Characterization of Geogrid Reinforced Ballast Behavior Through Finite Element Modeling

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Characterization of Geogrid Reinforced Ballast Behavior Through Finite Element Modeling

by

Bugra Sinmez

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering Department of Civil and Environmental Engineering College of Engineering University of South Florida

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Keywords: Railway, Geosynthetics, Finite Element Analysis, Vertical Surface Deflection, Reinforcement, Vertical Stress and Strain

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DEDICATION

To My Father Dr. Ali Sinmez

And

The Republic of Turkey
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ABSTRACT

Recently, the railway pavement structure system, as an integral part of the transport infrastructure, has been under fast development in some countries such as China, Turkey, and some European Union countries, particularly for the use of high-speed trains. In designing and constructing the railway pavement structure, it is necessary to take into account the infrastructure demand of the High-Speed Railway Lines (HSRL). Compared to traditional railway trains, HSRL can cause more significant problems to the ballast or base layer of commonly used ballasted railway pavements. The deteriorated ballast or base layer may further result in substructure degradation that may cause safety issues and catastrophic accidents. As a consequence, heavy goods or high-speed trains will affect railway efficiency. As a countermeasure, a railway pavement structure may be reinforced by geosynthetic materials in the ballast or base layer. In the literature, however, there is still a need to quantify the effect of geosynthetic materials, geogrid in particular, on the mechanical responses of railway pavement structures to HSRL loads, which is necessary knowledge in supporting the selection of appropriate material and placement location of geogrid. Therefore, the goal of this study is to investigate how a geogrid reinforcement layer can change the essential characteristics of a ballasted railway pavement structure, with focus on the material type and placement location of geogrid that can help minimize the rate of deterioration of the railway pavement structure system. This research attempts to validate the advantage of geogrid reinforcement through numerical simulation in a realistic railway setting.
All technical literature on the use of geogrids in the railway system has been studied. A three-dimensional (3D) finite element model was constructed for the numerical simulation, in which three different types of geogrid placed at two different locations (i.e., within the ballast layer, between the ballast and the sub-ballast layer) within a railway pavement structure were analyzed under a range of vertical wheel loads. Therefore, four possible applications of geogrid reinforcement systems (G0: no-reinforcement; G1: reinforced with geogrid having the lowest density and Young’s modulus; G2: reinforced with geogrid having the intermediate Young’s modulus and density; G3: reinforced with geogrid having the highest density and Young’s modulus) were modeled to represent different situations in ballasted railway systems. Railway mechanical responses, such as vertical surface deflection, maximum principal stress and strain, and maximum shear stress were analyzed and compared among the four geogrid reinforcement scenarios and under four vertical wheel load levels (i.e., 75, 100, 150 and 200 kN). The advantages of such geosynthetics in ballast are indicated by result difference in the mechanical responses of railway pavement structures due to the use of different geogrid materials. The results also show that the reinforced structures have lower vertical surface deflection, lower maximum shear stress at the interface of sleeper and ballast, and maximum principal stress at the bottom of the ballast layer than a non-reinforced railway pavement structure.

Consequently, the addition of geogrid into the ballast layer, and between the ballast and sub-ballast layer has been shown to reduce critical shear and principal stresses and vertical surface deflection in a ballasted railway pavement structure. Besides that, the results of the analysis confirm that geogrid reinforced layers exhibit higher resistance to deformation than the non-reinforced layers.
CHAPTER 1: INTRODUCTION

1.1 Introduction

In addition to increasing the world's population, the railway system has been in demand as one affordable, quick, secure and green transport scheme. Also, increasing population has pushed countries to construct more and better railways as an alternative to other transportation systems (Guler et al. 2017). The railway structure system is an integral part of a country's transport infrastructure and plays a vital role in maintaining a healthy economy. In developed countries, such as the USA and some European Union (EU) countries, and some developing countries such as China, construction of the railway system has accelerated, and this system forms the most extensive worldwide transportation system (Guler et al. 2017). For instance, trains are immensely used in public transportation in the USA, as illustrated in Table 1.1 that shows the shares of transportation modes for unlinked passenger trips and miles (Neff and Dickens 2017).

Table 1.1 Unlinked Passenger Trips and Passenger Miles by Mode of Services in the USA (Neff and Dickens 2017)

<table>
<thead>
<tr>
<th>Mode of Service</th>
<th>Passenger Trips</th>
<th>Passenger Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions</td>
<td>Percent</td>
</tr>
<tr>
<td>Heavy Rail</td>
<td>3,928</td>
<td>36.5%</td>
</tr>
<tr>
<td>Hybrid Rail</td>
<td>7</td>
<td>0.1%</td>
</tr>
</tbody>
</table>
Public transportation supplied more than 10 billion disconnected passengers for more than 50 billion passenger miles in the USA for the ninth consecutive year in 2014 (Neff and Dickens 2017). According to Table 1.1, the mode of service in rails is higher than all other modes in 2014, with approximately 32,695 million passenger miles, which is 55 percent of public transportation in the USA. Additionally, heavy rail is the second largest passenger mode of service, which is 3,928 million passenger trips or 36.5 % of public transportation.

On the other hand, railway pavement structure design has two crucial categories: superstructure and substructure. The superstructure is the most noticeable part of a railway and is made up of rails, rail pads, sleepers, fixing systems, and cross members. The substructure, typically made up of ballast, sub-ballast and subgrade, constitutes a railway's geotechnical structure. (Selig
The ballast and sub-ballast layers are also known as the base layer. The significant function of each layer is to distribute stress from trains downwards and outwards and provides adequate vertical, lateral, and longitudinal resistance to deformation. Figure 1.1 presents the components of a conventional railway pavement structure. The ballast is the most significant ingredient of the railway substructure (i.e., ballast, sub-ballast, and subgrade) because it is the only limitation applied to the superstructure to restrict its deformation and displacement.

**Figure 1.1 Components of a Conventional Railway Pavement Structure (Selig and Waters 1994)**

The primarily function of the ballast, which consists of granular materials, in ballasted railways is to transfer and distribute stress from the rails to an appropriate point above the subgrade. (Ali et al. 2013). The ballast also has other vital tasks such as storing contamination materials, supplying water drainage on the railway structure, and rearranging railway structure geometry during a repair.

On the other side, the life and efficiency of the superstructure depends heavily on the ballast layer, as deformation in the ballast layer adversely influences the superstructure (Kwan 2006).
However, during vehicle loading, the ballast layer is deformed and degraded. The rise in velocity and load of the train causes deterioration, pumping and attrition of the railway substructure.

Deterioration of the vertical geometry of a railway structure is frequently understood to be caused primarily by differential settlements of the ballast and subgrade layer. Ballast is a random arrangement of stones, and the lack of homogeneity will cause an irregular distribution of load, creating an uneven settlement. For this reason, geogrids are recommended to be used for building a railway on a weak foundation in railway application and for strengthening the ballast layer to provide improved lateral stability and less railway pavement materials (Koerner 2012). To date, there has not been much research that is able to solve the ballast degradation problem.

In the last two decades, geogrid has been widely used in railway engineering applications to enhance the strength of railway infrastructure (Koerner 2012). The main functions of geogrid can be called separation, filtering, drainage, and strengthening. According to literature, many studies verify the impact of geosynthetic and, in specific, geogrid strengthening on the enhancement of railway infrastructure's bearing characteristics (Giroud and Han 2004; Qian et al. 2015). Research highlights the important effect of geogrid strengthening on the development of railway strength. This effect is more significant in the building of tracks for new-generation trains with greater speeds and loads than traditional railway systems. As a result, characterization of geogrid characteristics and size is essential to geogrid infrastructure pavement design (Selig and Waters 1994; Koerner 2012).

There are many studies on the application of geogrid in ballasted railways. Most researchers, however, used geogrid reinforcement either in only within the ballast or between the ballast and sub-ballast. For instance, Kwan (2006), Indraratna et al. (2011), and Qian et al. (2015) used geogrid reinforcement within the ballast. There is a need to compare the effect of geogrid
application with different geogrid materials and placement locations on the railway pavement structure for trains with higher speed and load.

1.2 Objectives of the Study

This study focuses on the mechanical responses of ballasted railway pavement structure under single wheel loads, and on the mechanical performance of three different geogrid reinforcement materials within the ballast layer and between the ballast and sub-ballast layers via utilizing a numerical analysis method, with the objective to investigate the benefits of using geogrid reinforcement in minimizing the rate of deterioration of ballasted rail track geometry. The primary differentiation of this study from previous research is the application of different types of geogrid reinforcement at different locations within the railway system. In recent studies, geogrid reinforcement was only utilized either within the ballast layer or between the ballast and sub-ballast layers. In order to compare the effectiveness of usage of geogrid materials within the ballast layer and between the ballast and sub-ballast layers, this study was performed.

Depending on the desired characteristics of the railway, geogrid can be placed at various locations. Usually, the geogrid is used in two ways to strengthen the railway substructure. The first way is to entrench the geogrid within a ballast layer. When incorporated in the ballast or base layer, the primary benefit is to extend the time period between ballast maintenances (i.e., ballast cleaning and replacement operations). The second way involves the use of geogrid in the substructure to reinforce the sub-ballast or the subgrade. The key advantage of this type of reinforcement is to boost the effective bearing capacity of a soft subbase or the subgrade (Das et al. 2010). This study focuses on both ways of reinforcement, which is to entrench the geogrid within a ballast layer (Figure 1.2) and between the ballast and sub-ballast layer, to explore which way is more useful in geogrid reinforcement.
Since the function of geogrid reinforcement in the ballasted railway system has not been extensively researched for heavier loads from HSRL, which may increase vertical deflection in the ballast and sub-layers and results in more significant problems compared to traditional railways, this thesis aims to determine the role of geogrid reinforcement in the ballasted railway system for HSRL. The numerical analysis was performed based on a three-dimensional (3D) finite element model (FEM) of ballasted railway pavement structure built in the software ANSYS (ANSYS 2018). The mechanical responses of the railway pavement structure, in terms of maximum surface deflection, maximum principal stress and strain, maximum shear stress, were analyzed for three different geogrid materials and four vertical wheel loads (i.e., 75, 100, 150 and 200 kN).
CHAPTER 2: MECHANICAL BEHAVIOR OF RAILWAY BALLAST AND GEOGRID

2.1 Introduction

This overall review of the literature is split into two primary parts. Section 2.2 explores railway parts and their different functions to provide a fundamental knowledge and comprehension of the functioning of a standard railway. Section 2.3 includes a review on the geogrid reinforcement and concludes with a presentation of the geogrid case studies.

Nowadays, railways are of great interest worldwide and have been built to connect major cities in developing countries. The railway system is an essential part of a country’s transportation system and plays a vital role in its economy. It is liable for the transport of freight and bulk commodities between main towns, ports and agricultural sectors, apart from transporting passengers in busy urban networks. (Indraratna et al. 2011). Trains enable passengers to reach their destinations while, at the same moment, causing different issues in the railway substructure system that threaten passenger safety (Indraratna et al. 2011). Therefore, railway pavement design, superstructure, and substructure are significant for railway passenger safety. This chapter aims to provide information about the importance of railway pavement design and geogrid reinforcement in railway systems.

2.2 Ballasted Railway Tracks

Railway structural design techniques have evolved from the first designs in 1830, which were two parallel rails positioned on wide wooden cross-links on the natural ground. It quickly
became apparent that the quality of the assistance should be enhanced under the links (Rose and Souleyrette 2015).

A railway pavement design generally consists of rails, sleepers, railpads, fastenings, ballast, sub-ballast, and subgrade, as shown in Figure 2.1. Geosynthetic materials such as geogrid, geotextile and geomembrane were applied to construct a railway on fragile subgrades in railway applications and to reinforce the ballast layer to improve lateral stability and reduce railway positioning. (Qian 2015). Additionally, the ballast layer is ignored in tunnels, and the rails are attached to concrete slabs on the railway. The railway pavement design is a necessary part of the railway infrastructure, and its components can be classified into two primary categories: superstructure and substructure. In the past, design emphasis was put on a railway superstructure consisting of rails, fasteners and sleepers with little regard to the ballast, subballast and subgrade substructure. This is ironic because substructure elements often carry a significant portion of the price of railway maintenance. According to Selig and Waters (1994), the absence of attention to the substructure can be ascribed to the problems in identifying the substructure's many factors compared with those of the superstructure. I will explain in detail the typical railway pavement structure in this section.

![Figure 2.1 Cross Sectional View of a Typical Ballasted Railway (Dahlberg 2003)](image-url)
2.2.1 Superstructure

2.2.1.1 Rails

Rails are elongated members of steel to guide the rolling stock, typically positioned on spaced sleepers. Their rigidity must be adequate to keep a fixed shape and uniform spacing, as they mostly resist different forces applied by the setup of rolling stock (Selig and Waters 1994). One of the rails primary functions is to carry and transfer wheel/axle loads to the supporting crossmembers. A flat-bottomed rail, also called the Vignole rail, is the best frequently implemented rail profile and is divided into three sections: railhead (upper surface contacting the wheel), rail network (supporting the railhead as the middle section like columns), and rail foot (lower portion of the network load distribution to the underlying parts of the superstructure) (Kaewunruen and Remennikov 2008).

2.2.1.2 Rail Pads

Rail pads are cushions for filtering and transfer of dynamic loads to sleepers from rails and fasteners. The elevated dashpot value of the rail pads reduces the over-high-frequency forces and gives flexibility between the rails and the sleepers, thereby reducing the crack and contact wear of the railway substructure (Kaewunruen and Remennikov 2008).

2.2.1.3 Sleepers

Sleepers are transversal beams that sit on ballast and support for the infrastructure. The sleepers’ primarily function is not only to distribute wheel loads on the ballast and the subballast, but also to stabilize the composite railway system under the rails and stop rail motion by anchoring the upper structure in the ballast. (Fong 2006). Ballast railway is currently being built with mono-block or twin-block concrete sleepers, as illustrated in Figure 2.2 (Grassie 1995). Mono-block concrete sleeper is widely used. Because mono-block concrete sleeper is more durable than other
types of sleeper. In recent decades, reinforced concrete sleepers have been introduced on modern railways due to their lengthy service life and durability.

Figure 2.2 Mono-block Concrete Sleeper (Left) and Twin-block Concrete Sleeper (Right)

2.2.2 Substructure

2.2.2.1 Ballast

Ballast is the material chosen to support the piece structure at the bottom of the rail. A standard ballast is a uniformly rough, non-cohesive, granular material. Traditionally, angular, crushed and difficult stones such as granite, limestone, slag or other crushed stones have been identified as useful ballast materials. The primary variables often considered in the choice of ballast materials were usability and financial intentions. (Dahlberg 2003). For instance, limestone commonly referred to as carbonate rock, is among the world’s most widely used mineral commodities, and its resources are extremely large (Hubbard and Ericksen 1973). Likewise, the ballast is an exclusive granular material positioned on the substructure, ensuring appropriate rail drainage, transmitting and distributing the load from the track to the reduced level and eliminating the reduced level stretching by decreasing lateral movement. Crushed granite and limestone ballast
with size ranging from 1½" to ¾" are widely used. This standard size has been used by the railway as ballast size since the late 1800s (Coleman 1990). The standard ballast thickness is 300 mm, but ballast can be filled around the sleeper ends up to about 500 mm to ensure lateral stability, as illustrated in Figure 2.3.

![Figure 2.3 One Example of Railway Ballast in Tampa (Photo by Bugra Sinmez)](image)

Moreover, ballast has several important tasks, including keeping the railway position, reducing the underlying materials bearing stress and storing polluting materials. The ballast must also be able to rearrange correction and alignment activities during maintenance stage (Tutumluer et al. 2006). Therefore, the ballast materials must be rigid, durable and angled, free of dust and dirt, and have relatively large cavities. Because ballast is a type of granular material, the conduct of such a material is well recorded in the literature on granular materials (Fong 2006).

### 2.2.2.1.1 Vertical Stress in the Ballast Layer

Both trains apply distinct load features to the railway substructure between high-speed passenger trains and freight trains. The most important aspect of ballast efficiency is its capacity
to resist axial and lateral forces. Hence, many studies have been done on this issue. For the analysis performed in this study, a single wheel load of 75, 100, 150, and 200 kN was used (Figure 2.4) because of the facts discussed below.

![Figure 2.4 Vertical Load in Railway Structure](image)

A study by Stagliano et al. (1981), the vertical stresses at the sleeper-ballast interface and in the center of the ballast layer instantly below the railway were evaluated as 175 kPa and 70 kPa, respectively, for a car with a wheel load of roughly 100 kN and a velocity of 85 km/h (Stagliano et al. 1981).

The maximum wheel load applied to the railway system, Turkey State Railways (TCDD), which is available in the system, and the maximum velocity of 120 km/h is 100 kN for locomotives and carriages (TCDD 1990).

Kempfert and Hu (1999) observed an evident rise in dynamic stress in the ballast layer between 150 km/h and 300 km/h within a train velocity. At a train velocity of 150 km/h, the
peak vertical dynamic stress in the center of the ballast layer below the rail was 70 kPa, while at a train velocity of 300 km / h it was 100 kPa.

2.2.2.1.2 Ballast Fouling

The railway pavement's life and efficiency depends heavily on the ballast layer. During traffic loading, the ballast layer is deformed and vertically degraded. There are some studies on these deformations and vertical degradation. Selig and Water (1994) listed five significant sources of ballast contamination listed in the literature: 1) ballast breakdown (i.e., ballast breakage due to repeated traffic loading, and handling), 2) infiltration of water or other materials from ballast surface (i.e., waterborne, wind-blown, splashing from adjacent wet spots, trash particles), 3) sleeper wear, 4) infiltration from underlying granular layers and 5) subgrade infiltration. Fouling materials are considered particles smaller than 6 mm in diameter.

A study by Indraratna et al. (2006), the sources of superior ballast quality were discovered to be restricted and, under dynamic loading circumstances, most ballast characteristics gradually altered due to breakage, deformation and fouling. Ballast fouling reduces permeability, resulting in hydraulic erosion, reduced stability owing to particle lubrication, subgrade abrasion and deterioration of the ballast (Indraratna et al. 2006).

Because of continuous ballast settlement and subgrade, railways may cause deformation and vertical deflection. Traffic loading from HSRL can result in such deformation depending on the quality and the behavior of the ballast, sub-ballast, and subgrade. The settlement's implications can be vast (Kwan 2006). Hence, the ballast is proven to be significant since it may cause deterioration of the vertical geometry on a railway structure and differential settlements in the substructure.
2.2.2.1.3 Ballast Deformation

An important requirement of any right railway structure is that track geometry must be maintained during train activities. Many superstructure failures, such as railway interruptions, are caused directly or indirectly by weak railway pavement structure. Weak vertical alignment of a ballasted railway pavement structure may result in discomfort for passengers, greater railway maintenance and renewal costs, velocity constraints, as well as potential derailment. The primary cause of fragile pavement structure is uneven deterioration or settlement of the railways.

The ballast layer must be capable of withstanding both vertical and lateral forces applied constantly by wheel loads. In addition, extreme elastic and plastic deformations must be avoided in the ballast layer. Otherwise, the front strength of the railway sleepers may decrease due to elevated tiredness triggered by bending, while the latter may result in continuous differential settlements that may distort the railway pavement structure (Kaya 2004).

According to Dahlberg (2003), the railway pavement structure may be deflected owing to permanent deformation of the ballast or the underlying soil due to repeated loading of traffic. The deflection is administered by several necessary ballast and subgrade behavior mechanisms:

- Volumetric condensation continues due to repeated train loading.
- Sub-ballast and sub-grade ballast material
- Ballast or subgrade particle lateral movement leads to a sleeper sinking deeper into the ballast layer.
- Ballast breakage under train loads causes a volumetric reduction.

Deterioration of a railway structure's vertical geometry is often known to be caused primarily by differential ballast and subgrade settlements (Kwan 2006). The ballast is therefore
very important for a secure railway structure. To decrease vertical ground deflection, emphasis must be put on the ballast material in the assessment and design of a railway pavement structure.

2.2.2.2 Sub-Ballast

A sub-ballast layer is entrenched under the ballast. It is a transition layer between the upper layer of significant ballast particulate quality and the reduced layer of fine grain. The sub-ballast used in new structures is aimed at preventing mutual penetration or mixing of the subgrade and the ballast and improving conversation against freezing (Dahlberg 2003). Any sand or gravel material can work as a sub-ballast material if it meets the filtration criteria that are suitable.

One of the key tasks of the sub-ballast layer is to avoid subgrade and ballast mixing. Sub-ballast separation can be accomplished by using sand or geosynthetic materials such as geotextile, geocell, and geogrids.

2.2.2.3 Subgrade

Subgrade is the basis of a railway structure and may consist of current natural soil or soil located. The main role of the subgrade is to provide the railway structure with a stable basis. Excessive settlement should therefore be prevented in the subgrade (Fong 2006). The subgrade is a material layer based on the subgrades of ballast and ballast. It is an essential component of the railway system and can lead to deterioration and bad railway structure if not well designed. (Li and Selig 1995). The subgrade is the last layer that carries and deploys with eternal depth the dynamic load result downwards. Recently, geogrids have been applied to upgrade the capacity of the subgrade.

2.3 Geosynthetics Reinforcement

Geosynthetics are manufactured from polymeric materials. They are used with soil, rock, earth or other geotechnical engineering materials as an integral part of a project, structure or system
Geosynthetic materials include eight main products: geotextiles, geogrids, geonets, geomembranes, geosynthetic clay liners (GCL), geofoams, geocells, and geocomposites. These materials are commonly applied in highways, railways, dams, canals, storage regions, retention facilities and numerous applications in civil engineering (Koerner 2012).

The geosynthetics in pavement design have a number of functions such as separation, reinforcement, filtration, confinement, stiffening, lateral drainage, sealing, and barrier (Holtz 2001). These applications are schematically represented in Figure 2.5. Geosynthetics were used to strengthen and separate railway projects in order to minimize unjustified entry (i.e., ballast materials of different sizes, garbage and so on) into the sub-ballast. It can also be used for a geosynthetic reinforcement function.

![Figure 2.5 Functions Performed by Geosynthetics in a Railway Pavement Design (Tencate 2019)](image-url)
The reinforcement feature is usually given by geogrids, while geotextiles are used in transport apps as reinforcement additives (Benjamin et al. 2007; Zornberg 2011). Separation is the use of a flexible, porous geosynthetic product between different materials; thus, the unity and performance of both materials are strengthened. This strengthening also offers a long-term relief of stress. Geosynthetic reinforcement rises the tensile strengths of the geosynthetics soil composite to maintain or advance its stability. The geosynthetic tensile strength is an important design characteristic of this function. Filtration in geosynthetics consents fluid to flow through the plane while retaining fine particles on the side of the plane. Stiffening by geosynthetics in the geosynthetics soil composite improves its stiffness to control deformations. Drainage in geosynthetic allows fluid (or gas) to flow through the material structure. A significant design feature for measuring this function is geosynthetic transmission (hydraulic conductivity embedded in the plane). More elaborations of the five (separation, reinforcement, filtration, stiffening, drainage) functions described above can be found in the literature (Zornberg and Christopher 2006; Koerner 2012).

2.3.1 Geogrid Reinforcement

Geogrids are formed by integrally bonded elements containing apertures larger than 6.35 mm (1/4 in.). Geogrids are generally applied with soil, rock, earth, and other peripheral materials to function primarily as reinforcement (ASTM D4439). Geogrids, with openings varying from 10 to 100 mm in size, have comparatively elevated power, elevated modulus, and low rupture potential after factory processing. These openings are rectangular, square or elongated ellipses. Geogrids is a significant factor in reinforcement (Koerner 2012). A typical example of a geogrid product can be seen in Figure 2.6.
Geogrids are split into the following two classifications depending on the stress direction during manufacturing: uniaxial and biaxial geogrids (Figure 2.7). A uniaxial geogrid is generated by introducing longitudinal strain to a methodically hollowed polymer sheet and is therefore more tensile in the longitudinal direction than in the transverse direction. The original extruded geogrids were produced by stretching a high-density polyethylene film perforated in one direction (Shukla and Yin 2014). A biaxial geogrid is a geogrid manufactured in both the longitudinal and the transverse directions of a polymer material that is regularly carved. Thus, it has an equal tensile strength in both longitudinal and transverse directions (Shukla 2014). These geogrids are typically generated in two perpendicular directions by stretching a perforated polypropylene layer.
The use of geogrids in path-based lessons provides a superb advantage to large geogrids. In the granular base course, geogrid can be created to provide an enhanced module, thus providing a lateral limit to the scheme. This lateral confinement is intended to resist the tendency for the base courses aggregate to move out from beneath under repetitive traffic loads imposed on the railway surface. Due to the dynamic load intensity, the scenario is the same for railway pavement structures (Koerner 2012). Studies show that the geogrid provides a reinforcing function to the railway system. Some possible contributions from geogrid include (Koerner 2012):

- Increase in stiffness
- Decrease in long term deformation
- Increase in tensile strength
- Reduction in cracking
- Improved cyclic fatigue behavior
- Holding together broken pieces
- Lower life cycle costs
Walters and Raymond (1999) the incorporation of geogrid reinforcement in the ballast granular support under the railway structure would enhance the soil's ultimate bearing capacity and reduce settlement. Figure 2.8 shows the reinforcement mechanism of geogrid in granular soil layer over a subgrade.

**Figure 2.8 Reinforcement Mechanism of Geogrid in Granular Soil Over a Subgrade (Perkins 1999)**

According to Perkins (1999), the mechanisms include: 1) limiting aggregates to the geogrid causes a reduction in the amount of lateral spread; 2) limitation causes increased lateral stress in the aggregate and hence increases the stiffness of the aggregates. This reduces dynamic deformation of aggregates for each load cycle. A drop in the shear stress within the substructure results in a lower vertical tension (Perkins 1999). Geogrids increase the bearing capacity of the system by forcing it to develop along higher shear-resistant surfaces. Besides, a geogrid with well compression capability can ensure tensile strength for the lateral behavior of aggregates (Holtz et al. 1997).
Chan (1990) showed that a substantial increase in permanent deformation resistance was accomplished with the implementation of a geogrid for fragile granular bases with low rigidity, such as those built of sand and gravel. The impact is most evident with the geogrid in the center or at the bottom of the ballast layer. A stiffer geogrid material also yielded better outcomes with decreased vertical deformation under elevated ballast stress. In Chan’s (1990) study, if the geogrid was too far down in the layer, there was minimal utility. In his opinion, the application of geosynthetics in the center of a ballast layer not exceeding 200 mm from the surface of the pavement provides optimum enhancement. Besides, he noted that their use in extremely loaded floors should be particularly helpful and would significantly reduce the frequency of maintenance compared to unreinforced pavement.

On the other hand, when assembled in the ballast and sub-ballast layers, geogrids can resort to decrease localization of ballast and sub-ballast materials associated with lateral spreading. Furthermore, geogrids can be used to discretize layers of the support structure, having different properties such as ballast, sub-ballast, and subgrade. The rapid movement of trains on railway structures makes the railway unstable. As a result, unwanted substrate particles can be pumped up into the granular layers, decreasing their strength and drainage ability. Geogrid reduces the penetration of granular particles into a subgrade, thus protecting the density and integrity of the granular layers and improving the durability of the pavement composition of the railway. Geogrid functions as a strainer for free filtering of water while capturing solid particles.

2.3.2 Geogrid Applications in Railway

Developing and optimizing railway ballast geogrid strengthening can decrease the rate at which ballast deforms. The proper use of geogrid reinforcement in the railway structure will allow longer maintenance cycles, resulting in cost savings, less disturbance and, in general, a safer means
of transport (Tencate 2019). The installation of geogrids is also comparatively simple and can be readily integrated into a routine maintenance procedure such as ballast cleaning.

The use of large aperture geogrids in a railroad ballast area can offer an advantage. Geogrids are placed in the ballast for two essential purposes. First, they reduce the fouling on the downstream side and enhance stability. Second, geogrids distribute the applied force uniformly and prevent the passage of unwanted trashes. When the geogrid is positioned within the granular foundation of a railway pavement, typically crushed stones, it offers the structure with a lateral break to improve the base rigidity. This lateral containment is designed to counteract the inclination of strengthening the ballast. The scenario also applies to the ballast under the railways, and perhaps more so because of the nature and intensity of the dynamic loads. The benefits of geogrid include increasing initial stiffness, reducing long-term vertical deformation, reducing long-term horizontal deformation, increasing tensile strength, reducing decay, improving cycle fatigue behavior and keeping the system together (Koerner 2012).

2.3.3 Geogrid Case Studies

Innovative geogrid applications in recent years have resulted in a steady increase in the use of geogrids as a supplement to the ballast or sub-ballast projects, particularly in the US and some parts of Europe. The following case history summarizes some of the projects using geogrid reinforced rail bearings.

2.3.3.1 Geogrid for Railroad in Alabama, USA

The Millstead railway pavement project in Alabama is North America's first geogrid implementation. The project deals with the application of a geogrid to reinforce the repair of a problem segment of a railway track. Geogrid was also used in this project involving the reconstruction of a 2-kilometer railway near the Tallapoosa River in Alabama. The railway was
operated by CSX Transportation, a prominent US railway company. The railway substructure was built on low-quality soils consisting of sand and weak clay with high groundwater (Walls and Galbreath 1987).

This stretch of railway line has been experiencing a lengthy history of issues. The heavy rail traffic led in excessive railway settlement owing to gradual shear failure of the subgrade, shoulder lifting and penalties being pumped through the ballast (Das et al. 2010). At one point in time, maintenance work was being undertaken every two to four weeks, and an 8 km/h speed restriction was in permanent effect.

Instead of implementing an alternative and more expensive solution to displace the runway, it was decided to balance the track foundation using geogrids for shear and tensile strength. Geogrids also incremented resistance to both vertical and lateral movements and strengthened the ballast layer.

In order to supply additional separation, a layer of geotextile (380 g/m²) was entrenched on the existent sub-ballast, and it was direct with a biaxial geogrid and a ballast layer 300 mm thick. As a result, during the reporting period, rail stability issues were not experienced and the peak velocity increased gradually, first to 56 km / h and finally to 80 km / h (Walls and Galbreath 1987). Consequently, the geogrid application had a significant benefit for heavy railway pavement project.

2.3.3.2 Geogrid for Railroad in Malaysia

As an example of the geogrid application in railways, high-speed railway pavement project in Malaysia was intended for 160-180 km/h speed trains. In the railway pavement project, a number of geosynthetics, such as biaxial geogrids and woven geotextiles, have been widely used for separation, filtering and reinforcement (Arulrajah et al. 2015). Geosynthetics have been applied
mainly in the following conditions: high fill areas under soft clays and loose sands. Geogrid reinforced piled fillings; geogrid fillings; geogrids in the approach to bridges and bridge transitions, geogrids under grilles, geogrids supported by stone columns, and geogrids supported by stone pillars. Woven geotextiles were also used in this project for cemented column research. Geotextile materials have been applied for excavation work and in the following conditions: nonwoven geotextile materials applied on top of the railway lower floor, nonwoven geotextile materials used as temporary retaining walls, and nonwoven geotextile materials for slope protection. This case project guarantees an elaborate concept of ballast development design and execution using geogrids and geotextiles. The use of geosynthetics in the project's multiple railway pavement apps guarantees secure and cost-effective alternatives to the multiple geotechnical and transport engineering problems faced (Arulrajah et al. 2015).
CHAPTER 3: MODEL DEVELOPMENT AND VALIDATION

3.1 Introduction

In this study, the three-dimensional (3D) finite element (FE) method is employed to capture the mechanical responses of railway pavement structures. Many researchers have utilized specific 3D FE programs to investigate railway reactions for railway pavement design. Kwan (2006), Leshchinsky and Ling (2013), and Satyal et al. (2018) studied the behavior of ballast and sub-ballast layer that were reinforced with different kinds of geosynthetics by experimental and analytical methods, and have developed some numerical models. In this study, the behaviors of non-reinforced and geogrid-reinforced ballasted system (within the ballast and between the ballast and sub-ballast layer) were investigated. Simulations were performed using a commercial FE program ANSYS for a non-reinforced ballast railway pavement system and a ballasted system reinforced with various geogrid materials.

This chapter firstly ensures an overview of the finite element models and several issues regarding the models such as the method of design, modeling of geogrid materials, and validation of existing models. The method of design, together with traffic loading is then individually presented. After that the overall procedure for determining model size and model material properties are explained.
3.2 Design Method

The thickness of the ballast layer was selected in several designs for an economic design that includes an effective ballast thickness that achieves the goal of reducing the stress in the railway subgrade. (Li and Selig 1998). Thus, the thickness of the ballast layer was chosen in several models to restrict the stress induced by traffic in the subgrade.

American Railway Engineering Association (AREA) recommends Talbot’s equation, which is based on field tests over many years, to determine the sufficient granular material thickness, $H$, and also suggests using 138 kPa for the allowable stress in the subgrade, $P_c$.

$$H = 0.24 \left( \frac{P_m}{P_c} \right)^{0.8}$$

where; $P_m$ is vertical stress applied on the ballast surface; $P_c$ is 138 kPa for the allowable vertical stress in the subgrade.

Raymond (1985) created a vehicle design chart weighing between 70 and 125 tons from the American Railway Engineering and Maintenance-of-Way Association (AREMA) by assuming ballast, sub-ballast, and subgrade are homogeneous half-space. This structure enables soil pressure to be reduced for three car weights, namely 70, 100 and 125 tons, as shown in Figure 3.1. To determine the granular layer thickness, a correlation that relates both vertical stress and the allowable soil pressure in the subgrade can be used (Raymond 1985).
3.3 Design Traffic Loading

As mentioned in Chapter 2, between a heavy haul freight train and a high-speed passenger train, their loads applied to the track foundation have different characteristics. Several researchers show that increasing train speed will raise the railway vibration (Li et al. 2017). Consequently, the distribution of stress caused varies with the train's weight and velocity.

The maximum wheel load applied to the railway system, Turkey State Railways (TCDD), which is available in the system, and 120 km/h maximum speed is 100 kN for traveling locomotives and wagons (TCDD 1990).

For all analysis, a single wheel load of 75, 100, 150, and 200 kN was used because of the facts discussed.
3.4 Previous Studies

Over a decade, several researchers adopted simulation models to determine the critical stress and strain and deformation behavior of railway structures. Results from the previous simulation models showed that the degradation of railway structures took place due to either a freight or passenger train passing on the railway tracks. Because the railway structure may be occasionally constructed on inadequate ballast that has a lower bearing capacity, methods of railway improvement such as installing new ballast layer and/or introducing new materials like geosynthetics that could increase the strength were suggested by several researchers. Table 3.1 presents a summary of the research that has been performed in the last two decades on railway pavement structures with geogrid reinforcement. In some previous studies, the continuous elastic beam model (Euler-Bernoulli beam) was applied to simulate three layers of the railway pavement, including the geogrid layer.

Table 3.1 Summary of the Previous Studies on Geogrid Reinforced Railway Pavement Structure

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Geogrid Application Location</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwan</td>
<td>2006</td>
<td>Ballast</td>
<td>Simulation based model</td>
</tr>
<tr>
<td>Leshchinsky et al.</td>
<td>2013</td>
<td>Between Ballast and sub-ballast</td>
<td>Simulation based model</td>
</tr>
<tr>
<td>Qian et al.</td>
<td>2015</td>
<td>Ballast</td>
<td>Simulation based model</td>
</tr>
<tr>
<td>Guler and Khosrowshahi</td>
<td>2017</td>
<td>Ballast</td>
<td>Simulation based model</td>
</tr>
</tbody>
</table>
Kwan’s research (2006) focused on geogrid reinforcement investigations with a willingness to decrease the rate of deterioration of the geometry of railway infrastructure. Research began with a series of element tests to evaluate the performance of discrete element modeling (DEM), namely the Pull-out and Geogrid Stiffness Test. The discrete element modeling was also compared to experimental data for validation. The aim of this computational job was to obtain a knowledge of ballast-geogrid mechanics modeling.

In a study of comparison of deflection, Yang et al. (2009) the standard two-dimensional track was simulated using the ABAQUS program to determine stress at 47.5 km / h freight train velocity. All track elements were simulated as a strong component with elastic properties. The results showed that shear stress was related to the speed of the train and as speed increased, it also boosted both the vertical stress and vertical deflection.

Galvin et al. (2010) studied the effect of reinforcement on the load-settlement characteristics. They simulated a standard railway under a train load at a velocity of 298 km / h to predict track and surrounding ground vibration. In this research, a car with two vehicles and eight passengers was depicted as a multi-body structure, and the boundary element model simulated a half-spaced railway. Results were shown on nine rectangular nodes and six quadratic triangular nodes.

Leshchinsky and Ling (2013) studied a model of ballasted railway via the ABAQUS program. The ballast model consisted of 152 cm and 61 cm square base and top width, respectively,
and 55 cm height. Vertical loading was applied to unreinforced ballast embankments with a single layer of geocell at medium height or a double layer of geocell. They used geosynthetic materials in between the ballast and sub-ballast layers. In this study, a flat strain slice of half a ballasted substructure of the railway was modeled with a finite element mesh refined to observe significant foundation conduct under loading, reinforcing the subgrade ballast interface with or without geocell.

Fu and Zheng (2014) analyzed a current railway pavement at four different speeds, which were 60, 80, 100, and 120 km/h, by using the ABAQUS program. Model simulation regarded the railway pavement design components as linear elastic materials. Bottom of the boundary or bed-rock was fixed in every direction to put a limit on ground movement after being analyzed. To present the results of the study, a hexahedral component was chosen. The analytical result shows that the vertical displacement is related to the speed of the train, as shown in Figure 3.2.

![Figure 3.2 Vertical Displacements Under Three Different Load (Fu and Zheng, 2014)](image-url)
A study by Qian et al states that triaxial shear strength tests with and without geogrid strengthening on both fresh and degraded ballast materials. They discussed several experimental and numerical methods to evaluate the application of geogrid materials between the ballast and sub-ballast, with particular reference to the applications of these materials in geogrid reinforcement. Two geogrid types, with square and triangular shaped apertures, were used in the laboratory to calibrate aggregate imaging based (DEM) approach. As a result, the highest shear stress values in the current study were obtained for ballast specimens reinforced using the square-aperture geogrid. (Qian et al. 2015)

A research by Satyal et al. that conducted a number of large-scale fitted loading trials and numerical simulations on geosynthetics restricted ballast overlaying a fragile subgrade material to explore the efficacy of containment of geosynthetic material on ballast railway embankments. They used geosynthetic materials in between ballast and subgrade. The agreement of findings from trials and simulations served as a basis for simulating practical design and performance of railway pavement for various geosynthetic material configurations and subgrades using 3D finite element (FE) analyzes. The research showed that geocell strengthening significantly reduced the settlement of the railway structure, reduced subgrade deformations with a reduced and uniform distribution of vertical stress on the subgrade and inhibited lateral deformation and serviceability under cyclic loading, as shown Figure 3.3. These findings show that geocell containment can be an efficient solution to improving the surface or shorter maintenance cycles, especially on fragile substructures. (Satyal et al. 2018)
As a result, the main advantages and limitations of some theoretical and numerical methods for the studies of ballast–geosynthetics were presented, new applications of these methods were addressed, and the need for improvements in the numerical techniques for a better understanding of ballast–geosynthetic interactions was highlighted.

3.5 Railway Trackbed Validation

The actual geometry of the railway trackbed is simulated in this study. Here the word “track” refers to a combination of all railway components, such as sleepers, ballast layer, and sub-ballast layer.

3.5.1 Stress Below a Trackbed Area

The total stress increase, $\Delta \sigma$, at any point under a rectangular trackbed area may be calculated from the relationship between the applied load, $q0$, over an area, $Da=dx\,dy$, and foundation dimensions (B and L) to obtain the preceding equation shown as (Das et al. 2015).
\[ \Delta \sigma = \int \int_{y=0, x=0}^{l, b} \frac{3q_0(x) dxdy z^3}{2\pi(x^2 + y^2 + z^2)^{\frac{5}{2}}} \]

Alternatively, the increments in total stress, \( \Delta \sigma \), is calculated from the applied load, \( q_0 \), multiple with by an influencing factor, \( I \), which is derived from a ratio of the rectangular area, as shown in Figure 3.4, divided with the depth \( z \) substituted into influence factor equation.

\[ \Delta \sigma = q_0 l \]

\[ I = \frac{1}{4\pi} \left( \frac{2mn\sqrt{m^2 + n^2 + 1}}{m^2 + n^2 + m^2n^2 + 1} \cdot \frac{m^2 + n^2 + 2}{m^2 + n^2 + 1} + \tan^{-1} \left( \frac{2mn\sqrt{m^2 + n^2 + 1}}{m^2 + n^2 + m^2n^2 - 1} \right) \right) \]

where;

\[ m = \frac{B}{z} \quad n = \frac{L}{z} \]

![Figure 3.4 Example of Rectangular Loaded Area (Das et al. 2015)](image-url)
The stress at a depth \( z \) below point \( O \) or the intersection of four rectangles is calculated from the summation of influence values from \( I_1 \) to \( I_4 \) multiplied by the applied load.

\[
\Delta \sigma = q_0(I_1 + I_2 + I_3 + I_4)
\]

Comparison of the outcomes acquired in this research from the FEM model and the theory of elasticity (Applying the stress technique below a rectangular region) will assist validate the present model and its precision to predict vertical stress.

In the study by Wattanapanalai (2018), in this research, model simulation also utilizes real geometry. This model also utilizes average characteristics as input. Applied pressure is 900 kPa, which is equal to a train with 235 km/h speed. The value of vertical stress from the railway pavement surface is assessed at a depth of 17.7 cm (Wattanapanalai 2018). Overall of the result shows the vertical stress spreads. However, the result of vertical stress in the efficient model at the middle down the rectangular floor is around 239.26 kPa, which is slightly greater than the equation's vertical stress this slight decrease in stress may be due to the distinct assumptions in the dispersion of the vertical stress. The simulation demonstrates extremely concentrated vertical stress around the center of the rectangular space, as illustrated in Figure 3.5.
Wattanapanalai (2018) used the FE program ABAQUS to model a three-dimensional half-railway pavement structure. In his model, a total of 55,677 eight-node brick elements were utilized. To determine the interactions between the surfaces of each layer, an appropriate surface-to-surface contact should be generated. The vertical loads ranging from 14 kN to 47 kN on top of the rail were applied both longitudinally and transversally to obtain symmetric boundary condition in the models.

The outcome of this simulation was gathered at the bottom of the sleeper to examine and compare the vertical stress under different loads, ranging from 14 kN to 47 kN. Figure 3.6 shows the vertical stress distribution under the applied load.
As a result, the load (660 kPa) applied on the system produced a maximum vertical stress of 154.24 kPa and maximum displacement of 0.0883 mm. In addition, various loads applied to the model showed that stress and displacement boosted with increased loads.

### 3.6 Modeling Procedures in ANSYS

In the analysis using the ANSYS program, it started with creating the geometry of the FE model by sketching each part of the railway pavement structure into a part module and the material properties were defined at the property module. Step and mesh modules were related to the calculation method and the accuracy of the result. Finally, the results of the analysis were illustrated in a visualization module.

### 3.7 Ballasted Railway Model with Geogrid Reinforcement

In general, the ballast layer thickness, which had to be designed first, varies from 20 cm to 35 cm. Considering the infrastructure of (HSRL) for train speed of 120-160 km/h and annual gross tonnage >50 million gross tons (MGT), a ballast layer thickness of 35 cm was selected based on
Table 3.2 from Dareeju et al. (2014). Therefore, this study simulated the railway pavement structure design with a ballast layer of 35 cm thickness under the four different vertical loads (i.e., 75, 100, 150, and 200 kN).

**Table 3.2 Layer Thickness Variations Based on Chinese Codes (Dareeju et al. 2014)**

<table>
<thead>
<tr>
<th>Train Speed (km/h)</th>
<th>Ballast Layer Thickness (m)</th>
<th>Annual Gross Tonnage (MGT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 80</td>
<td>0.20</td>
<td>&lt;8</td>
</tr>
<tr>
<td>≤100</td>
<td>0.22</td>
<td>8 - 15</td>
</tr>
<tr>
<td>≤120</td>
<td>0.25</td>
<td>15 - 25</td>
</tr>
<tr>
<td>≤160</td>
<td>0.35</td>
<td>25-50</td>
</tr>
<tr>
<td>120-160</td>
<td>0.35</td>
<td>&gt; 50</td>
</tr>
</tbody>
</table>

Chan (1990), a notable recovery was achieved by the use of geogrid equipment in the center of a ballast layer not exceeding 15-20 cm deep. The current research also explored the combination design of the geogrid layer positioned between ballast and subballast at a depth of 15-20 cm with three distinct kinds of geogrid components:

- 20 cm down from the top (sleeper) (location of geogrid)
- Three different geogrids in the ballast layer under four different load applications
- Three different geogrids between the ballast and the sub-ballast layer under four different load applications

The reason for choosing this geogrid depth is that the geogrid layer was installed at a somewhat limited altitude for a ballasted railway, typically at medium height. (Chan 1990).

Effects of geogrid on various type of stress, strain, and displacement responses of the railway pavement structure are presented in this chapter. Later the results will show how the design method could boost the strength of the railway pavement structure. Figure 3.7 shows the geometry of a conventional railway structure. To understand the influence of the railway pavement structure
design due to different parameters (i.e., railway structure components). Therefore, the simulation was divided into four parts, sleeper, geogrid layer, the ballast layer, and the sub-ballast layer.

![Image of railway structure model](image)

**Figure 3.7 FE Model of Conventional Railway Structure Built in ANSYS**

### 3.7.1 Geometry in Simulation

The railway components were simulated in three dimensions by following the design standard of American Railway Engineering and Maintenance-of-Way Association (AREMA). In this research, SI-units were used for consistency measurements and parameters. A parametric study was based on the normal railway substructure geometry supplied by the design requirements of the National Railroad Passenger Corporation (AMTRAK). The ballasted railway pavement structure design was 5.2 m in width, 2.7 m in length, and 0.6 m in height. Likewise, I used half railway substructure geometry for my analysis. Therefore, I chose, ballast dimensions of 35 cm height, 150 cm length and 100 cm width from for finite element simulations, and sub-ballast were chosen as 20 cm in height and 100 cm in width (Figure 3.8). All components of the railway design
parameters like the sleeper, three different types of geogrid, ballast layer and sub-ballast layer were presented in Table 3.3. This 3-D simulation model is a beam (rail) on the support structure (ballast) on another beam (sub-ballast).

**Figure 3.8** Railway Geometry with Geogrid Confinement

**Table 3.3** Dimensions of Sleeper, Geogrids, Ballast and Sub-Ballast

<table>
<thead>
<tr>
<th>Components</th>
<th>Width (cm)</th>
<th>Length (cm)</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeper</td>
<td>100</td>
<td>40</td>
<td>12.5</td>
</tr>
<tr>
<td>Geogrid G1</td>
<td>150</td>
<td>100</td>
<td>0.75</td>
</tr>
<tr>
<td>Geogrid G2</td>
<td>150</td>
<td>100</td>
<td>0.75</td>
</tr>
<tr>
<td>Geogrid G3</td>
<td>150</td>
<td>100</td>
<td>0.75</td>
</tr>
<tr>
<td>Ballast</td>
<td>150</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>Sub-ballast</td>
<td>150</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>
Results were used to observe the correlation between a thickness of the ballast layer and an influence of applied vertical load in terms of, principal stress, principal elastic strain, and vertical surface deflection in the railway pavement structure.

As a recap, in order to compare geogrid reinforcement at two locations (i.e., within ballast, and between the ballast layer and the sub-ballast layer), this study simulated the design of the railway structure in the FE program ANSYS. The model was constructed with a 35 cm thickness ballast layer, and a 20 cm thick sub-ballast layer, and the mechanical responses of the conventional railway structure with and without geogrid reinforcement were compared.

### 3.7.2 Properties of Materials

#### 3.7.2.1 Ballast Modeling

The ballast's basic function is to evenly transfer and deploy loads from the structural to the reduced ballast layer, which consists mainly of granular materials (Ali 2013). Ballast is a widespread and significant material used to support railway substructure bearings; hence, material selection, dimensions, and features are crucial. Ballasts must have good features to be a useful model. According to Dahlberg (2003), the ballast must meet the following conditions:

- Ballast must be hard enough to resist distortion by breakage.
- Ballast must be hard enough to resist attrition through wear with neighboring ballast particles.
- The ballast must be sufficiently intensive to resist the lateral forces to anchor the sleepers.
- Ballast must be weather-resistant to prevent ballast weakening owing to crystallization or acidity.
- Ballast particles with rough surfaces must be angular and of equal size to guarantee maximum friction.
The ballast type selected for the railway pavement design used in my finite element analysis is limestone. I used limestone because its use as railway ballast is very common. For instance, limestone is prevalent in some southern US states such as Florida. It was more available locally than in other regions. Typical functions (i.e., density, Young’s modulus, Poisson’s ratio and so on) are provided for different material types in the FE program ANSYS. These example functions are useful when the models need to be installed quickly. All parameters, particularly Young’s modulus, from those components profoundly affect the outcome of the track modulus. Average values from previous researches, as shown in Table 3.4, were used in my analysis. The ballast density of 2200 kg/m$^3$ was determined using ASTM D4253 Guidelines.

**Table 3.4 Limestone Ballast and Sub-Ballast Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ballast</th>
<th>Sub-ballast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, E (MPa)</td>
<td>110</td>
<td>85</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Density (kg/ m$^3$)</td>
<td>2200</td>
<td>1800</td>
</tr>
</tbody>
</table>

### 3.7.2.2 Geogrid Properties

In this study, in terms of density, Young’s modulus and Poisson’s ratio, three different types of geogrid used as ballast reinforcement were included in the analysis, with name designations of G1, G2, and G3. The objective is to analyze how different geogrids behave in reinforcing railway pavement structure under vertical train load. The basic material properties of these geogrids are shown in Table 3.5. These geogrids are all square aperture ones in accordance with previous results (Qian et al. 2015).
In order to feature the properties of the geogrids within the ballast, a same thickness of 7.5 mm was selected for the three different geogrids in my analysis. It ought to be noted that the actual geogrid thickness may vary in a wide range for different types and brands of geogrids.

**Table 3.5** Material Properties of Three Different Geogrids Modeled in ANSYS

<table>
<thead>
<tr>
<th>Geogrid Type</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/ m³)</td>
<td>600</td>
<td>800</td>
<td>1100</td>
</tr>
<tr>
<td>Young’s Modulus (MPa)</td>
<td>7</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.300</td>
<td>0.300</td>
<td>0.316</td>
</tr>
</tbody>
</table>
CHAPTER 4: NUMERICAL ANALYSIS OF GEOGRID REINFORCED BALLAST BEHAVIOR IN RAILWAY

4.1 Introduction

Accurately predicting the maximum principal stress, principal elastic strain, and vertical surface deflection in railway systems under realistic loading conditions requires a three-dimensional (3D) finite element (FE) model, as discussed in Chapter 3. This chapter describes the FE modeling analysis and results for a total of 80 separate analyses, in which the effectiveness of geogrid in reducing vertical surface deflection and critical stresses of a ballasted railway pavement structure was evaluated. Besides, the effect of geogrid location (i.e., within the ballast and between the ballast and the sub-ballast layers) was evaluated in comparison to a non-reinforced railway pavement structure (Figure 4.1). These analyses were carried out in ANSYS, and the mechanical responses of the railway pavement structure were evaluated in terms of vertical surface deflection, maximum principal stress and strain, and maximum shear stress. The non-reinforced ballasted railway system was modeled first, and then geogrid-reinforced ballasted system was modeled and analyzed by placing different types of geogrid materials within the ballast and between the ballast and sub-ballast layers.
4.2 Boundary Conditions and Mesh Properties

In numerical modeling, the choice of boundary conditions plays an important role, and boundaries are equally important in FE modeling. A critical decision in setting up a FE model simulation is to decide on the spatial domain that will be considered. The FE model of the railway...
pavement structure used in this study is made up of four layers, including sleeper layer, geogrid layer, ballast layer, and sub-ballast layer. Each layer has its material properties and thickness.

The dimensions of each mesh element are not the same, as shown in Figure 4.2. For instance, meshes of an approximate global size of 0.25 mm were specified for the ballast layer in numerical analysis. In cases where the magnitudes of stress and displacement are higher, refined mesh elements are used around the wheel loads. The maximum stresses and strains at the bottom of the ballast layer or the maximum surface deformation are generally used as criteria to design the railway pavements. In general, with other conditions (i.e., traffic load, boundary conditions, model size, material properties and so on) kept the same, the case with a relatively large number of FE elements will yield more accurate results than the one with less FE elements.

![Figure 4.2 Meshing of Simulation (ANSYS 2018)](image)

**Figure 4.2** Meshing of Simulation (ANSYS 2018)
The boundary conditions used in this study are shown in Figure 4.3, where the nodes on each face except the surface are constrained from moving along the direction perpendicular to that face and are free to rotate. The bottom boundary is considered to be fixed, and all other four boundaries can only have vertical displacement. The z-x plane's vertical limits were restricted in the y-direction from lateral displacement. Likewise, the vertical planes in the outer corners of the z-y planes were restricted in the x-direction from lateral movement. The base of the model was constrained from all displacements.

The meshing of this model uses a total of 20,480 elements. Other meshing models in this study are different from this meshing model due to varying dimensions according to where the meshing model is used and the materials used. These boundary conditions were determined based on the fact that the railway pavement structure is symmetric in the longitudinal and the transverse directions, as shown in Figure 4.3.

The mesh properties are defined by the approximate square element size, as shown in Figure 4.2. Mesh was generated for each model. The number of elements and the test surfaces were determined by increasing them until there were no changes in the results after any further operation.
4.3 Analysis of Stress, Strain, and Deflection in Structures with Geogrid in Ballast

Four types of responses (i.e., maximum principal and shear stresses, principal elastic strain, and vertical surface deflection) were analyzed under the application of single wheel load of 75, 100, 150 and 200 kN. These mechanical responses are essential components in the analysis of railway pavement structure systems. Since damage is likely to take place in the railway pavement structure when different types of load are applied by new High Speed Rail Lines (HSRL) trains, it is necessary to consider the demand of HSRL on the infrastructure. Compared to conventional trains, HSRL can potentially cause a more significant problem which may impact the ballast and sub-ballast layers negatively. Thus, critical stresses, strains, and deflections on the substructure are also key parameters to design the railway structure. This section aims to investigate how a geogrid reinforcement layer may affect the fundamental properties of the railway structure. In the characterization of the four mechanical responses, the analysis was performed by applying a
vertical consolidated wheel load on the ballasted system and measuring the vertical deflection of the surface layer.

4.3.1 Maximum Shear Stress Analysis in Ballasted System

Shear stress, $\tau$, results from shear forces that are pairs of equal and mutual forces, $F$, acting on opposite sides of an object with an area of $A$ (i.e., $\tau = F/A$).

Eight runs of shear stress analysis were conducted on various geogrid reinforced samples and samples without geogrid in the ballast. From Figure 4.4, it can be seen that with the increase of the load, the shear stress at the top of ballast increases almost linearly. According to the results, the maximum development of the shear stress occurs in the scenario of the non-reinforced sample under vertical load of 200 kN. For the same ballast thickness, an increase in the vertical load from 75 to 200 kN caused about a 29% increase in the maximum shear stress in the reinforced concrete sleeper and ballast layer interface.

Results shown in Figure 4.5 (b)-(d) indicate that all three types of geogrid containment increase maximum shear stress in the geogrid in the reinforced railway structure, but the maximum shear stress at the interface of the sleeper and the ballast layer is reduced compared to that in Figure 4.5(a) where geogrid is not used.
Figure 4.4 Effect of Reinforcement on Maximum Shear Stress at the Interface of Sleeper and Ballast in the Non-reinforced Structure
Figure 4.5 Maximum Shear Stress for All Application Types of Geogrid Within the Ballast Under Applied Load of 200 kN. (a) Without Reinforcement; (b) With G1; (c) With G2; (d) With G3 (ANSYS 2018)
Figure 4.5 (Continued)
4.3.2 Vertical Surface Deflection Analysis in Ballasted System

Placing a geogrid in the ballast will cause wheel pressure not to be transmitted to all ballast sides because geogrid has the ability to separate material properties. To evaluate the effects of geogrid on the pressure distribution in the ballast an analysis was performed to simulate pressure-related deformation. For simplicity, it is important to note that the horizontal geogrid configuration is used to change pressure distribution.

Model analysis indicates that there was vertical surface deflection in all ballasted railway pavement structures, but the deflection was reduced after the use of the geogrid in the ballast. Frankly, geogrid contributes to the reduction of deflection, as illustrated in Figure 4.6, in which
the red area has high deflections, while the green and light blue areas have low deflections and the dark blue area means there is virtually no deflection.

**Figure 4.6** Vertical Surface Deflection for All Application Types of Geogrid Within the Ballast Under Applied Load of 200 kN. (a) Non-Reinforcement; (b) With G1; (c) With G2; (d) With G3 (ANSYS 2018)
Figure 4.6 (Continued)
Additionally, the maximum deflections appeared along with the point where the load was applied. Compared to the control structure (i.e., non-reinforced railway pavement structure), the railway pavement structure reinforced with geogrid G3 has the deflection reduced the most, while the structures reinforced with geogrid G1 or G2 has the deflection reduced slightly less. Among the all analysis scenarios, the maximum deflection appears in the non-reinforced structure, as shown in Figure 4.6(a). The relationship between the maximum surface deflection and load for the four railway pavement structures is summarized in Figure 4.7. As can be seen, the vertical surface deflection increases approximately linearly with the wheel load in all ballast reinforcement scenarios.
Figure 4.7 shows that under a wheel load of 200 kN, the maximum vertical surface deflection is 7.22 mm in the non-reinforced structure but reduced to 6.63 mm in the structure reinforced with geogrid G3.

![Figure 4.7](image)

**Figure 4.7** Vertical Surface Deflection in Structures with Different Types of Geogrid Under Different Loads

As a result, a significant improvement in vertical surface deflection resistance may be achieved with the introduction of a geogrid layer in the middle of the ballast layer. A stiffer geogrid gives better results. Moreover, the results from this analysis show that the vertical surface deflection is decreased by 6.80%, 8.04%, and 11.07%, respectively, by the use of, geogrid G1, G2, and G3 reinforcement.
4.3.3 Maximum Principal Stress Analysis in Ballasted System

Maximum principal stress in the ballast contributes to potential failure of ballast in terms of particle separation and attrition. In this study, the maximum principal stress at the bottom of the ballast layer was compared among the railway pavement structures with and without geogrid reinforcement. Figure 4.8 shows a summary of the maximum principal stresses identified from various structures by the 3-D FE analysis. It should be noted that a positive value represent tension.

Results showed that the design without geogrid reinforcement experienced maximum principal stress at the bottom of ballast greater than the maximum principal stress in railway pavement structures with geogrid reinforcement. A stiffer geogrid reinforcement leads to more reduction in the maximum principal stress at the bottom of the ballast. These findings suggest that the maximum principal stress at the bottom of ballast is affected by geogrid materials and this effect may be sufficient to improve the railway pavement performance. In addition, as shown in Appendix A, high stress zones are found in the geogrid layer, indicating the geogrid layer contributes to the carrying of the wheel load.
Figure 4.8 Maximum Principal Stress Within the Ballast in Structures with Different Types of Geogrid Under Different Loads

4.3.4 Maximum Principal Elastic Strain Analysis

Similar to the analysis of maximum principal stress, results of the maximum principal elastic strain at the bottom of the ballast from the FE analysis are plotted in Figure 4.9. Some screenshots of the distribution of maximum principal strain in the model structures are shown in Appendix B.

As can be seen from Figure 4.9, the inclusion of geogrid in the ballast layer reduces the maximum principal elastic strain at the bottom of ballast, and among the three types of geogrid, G3 that has the highest stiffness reduces the maximum principal elastic strain the most. This indicates that the inclusion of geogrid in the ballast layer improves its strain properties.
4.4 Analysis of Stress, Strain and Deformation in Structures with Between Ballast and Sub-Ballast

Similar analysis was also performed on the railway pavement structures with geogrid reinforcement placed between the ballast layer and the sub-ballast layer. The results are discussed and summarized as follows.

4.4.1 Vertical Surface Deflection Analysis in Ballasted System

In this section, I applied the three types of geogrid in between the ballast and the sub-ballast layers instead within the ballast layer and repeated the FE analysis as discussed in the previous section. Results for the load of 200 kN are illustrated in Figure 4.10. Similar to the results when geogrid is placed within the ballast layer, placing the geogrid at the interface of the ballast and

Figure 4.9 Maximum Principal Elastic Strain Within the Ballast in Structures with Different Types of Geogrid Under Different Loads
sub-ballast layers also reduces the vertical surface deflection of the railway pavement structure. The level of reduction, however, is slightly less than in the scenarios when geogrid is placed within the ballast layer. The results from this analysis show that the vertical surface deflection is decreased by 4.5%, 6.5%, and 8.8%, respectively, by the use of geogrid G1, G2, and G3 reinforcement, as can be observed from Figure 4.11.

Figure 4.10 Vertical Surface Deflection of Structures with Geogrid in Between Ballast and Sub-Ballast Under Applied Load of 200 kN. (a) Without reinforcement; (b) With G1; (c) With G2; (d) With G3. (ANSYS 2018)
Figure 4.10 (Continued)

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Figure 4.10 (Continued)
4.4.2 Maximum Principal Stress in Ballasted System

The maximum principal stresses in structures with geogrid placed in between the ballast and sub-ballast layers are summarized and plotted in Figure 4.12. These maximum values appear at the bottom of the ballast layer. As can be seen, placing geogrid between the ballast and sub-ballast layers also reduces the maximum principal stress at the bottom of the ballast layer. Compared to the results in Figure 4.8 for geogrid reinforcement within the ballast layer, the maximum principal stresses are slightly higher when the geogrid is in between the ballast and the sub-ballast layers. Therefore, the place of geogrid, geogrid materials, and applied load all impact the maximum principal stress at the bottom of the ballast layer.
Figure 4.12 Maximum Principal Stress in Structures with Geogrid Placed in Between Ballast and Sub-Ballast Non-reinforced and Reinforced

Figure 4.12 indicates that with the increase of vertical load, the effect of geogrid on the reduction of maximum principal stress at the bottom of the ballast layer is more significant.

4.4.3 Maximum Shear Stress Analysis in Ballasted System

The maximum shear stress results for railway pavement structures with geogrid placed in between the ballast and sub-ballast layers are illustrated in Figure 4.13 and summarized in Figure 4.14. From Figure 4.13, it can be seen that the application of geogrid between the ballast and the sub-ballast layers reduces the maximum shear stress at the interface of sleeper and ballast. The maximum shear stress along the geogrid and ballast/sub-ballast interface increases with the increase of geogrid stiffness. Compared to the results in the scenarios when the geogrid is placed within the ballast layer, the effect of geogrid on the reduction of the maximum shear stress at the
interface of sleeper and ballast is less significant when the geogrid is placed at the lower position (i.e., between ballast and sub-ballast).

**Figure 4.13** Maximum Shear Stress for All Application Types of Geogrid in Between the Ballast and Sub-Ballast Layer Under Applied Load of 200 kN. (a) Without reinforcement; (b) With G1; (c) With G2; (d) With G3 (ANSYS 2018)
Figure 4.13 (Continued)
Figure 4.13 (Continued)

Figure 4.14 Maximum Shear Stress in Structures with Geogrid Placed in Between Ballast and Sub-ballast to the Applied Different Load
4.5 Comparison of Reinforcement at Different Locations

To determine the effect of geogrid placement position on critical mechanical responses of railway pavement structure under a vertical wheel load, the analysis results presented in the previous sections are summarized here and compared. Figure 4.15 shows the surface vertical deflection values in railway pavement structures without geogrid reinforcement, with geogrid within the ballast, and with geogrid between the ballast and the sub-ballast layers. It can be seen that the application of geogrid in the railway pavement structure generally reduces the vertical surface deflection, and the reduction is more significant when the geogrid is placed within the ballast layer.

Figure 4.15 Comparison of Surface Vertical Deflections in Structures with Geogrid within Ballast and in Structures with Geogrid in Between the Ballast and Sub-Ballast
Figure 4.16 shows the maximum principal stresses at the bottom of the ballast layer in railway pavement structures without geogrid reinforcement, with geogrid within the ballast, and with geogrid between the ballast and the sub-ballast layers. It can be seen that the use of geogrid in the railway pavement structure generally reduces the maximum principal stress, and the reduction is slightly more significant when the geogrid is placed within the ballast layer.

Figure 4.16 Comparison of Maximum Principal Stress in Structures with Geogrid within Ballast and in Structures with Geogrid in Between Ballast and Sub-Ballast

Figure 4.17 shows the maximum shear stresses at the interface of sleeper and ballast in railway pavement structures without geogrid reinforcement, with geogrid within the ballast, and with geogrid between the ballast and the sub-ballast layers. It can be seen that the use of geogrid in the railway pavement structure generally reduces the maximum shear stress, and the reduction is more significant when the geogrid is placed within the ballast layer. The results show that the
maximum shear stress at the interface of sleeper and ballast is reduced by 32% when geogrid G3 reinforcement is used.

![Graph](image.png)

**Figure 4.17** Comparison of Maximum Shear Stress at the Interface of Sleeper and Ballast

As a result, this study shows that geogrid reinforcement significantly decreased vertical surface deflection, maximum principal stress at the bottom of the ballast layer, and maximum shear stress at the interface of sleeper and ballast.
5.1 Discussion

This study analyzed the effect of geogrid reinforcement in ballasted railway pavement structure on its mechanical responses. The finite element (FE) technique used numerical simulations. Geogrid systems are one of the most effective ways to improve railway pavement performance. The effect of geogrid reinforcement was investigated in terms of change in vertical surface deflection, maximum principal and shear stresses, and maximum principal strain in railway pavement structures with and without the inclusion of three types of geogrid. Also, the effect of the geogrid placement location was also investigated.

Previous studies have shown that geogrid placement has a positive effect on railway structure performance. The results of this research support and expand these findings by showing that the rise in safety factors of a railway structure can be important owing to geogrid strengthening based on the type of geogrid material and the place of the implementation. It has also been shown that the use of more than one geogrid reinforcement can significantly reduce the deformation problems of ballast by increasing the geogrid reinforcement factor.

The type of geogrid has a significant effect on its function in the railway pavement structure. In this study, three different types of geogrid were included in the analysis, characterized in terms of density, Young’s modulus, and Poisson’s ratio, with values obtained from typical geogrids with rectangular-shaped apertures. In practice, the choice of features and types of geogrids for the basis of railways is very important in the design phase. The results from this study
clearly demonstrated the impact of the difference in three geogrids (G1, G2, and G3) on mechanical responses of the railway pavement structure. For geogrid itself, it is significant to note that increasing its stiffness will have a positive effect on its mechanical properties such as a reduction in stress and increased resistance to tear and degradation. In this study, the geogrid layer was assumed to be a homogeneous linear elastic material, which ignored the aperture features of geogrid. Analysis including this level of details of geogrid may improve the accuracy of the analysis.

5.2 Summary of Research Findings

This thesis research is a useful step in the comparison of geogrid properties, geogrid locations, and applied load for geogrid-reinforced railway pavement structure design. The following results are obtained from this study:

- The aim of this thesis was to quantify the benefits of geogrid reinforcement on the ballasted railway and to study the mechanical characteristics of geogrids which would provide optimum performance at separate places. Results were generated that are intended to be accessible to the geogrid-reinforced pavement structure developers in a straightforward format.

- The possible use of three different types of geogrid to improve the performance of ballasted railway was investigated. The analysis findings showed that the inclusion of geogrid reinforcement enhances the performance of ballasted railway. The results obtained from the FE models were reasonably consistent with the literature.

- The use of geogrid reinforcement reduced the vertical deflection. Geogrid reinforcement did assist in redistributing stresses more evenly, which may prevent the development of high deformation and failure in the railway base and subgrade. Results from this study
show that the vertical surface deflection is decreased by 4.5%, 6.5% and 8.8%, respectively, when geogrid G1, G2, and G3 reinforcement used within the ballast.

- In addition to reducing vertical surface deflection, geogrid reinforcement reduces the maximum shear stress at the interface of sleeper and ballast and reduces the maximum principal stress at the bottom of the ballast layer.
- Geogrid shows more reinforcement efficiency at higher vertical loads.
- The results show that the maximum principal stress at the bottom of the ballast layer, the maximum surface vertical deflection, and maximum shear stress at the interface of sleeper and ballast are reduced by 41.6%, 11.8% and, 32.2% respectively, when geogrid G3 reinforcement is used.
- The FE simulation platform can adequately simulate the stress and stress behavior of both the non-reinforced and geogrid reinforced ballasted railway pavement structures. Some critical information such as volumetric change and geometry change can be easily obtained from FE simulations due to the sample swelling, which is difficult to measure in lab tests.
- Geogrid reinforcement within the ballast is more useful than geogrid reinforcement between the ballast and the sub-ballast layer. Surface vertical deflection of the railway pavement structure is about 12% lower when geogrid is in the ballast than that when geogrid between the ballast and the sub-ballast layers. Also, maximum principal stress of the railway pavement structure is about 9.4% lower when geogrid is in the ballast than that when geogrid between the ballast and the sub-ballast layers.
- The results presented in this study paved the way for subsequent research assignments involving numerical simulation of the actual railway structure using the FE modeling strategy to compare the impacts of various geogrid places.
It should be noted that the purpose of this study is not to compare the performance of geogrids themselves, but to evaluate their reinforcement effect in ballasted railway pavement structures.

5.3 Recommendations for Future Research

Verification of the results from analysis programs is very crucial. Thus, it is recommended that the results of this study be verified using another computer software capable of performing a boundary-balance analysis.

In this study, a simple ballasted pavement structure system was analyzed. More complex situations, such as those with higher functions, may be modeled in the FE analysis.

Using several geogrids in succession may minimize the risk of errors, even if the cost will increase. Therefore, the future analysis may include multiple layers of geogrid in the railway pavement structure to evaluate their performance.

Subsequently, results from such numerical simulations can be expanded for field testing and execution in real-life ballast track projects. Further investigation is needed to thoroughly investigate the impact of geogrid reinforcement on the railway pavement structure.
REFERENCES


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Appendix A: Maximum Principal Stress in Ballasted System

Figure A1 Maximum Principal Stress for All Application Types of Geogrid Within the Ballast Under Applied Load of 200 kN. (a) Without reinforcement; (b) With G1; (c) With G2; (d) With G3; (ANSYS 2018)
Figure A1 (Continued)
Figure A1 (Continued)
Appendix B: Maximum Principal Elastic Strain in Ballasted System

**Figure B1** Maximum Principal Elastic Strain for All Application Types of Geogrid Within the Ballast Under Applied Load of 200 kN. (a) Without reinforcement; (b) With G1; (c) With G2; (d) With G3; (ANSYS 2018)
Figure B1 (Continued)

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d)

Figure B1 (Continued)
Appendix C: Copyright Permission to Use Some Figure of Schematic of Geogrid Reinforcement of Ballast Layer or Main Components of the Railway

The following e-mail gives Bugra Sinmez permission to use Figure 1.2 by Professor Buddhima Indraratna. These tables were used in Chapter 1 as a part of a literature review of this thesis.

---

**Bugra Sinmez**

Hello Buddhima Indraratna, I am graduate student in University of South Florida/ US. I am studying about 'Characterization of geosynthetic a...

---

**Buddhima Indraratna**

8:41 PM (12 minutes ago)  ⭐

Yes, as long as you properly cite and acknowledge in your text and on the figure caption.
Kind regards,
Buddhima Indraratna

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**Bugra Sinmez**

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**From:** Bugra Sinmez [mailto:bugrasinmez@mail.usf.edu]

**Sent:** Wednesday, 2 January 2019 12:41 PM

**To:** Buddhima Indraratna

**Subject:** get permission to figure

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ABOUT THE AUTHOR

Bugra Sinmez has a bachelor’s degree in civil engineering at Mustafa Kemal University/Turkey. He was rewarded with a graduate of the Faculty of Civil Engineering degree in 2012. Throughout his years as an undergraduate student, he took several courses related to the subject. He was in the top one percent of the class. Furthermore, as the faculty leader of the Mustafa Kemal University, he used his leadership skills to organize activities. Subsequently, he started at the Yildiz Technical University for a master’s degree in 2013, Istanbul/Turkey; meanwhile, he worked in a private company in Istanbul between 2012 and 2015. He was a part of a team that has done business planning and project control in the construction area. Therefore, he gained valuable working experience in his life. The year of 2015 was a turning point in his life because he took the scholarship Republic of Turkey state for a master's degree. He attended an English course at the Ohio University/US between 2016-2017, and since 2017, he has been a graduate student in the Civil and Environment Engineering (CEE) Department at the University of South Florida (USF). Besides, he was a candidate in Student Government of the USF, and he founded the Turkish Association in the USF.