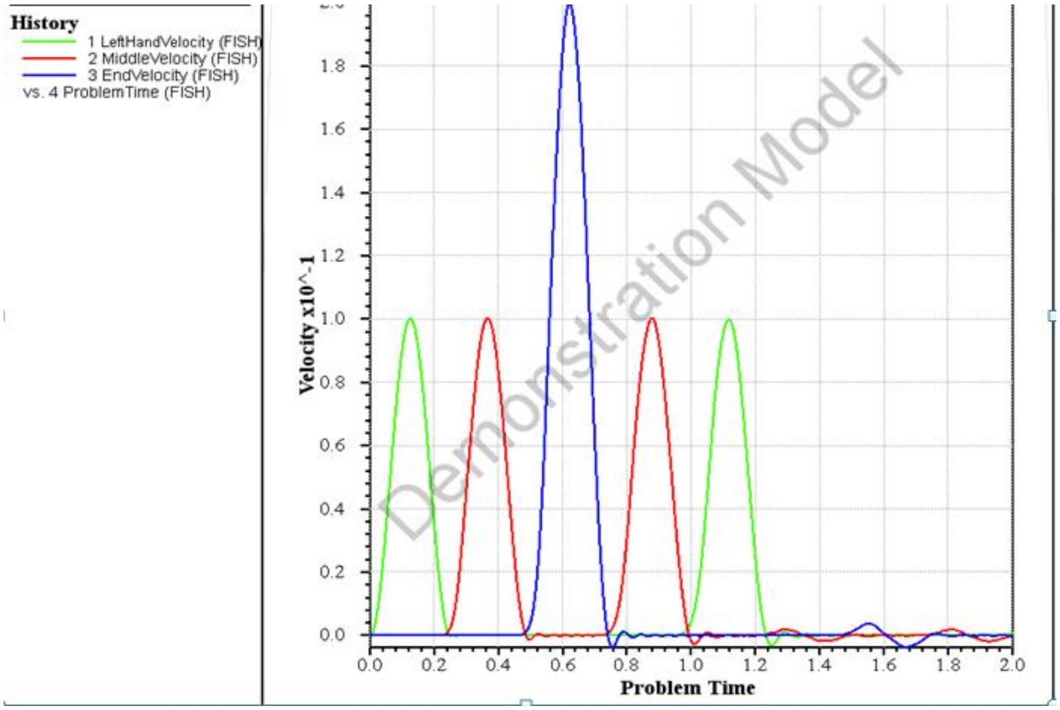


Figure 3.32 Dynamic response of ground vibrations of railway ballast

A. Results and Discussion

It is important to consider the response of the sub-ballast and subgrade to loadings coming from the train as well as loadings produced by natural events, such as mild seismicity increase the ballast fragmentation increase with mechanical age the of ballast track. High-speed train induced vibrations of track structure and underlying soils differ from that induced by low-speed train. Determining the critical speed of train operation remains difficult due to the complex properties of the track, embankment and ground.

3.3.2.3 YADE-DEM simulation of ballast flying

YADE- DEM solves numerical equation of motion, which is according to perfect rigidity assumption idealization as a mass point with 6-dgrees of freedom (3 displacement and 3-rotation. Forces and moments in equation of motion can be prescribed (gravity for instance) or are computed according to constitutive laws from mutual displacement and rotation of individual particles (J. Kozicki∗ and F.V. Donz´e†, 2008).

In this work the normal force between two particles is directly proportional to the volume of intersection of two particles or zero if there is no interaction (YADE oline documentation manual version5.1, 2015).

1. <u>Simulation procedure particle by YADE</u>

First the 500 particle established with new interaction which consist of; detecting collision of particles, creating new interaction and determining its properties (such as stiffness) which is derived from properties of particles and force application to the particles. The following steps are carried out during the simulation:-

I. Creating body object

- shape of particle: spherical
- bound: unbound ballast aggregate
- state: rigid body
- material: granularly material(aggregate)

II. Defining the material: the following material properties for simulation are used as shown in table below,

Table 3.10 Ballast parameters properties for YADE simulation

Ballast properties	Value
Density	1500kg/m3
Young’s modulus	70-170MPa
Poisson ratio	0.5
Damping ration	0.3
coefficient friction	0.6

III. Clumping particle together: create rigid aggregate of individual particle (particle will retain their mutual position during simulation) which is called clump.

Generally, a typical DEM simulation in YEDE does at least the following at each step;

a) Reset force from previous steps

b) Detect new collisions

c) Handle interactions

d) Apply force/load/ and update position /motion /particle.

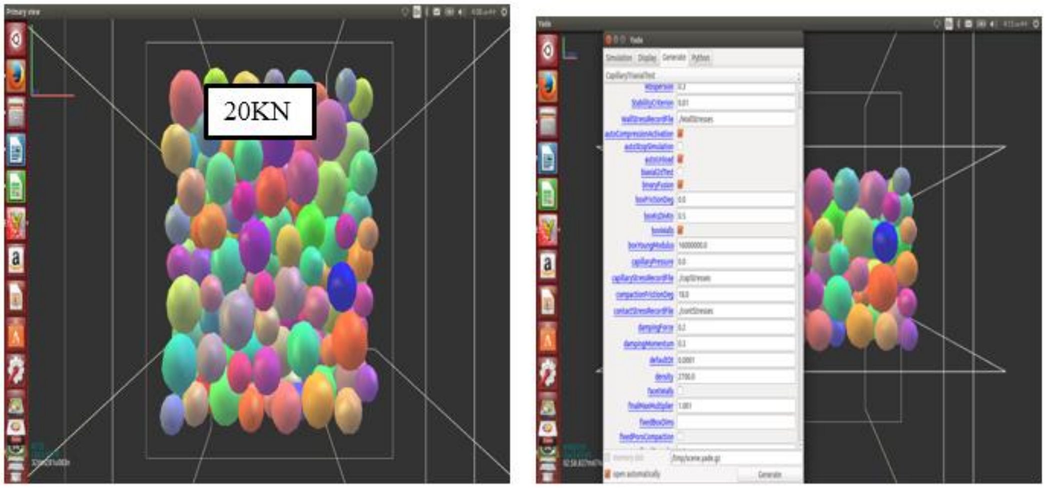


Figure 3.33: YADE-DEM particle simulations

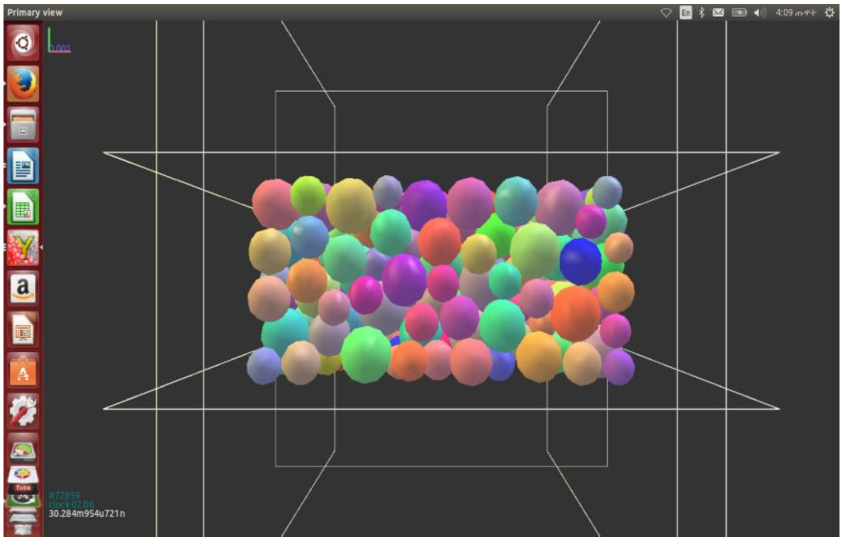
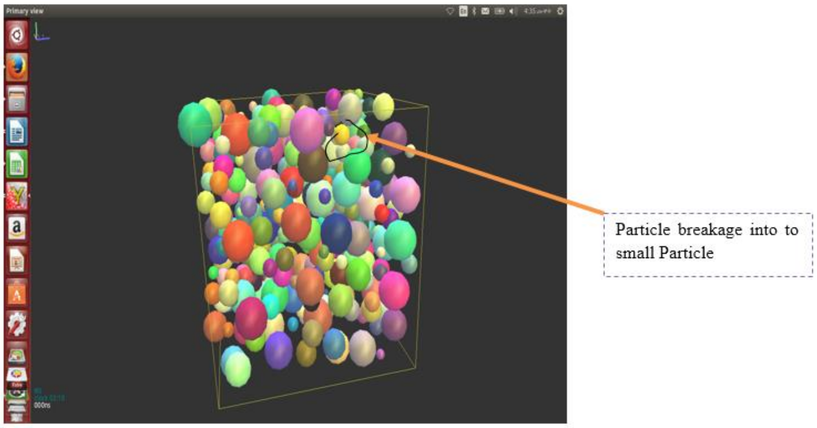


Figure 3.34 YADE particles modeling result

2. Results and discussion on YADE simulation

Under this section the influence of dynamic load applied on the ballasted railway track was investigated. And the influence of cyclic dynamic load through life cycle of track Couse railway ballast degradation or produce some breakage of ballast particle into different size; at this stage the ballast particle displaced from original potion at end lead to ballast flying. From YADE simulation output (figure3.31)below it can be that as load applied on the particle increase though life time of track the breakage of unbound particle increase and leads to particle acceleration from original position and the interlock ability between particle decreases because the gradation mass of particle are changed from original specification.



Particle breakage into to small Particle

Figure 3.35 YADE simulation output of particle breakage under long term of mechanical loading

3. Effect of Lateral Stability of Ballast

There are many factors which may influence the ballast lateral resistance. Aggregate shape and maintenance activities are among the most important factors. Under repeated wheel loading, railroad ballast is gradually consolidated gaining strength from aggregate interlocking. Meanwhile, the ballast layer accumulates permanent deformation after certain amount of traffic which often causes rough track profile. Maintenance activities such as tamping aims to raise the ballast layer and correct the track profile. During tamping, tie is raised followed by inserting the tamping arms; squeezing and vibrating the ballast and displacement from its original position which cause ballast flying.

Usually railroad profile can be corrected by one to several rounds of tamping. However, tamping dramatically decreases the ballast strength and stability by disturbing the consolidated ballast. In this section, ballast flying simulated in DEM before and after tamping railway ballast.

A. *DEM Sample Preparation*

Model parameters including: $K_N = 2$ MN/m; $K_S = 1$MN/m; and $\theta = 35^o$ were used for DEM simulation.

B. *The simulation procedure:*

1. Generate a layer of aggregates, typically 45 mm to 56 mm, assign material and environment constants such as density, surface friction angle, gravity and etc.
2. Compact each ballast sample by first decreasing aggregate surface friction angle.
3. Place the tie back on the top of the tamped ballast layer.
4. Apply 30KN vertical force on the tie followed by 25mm lateral displacement to the tie for the same sample and record the mobilized lateral resistance.

Step (i): Original potion before load applied particle

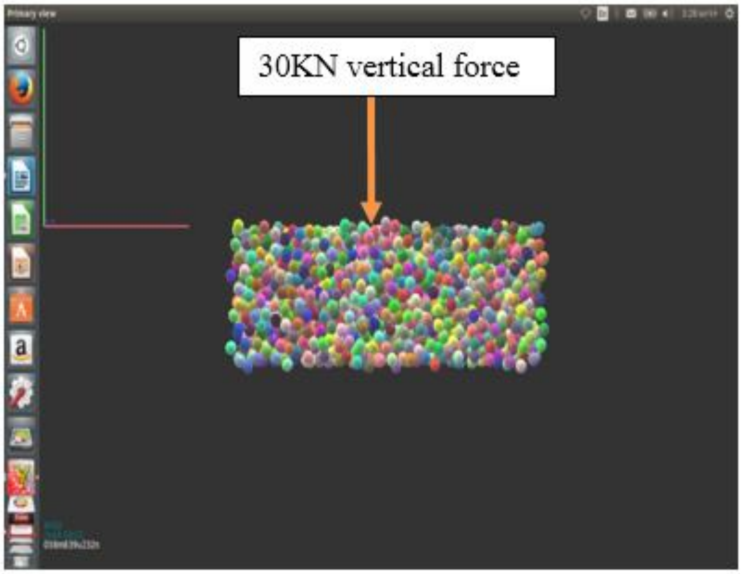


Figure 3.36 YADE simulation of particle at original position.

Step (ii): after load applied particles

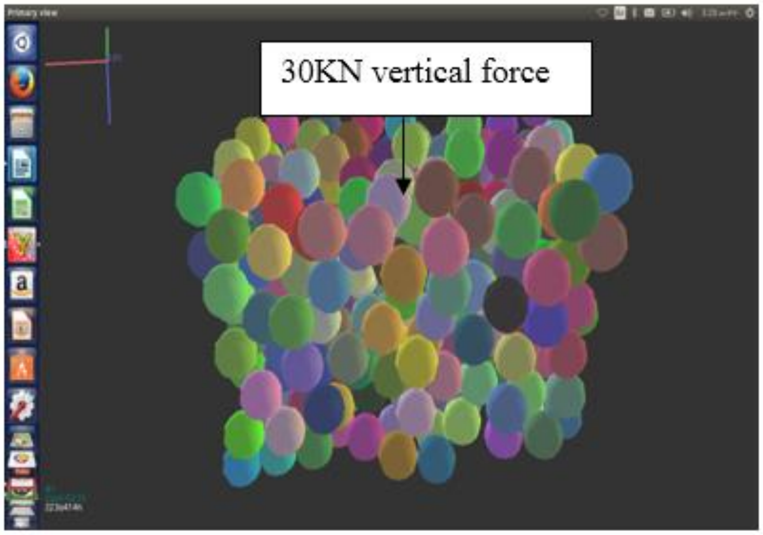


Figure 3.37 YADE simulation of particle at mechanical age of particle

Step (ii): Out put

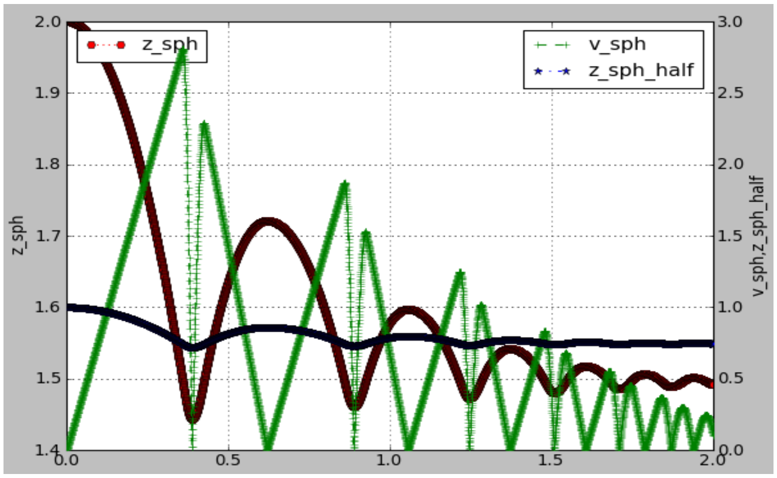


Figure 3.38 Lateral Stability of Ballast

Ballast flying is related to the breakage of particle contacts under the high stress and especially likely to occur under the sleeper. Increasing the surface area of the sleeper should increase the number of particle contacts, while the use a softer sleeper material should increase the area of each contacts point. Both of this reduces particle-sleeper contacts stress and hence ballast flying rates increases.

CHAPTER 4 CONCLUSION AND RECOMMENDATION

4.1 Conclusions

This paper investigated the effect and influence of ballast flying using a Discrete Element Modeling (DEM) approach. Mechanical behavior of ballast layers with different aggregate gradations, ground vibration (Ballast bed vibration), shape and mass of ballast aggregate, fragmentation of ballast and ground condition have been considered. The characterizing and influence of ballast flying mechanism of high speed train have been numerical investigated. With ballast surface area and mass classification and determination, ballast flying mechanism is illustrated. Mechanics formula and numerical DEM modeling used for discover factor that effect ballast flying phenomena. Ballast flying has been characterized by ballast shape mass ratio, ballast inter particle motion (acceleration), ballast gradation, ground vibration of sleeper and aerodynamic induced by the train.

The research focus of discrete element modeling of railroad ballast flying aggregate properties and morphology characterization of ballast particle. Major findings are highlighted as follows:

- According to the result of this study the characterizing of ballast flying affected by Aggregate gradation, ballast shape, mass and ballast interlock ability and were found to have significant impact on stability of aggregate assembly. From DEM output conclude that finer and non-uniformly graded aggregate are easily fly under railway track during operation and ballast with high angular shape resulted in the highest shear resistance or high stability.
- Repeating loading analysis was conducted for angular particles relatively low confining pressure for analysis of particle fragmentation the generated assembly of angular particles undergoing fragmentation at various load cycle. From the simulation observe that though the mechanical load increase the fragmentation of railway ballast increases and finally leads to ballast displacement which lead to ballast flying.
- Simulation results from YADE- DEM ballast flying is related to the breakage of particle contacts under the high stress and especially likely to occur under the sleeper. Increasing the surface area of the sleeper should increase the number of particle contacts, while the use a softer sleeper material should increase the area of each contacts point. Both of this reduces particle-sleeper contacts stress and hence ballast flying rates increases.

4.2 Recommendation for future research

It is recommended that further research on the subject shall be considered,

1. Especially when considering that high speed railway line will be eventually built. Research tools could include, but are not limited to computer modeling like DEM and field test in a closed environment must be carried out considering train speed.
2. Additional laboratory and field experiments are needed to further validation the railway ballast flying investigation and marching with DEM prediction.
3. With combination of the DEM, laboratory and field experiment further validating countermeasure for railway ballast flying shall be done.
4. Ballast flying shall be studying by combining image aided DEM simulation with direct shear box test.

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