PARAMETRIC STUDY OF GEOGRID REINFORCED ROAD EMBANKMENT OVER SOFT SOIL

By: Betel Biru Habte

A Thesis Submitted to the department of Civil Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Civil Engineering

(Specialization in Geotechnical Engineering)

Office of Graduate Studies

Adama Science and Technology University

June, 2023

Adama, Ethiopia

PARAMETRIC STUDY OF GEOGRID REINFORCED ROAD EMBANKMENT OVER SOFT SOIL

By: Betel Biru Habte

Advisor: Srikanth Vadlamudi(PhD)

A Thesis Submitted to

The department of Civil Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Civil Engineering (Specialization in Geotechnical Engineering)

Office of Graduate Studies

Adama Science and Technology University

June, 2023

Adama, Ethiopia

Declaration

I hereby declare that this Master Thesis entitled “Parametric study of geogrid reinforced road embankment over soft soil” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Betel Biru ______________________ _______________

Signature Date

Recommendation

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "Parametric study of geogrid reinforced road embankment over soft soil" prepared under my guidance by Betel Biru submitted in partial fulfillment of the requirements for the degree of Mater's of Science in in Civil Engineering (specialization in Geotechnical Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Srikanth Vadlamudi (PhD)	_______________________	________________
Advisor	Signature	Date

Approval of Advisors

I the advisor of thesis entitled “Parametric study of geogrid reinforced road embankment over soft soil” and developed by Betel Biru hereby certify that the recommendation and suggestion made by the board examiners are appropriately incorporated in to final version of thesis.

Srikanth Vadlamudi(PhD)	______________________	_______________
Advisor	Signature	Date

Approval of Board of Examiners

We, the undersigned, members of the Board of Examiners of the thesis by Betel Biru have read and evaluated the thesis entitled "Parametric study of geogrid reinforced road embankment over soft soil" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Civil Engineering (specialization in Geotechnical Engineering).

Name	Signature	Date
______________________	______________________	______________________
Chairperson		
______________________	______________________	______________________
Internal Examiner		
Dr. Tezera Firew Azmatch	______________________	August 17, 2023
External Examiner		
______________________	______________________	______________________
Department Head		
______________________	______________________	______________________
School Dean		
______________________	______________________	______________________
Office of Postgraduate Studies,		

Acknowledgement

First of all, I would like to thank GOD for helping me in every activity of my life including doing my research work. I would like to express my sincere gratitude to my advisor Dr. Srikanth Vadlamudi for his continuous guidance, support, and valuable suggestions throughout- the thesis. I also would like to thank Department of civil engineering at ASTU for all the help and motivation during the entire duration.

Finally, my deep thanks go to my parents for the love and support they gave to me from my birth.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS, ABBREVIATIONS AND SYMBOL

γunsat	unsaturated unit weight
γsat	Saturated unit weight;
υ	Poisson's ratio;
ϕ	Angle of internal friction; and
ψ	Angle of dilatancy.
2D	Two-dimensional;
3D	Three-dimensional;
AASHTO	American Association of state Highway and Transportation Officials;
AC	Asphalt Concrete;
CBR	California Bearing Ratio;
F E A	Finite Element Analysis
ERA	Ethiopian Road Authority;
ESAL	Equivalent Single Axle Load
PLAXIS	Plane strain and axial symmetry;
XDM	Cross-Machine Direction;
MD	Machine direction
TX	TEMA-Xgrid

ABSTRACT

All roads, whether they are built above or below the ground surface, use naturally occurring soils and rocks as the basic foundation and construction materials. The construction of embankment over soft soil is increasing due to lack of suitable land for infrastructure and other development. Embankment foundation containing soft grounds is often a challenge for geotechnical engineers to ensure stability depending on the nature of the soil. Construction of pavement on weak or soft soil is highly risky because such soil is susceptible to differential settlements, poor shear strength, and high compressibility. Instability problems such as lateral deformations and excessive settlement often occur in structural and geotechnical construction on soft soils. , Various methods exist to improve compressible soils commonly applied on-site including preloading, lightweight fill, geosynthetic reinforcement, over-excavation and replacement, vertical drains, rigid piles, and injection. Despite the fact that existing methods may mitigate stability problems, selection factors need to be considered, such as sustainability, cost, and time of construction. Enhancing density, increasing shear strength, and reducing compressibility can help in promoting stability. Thus, the present study is aimed to address these issues by developing a model of geogrid reinforced road embankment over soft soil under traffic load. PLAXIS 2D software is used for this research in conjunction with the Mohr-Coulomb model, which is adopted for the subgrade soil and embankment and Linear Elastic Model for the AC pavement and Geogrid reinforcement. parametric study on side slope, Axial stiffness and height of embankment is also conducted in order to know their influence in performance of embankment. The modeling has shown that the performance of geogrid reinforced road embankment for efficient combination is side slope of *3H:1V, TEMA-Xgrid-300(EA-1600kN/m) for 1m selected and recommended as the most efficient combination of the rest all. The settlment of the reinforced embankment was reduced by 33% and lateral displacement reduced by 15% of unreinforced one. The performance of geogrid reinforced road embankment for 2m and 3m , height with respect to settlment efficient combination is side slope of 1.5H:1V and TEMA-Xgrid-300(EA-1600kN/m) in which settlment of the reinforced embankment was reduced by 30%and 25% respectively of unreinforced one.*

Key words: soft soil, Geogrid, PLAXIS 2D, Mohr-coulomb model

CHAPTER ONE

1.INTRODUCTION

1.1. Background of the study

Recently, Ethiopia has become one of the fastest growing producing economies in the world. Among others, the construction sector is instrumental in catapulting the nation to higher levels of development. The construction of roads is one of the major focal areas of the government to fast-track economic growth, as it provides the dominant mode of freight and passenger transport. All roads, whether they are built above or below the ground surface, use naturally occurring soils and rocks as the basic foundation and construction materials. Unlike man-made materials, the properties of these soils and rocks are highly variable and a function of the complex natural processes that occurred in the geologic past. Construction of pavement on weak or soft soil is highly risky because such soil is susceptible to differential settlements, poor shear strength, and high compressibility Alemineh et.al(2020).

In road construction, the embankment is used to increase the height of the road compared to the height of the surrounding area. It is a large earth structure and is often used in civil engineering applications related to infrastructure projects. The embankment foundation containing soft grounds is often a challenge for all engineers to ensure stability depending on the nature of the soil. Soft ground with fine particles such as silt, clay, and peat have high moisture content and are located near or below the groundwater level. These soils also have the characteristics of high compressibility, high plasticity, high sensitivity, low shear strength, and low permeability. If the soft soil deposit is very thick, removing and replacing it with a soil that has better engineering properties can be cost-prohibitive. Therefore, a good understanding of the soft soil is essential at the design stage of the highway project to assess the feasibility of designing a roadway structure on soft soil in such a way to alleviate problems (Che Mamat R. 2013).

Various methods exist to improve compressible soils. Geosynthetic reinforcement has a wide acceptance due to its cost effectiveness, aesthetics, reliability, simple construction techniques, good seismic performance, and the ability to tolerate large deformations without structural distress (Zornberg, J.G. 2007).

Where embankments are required to be built over soft soil, stability and settlement issues should be carefully evaluated. This research is made in order to provide a better understanding geogrid performance on stability and deformation of embankment constructed over soft soil by making Numerical analysis using Plaxis 2D software. Parametric study is conducted to know their effect on performance of geogrid and to apply the technology and techniques in an effective manner.

1.2. Statement of the problem

Embankment foundation containing soft grounds is often a challenge for geotechnical engineers to ensure stability depending on the nature of the soil These soils have the characteristics of high compressibility, high plasticity, high sensitivity, low shear strength, and low permeability. Road constructed on Compressible soil is susceptible to large settlements and deformations. If is not treated, large surface depressions with random cracking can develop. The surface depressions can allow water to pond on the road surface and readily infiltrate the pavement structure, potentially creating further problems. . Stability problems in the most often occur when the embankment is built over soft soils such as low strength clays and silts, or when the foundation soil is overstressed during or immediately after construction (Idrus,et.al 2016).

Instability problems such as lateral deformations and excessive settlement often occur in structural and geotechnical construction on soft soils. Soil with poor geotechnical properties, such as soft clay, requires improvement technique application. Various methods exist to improve compressible soils commonly applied on-site including preloading, lightweight fill, geosynthetic reinforcement, over-excavation and replacement, vertical drains, rigid piles, and injection. Enhancing density, increasing shear strength, and reducing compressibility can help in promoting stability. The reinforcement improves the resistance to shear stress and hence improves the stability of the embankment. In addition, they may reduce excessive and differential settlement and lateral deformation (Latha et al., 2006).

Geosynthetic (i.e., Geogrid) reinforcement has a wide acceptance due to its cost effectiveness, aesthetics, reliability, simple construction techniques, good seismic performance, and the ability to tolerate large deformations without structural distress.(Zornberg, J.G. 2007). Thus, purpose of this thesis was solving problems associated with stability and deformation on embankments over soft soil using geogrid reinforcement in order to reduce deformation.

1.3. Objective of the study

1.3.1. General objective

- The general objective of this study is to do a parametric study on geogrid reinforced embankment built over soft soil by making numerical analysis using finite element based software plaxis 2D.

1.3.2. Specific objective

- Simulate unreinforced and reinforced embankment structure performance under surcharge loadings by using finite element analysis.
- To evaluate settlement analysis of embankment over soft soil with and without geogrid reinforcement.
- To study influence of variation of parameters like side slope, height of embankment and stiffness of geogrid material on performance of embankment.
- To indicate effective ways of application of geogrid reinforcement.

1.4. Research question and hypothesis

- What are reasons for instability problems on embankment over soft soil?
- What are the factors that should be considered in selecting methods for improving compressible soil?
- How geogrid material enhances stability of road embankment constructed over soft soil?
- How parameters like side slope , slope height and stiffness of geogrid material influences the perfomance of geogrid reinforced road embankment?

1.5.Significance of the Study

Soil reinforcement is now a highly attractive alternative for stabilization of earth slopes due to its economic benefit, aesthetics, reliability, simple construction techniques, good seismic performance, and the ability to tolerate large deformations without structural distress. Parametric study of geosynthetic reinforced soil slopes is important to know the influence of variation of different parameters like slope height, axial stiffness and side slope on the performance of embankment. Generally, significance of this study:

- To provide insight regarding the behavior of geosynthetic(i.e., geogrid) reinforcement stabilization of embankment constructed over soft soil.
- To evaluate How parameters side slope, axial stiffness and height, influences the performance of embankment with respect to deformation.
- Prove studies done before in this area and appreciate the use of geosynthetic reinforced slopes with appropriate parameters selection to construct efficient and stable reinforced soil slopes.
- Contribute as reference for other future work.

1.6.Scope and delimitation of the study

1.6.1.Scope of the study

The construction industry has been using various ground improvement techniques for construction of embankment over soft soil. However, this research focuses on road embankment with geogrid reinforcement. This study mainly deals improving the weak subgrade using the above mentioned technique to provide an increased a considerable reduction in settlement. Influence of variation of parameters (slope side, embankment height and stiffness of geogrid) on settlement and deformation also studied using finite element based software plaxis 2D.

1.6.2. Delimitation of the study

The modeling is done for geogrid reinforced road embankment over soft soil with consideration of uniform type of soil within the limited depth and some parameters are studied to know their influence on the performance of geogrid reinforced embankment but also there are other like weight of fill material, spacing of reinforcement, angle of internal friction, number of reinforcement layers.

1.7.Organization of Thesis

This thesis is organized into five chapters: Chapter 1 provides general introduction with the research objectives, question and hypothesis, scope and significance of the study. Chapter 2 outlines detailed literature review of road embankment construction over soft soil including challenges, ground improvement using geosynthetics, numerical analysis of the geogrid reinforced road embankment of previous research works. Chapter 3 presents description material parameters soil profile, geogrid and asphalt concrete(AC) adopted for modeling, preliminary checks for sensitivity analyses and generation of finite element analyses using PLAXIS 2D plane strain code. In Chapter 4 analysis of results, and discussion is presented. Parametric study regarding the influence of key design parameters is also included. The last chapter, Chapter 5, discusses the conclusions derived from this study and recommendations for future work.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

In developing countries like Ethiopia transportation facilities are very important for sustainable development. The construction of embankment over soft soil is increasing due to lack of suitable land for infrastructure and other development. Soils are naturally occurring materials that play a vital role in the design, construction, and performance of civil engineering structures. However, not all naturally occurring soils are appropriate for all uses due to the mechanical, physical, and chemical properties, as well as constructability. Soils are characterized in several ways, and one of which is its designation as soft. Such soils possess poor geotechnical properties such as high natural moisture content (close to liquid limit), high compressibility and low shear strength.(Almineh et al. 2020)

The embankment foundation containing soft grounds is often a challenge for all engineers to ensure stability depending on the nature of the soil. Several methods such as stage construction with vertical drains, use of columns (such as concrete piles, stone columns and deep soil mixed piles) extending into the soft ground, and geosynthetic basal reinforcement (in the form of geotextiles, geogrids and geocells) etc., have been developed for economically and safely constructing embankments on soft ground. With such a vast variety of techniques, eventually the final choice depends upon the subsoil characteristics, project cost and time of completion, as well as the long term benefits.

2.2. Road Embankment

In road construction, the embankment is used to increase the height of the road compared to the height of the surrounding area. It is a large earth structure and is often used in civil engineering applications related to infrastructure projects. The construction involves two essential construction components namely fill and foundation (Jianhui et al.2017). These two components act as definitive parameters to analyse the embankment to find failure slope. Hence, a deep understanding and interpretation of the behaviours of these components such as deformation mechanisms can produce the collapse mechanism of the embankment.

Embankments form the heart of the land component of the transportation sector and are necessary to bring the elevations of existing low-lying areas up to functional elevations for roadways and rail-ways. A road embankment may be constructed from either rock-fill or earth-fill. Fills that comprise both coarse and fine grained materials and are known as earth-rock (composite) embankments (ERA Geotechnical design manual 2013). For the design of embankments, the following areas of concern should be addressed:

- Foundations conditions, with their associated potential problems of settlements and stability.
- Embankment materials and related topics regarding specified methods of placing and compaction.
- Protection of the completed embankment slopes.

Embankments provide adequate support for roadways if the additional stress from traffic loads and pavement structures does not exceed the shear strength of the soils. Overstressing the embankment may result in slope failure. In addition to issues related to side slope stability, any anticipated settlement problem must also be considered. This settlement can be short term created as a result of the addition of increased load on the soil beneath the embankment (bearing failure during placement of the fill) or long-term due to consolidation.

The primary design issue is whether the existing foundation soil can support the new embankment loads without undergoing bearing failure, or excessive settlement. These conditions are most critical when soft cohesive soils are present below the embankment. Staged construction may need to be considered whereby the embankment is constructed in a number of stages and excess pore water pressures allowed to dissipate over a period of time before the next lift is constructed. The second type of load is the long-term operational loading. This loading occurs after the embankment is constructed to the final grade and excess pore-water pressures have dissipated. The long-term stability of embankment slopes should be analysed especially in fine grained soils. When foundation soils are cohesive and not heavily over-consolidated, potential settlement will be a design consideration. Consolidation settlement and secondary compression can continue for many years and, depending on the thickness of soils, the amount of settlement can be very high. (ERA Geotechnical design manual 2013).

2.2.1.Embankment over soft soil

The construction of embankments over soft, compressible ground is increasing due to lack of suitable land for infrastructure and other developments. The soil profile consists of a layer of crust at the top followed by a soft soil layer of either limited or unlimited thickness underneath. This soil is brown from light to dark (Che Mamat R. 2013). There are several approaches for identifying and classifying soft soils. The properties of fine-grained soil are assessed by its degree of firmness, which is called consistency, and it is expressed by terms such as soft, stiff, and hard. These terms are relative and they may have a different interpretation for different geotechnical engineers. Based on quantitative measurements, consistency is associated with shear strength and compressive strength. Clay soils with an unconfined compression strength of less than 50 kPa and a liquid limit of more than 50% are categorized under soft soils . (Wagner, J 2013). Soft soil has a coefficient of permeability that is less than 1.0 x 10^{-7}m/s, according to (Kempfert and Gebreselassie 2006). In general, soft soil such as clay is dominated by particles of less than 0.002 mm in size and is pliable. It is formed from a combination of clay and mud and with almost 50% clay content . The structure of this soil is identified as being dispersed, flocculated, bookhouse, turbostratic, and cohesive (Le et al. 2012).

Constructing an embankment over very soft subsoil of low shear strength and high compressibility, the engineering tasks are to ensure stability of the embankment against possible slope failure and to control the subsoil deformation or settlement to within allowable limits. The earliest method or technique employed for stable construction of embankments on soft ground was the use of vertical drains combined with stage construction. However, with growing demand for rapid construction and associated difficulty in meeting the project deadline, column-supported embankments have emerged as an appropriate technical solution. In addition, geosynthetics in the form of basal reinforcement are extensively being used at present for embankments on soft ground, to improve the bearing capacity, reduce differential settlement and prevent slope instability (Mamat et.al 2019).

(ERA geotechnical design manual,2013) describes that embankments on soft ground also have a tendency to spread laterally because of horizontal earth pressures acting within the embankment. These earth pressures cause horizontal shear stresses at the base of the embankment that must be resisted by the shear strengths of foundation soils. Soft soils do not have adequate shear strength and failure may occur as a result. Embankment fills over soft ground are frequently stronger and stiffer than their foundations. This leads to the possibility that an embankment will deform as the foundation fails under the weight of the embankment and the possibility of progressive failure because of stress–strain incompatibility between the embankment and its foundation.

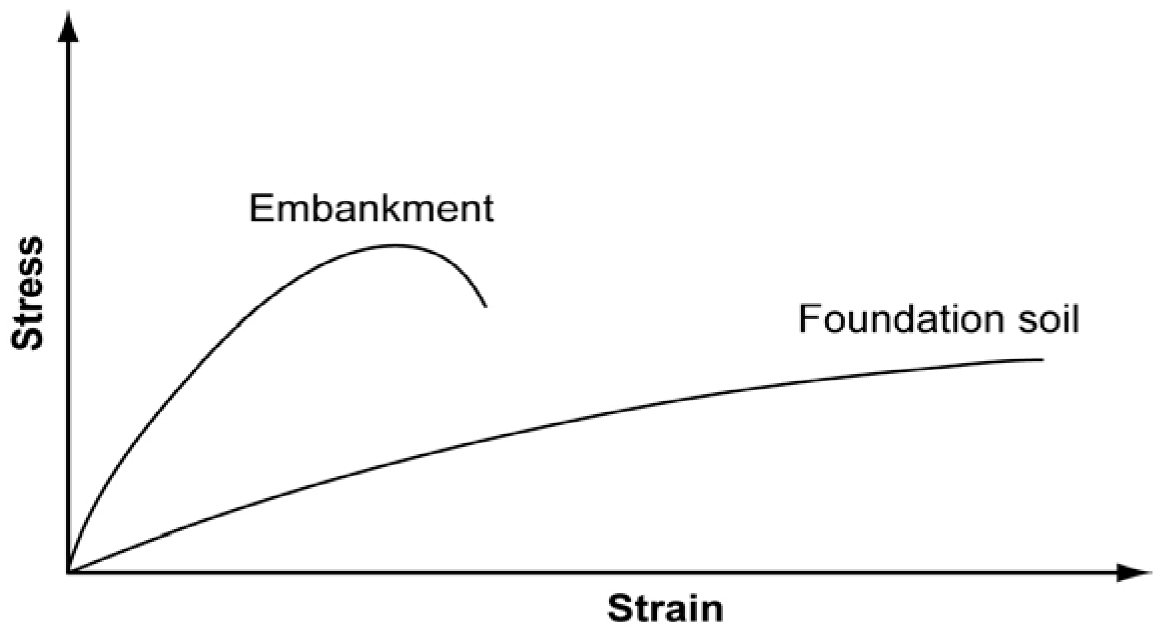


Figure 2. 1:Example of stress-strain incompatibility. From Abramson et al (2002)

Where embankments are required to be built over soft ground, stability and settlement of the fill should be carefully evaluated. Embankments under 5 m high in areas of stable ground and with slopes not greater than 1.5H:1V generally do not require a detailed geotechnical investigation and analysis. These embankments can be specified particularly when based on past experience in the same region and on engineering judgment. On the same basis, embankments over 5 m high and those constructed over soft ground will usually require a detailed geotechnical analysis.

2.2.2. The Challenges of Construction Embankment Over Soft Soil

Instability problems such as lateral deformations and excessive settlement often occur in structural and geotechnical construction on soft soils (Oser C,2017). The load generated by the embankment fill drives the increase in soil stress and pore water pressure leading to deformation mechanisms. This causes the load to be undrained, where the behaviour is similar to the viscous fluid that can lead to critical conditions against structures such as bearing capacity problems. To ensure embankment stability, the geotechnical design typically requires consideration of three factors namely: strength, deformation, and permeability or hydraulic conductivity. Bearing capacity and slope stability are among the important elements in the strength factor. Deformation is influenced by differential settlement, surface settlement, and lateral displacement of the ground while pore water pressure and seepage are elements affecting permeability (Mamat et.al2019).

Bearing Capacity

Bearing capacity is one of the necessary steps in the design of the embankment. It is the ability of the soil to bear the structural burden on the ground safely without any shear failure by accommodating a large settlement. This means that the foundation with shear failure involving general, local, or punching shear failure mechanisms will experience structure instability. (Davis and Booker 1973) have significantly contributed to understanding of the problem of clay-bearing capacity with increased strength with depth. Over the last few decades, much research has emphasized that embankment instability is due to a possible loss of bearing capacity of the foundation soil. During soft soil failure under the embankment, the fill moves downward with part of the foundation soil as a rigid body (Michalowski RL. 1992).

Settlement

Settlement is the total size of the vertical deformation on the soil surface. In theory, embankment settlement occurs when increased compressive stress is generated by base load compression. This process will cause vertical and horizontal deformation of the soil foundation. Besides changes in water content, soil mass and temperature can also distort soil. It is often associated with cohesive soil such as soft soil and can produce a large settlement for an extended period even under load (Che Mamat R. 2013).

The total settlement consists of three modes, namely elastic, consolidation, and creep deposition. Elastic settlement occurs due to the deformation of soil that is loaded without changes in water content and occurs within a short period (Kong X. 2016). It is also known as an undrained or immediate settlement. This type of settlement occurs instantaneously during the loading process with saturated soil that has low permeability and drainage ability. Consolidation settlement occurs due to the consolidation of soil in which water is slowly expelled from the soil cavity. During the consolidation process, the deformation of the soil occurs with volume reduction over a long period. Creep or secondary compression is the same as compaction. It can occur when soil attempts to reposition itself in the cavity left by the water during consolidation settlement (Zou C et.al2016). In the typical case, during embankment design, the computation of settlement involves elastic settlement and consolidation while post-construction involves creep.

2.3. Soft Ground Improvement

An engineer must possess several strategies that may be adopted to achieve project goals when dealing with troubled ground conditions at the site. Various methods exist to improve compressible soils commonly applied on-site including preloading, lightweight fill, geosynthetic reinforcement, over-excavation and replacement, vertical drains, rigid piles, and injection (Mamat et.al2019).

As mentioned in the literature review, enhancing density, increasing shear strength, and reducing compressibility can help in promoting stability. On the other hand, influencing permeability also decreases groundwater flow to increase consolidation rates. Despite the fact that existing methods may mitigate stability problems, selection factors need to be considered, such as sustainability, cost, and time of construction. All have become the topic of intense debate within the scholar community.

(Dafalla MA. 2009) studied the performance of a stabilized soft ground settlement using the preloading and prefabricated vertical drains (PVDs) method. The study concluded that this method reduces 20% to 50 % of total settlement with sufficient time to prevent deformation. It can increase the strength of soft soils by accelerating the consolidation process so that the ground is able to bear the load. It is clear from the above study findings that the installation of the preloading and PVDs methods has advantages. A combination of both methods is efficient to be used in areas with soft ground. This method does not meet the green technology needs that emphasize the environmental impact of construction. This is because the surcharge fill usually involves cutting of high places such as hills, leading to various degrees of destruction and disasters.

Construction challenges on soft grounds and lack of suitable soil for reclamation work and environmental preservation led to a massive demand for innovative methods. The use of lightweight materials to replace fill material such as clay is an alternative (Mamat et.al2019). The use of geofoam is well received because it is more practical as a readily-available source, and there are many manufacturers and suppliers around the world The magnitude of primary settlements of the embankments on layers of soft soils is a function of increased vertical stress caused by the embankment built on the soft soil layer. Therefore, the use of lightweight materials in the embankment reduces the magnitude of these settlements. This technique, known as lightweight fill has the additional advantage of improving stability. (Marradi et al 2012)

Based on literature and observations through some historical cases, preloading and prefabricated vertical drains and geofoam as lightweight fill materials are widely used today. The study found that both techniques are environmentally friendly. However, both of these techniques require a long construction time. The preloading and prefabricated vertical drains technique takes up 6-12 months for the soft ground to consolidate. Installation of geofoam is very complicated and requires the construction of a linked network that takes a long time. This problem can lead to cost implications for construction (Mamat et.al2019).

Despite the fact that existing methods may mitigate stability problems, selection factors need to be considered, such as sustainability, cost, and time of construction. Thus, this is an important issue for further research and development. Features that improved when geosynthetics were used as a reinforcement material included an increase in pavement service life and a reduction in base course thickness . The use of geosynthetics reduced the amount of stresses that are transferred to the subgrade from traffic loads when compared with unreinforced flexible pavement. Additionally, the geosynthetic reinforcement improved the performance of the pavement by through three mechanisms lateral restraint increased bearing capacity and tensioned membrane support (Zornberg 2011).

2.3.1.Geosynthetic Reinforcement

Geosynthetics are manufactured synthetic materials (i.e., made from polymer or hydrocarbon chain) that are used for a wide range of engineering application. Nine categories of geosynthetic materials are manufactured (Korner, 2005): geotextile, geogrid, geomembrane, geonets, geofoam, geopipes, geocells, and geocomposite and geosynthetic clay liners.

Main function of geosynthetics according to IGS 2018 (international geosynthetic society specification) is:

- **Separation:** the prevention from intermixing of adjacent dissimilar soils and or materials.
- **Filtration:** the retaining of soil or other particles subject to hydrodynamic forces while allowing the passage of fluids into or through the geosynthetic.
- **Reinforcement:** the use of the properties of a geosynthetic to improve the mechanical properties of soil or other construction materials.
- **Drainage:** the collecting and transmitting of precipitation, ground water and or other liquids or gases along the plane of the geosynthetic.
- **Barrier:** the prevention or reduction of the movement of any fluid through a construction by the use of a geosynthetic barrier.
- **Protection:** the use of a geosynthetic material as a localised stress reduction or dissipation layer to prevent or reduce damage to a given surface, material or layer.
- **Surface erosion control:** the use of a geosynthetic to prevent soil or other particle movements on the surface of a slope.
- **Stabilization:** improvement of the mechanical behaviour of an unbound granular material by including one or more geosynthetic layers such that deformation under applied loads is reduced by minimizing movement of the unbound granular material.

Reinforcing of soil reduce horizontal and vertical displacements of the underlying soil and thus reduce differential settlement. It should be noted that the reinforcement will not reduce the magnitude of long-term consolidation or secondary settlement of the embankment .Properly designed horizontal layers of high-strength geotextiles or geogrids can provide reinforcement which increase stability and prevent such failures.

The use of reinforcement in embankment construction may allow for:

- increase in the design factor of safety.
- increase in the height of the embankment.
- reduction in embankment displacements during construction, thus reducing fill requirements.

- improvement in embankment performance due to increased uniformity of post-construction settlement.

Geosynthetics are often used to improve performance of embankments over soft foundation soils. The reinforcement by geotextiles or geogrids helps to increase the stability against the overall failure of embankment and foundation soil.Also, increase the embankment stability against sliding failure along reinforcing material surface and guarantee more uniform settlement. Ehrlich and Becker (2010) have briefly showed the various types of geosynthetics used for soil reinforcement, as well as some relevant properties of these materials. Geosynthetics have a 40+ year history of successful use for the stabilization of very soft wet subgrades. Based on experience and several case histories summarized by Haliburton, Lawmaster, and McGuffey (1981) and Christopher and Holtz (1985), the following subgrade conditions are considered optimum for using geosynthetics in roadway construction are Poor soils (AASHTO: A-5, A-6, A-7-5, and A-7-6), Low undrained shear strength: $\tau f = cu < 2000$ psf (90 kPa)CBR < 3 (Note: Soaked Saturated CBR as determined with ASTM D 4429),High water table and High sensitivity.

Geogrid

A geogrid is defined as a geosynthetic material consisting of connected parallel sets of tensile ribs with apertures of sufficient size to allow strike through of the surrounding soil, stone, or geotechnical material (Korner, 2005). Extruding and drawing sheets of Polyethylene (PE) or Polypropylene (PP) plastic in one or two directions or weaving and knitting Polyester (PET) ribs are methods used to produce geogrids. Geogrids are designed mainly to satisfy the reinforcement function.

The ribs of a geogrid are defined as either longitudinal or transverse. The direction which is parallel to the direction that geogrid is fabricated on the mechanical loom is known as roll length direction, Machine Direction (MD), or longitudinal direction. On the other hand, the direction which is perpendicular to the mechanical loom and MD in the plane of geogrid, is known as Transverse Direction (TD) or cross machine direction. In other words, the longitudinal ribs are parallel to the manufactured direction (a.k.a. the machine direction); the transverse ribs are perpendicular to the machine direction. Some mechanical properties of geogrid such as tensile modulus and tensile strength are dependent on the direction which geogrid is tested. Also, geogrid installation in pavements is usually in a way that traffic path is parallel with the ribs produced in machine direction (Kwon, Tutumluer, & Al-Qadi), Validated mechanistic model for geogrid base reinforced flexible pavements, 2009). In a geogrid, the intersection of a longitudinal rib and a transverse rib is known as a junction. Junctions can be created in several ways including weaving or knitting. Figure 2.9 shows a section of geogrid in plan view and labels the different grid components.

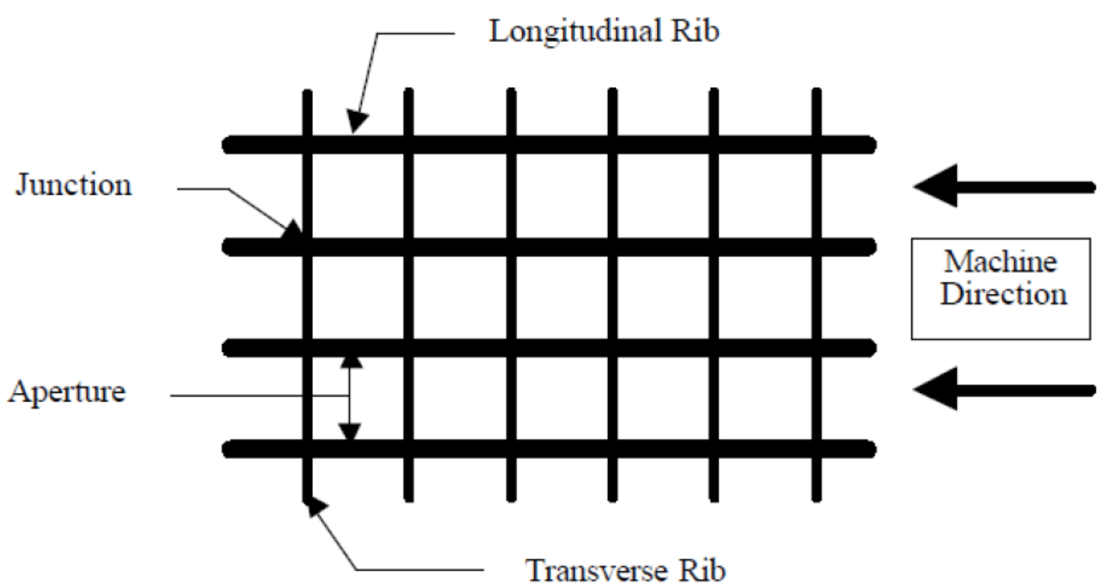


Figure 2. 2: Geogrid Component Nomenclature (Stadler, 2001).

Geogrids can be categorized in three main groups based on their aperture: uniaxial, biaxial and triaxial. Uniaxial geogrid has a tensile strength in one direction. It is mainly used for reinforcing slopes, retaining walls, and embankments. Biaxial geogrids have tensile strength in two dimensions and they are often used for reinforcement of pavements including unpaved roads, railroads, and flexible pavements (Dong et al.2010). Triaxial geogrids are triangular aperture geogrid with ribs in three directions. This feature causes two benefits. First of all, the apertures allow soil particles to interact better with ribs. Secondly, triaxial geogrid can provide uniform tensile strengths in all directions as compared with uniaxial and biaxial geogrids. This is because of the fact that triangular aperture geogrid has a more stable grid structure than rectangular aperture geogrids Dong et al. (2011).

Common geogrid types currently available in market include welded geogrid, extruded geogrid, and woven geogrid Das, B.(2010). Extruded geogrid is produced from a polymer plate which is punched and drawn in either one or more ways. Polypropylene (PP) or polyester (PET) fibers are generally used to produce woven geogrids. In most cases, these fibers are coated to increase the abrasion resistance of produced geogrid (Berg, et.al 2000).

Manufacturing process of welded geogrid is by welding the joints of extruded polymer woven pieces. Geogrids are also categorized in two main groups based on their rigidity. Geogrids made from polyethylene (PE) or polypropylene (PP) fibers are usually hard and stiff and they have a flexural strength more than 1,000 g-cm. Flexible geogrids, are often made from polyester (PET) fibers by using a textile weaving process. They usually have a flexural strength less than 1,000 g-cm (Koerner 2005). Geogrids are commonly used to reinforce sub-bases or subsoils below roads, as well as retaining walls or other structures. They are also applied to stabilize the subgrade for construction of embankments in the railway and highway sectors and in the stabilization of soils with high water table levels or low bearing strength where laying of foundations to carry heavy loads becomes critical.

Geogrids could be very useful in reducing settlement of embankment of slopes and geosynthetic materials can complement low strength soils Insertion of a geogrid reinforcement layers at a suitable location within the slope fill considerably improves the load carrying capacity of footings located on such slopes. Experimental and Numerical Study on Reinforced Soil Slope shows that geogrid reinforced slope is better to reduce deformations compared to the geotextile reinforced slope (Salahudeen, B and Sadeeq, J. 2016).

2.3.2 Reinforcement mechanism

The mechanism of reinforcement for an embankment constructed over a uniform deposit of saturated clay is to stiffen the, base of the embankment and reduce shear stress magnitudes and plastic shear deformations in the foundation. Tensile reinforcing elements may be used to increase the stability of embankments constructed over weak foundations. In this type of application, horizontal strips or layers of reinforcement are placed on the natural soil or within the base of the embankment with the remainder of the embankment constructed in the conventional manner.

Materials used as tensile reinforcement include steel strips, bars, or meshs geotextiles , geogrids and other materials. Geosynthetic inclusions within a soil mass can provide a reinforcement function by developing tensile forces which contribute to the stability of the geosynthetic-soil composite (zornberg 2007).

A reinforced soil mass is so what analogous to reinforced concrete in that the mechanical properties of the mass are improved by reinforcement placed parallel to the principal strain direction to compensate for soil's lack of tension resistance. The improved tensile properties are result of the interaction between the reinforcement and the soil. The composite material has the following characteristics:

- Stress transfer between the soil and reinforcement takes place continuously along the reinforcement.
- Reinforcements are distributed throughout the soil mass with a degree of regularity and must not be localized.

Stress is transferred between soil and reinforcement by friction or passive resistance depending on reinforcement geometry. The contribution of each transfer mechanism for a particular reinforcement will depend on the roughness of a surface, normal effective stress, grid opening dimension and elongation characteristics of reinforcement. The primary function of reinforcement is to restrain soil deformation. In so doing, stress is transferred from the soil to reinforcement. These stresses are carried by the reinforcement in tension or in shear and bending.

The use of geosynthetics reduced the amount of stresses that are transferred to the subgrade from traffic loads when compared with unreinforced flexible pavement, as shown in Fig. 2.3. Additionally, the geosynthetic reinforcement improved the performance of the pavement through three mechanisms: i) lateral restraint, ii) increased bearing capacity, and iii) tensioned membrane support. These three mechanisms are shown in Fig. 2.4 .

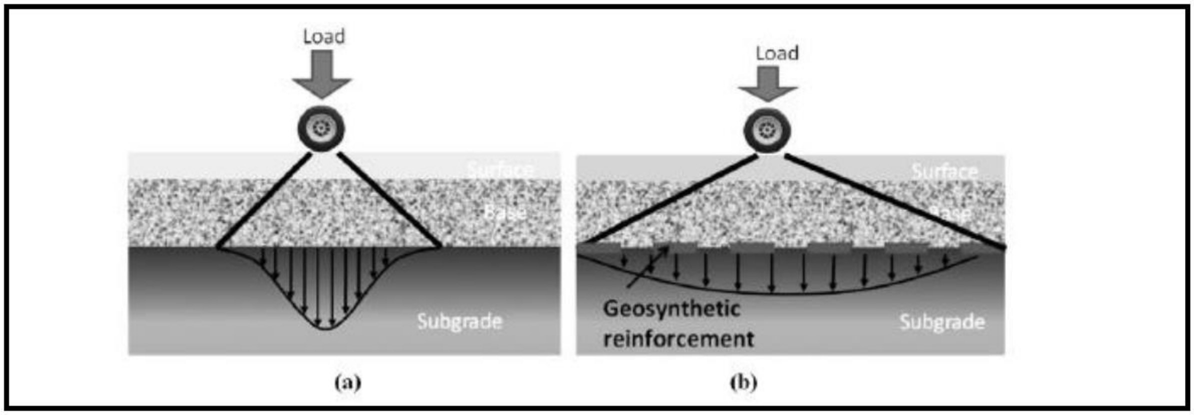


Figure 2. 3:Relative load magnitudes at subgrade layer level

for (a) unreinforced flexible pavement and (b) geosynthetic-reinforced flexible pavement Zornberg (2011).

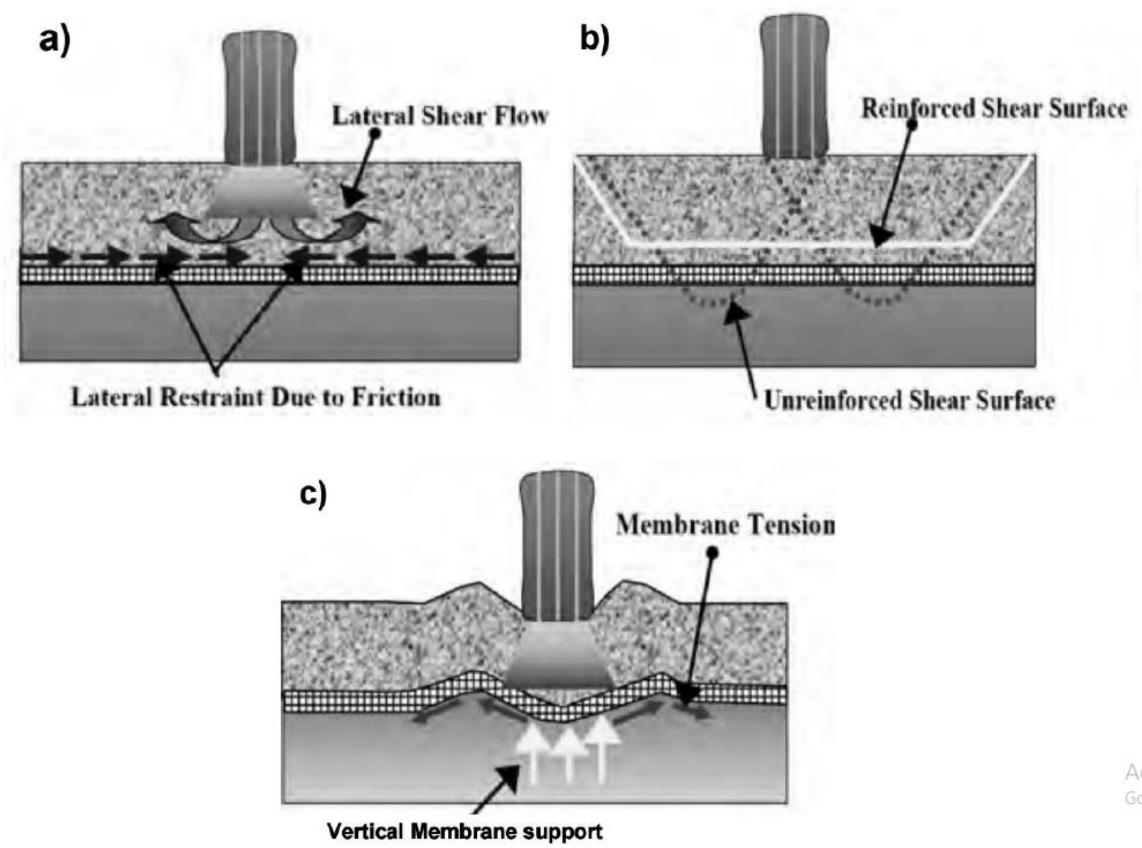


Figure 2. 4:Reinforcement mechanisms induced by a geosynthetic layer used for base reinforcement (Zornberg & LaRocque, 2008):Lateral restraint; (b) Increased bearing capacity; (c) Membrane-type support

The second mechanism that is increased is bearing capacity, shown in Fig. 2.4b. The bearing capacity of soil increases when reinforced by geosynthetics because the shearing stresses induced from traffic loads are transferred to geosynthetics. As a result, the subgrade is subjected only to normal stresses. The third mechanism results from tensioned membrane effects, shown in Fig. 2.4c. This phenomenon happens when the aggregate layer deforms under heavy or repeated loading. This deformation will force the geosynthetics layer to deform as shown in Fig. 2.4c. However, the normal stresses in the soil acting on each side of the reinforcement will not be equal if the tensile forces are coincident with an appreciable curvature of the reinforcement. Therefore, the normal stresses that transfer to the subgrade underneath the load will be reduced, which increases the capacity of the road (Brocklehurst 1993).

2.4. Stability analysis of road embankment

The design of the embankment is extremely complex because it depends on the purpose of construction, the environment, and the ground foundation conditions. When designing an embankment, engineers must plan, define geometric data, and analyse stability. The road embankment especially consists of a series of compacted layers placed on top of each other until the subgrade surface level is reached. It is also known as structural embankment and is divided into two types: the unreinforced and reinforced, which serves to distribute traffic load to soil foundation. Therefore, appropriate stability assessment and geometric data methods are essential to ensure the desired efficiency of construction.

The driving force along the slopes that is greater than the resisting force restraining the movement of the slope is the basis of slope stability. Force imbalances such as increased resisting force will fail. Both forces are elements in slope design. The main driving force in most earth movements is gravity while the main resisting force is the material's shear strength. Slope stability is evaluated by calculating and assessing the stability index, or the FoS, defined as the ratio of ground resistance force along the failed surface to the instability force that illustrates the capabilities of a structure, such as an embankment Duncan JM (1996). Also explains that FoS is the ratio of real ground shear strength to the minimum shear strength required to prevent failure. Theoretically, a FoS value greater than 1 indicates a stable slope while a FoS value equal to 1 implies that the slope is in equilibrium.

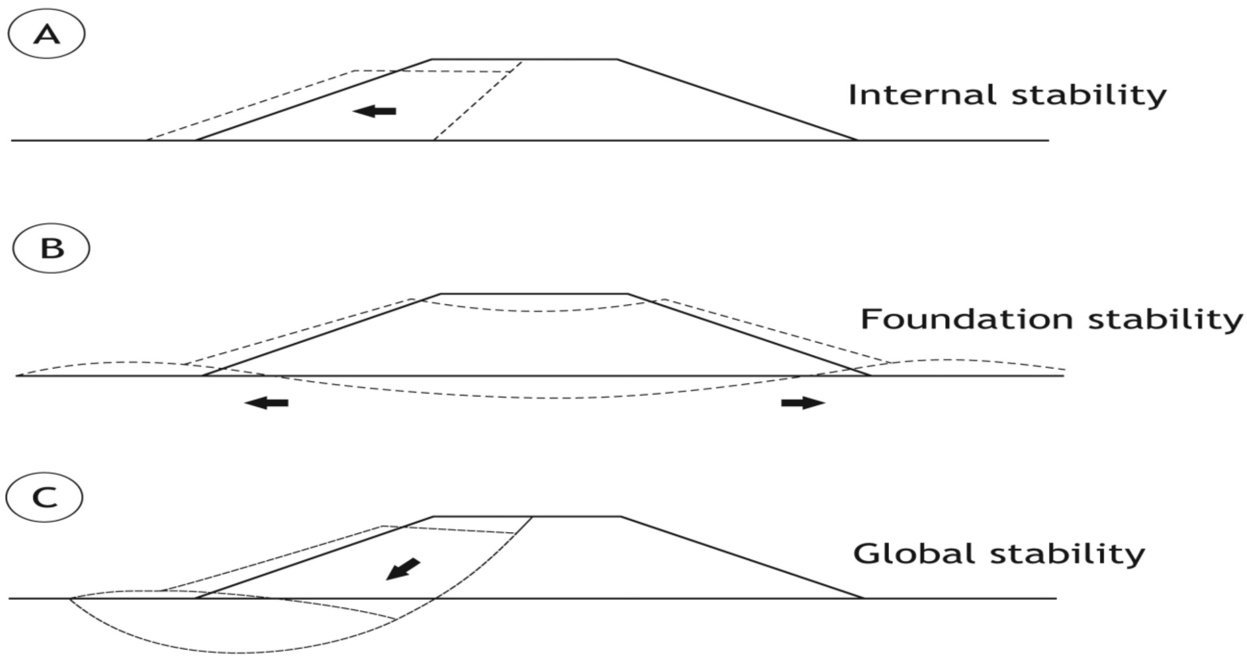


Figure 2. 5Failure modes of unreinforced embankments:(A) lateral sliding of the embankment, (B) failure in foundation clay Jewell, (1982), (C) overall failure embankment-foundation.

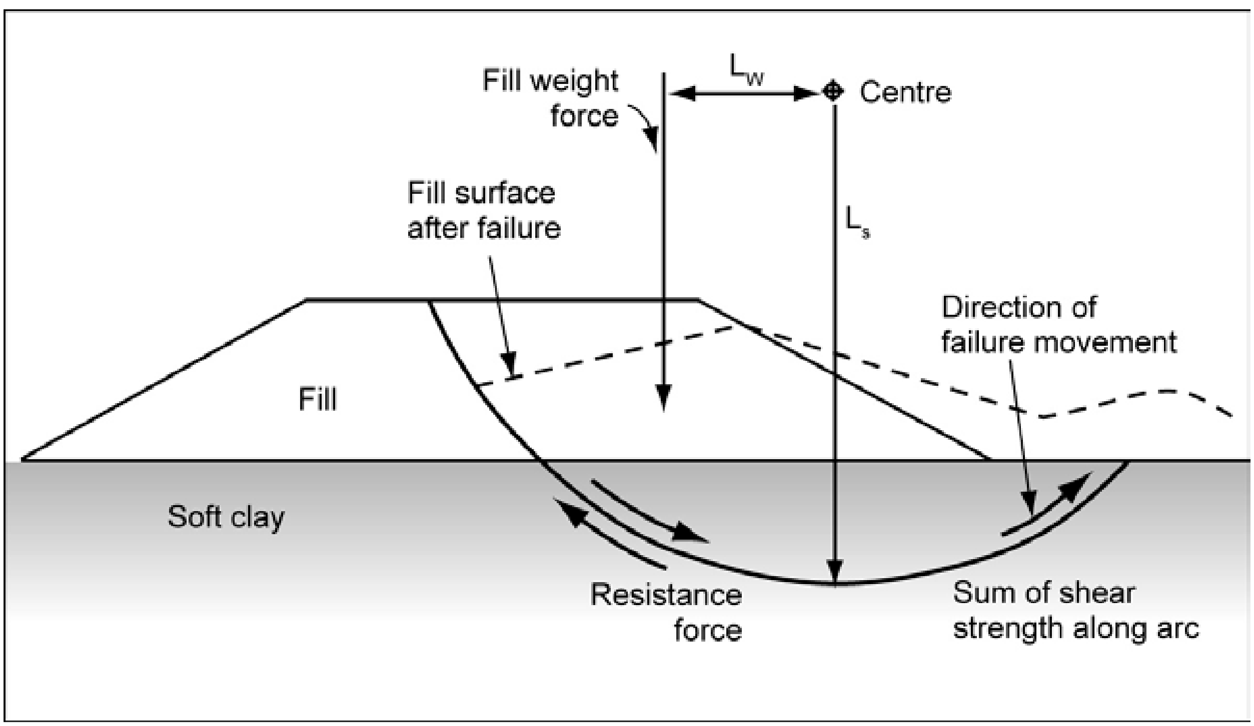


Figure 2. 6:Typical circular arc failure mechanism. From US DOT FHWA (2006B)

The main failure modes for a reinforced embankment on soft clay that should be taken into consideration are as follows

- Rotational stability of the embankment
- Lateral sliding stability of the embankment fill .
- The overall stability of the embankment

In general, embankments that are 5 m or less in height with 1.5H:1V or flatter side slopes, may be designed based on past precedence and engineering judgment provided there are no known problem soil conditions such as organic and soft soils. Embankments over 5 m in height or any embankment on soft soils, in unstable areas, or those comprised of lightweight fill require more in-depth stability analyses, as do any embankments with side slope inclinations steeper than 1.5H : 1V.

2.4.1. Numerical Analysis

Conventional limit equilibrium and finite element is the two most common analysis method used by geotechnical engineers for designing and predicting the mechanical behavior of reinforced and unreinforced embankment. The majority of today's engineers and researchers model the embankment design using FEM. It is a numerical method that aims to design and analyse various engineering problems of both practical or research. It is also useful for problems with complicated geometries, loadings and material properties where analytical solutions cannot be obtained. There are three types of finite elements that are often used, namely one-dimensional (line), two dimensional (plane), and three-dimensional (solid). From the literature, the use of two dimensional is the choice of many researchers in the study of embankment stability. Plaxis , Abaqus and Fast Lagrangian Analysis of Continua (FLAC) are some popular software's used for analysis, testing, and design in geotechnical engineering. However, the use of FLAC is less common in the study of the road embankment. Researchers and engineers more popularly use Plaxis as it is friendlier in soil modelling to solve simple problems in complex strata. Beyond that point, it can analyse all cases in geotechnical engineering including slope stability (Rabie M. 2014).

Plaxis is a commercially available finite element program which is used commonly in geotechnical engineering for the deformation and stability analysis. The software can make numerical solutions based on the finite element method. The finite element technique is well recognized as powerful analysis and design tool. Methods of analysis such as limit equilibrium method provide no information about deformations or strains, which develop in the reinforcement for a given reinforced embankment (Javad et al 2013).

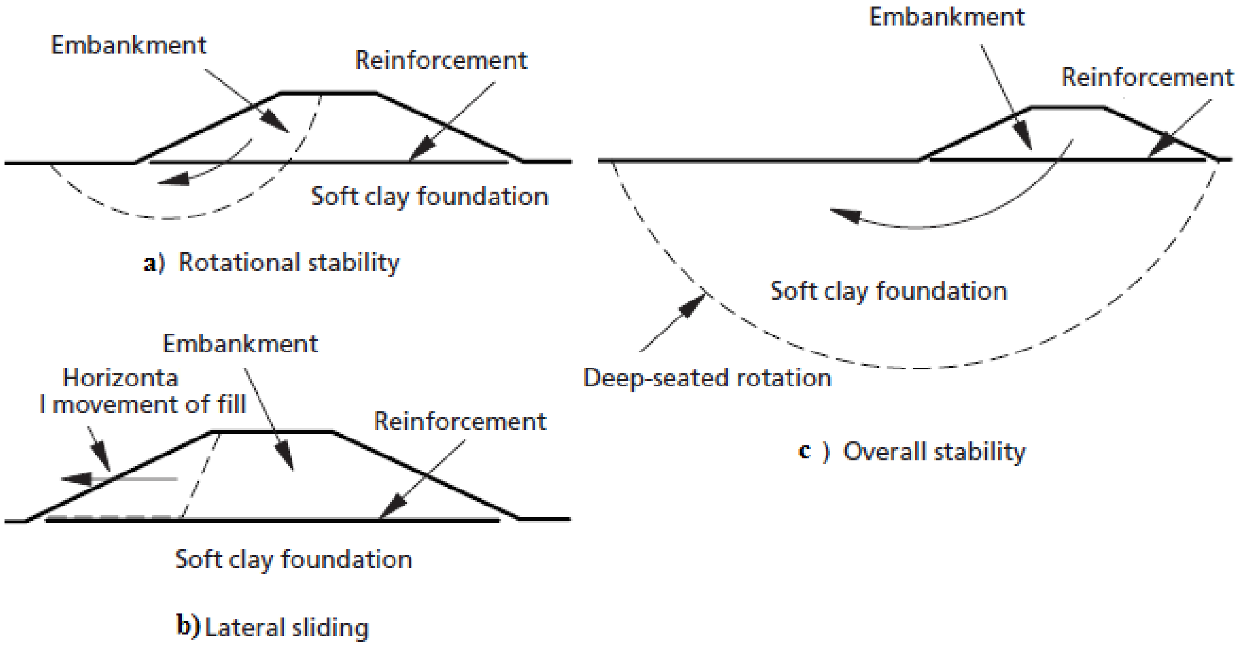


Figure 2. 7: Failure modes for the reinforced embankment on soft clay (after BS 8006-1,2010)

The main advantage of finite element analysis over the conventional method is that complete interaction of the embankment foundation system can be simulated. In the case of limit equilibrium method, the maximum tensile force developed in the reinforcement due to the embankment loading need to be determined beforehand. Abdulaziz et al.(2005).Finite element method of analysis is generally based on quasi-elastic continuum mechanics approach in which stresses and strains are estimated throughout the mass. In this method both deformation and strength parameters, modulus of deformation (E), Poisson's ratio(υ),cohesion(c),angle of shearing resistance, ϕ, and angle of dilation (ψ) are required for design. Some researchers have compared the results between LE method and FEM , concluding that FEM provides the best and most accurate FoS result, as it is better able to explain the behaviour of soil stress and eliminate stress assumptions used in the LE method Liu et al,(2015).

Javad et al. (2013) conducted finite element analysis (FEM) of geosynthetic reinforced embankment constructed on soft cohesive foundation under partially drained condition using PLAXIS 2D software. Factors considered include the elastic-plastic properties of the foundation soil, the non-linear elastic behavior of the fill, reinforcement stiffness, and the construction and uniform surcharge rates. The effects of the reinforcement stiffness on the horizontal and vertical displacements, mobilized reinforcement force and embankment failure surcharge were considered. Results show that Geosynthetic reinforcement can substantially increase the stability and failure surcharge of embankments on soft foundations. Increasing the reinforcement stiffness does not contribute much to the reduction in vertical displacement compared to the horizontal displacement.

Alamshahi and Hataf (2009) assessed the effect of a new type of geogrid inclusion on the bearing capacity of a rigid strip footing constructed on a sand slope. An extensive series of boundary conditions, including unreinforced cases, were tested by varying parameters such as geogrid type, number of geogrid layers, vertical spacing and depth to topmost layer of geogrid. In the following, many finite element models were developed in order to investigate behavior of embankments in prototype scale. Regarding to the obtained results, the optimum embedment depth and vertical spacing of the reinforcement layer, which resulted in the maximum bearing capacity of the geogrid-reinforced slope, was about 0.75 times the width of the foundation. In addition, the optimum number of geogrid reinforcements was two.

Salahudeen, (2016) investigated the use of geosynthetics for ground improvement based on numerical analysis using PLAXIS software. Geosynthetics were applied in varying locations where shear stresses are expected to be generated. The reinforced mechanism of geosynthetics was analysed based on modelling outputs and results. Output results from the PLAXIS software showed a significant decrease in displacement after reinforcing the soil with geosynthetic materials. The total displacement in the unreinforced slope is 569.00 mm which reduced to 65.80 mm when reinforced with geogrids. This reduction is over 800 % of the original total settlement. The shear strains increased from 9.71 x 10-3 % for the unreinforced slope embankment to 29.13 x 10-3 % when the slope was reinforced. Based on the results of this study, it was concluded that geosynthetics could be used as soil reinforcement materials to improve the shear strength of the soil and reduce its settlement potential significantly.

Suman et al. (2018) Experimental and Numerical Study on Reinforced Soil Slope. The numerical analysis has been performed by PLAXIS 2D using parameters obtained from the laboratory investigations and comparison are noted down. Modeling is performed for all three types of unreinforced slope, reinforced slope. Results are compared with laboratory modeling. The result shows that geogrid reinforced slope is better to reduce deformations compared to the geotextile reinforced slope. The experimental results of laboratory modeling have been also verified through the two-dimensional finite element method.

Nazzal et al. (2010) developed a finite-element model with ABAQUS software package to investigate the effect of placing geosynthetic reinforcement within the base course layer on the response of a flexible pavement structure. Finite-element analyses were conducted on different unreinforced and geosynthetic reinforced flexible pavement sections. The results of this study demonstrated the ability of the modified critical state two-surface constitutive model to predict, with good accuracy, the response of the considered base course material at its optimum field conditions when subjected to cyclic as well as static loads. The results of the finite-element analyses showed that the geosynthetic reinforcement reduced the lateral strains within the base course and subgrade layers. Furthermore, the inclusion of the geosynthetic layer resulted in a significant reduction in the vertical and shear strains at the top of the subgrade layer. The improvement of the geosynthetic layer was found to be more pronounced in the development of the plastic strains rather than the resilient strains. The reinforcement benefits were enhanced as its elastic modulus increased.

Perkins et al.(2004) developed design criteria for geogrid-reinforced paved sections using Mechanistic-Empirical Pavement Design Guide. Two-dimensional axisymmetric finite element models, as one of the ME design components for unreinforced paved roads, were developed in ABAQUS software by following the guidelines suggested for nonlinear response models. The authors could not develop a unique response model for reinforced paved roads to explain the improvement by geogrid inclusion, but they suggested a multi-step modeling procedure to address the compaction level and surface loading effects on the confinement level of the base course layer by inclusion of geogrid in paved roads. In this simulation, geogrids were considered as a linear elastic membrane. Contacts were allocated to the up and down faces of the reinforcement layer and the neighboring pavement layers, based on the Coulomb friction model. The multi-step finite element modeling showed that shear stresses at layers interfaces increase with an increase in compaction level and traffic loading cycles. The shear stresses observed at layers interfaces contribute to the lateral confinement of aggregate base layer. Similar predicted results in rutting depth were observed between the data obtained from testing program and the results of developed finite element models based on critical pavement responses.

Saad et al.(2006) used ADINA software to develop a dynamic 3 dimensional finite element model to predict geogrid-reinforced flexible pavements behavior. The soil granular layer was simulated by the modified CamClay model and the aggregate base layer was simulated through the elastoplastic Drucker-Prager simulation. Both HMA and geogrid layers were considered as a linear elastic membrane. A triangular wave shape dynamic loading with the duration of 0.1 second was performed to the pavement model. The interface between the geosynthetic and the pavement layers was assumed to be fully bounded. A parametric study was performed in order to investigate the factors that could influence the effectiveness of geosynthetic reinforcement such as aggregate base materials thickness and quality, and subgrade soil strength.

Howard and Warren (2006) developed an axisymmetric finite element model to analyze data obtained from seventeen heavily instrumented test sections. Triangular elements with either 6 or 15 nodes in all layers were used in their model for asphalt, crushed limestone, compacted subgrade, and natural ground. One dimensional tension element was used to model the geosynthetic. A linear elastic model was used to capture the behavior of asphalt. A hyperbolic model was used to describe the non-linear stress dependent behavior of the granular materials. The same model was also used to model the non-linear properties of compacted subgrade. The perfectly-plastic Mohr-coulomb model was used to model the properties of natural soil.

Table 2. 1: Summary of Literature

Author	Software used	Analysis type used	Materials model type
Perkins et al. (2004)	ABAQUS	2D finite element Axisymmetric	Liner elastic Coulomb friction
Saad et al. (2006)	ADINA	3D- Finite Element analysis	Modified cam clay Elasto-plastic Drucker Prager Linear Elastic
Howard and Warren (2006)	PLAXIS	Axisymmetric	Linear elastic Mohr-coulomb
Alamshahi and Hataf (2009)	PLAXIS	Plain strain	Mohr-coulomb
Nazzal et al. (2010)	ABAQUS	Axisymmetric	Linear elastic-perfectly plastic Cam Clay Isotropic linear elastic
Javad et.al (2013)	PLAXIS	2D Finite element analysis Plain strain	Soft soil Hardening soil Linear elastic Elastic-plastic
Salahudeen (2016)	PLAXIS	2D Finite element analysis Plain strain	Modified Mohr-Coulomb
Suman et al. (2018)	PLAXIS	2D Finite element analysis Pain strain	Mohr-coulomb

CHAPTER THREE

3. MATERIAL AND METHODOLOGY

3.1. Introduction

Embankment construction involves two essential construction components namely fill and foundation . These two components act as definitive parameters to analyse the embankment to find failure slope. Hence, a deep understanding and interpretation of the behaviours of these components such as deformation mechanisms can produce the collapse mechanism of the embankment. Embankment fill is defined as selected fill placed and compacted with proper specifications so that it can exhibit the required engineering performance. Even if the embankment fill has the best material properties, instability can occur if it is built on unstable soft ground or soil with properties needing improvement. The foundation serves as a placement for embankment structure and it may to be stable or unstable. Embankment stability is critical in road construction. Materials data are used in the engineering design of the embankment.

The aim of this chapter is to build and develop a numerical model to simulate a road embankment reinforced with geogrid laid on weak soil. To develop a realistic model for a road embankment reinforced with geogrid laid on soft soil, the modelling process should involve the appropriate approach for simulation, dimension of the model, mesh geometry, boundary positions, selection of parameters used in the analysis and the right choices for the constitutive model that represent the studied soil. For this study by using finite element method first unreinforced stability analysis then the analysis of reinforced embankment with geogrid followed.

3.2. Material parameters

3.2.1. Subgrade soil

The soft soil characterization and an assessment of the engineering properties were determined while using information from the literature review and by using laboratory test results which are conducted by Alemineh et.al(2020) which is "Engineering Characterization of Subgrade Soils of Jimma Town, Ethiopia, for Roadway Design". Their study aims to assess the existence and know the basic engineering properties of soft subgrade soils in Jimma town of Ethiopia while using laboratory tests. The samples were collected from the Jimma town around Kidane-Mihret Church and Rift Valley University College based on field observation and some literature that showed areas where weak soils may exist in the town to understand the engineering properties of very weak soil in the area. Disturbed and undisturbed soil samples were collected from different locations and taken samples from 1.5–3m depth. The laboratory tests that were conducted for this study were moisture content, specific gravity, grain size analysis, Atterberg limits, Proctor compaction test, California Bearing Ratio, unconfined compression, X-ray diffraction, and triaxial compression tests. The laboratory test results are described in appendix-1.

The Ethiopian Road Authority (ERA) also suggests that moisture content, sieve analysis, plasticity index, compaction, and CBR tests are the necessary engineering tests that are to be considered for pavement design. Test results indicate that that the soil samples are highly plastic. The liquid limits and plasticity index of the studied soils are both greater than the values recommended by ERA , which is suggests that the liquid limit should be less than or equal to 30% and the plasticity index should be less than or equal to 10% for suitable materials for subgrade. The unconfined compression strength test shows the specimen fails at 50 kPa or less. Clay soil with UCS less than 50 kPa and liquid limit greater than 50% categorized under soft soil Terzaghi (1996). The subgrade soil considered in this study were A-7-5, as per AASHTO soil classification system and have a very low load-bearing capacity and high compressibility, which makes the soils unsuitable for subgrade without improvement.

3.2. 2.Embankment fill material

Embankment fill is defined as selected fill placed and compacted with proper specifications so that it can display the required engineering performance. Selection of poor quality embankment materials and/or improper placement of the embankment fills will lead to internal instability of embankment. The general parameters used for Mohr- coulomb model are young's modulus(E) , passion's ratio(ν), friction angle(ϕ^0) ,cohesion(C), Dilatancy angle(Ψ).

Table3. 1:Material properties of subgrade soil and embankment

Soil parameter	Subgrade soil	Embankment fill	unit
Material model	Mohr-coulomb	Mohr-coulomb	-
Type of material behaviour	Undrained	Drained	-
Saturated unit weight(γunsat)	16.6	20	KN/m^3
Unsaturated unit weight (γunsat)	14.1	17	kN/m^3
Young's modulus (E)	1000	30000	kN/m^2
Poisson's ratio (ν)	0.35	0.3	-
Cohesion (Cref)	38	1	kN/m^2
Friction angle (ϕ‛‛)	5	34	
Dilatancy angle (ψ)	0	4	-
Over-consolidation ratio	1	1	-
Depth	0-3.0	1	m

3.2.3. Geogrid Reinforcement

A linear elastic model was used to describe the behaviour of geogrid material since the induced strain in the geogrid is very small (<1%) and is considered within the linear elastic range of the geogrid layer. Three types of geogrids with different Axial stiffness were used in the finite element analysis to investigate the effect of geogrid tensile strength on pavement response and performance.

Table3. 2:Geogrid material properties

Geogrid type	Nominal Tensile strength(kN/m)	Axial stiffness(EA) (kN/m)
TEMA Xgrid 300 **	300	1600
TEMA Xgrid 200**	200	1100
TEMA Xgrid 150**	150	800

**Parameters from the manufactures

3.2.4. Asphalt Concrete (AC) Layer

In this study, the linear elastic model was used to describe the behaviour of asphalt concrete (AC) layer. Pavement properties used after (Sabahat A. Khan and Syed M. Abbas 2014).

Table3. 3:Pavement material properties

Pavement properties	Asphalt concrete	Unit
EA	1.580 E+07	kN/m
EI	1.179 E+05	$kN/m^2/m$
W	1.8	kN
ν	0.15	-

Interface properties

Plaxis 2D models the geogrids, the embankment soil and the interaction between the geogrid structure and the soil. According to Bergado and Teerawattanasuk (2008), Rintr has been considered as 0.9 (Rintr = 0.9) In Plaxis, the interface properties were calculated from the soil properties by applying the following rules:

3.3. Material Model

The material model used for subgrade soil and embankment fill material is Mohr-coulomb. This is a first order model which idealises soil as an elastic-perfectly plastic material. The behaviour of soil before failure is approximated by Hooke's law of elasticity. The failure of soil is based upon the Mohr-Coulomb failure criterion which is defined by two parameters, angle of internal friction (ϕ) and cohesion (c). The model does not generate irreversible strains below the yield surfaces irreversible plastic strains resulting from shearing are captured using a nonassociated flow rule, which is defined by an angle of dilation (ψ).This model requires total of five parameters which are generally familiar to most geotechnical engineers and which can be obtained from basic tests on soil samples (Young's modulus (E) , Poisson's ratio (ν) , Cohesion (Cref), Friction angle (ϕ) , Dilatancy angle (ψ). Linear elastic model is used for geogrid and pavement material(AC).

3.4.Model Development

3.4.1. Preliminary Checks for Finite Element Analysis

The Finite Element Method (FEM) is a powerful tool used for analysing complex engineering problems. The FEM is an approximate technique which uses the principle of virtual work to estimate the distribution of stresses and strains throughout a continuum. In addition, as the FEM is an approximate technique it is necessary to carry out a number of preliminary checks, such as mesh sensitivity and distance to the boundary, to ensure accurate numerical analyses.

Geometry of the model

Analysis through FEM requires the establishment of data in constitutive relationships and geometric modelling. Geometric data namely height, crest width, and gradient of side slope are among the important parameters in the production of design drawings. For this analysis the cross section of the embankment is height 1m, crest width 7m and side slope 2:1 is used.

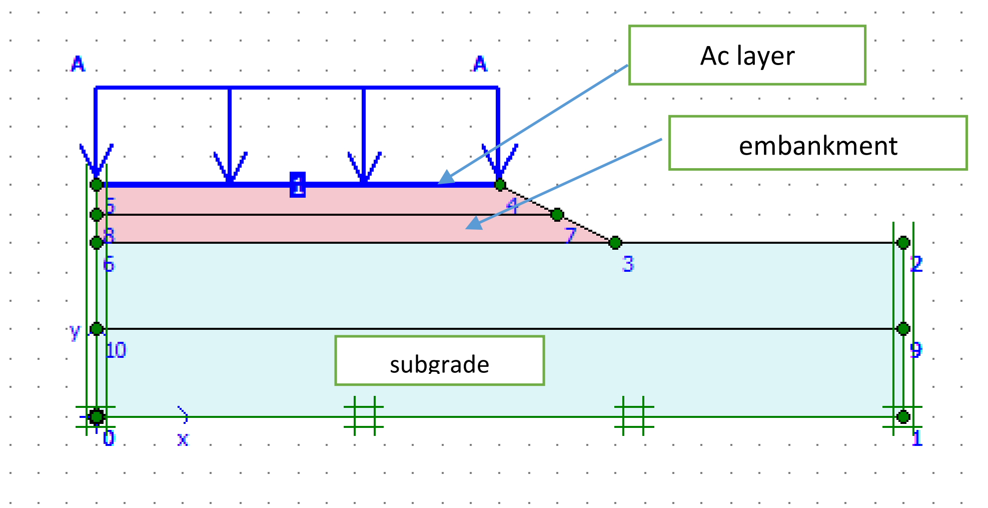


figure 3. 1:Lay out of model

Influence of distance to boundary

Positions of boundary restraints can significantly affect finite element simulation results. Since the generated reaction forces and displacement in these boundaries can influence the impact of the applied forces on the zones of interest. So, to avoid any restriction that reflected on the accuracy of the finite element model, a user should select the location of this boundaries to be sufficient distant from any zone of interest, but at the same time the user should consider them not to be exceedingly far, costing more time in the analyzing process (Ammari, and Clarke, 2016). The sensitivity analysis was conducted on selected 7m embankment cross-section the vertical displacement was measured at point A, B, C. which are 0, 1.5 and 2.5 m below the embankment. The location of distance to the boundary from the footing center ranged from 2B-12B (Killen, 2012).

The accuracy of relevant boundary distance is determined by comparing the normalized error for vertical displacement (uy) at a selected point where the side boundary is located at a distance xB against that of 12B.

$$\text{Normalized error for vertical displacement} = \quad Uy = \frac{Uy(xB)-Uy(12B)}{Uy(12B)} \times 100$$

Where: - Uy(xB) is vertical displacement at the selected point for the case of side boundary is located at (xB) m from the center of the roadway.

Uy(12B)- is vertical displacement at the selected point for the case of side boundary is located at (12B) m from the center of the roadway.

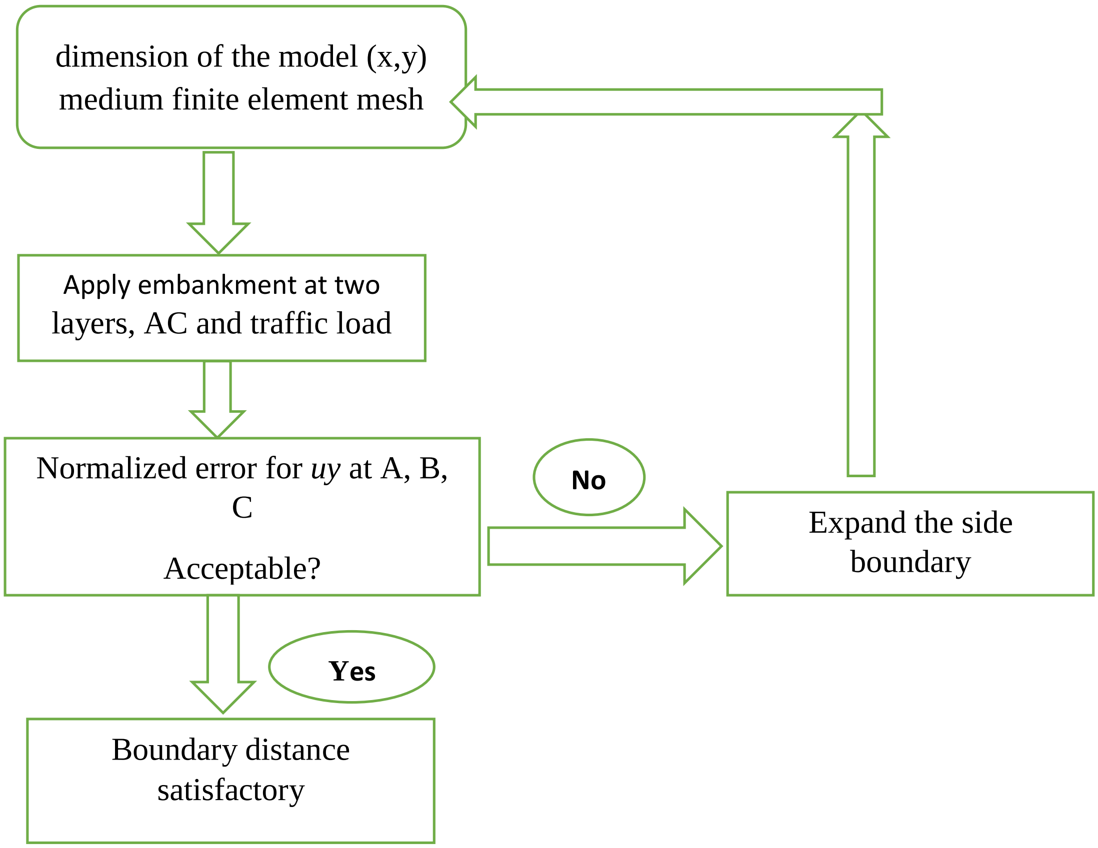


figure 3. 2:Flowchart of preliminary analysis for boundary distance

Table3. 4:Influence of the distance to boundary upon the Vertical displacement of a 7 m road cross-section.

Distance to boundary	Vertical Displacement uy (mm) At point				**Normalized error (%)**
(B = footing width)	A	B	C	Extreme Uy,max	Extreme
2B	33	10	0	45.26	0.4
4B	33	11	0	45.92	1.03
6B	15	3.17	0	46.52	2.35
8B	8	1.45	0	45.35	0.2
10B	6.96	1.06	0	43.16	5.03
12B	7.28	1.84	0	45.45	0

Table3. 5:Influence of the distance to boundary upon the horizontal displacement of a 7 m road cross-section.

Distance to boundary	Horizontal Displacement Ux (mm) At point				**Normalized error (%)**
(B = footing width)	A	B	C	Extreme Uy,max	Extreme
2B	25	46	8.64	61.5	3.60
4B	25	46	18	63.65	0.20
6B	54	55	20	63.01	1.20
8B	59	55	20	63.23	0.91
10B	61	55	20	63.20	0.95
12B	61	54	19	63.81	0

Table3. 6:Influence of the distance to boundary upon the effective stress of a 7 m road cross-section.

Distance to boundary	Effective stress , σyy (kN/sq.m)	Normalized error (%)
(B = footing width)	Extreme	Extreme
2B	73.70	0.6
4B	73.62	0.7
6B	79.59	7.3
8B	73.73	0.5
10B	82.31	11
12B	74.15	0

positioning the boundary closer than 6B to the center of the footing induces more settlement in embankment . The distance to the boundary from the center of the footing is conservatively chosen at 8B for all the subsequent FEA.

3.4.2.Mesh Sensitivity Analysis

The influence of the number of elements upon the accuracy of the FEM was investigated by conducting a mesh sensitivity analysis. In plaxis 2D during generation of mesh clusters are divided in to triangular elements. A choice can be made between 15-node and 6-node elements. the powerful 15-node element provides an accurate calculation of stress and failure loads. The accuracy of the FEM depends on the number and type of the elements into which the domain is discretized. Mesh sensitivity analyses are conducted for where the accuracy of medium and fine meshs are compared against very fine (vf) mesh.

Normalized error for vertical displacement, $= \frac{Uy(vf) - Uy}{Uy(vf)} \times 100$

Where Uy- vertical displacement at the selected point for the medium and fine meshed elements

Uvf- is vertical displacement at the selected point for very fine meshed elements

Table3. 7:Influence of the mesh sensitivity on the vertical displacement at points A, B and C

Mesh	Vertical displacement, uy (mm) At Point				Normalized error (%)
	A	B	C	Extreme	Extreme
Medium	8.17	1.48	0.00	45.26	2.8
Fine	32	5.14	0.00	45.76	1.7
Very fine	34	7.39	0.00	46.57	0.0

Table3. 8: Influence of the mesh sensitivity on the horizontal displacement at points A, B and C

Mesh	Horizontal displacement, uy (mm) At Point				Normalized error (%)
	A	B	C	Extreme	Extreme
Medium	59	55	20	63.23	0.2
Fine	33	53	13	63.37	0.0
Very fine	32	52	14	63.38	0.0

Table3. 9:Influence of the mesh sensitivity on the extreme effective stress

Mesh	Effective stress , σyy (kN/sq.m)	Normalized error (%)
	Extreme	Extreme
Medium	79.59	7.8
Fine	73.73	0.59
Very fine	73.83	0

3.5 . Geogrid Reinforced Embankment Analysis

Finite element analysis plaxis 2D version 8.2 was used for the plane strain model. The FEA were performed using a small strain formulation and a staged construction process was modeled. Road Embankment with cross section of crest width 7m ,height (1m, 2m and 3m) and side slope (1:1.5, 2:1, 3:1) modeled. the traffic loading of 50 kPa ,which was considered based on the recommendation of ERA manual 2013 was applied. After performing the Geometric modelling, the next step is initial phase calculation. The initial stress in a soil body is influenced by weight of material and history of its formation. In the early phase, the self-weight strains have been present for a long time, rendering the formation of excess pore water pressures meaningless.

Initially, "ignore undrained behavior" is chosen. This option is not selected for other phases since extra pore water pressures must be considered throughout the construction and after all loading processes. The next phase is embankment staged construction. Embankment construction consists of two phases each taking 30 days. The geogrid reinforcement is applied on bottom and middle layer of embankment. Then The surface wearing (asphalt concrete) construction assumed to be done within 28 days. Lastly 50 kN of traffic load is applied.

The analysis is two types first for unreinforced embankment analysis done then geogrid reinforced embankment at bottom and middle with different amount of stiffness ,slope gradient, and slope height done to analyse their effect on deformation.

3.5.1.Validation (verification) of Finite Element Analysis

In order to verify the suitability of the adopted material models for the soil, geogrids, and geogrid-soil interaction, finite element analyses were first checked against the results from laboratory model tests. To evaluate the adequacy of the selected material models for the soil geogrids interaction finite element studies were initially compared to laboratory model experiments for geogrid reinforced road embankment on silty clay subgrade soil published by chen (2007). Steel plates with dimensions of 152 mm x 152 mm x 25 mm (length, breadth, and height) were employed in the laboratory, and the model tests were carried out in a 1.5 m long, 0.9 m wide, and 0.9 m deep steel box.

Figure 3.3 show a comparison of finite element studies and laboratory model testing for one layer geogrid reinforced road embankments on silty clay subgrade soil.

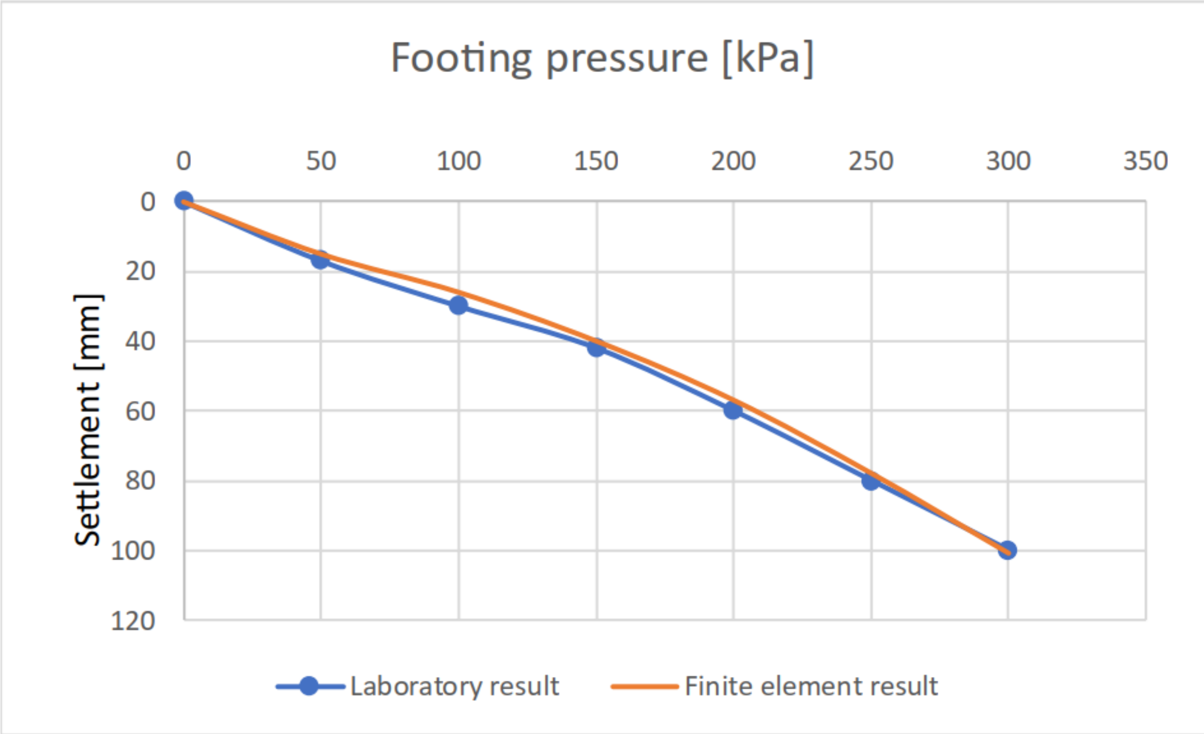


figure 3. 3 :Comparison between the finite element analyses and the laboratory model tests.

3.5.2. FEM Matrix

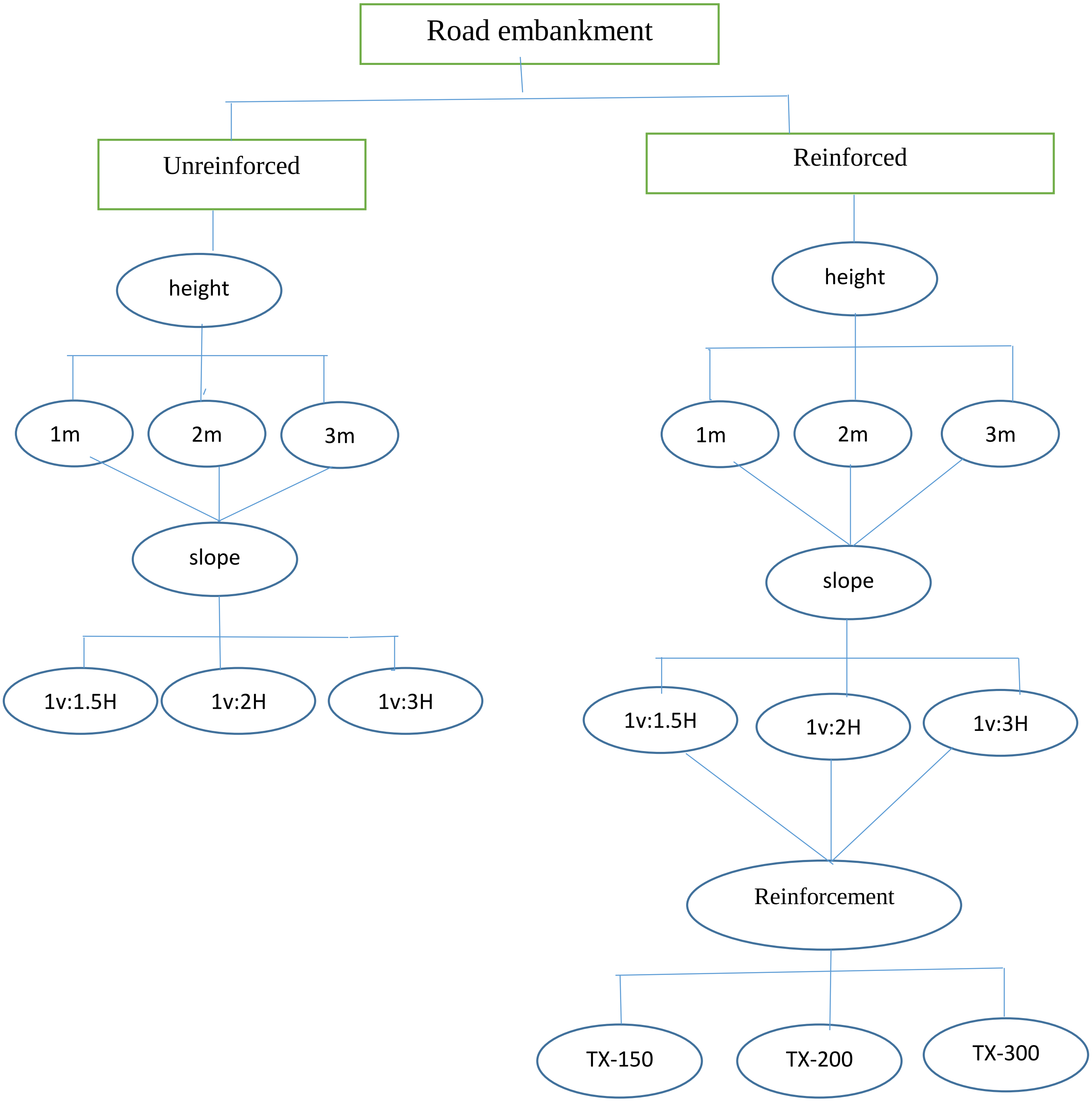


figure 3. 4:Schematic illustration of FEM matrix.

CHAPTER FOUR

4.RESULTS OF FEA AND DISCUSSION

4.1. Introduction

The main focus of this research is to develop a better understanding of geogrid reinforced road embankment over soft soil using finite element analysis by determining horizontal and vertical displacement. Parametric study is performed to know their effect on performance or deformation of embankment. A series of 36 FEA were conducted to understand the vertical and horizontal displacement reduction of road embankment. Three kinds of geogrid material with varying stiffness ,side slope and height variation of embankment were done. This chapter discusses the findings of the results, including the confirmation of those conclusions using FEA, the effect of essential design factors, and the explanation of those results.

4.2.Results of Finite Element Analysis

FEA was carried out with the help of the PLAXIS 2D to investigate the impact that key design factors had on the overall performance of the geogrid reinforced road embankment. The unreinforced and reinforced road embankment analysis were conducted for 1m, 2m and 3m height of embankment with side slope H:V (1.5:1, 2:1, 3:1) and geogrid reinforcement with different axial stiffness EA (800 kN/m,1100 kN/m, 1600 kN/m) carried out on road embankment laid on soft clay.

This section provides a summary of the results obtained from finite element studies using the PLAXIS 2D plain strain code for both unreinforced and reinforced road embankment in terms of extreme value of horizontal displacement, vertical displacement and effective stress of each model output.

Table4. 1:The results of FEA of a road embankment at 1m height

Slope height	Slope H:V	Reinforcement	Parametric results		
			Horizontal displacement [mm]	Vertical displacement [mm]	Effective mean stress [kN/m^2]
1m	1.5:1	Unreinforced	64.2	45.76	78.70
		Reinforced with TX-150	58.2	35.9	76.16
		TX-200	57.03	33.7	75.02
		TX-300	55.45	31.8	74.84
	2:1	Unreinforced	63.67	45.76	77.27
		Reinforced with TX-150	56.66	33.52	75.38
		TX-200	55.63	32.27	75.34
		TX-300	54.06	30.48	74.41
	3:1	Unreinforced	61.18	45.32	77.36
		Reinforced with TX-150	55.03	34.08	67.89
		TX-200	53.93	32.43	63.98
		TX-300	52.4	30.23	63.48

Table 4.1 presents the FEA results observed from modelling for both unreinforced and reinforced road embankment, 1m height of embankment and 1.5:1, 2:1, 3:1 slope.

The following results are samples obtained from the finite element analysis for road embankment 1m height and 1.5H: 1V shows effect of reinforcement on horizontal and vertical displacement including effective stress. Note: TX-150(EA=800 kN/m), TX-200(EA=1100 kN/m) and TX-300(EA=1600 kN/m).

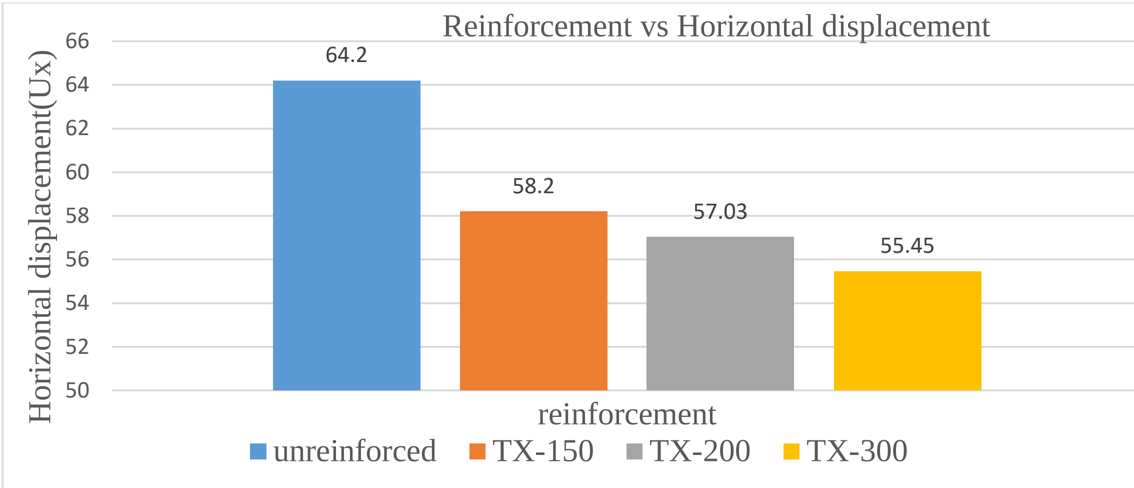


Figure 4. 1: Horizontal displacement [mm] at slope of 1:1.5 reinforced and unreinforced embankment.

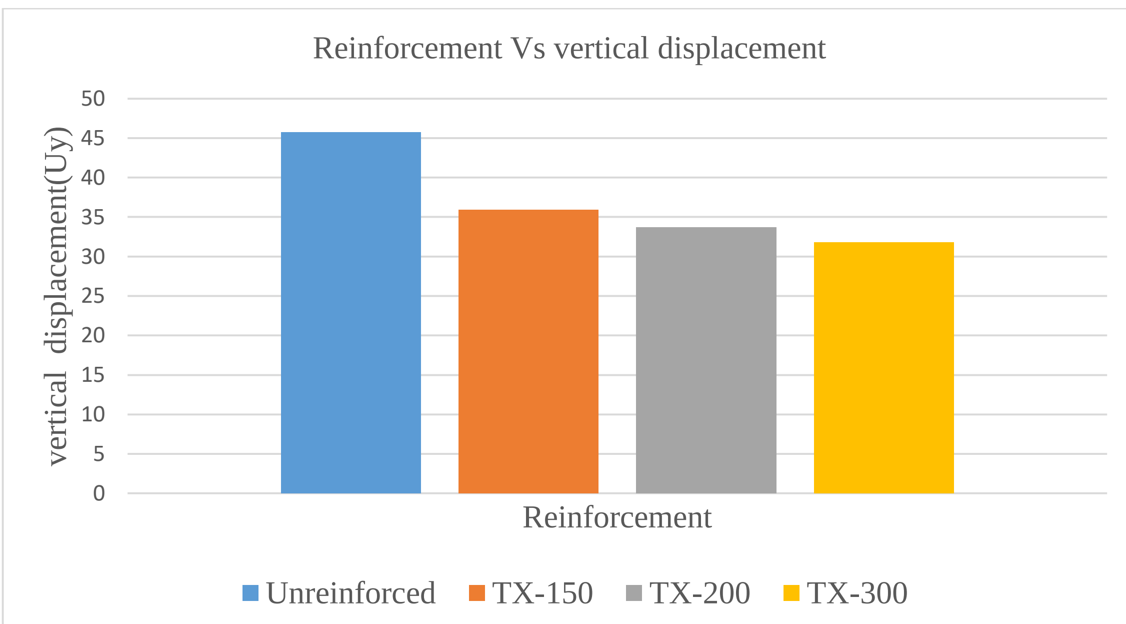


Figure 4. 2: Vertical displacement [mm] at slope of 1:1.5 at 1m height reinforced and unreinforced embankment.

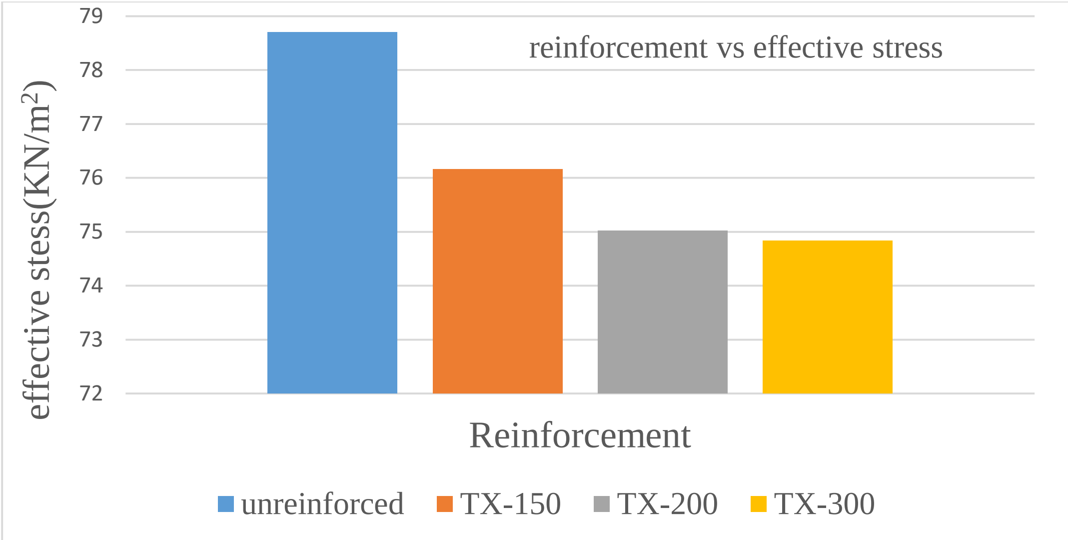


Figure 4. 3:Effective stress [kN/m^2] at slope of 1:1.5 at 1m height for reinforced and unreinforced embankment.

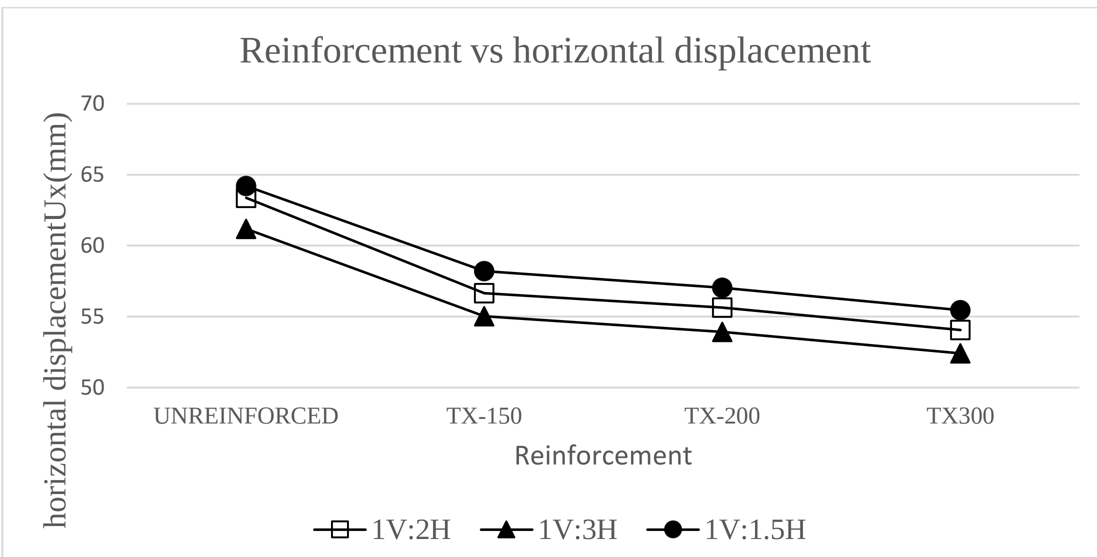


Figure 4. 4:Horizontal displacement [mm]vs reinforcement at 1m height of embankment with different slopes.

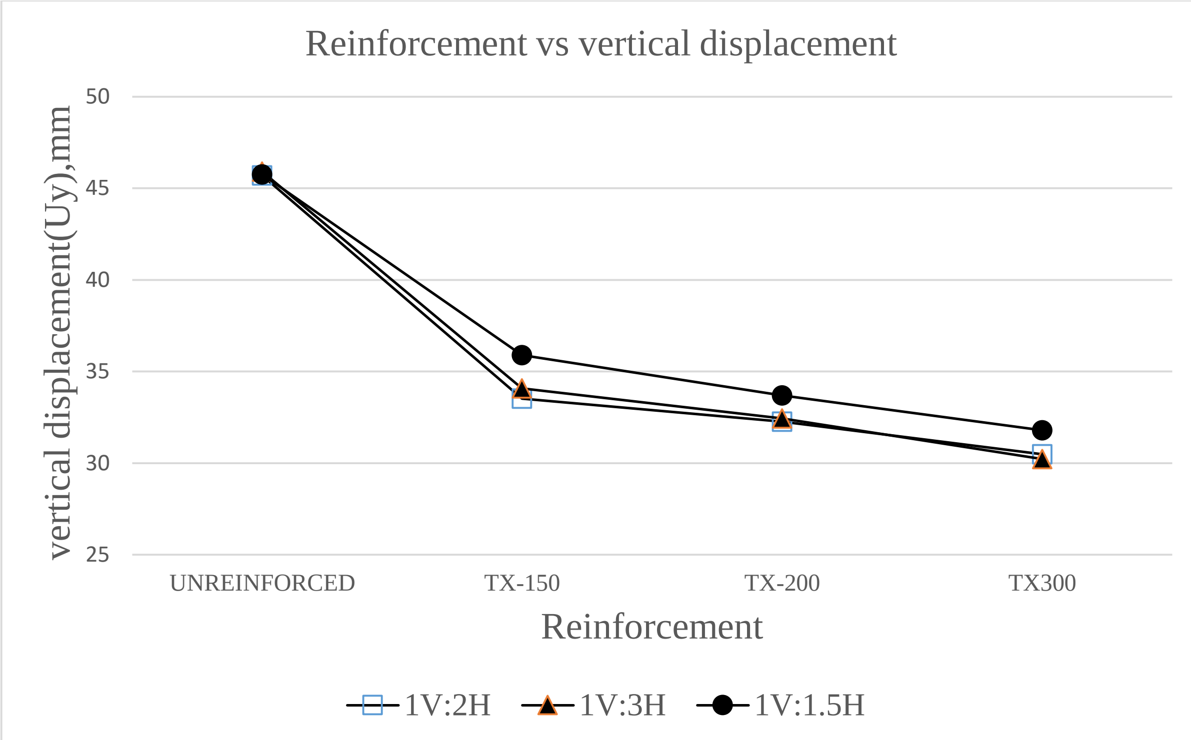


Figure 4. 5:Vertical displacement [mm]vs reinforcement at 1m height of embankment for unreinforced and reinforced.

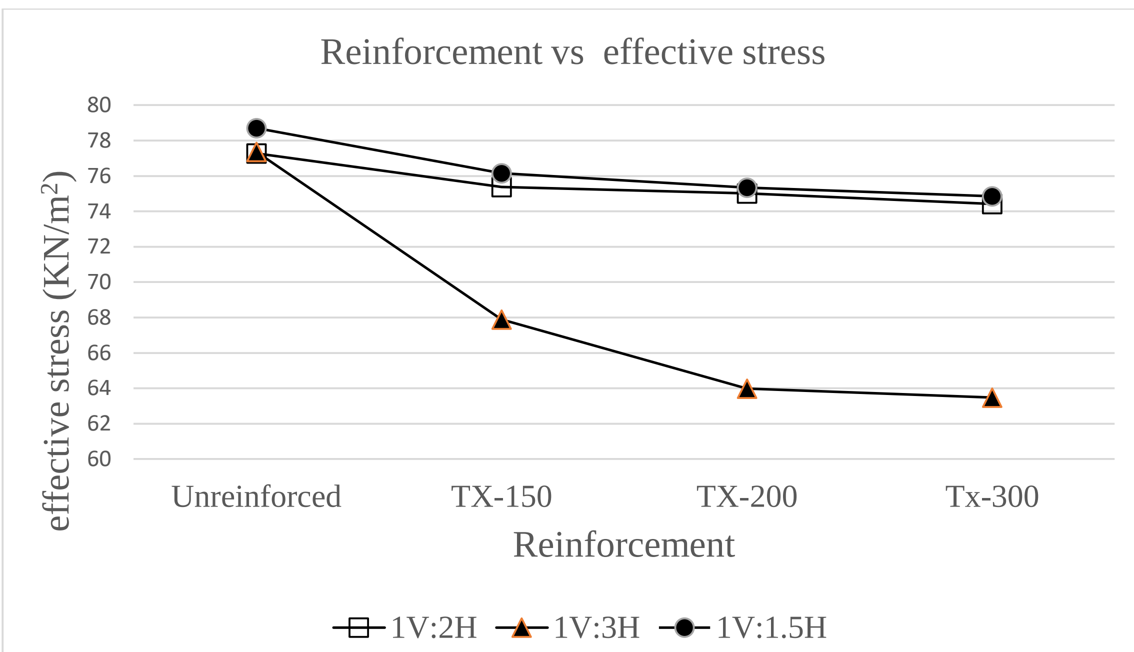


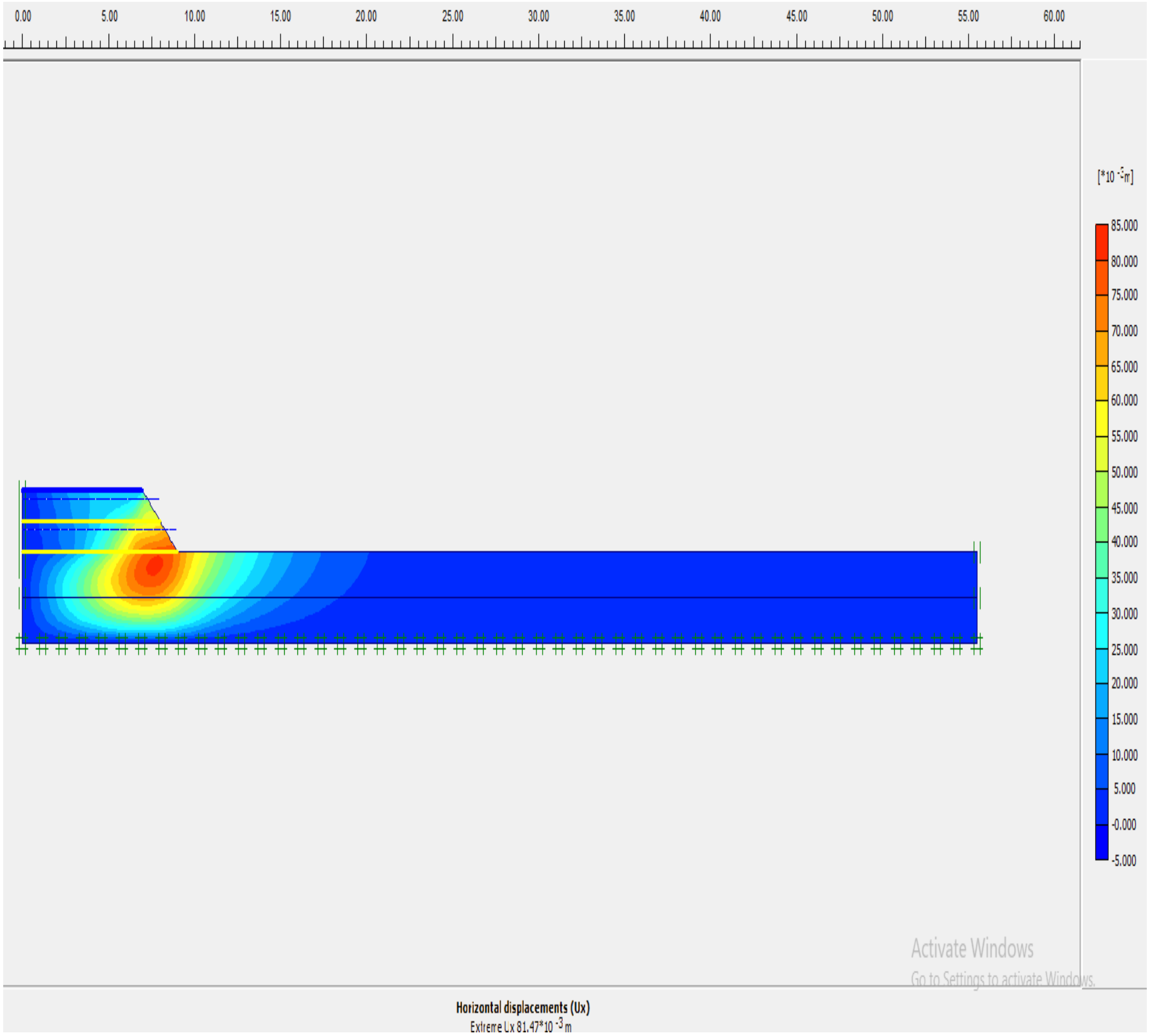
Figure 4. 6:Effective stress [kN/m^2] vs reinforcement at 1m height for unreinforced and reinforced embankment.

The above figures from figure 4.1-to-4.6 shows results obtained from plaxis 2D analysis of unreinforced and reinforced embankment horizontal displacement, vertical displacement and effective stress of 1m embankment height with slope 1:1.5,1:2,1:3 .

Table4. 2:The results of FEA of a road embankment at 2m height

Slope height	Slope H:V	Reinforcement	Parametric results		
			Horizontal displacement [mm]	Vertical displacement [mm]	Effective mean stress [kN/m^2]
2m	1.5:1	Unreinforced	93.35	61.04	73.20
		Reinforced with TX-150	77.44	48.49	62.07
		TX-200	75.21	46.28	60.39
		TX-300	72.09	43.15	59.17
	2:1	Unreinforced	87.16	58.93	72.02
		Reinforced with TX-150	81.47	50.07	63.64
		TX-200	72.14	44.9	58.69
		TX-300	68.99	41.79	57.53
	3:1	Unreinforced	69.17	51.07	68.4
		Reinforced with TX-150	61.33	47.2	59.96
		TX-200	59.85	39.72	57.64
		TX-300	57.73	37.14	55.11

Table 4.2 presents the FEA results detected from modelling for both unreinforced and reinforced road embankment at slope of at 2 m height of embankment and 1.5:1,2:1, 3:1.The outputs obtained from the model are the extreme value of horizontal displacement, vertical displacement and effective stress of each model.



Extreme horizontal displacement Ux(mm)=81.47

Figure 4. 7:Sample of plaxis 2D output of horizontal displacement (mm) of 2m height reinforced embankment.

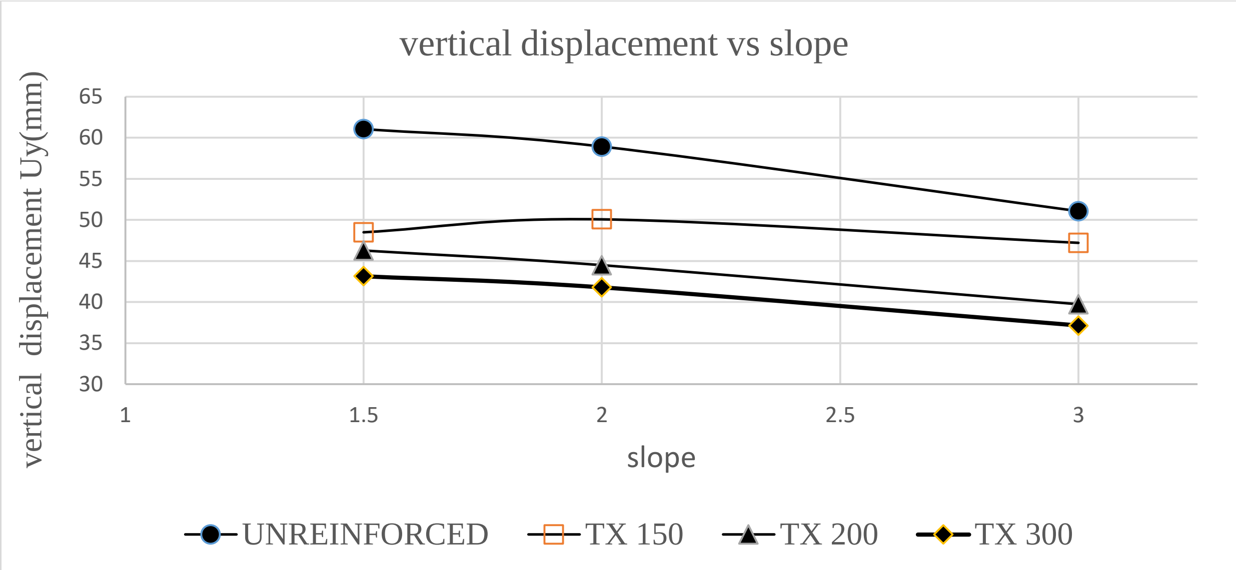


Figure 4. 8:Vertical displacement [mm]vs slope at 2m height for unreinforced and reinforced embankment.

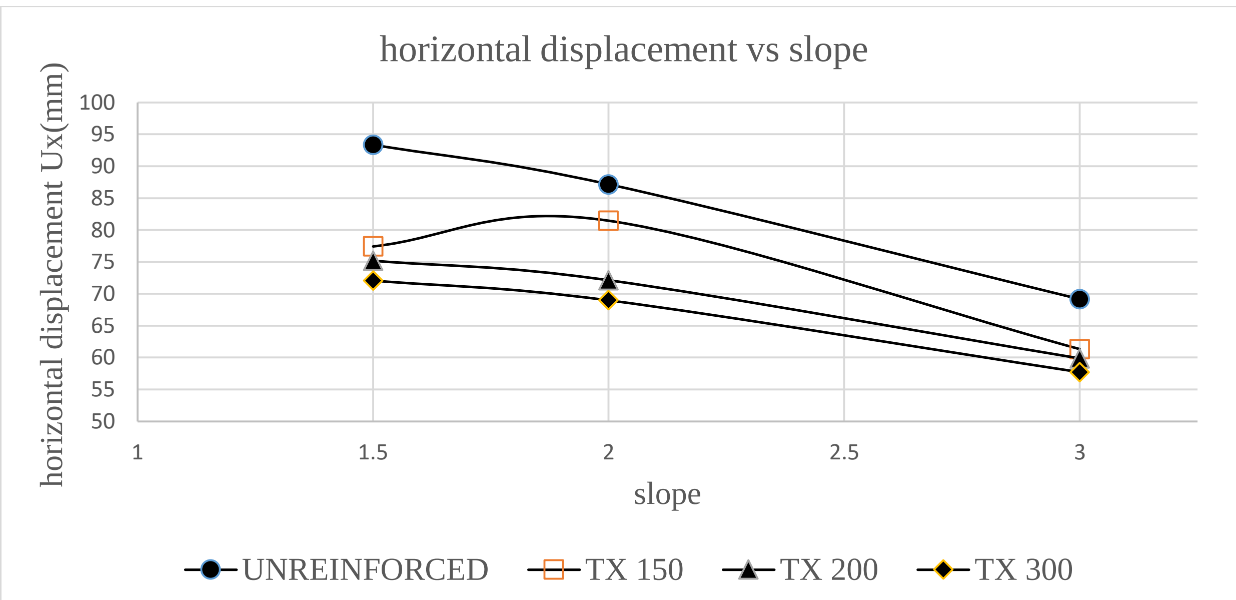


Figure 4. 9: Horizontal displacement vs slope at 2m height for unreinforced and reinforced of embankment.

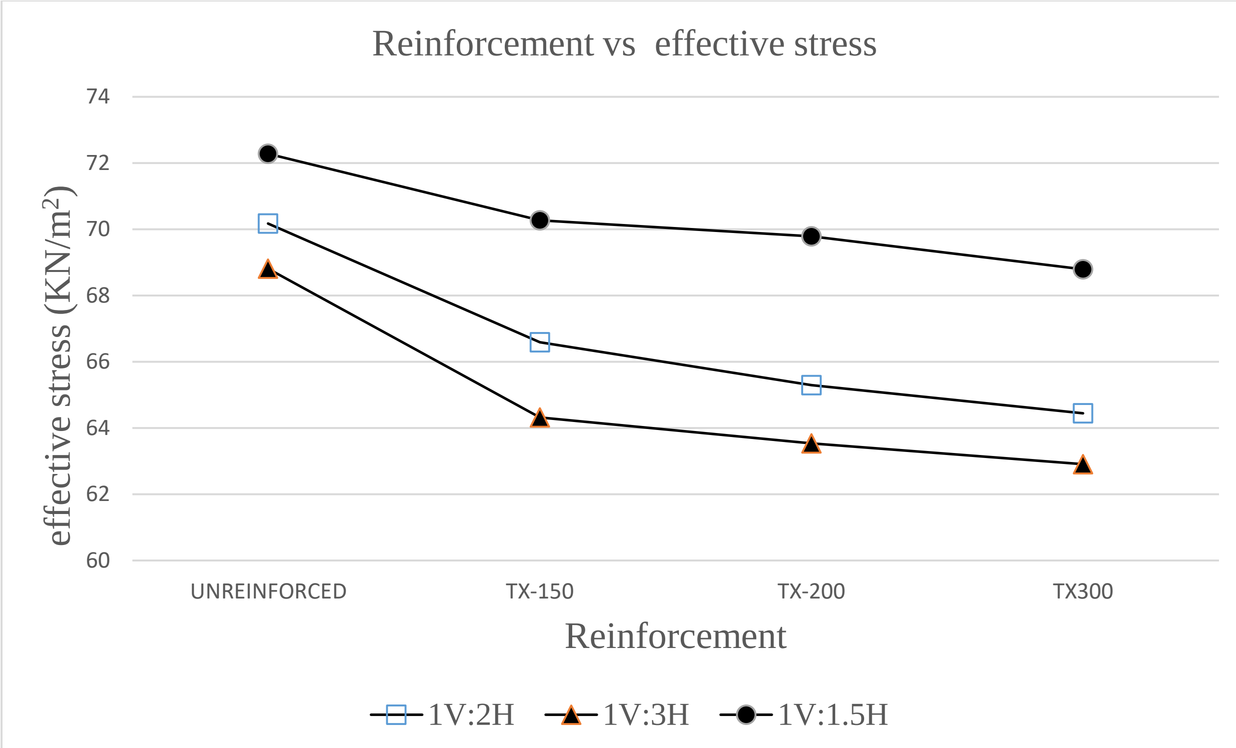


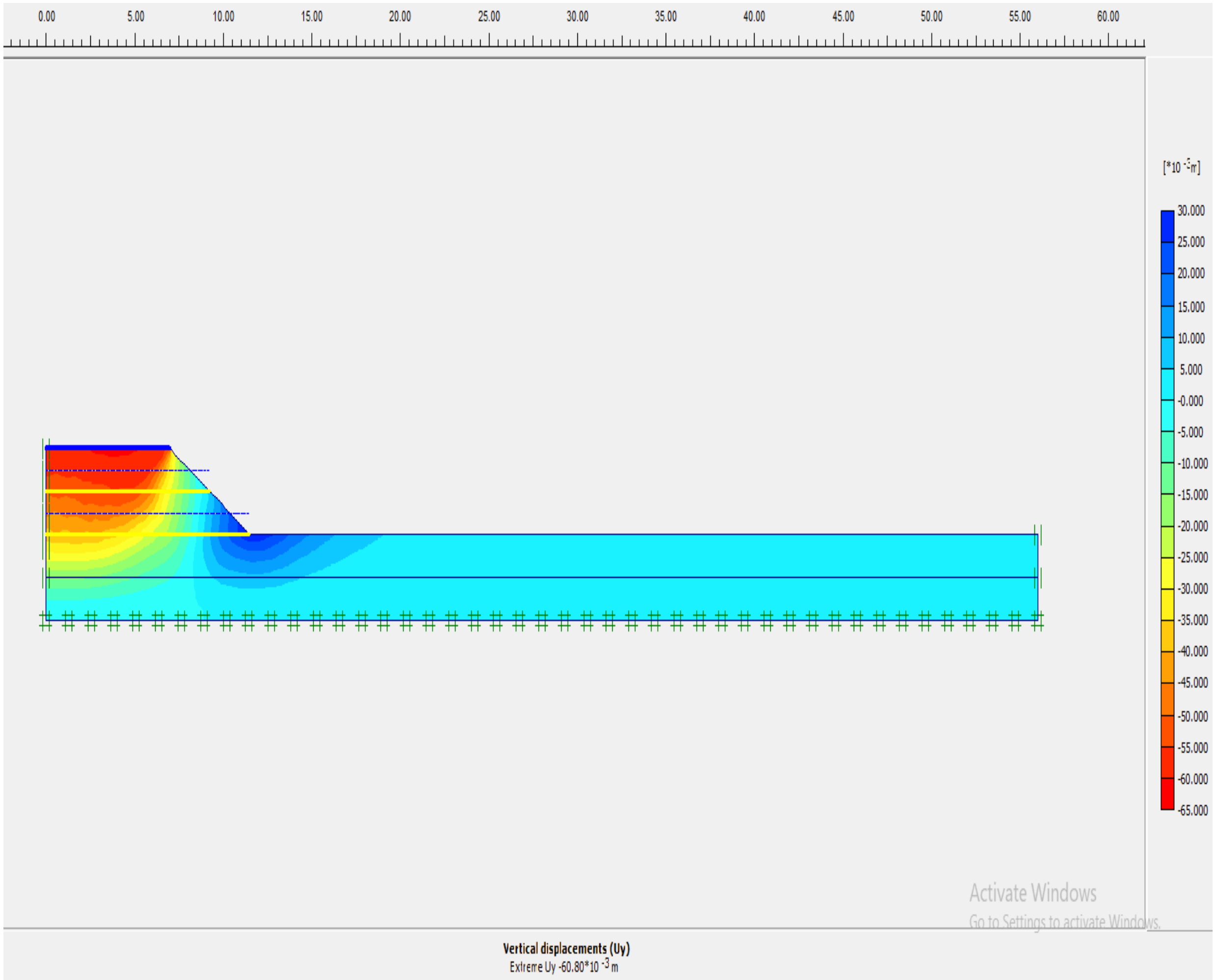
Figure 4. 10:Effective stress(kN/m^2) vs reinforcement for 2m height of embankment with different slopes.

Figures 4.8,4.9 and 4.10 shows results obtained from plaxis 2D analysis of unreinforced and reinforced embankment horizontal displacement, vertical displacement and effective stress of 1m embankment height with slope 1:1.5,1:2,1:3 .

Table4. 3:The results of FEA of road embankment at 3m height

Slope height	Slope H:V	Reinforcement	Parametric results		
			Horizontal displacement [mm]	Vertical displacement [mm]	Effective mean stress [kN/m^2]
3m	1.5:1	Unreinforced	120.35	80.32	72.28
		Reinforced with TX-150	103.53	67.64	70.27
		TX-200	99.13	64.95	69.79
		TX-300	91.94	60.80	68.79
	2:1	Unreinforced	114.17	70.57	70.17
		Reinforced with TX-150	104.65	68.96	66.59
		TX-200	102.09	61.31	65.29
		TX-300	97.73	58.32	64.44
	3:1	Unreinforced	99.74	68.96	68.81
		Reinforced with TX-150	84.32	60.34	64.32
		TX-200	79.15	58.23	63.54
		TX-300	77.16	54.83	62.91

Table 4.3 presents the FEA results detected from modelling for both unreinforced and reinforced road embankment at slope of at 3 m height of embankment and 1.5:1,2:1, 3:1.The outputs obtained from the model are the extreme value of horizontal displacement, vertical displacement and effective stress of each model



Extreme vertical displacement Uy(mm)=60.80mm

Figure 4. 11:Sample of plaxis 2D output of vertical displacement (mm) of 3m height reinforced embankment

.

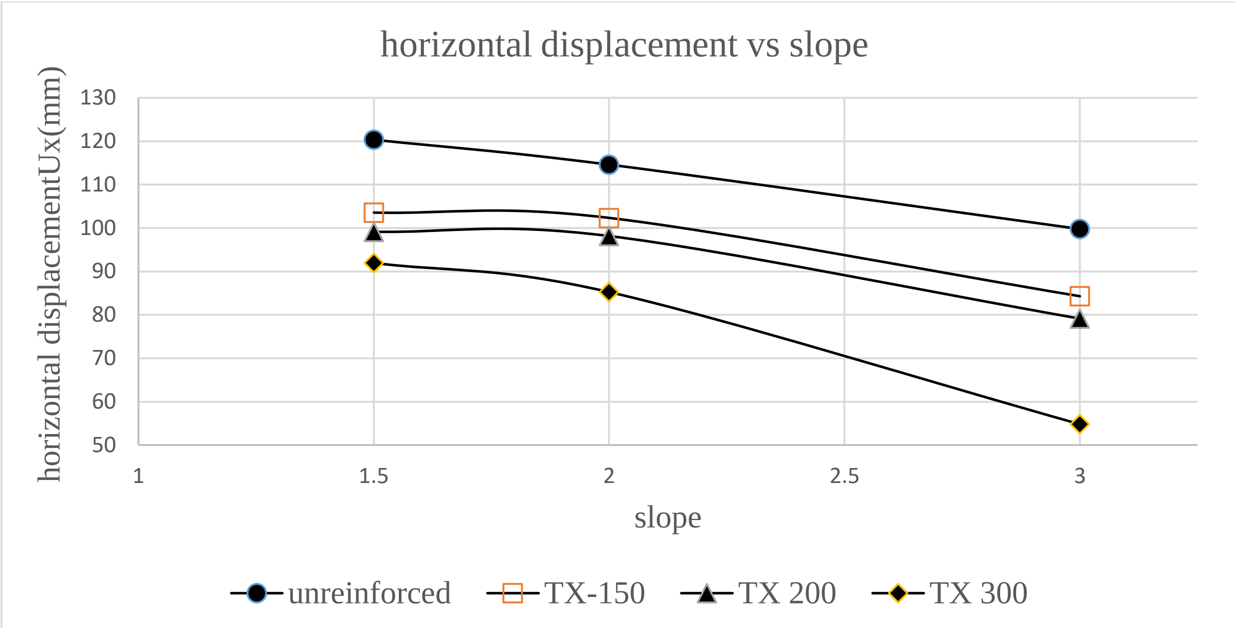


Figure 4. 12:Horizontal displacement [mm]vs slope at 3m height of embankment reinforced and unreinforced embankment.

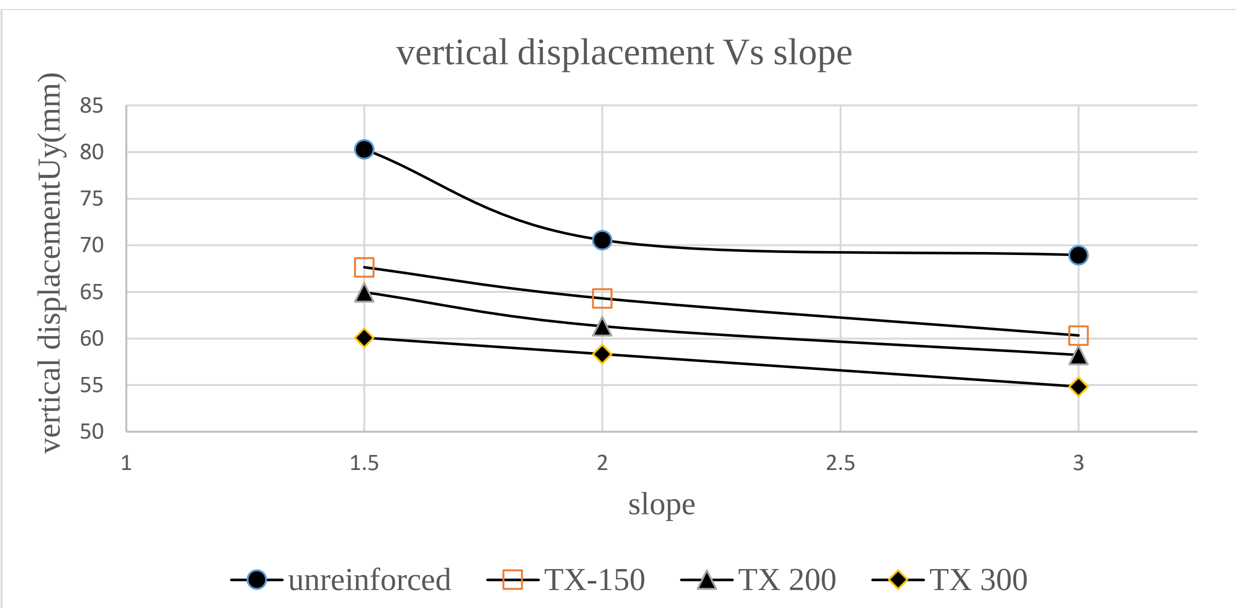


Figure 4. 13:Vertical displacement [mm]vs slope at 3m height of embankment reinforced and unreinforced embankment.

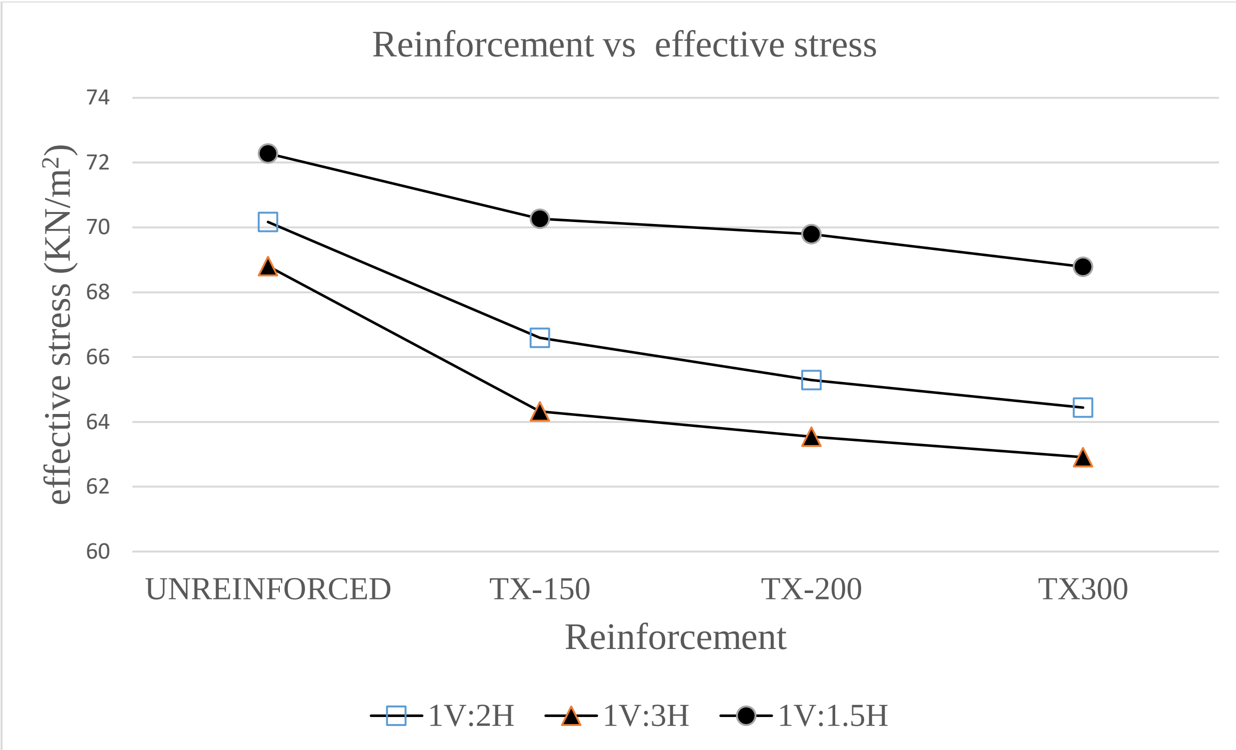


Figure 4. 14:Effective stress vs reinforcement for 3m height of embankment with different side slopes

Figure 4.12, 4.13and 4.14 shows plaxis 2D analysis results of 3m reinforced and unreinforced vs road embankment horizontal displacement, vertical displacement with side slopes of 1:1.5,1:2, 1:3.

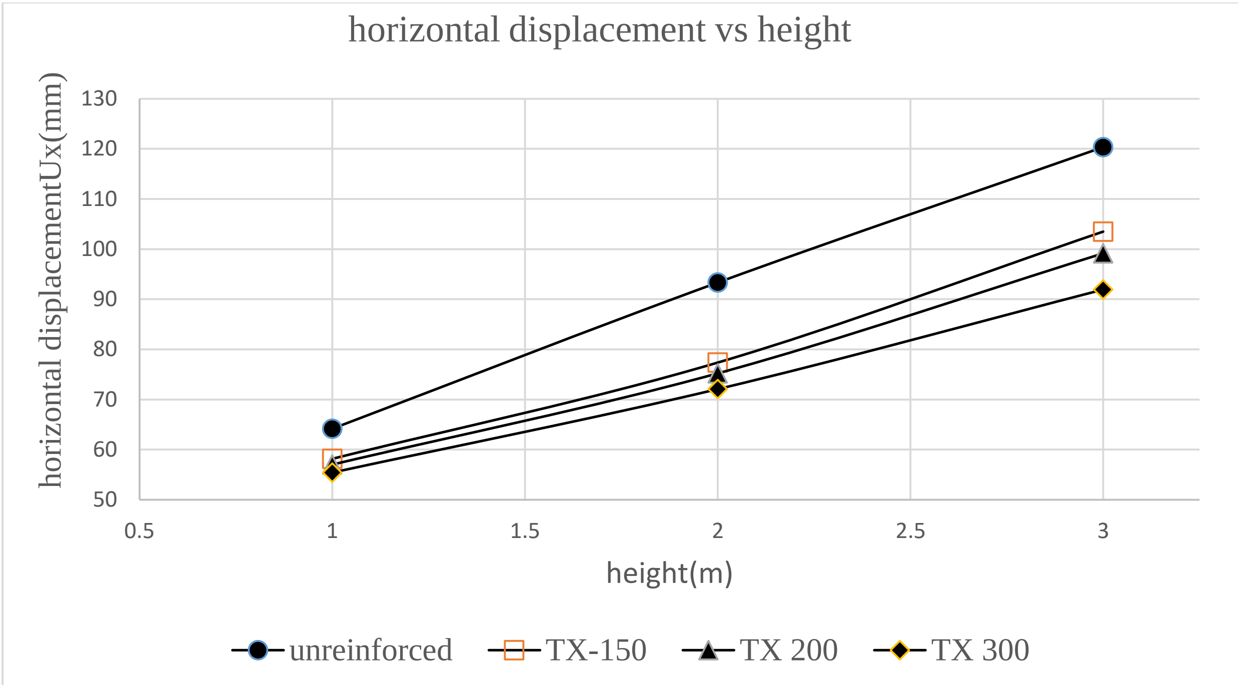


Figure 4. 15:Horizontal displacement [mm]vs height for side slope 1v:1.5H for reinforced and unreinforced embankment

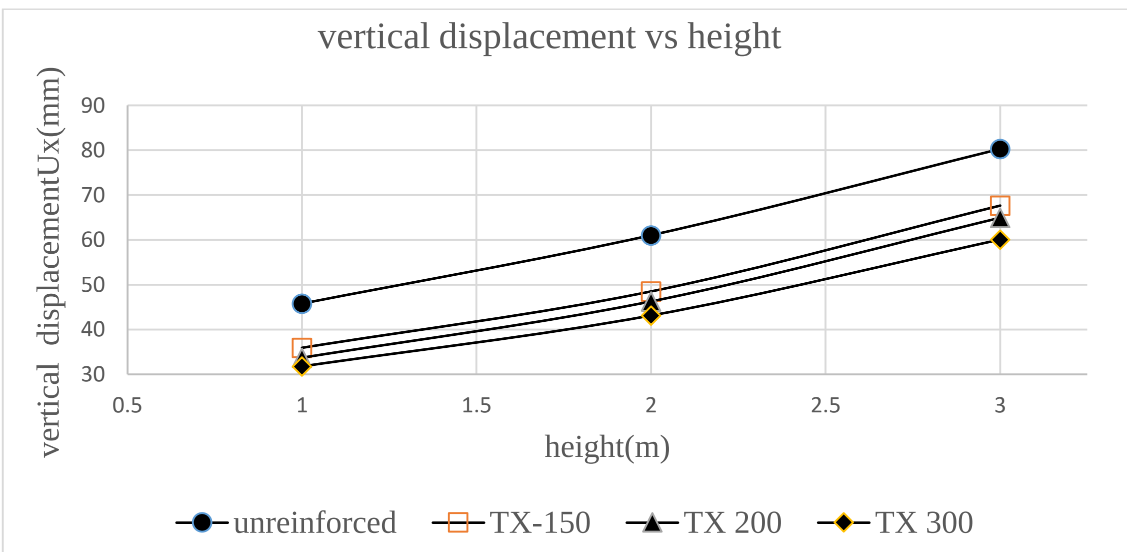


Figure 4. 16:Vertical displacement [mm] vs height for side slope 1v:1.5H reinforced and unreinforced embankment

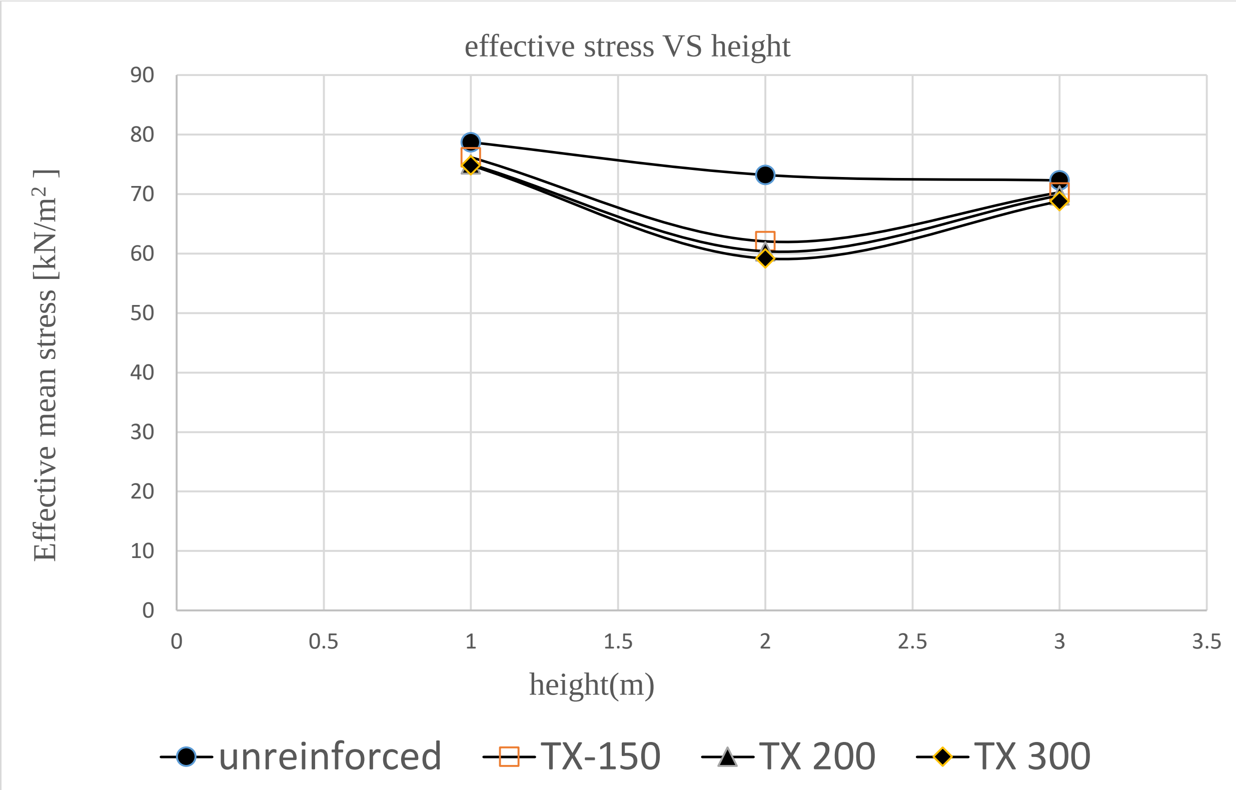


Figure 4. 17:Effective stress [KN/m^2] vs height 1:1.5 side slope reinforced and unreinforced embankment.

Figure 4.15,4.16 and 4.17 shows plaxis 2D analysis results of horizontal displacement, vertical displacement and effective stress vs height with for slope 1:1.5 of unreinforced and reinforced embankment.

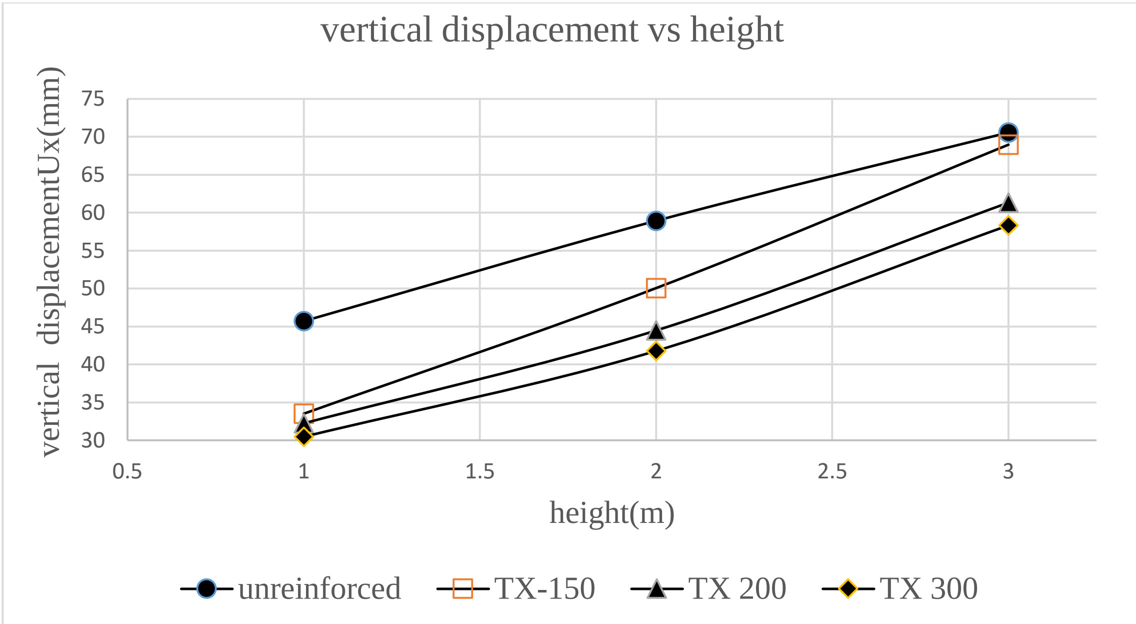


Figure 4. 18:Vertical displacement [mm] vs height (m) for side slope 1V:2H reinforced and unreinforced embankment.

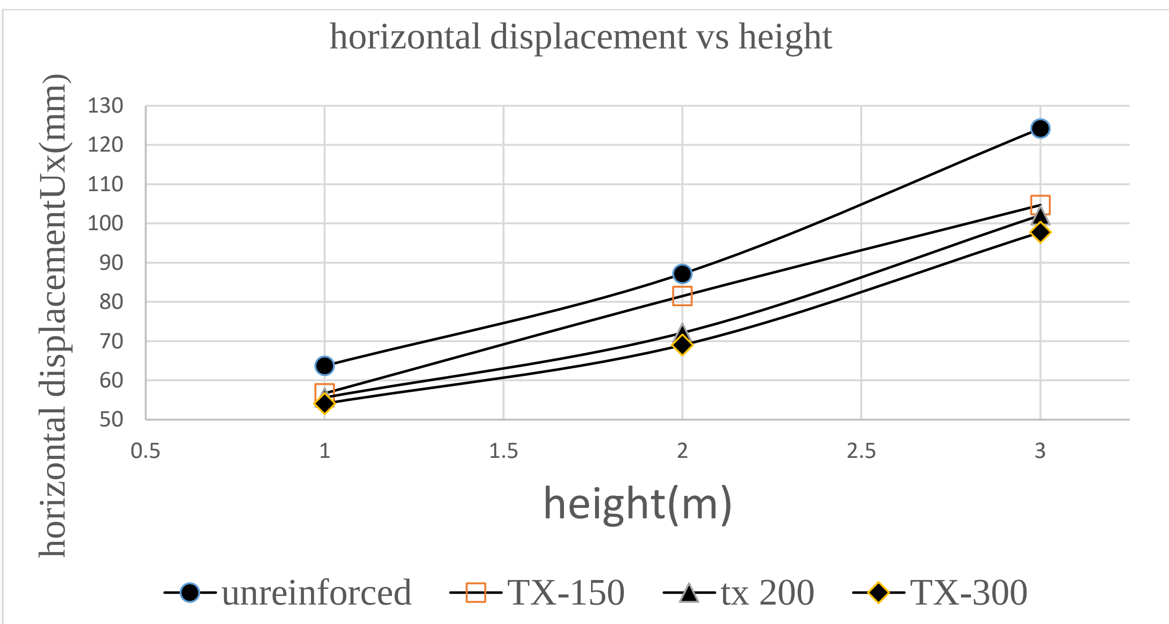


Figure 4. 19: horizontal displacement [mm] vs height (m) for side slope 1V:2H reinforced and unreinforced embankment.

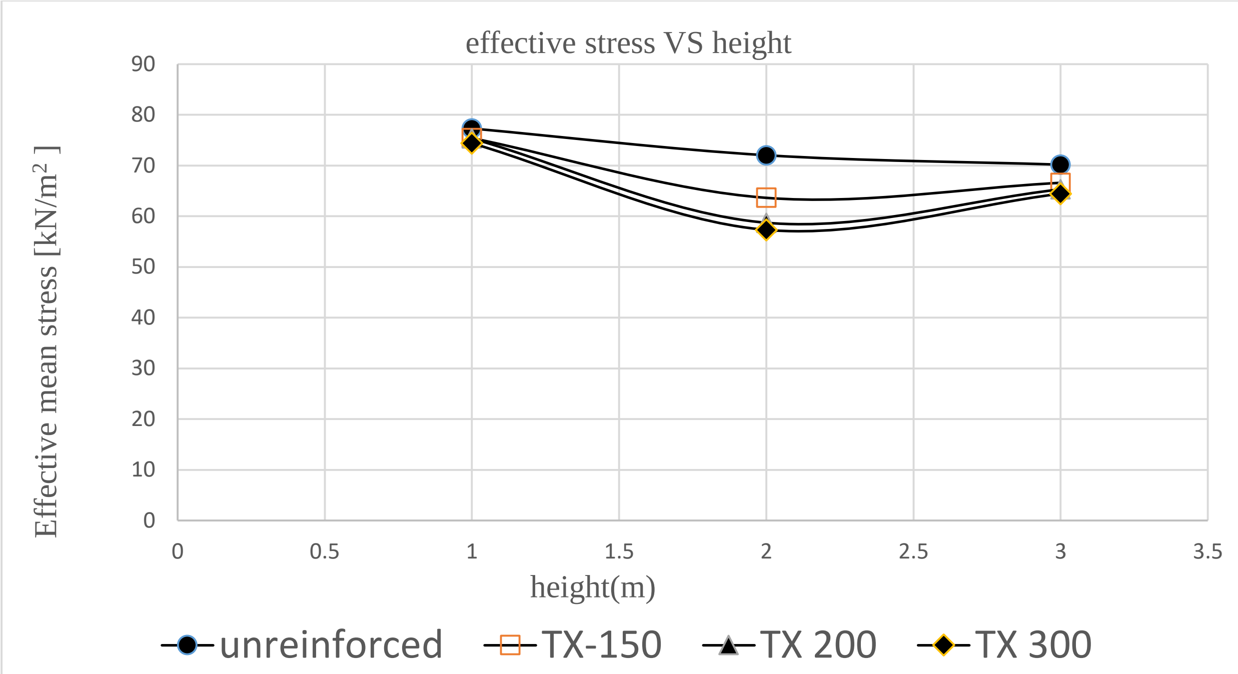


Figure 4. 20:Effective stress(kN/m^2) vs height (m) for 1V:2H side slope reinforced and unreinforced embankment.

Figure 4.18, 4.19 and 4.20 shows plaxis 2D analysis results of horizontal displacement, vertical displacement and effective stress vs height with for slope 1V:2H of unreinforced and reinforced embankment.

.

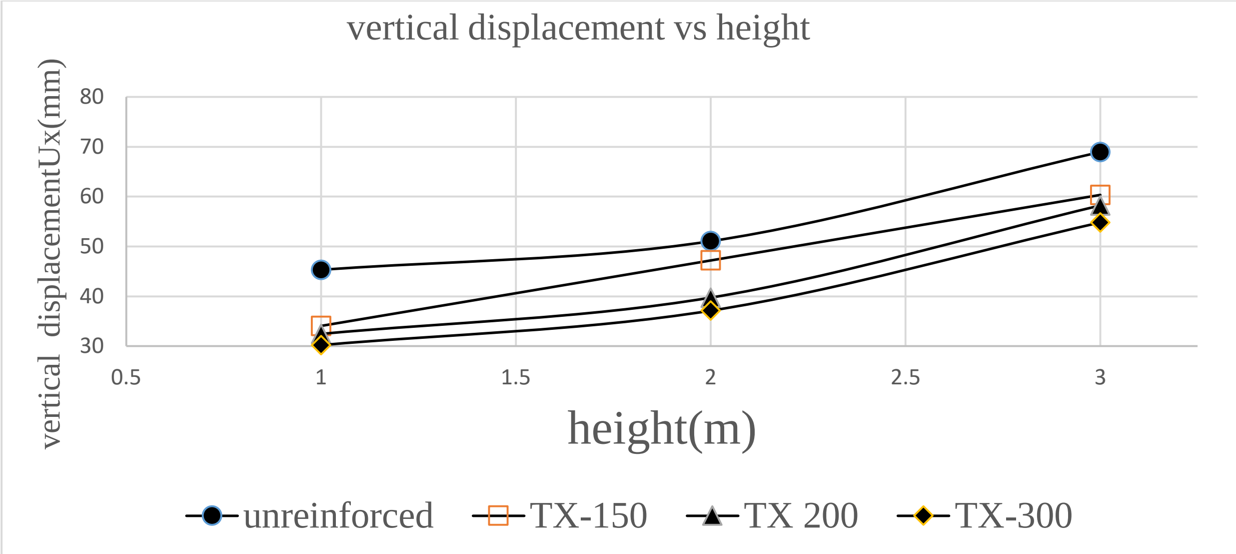


Figure 4. 21: Vertical displacement [mm] vs height (m) for side slope 1V:3H reinforced and unreinforced embankment.

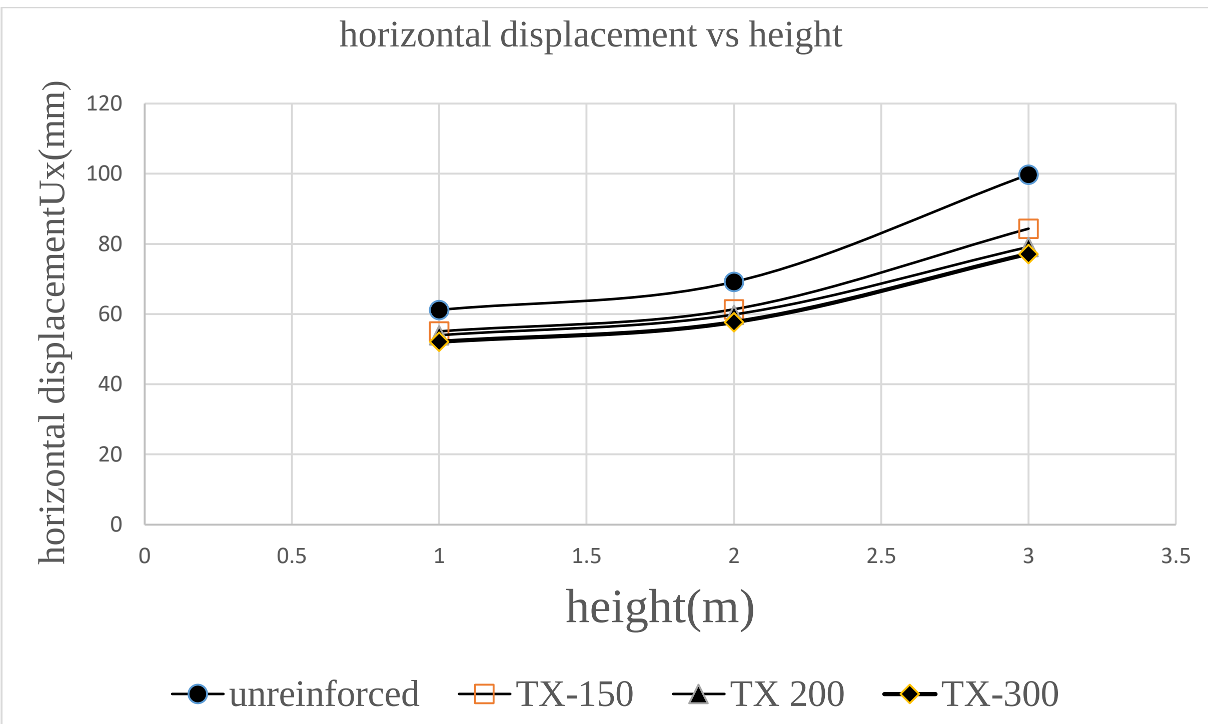


Figure 4. 22: Horizontal displacement [mm] vs height (m) for side slope 1V:3H reinforced and unreinforced embankment.

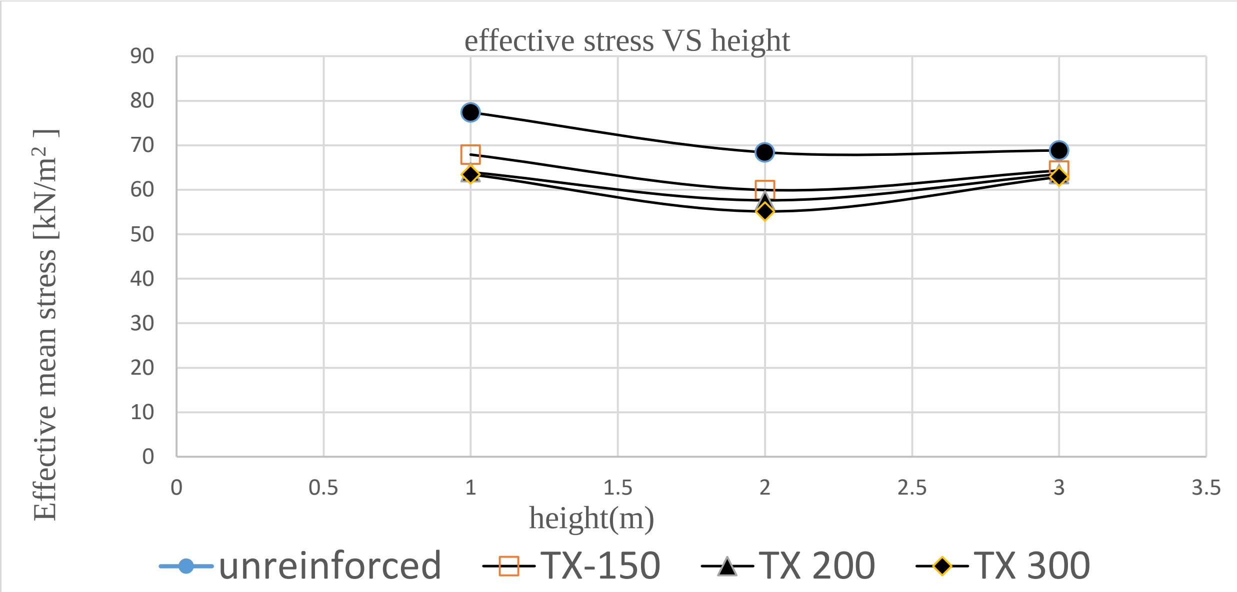


Figure 4. 23:Effective stress (kN/m^2)vs height (m) for 1:3 side slope.

Figure 4.21, 4.22 and 4.23 shows plaxis 2D analysis results of horizontal displacement, vertical displacement and effective stress vs height with for slope 1V:3H of unreinforced and reinforced embankment.

4.3.Parametric Study Discussion

In this study a series of finite element analysis is performed in order to investigate the influence of side slope, axial stiffness of geogrid material and height of embankment with regarding to horizontal displacement, vertical displacement and effective stress on the performance of embankment.

Effect of side slope

In this FE modeling, of side slope choices for the road embankment model is 1:1.5, 1:2, and 1:3. The influence of variation of these slopes on vertical settlement, horizontal displacement, and effective stress on the performance of the road embankment is indicated from figures (4.5-to-4.14) of embankment for unreinforced and reinforced one. The finding suggests that horizontal displacement, vertical displacement and effective stress decreases when side slope increases . In a construction of road embankment slope stability is an essential feature. The finding indicates that the gentler the slope, the minor deformation and settlement will occur. From the graph, the failure criteria often decrease when the ratio decreases from 1:1.5 to 1:2 and gradually from 1:2 to 1:3. Based on this conclusion, we may determine which side slopes are the most effective for designing a safe and cost-effective geogrid-reinforced road embankment.

Effect of geogrid Axial stiffness

The influence of type of geogrid material choices for the road embankment model is TEMA Xgrid-150(TX-150), TEMA Xgrid-200(TX-200)and TEMA Xgrid (TX-300) with axial stiffness(EA) of 800kN/m, 1100kN/m and 1600kN/m respectively. In this FE modeling, vertical settlement, horizontal displacement, and effective stress are used to illustrate the impact of the axial stiffness on the performance of the road embankment in figure(4.1-to 4.6). The findings shows that horizontal displacement and vertical displacement decreases when axial stiffness of geogrid increases. Based on these findings increasing axial stiffness results reduced lateral strain and vertical displacement.

Effect of embankment height

The influence of height of embankment for road embankment model is 1m, 2m and 3m. In this FE modeling, vertical settlement, horizontal displacement, and effective stress are used to illustrate the impact of height of embankment on the performance of the road embankment in figure(4.15-to-4.23).The findings shows that vertical and horizontal displacements increases when embankment height increases. The findings also show that in increasing height even we increase the axial stifness of geogrid material the reduction factor decreseases when compared to lower heights.

A series of two-dimensional FEA were conducted to investigate the effect of critical design factors on the deformation performance of geogrid-reinforced road embankments since design of foundations on weak soils usually governed by deformation criteria due to its high compressibility.

The road embankment modeled in a 2D FEA simulation with varying side slope, Axial stiffness and height embankment was analyzed in terms of lateral deformation (horizontal displacement), settlement (vertical displacement), and effective stress. The parametric study the geogrid reinforced road embankment with side slope of 1:3, TEMA-Xgrid-300(EA-1600kN/m) for 1m selected and recommended as the most efficient combination of the rest all. The vertical displacement of the reinforced embankment was reduced by 33% and lateral displacement by 15% of unreinforced one. The performance of geogrid reinforced road embankment for 2m and 3m , height with respect to settlement efficient combination is side slope of 1.5:1 and TEMA-Xgrid-300(EA-1600kN/m) in which settlment of the reinforced embankment was reduced by 30% and 24% respectively of unreinforced one.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1.Conclusion

In this study a serious of 10 preliminary checks for sensitivity analyses and 36 subsequent FEA were conducted and the extreme values of horizontal displacement, U_x, vertical displacement, U_y and effective stress, σ_{yy}, of each model was obtained to understand the influence of the selected parameters side slope, axial stiffness and height of embankment on the performance of geogrid reinforced road embankment over soft soil. Generally based on analysis and findings:

- The finding suggests that horizontal displacement, vertical displacement and effective stress decreases when side slope increases . The finding indicates that the gentler the slope, the minor deformation and settlement will occur. From the graph, the failure criteria often decrease when the ratio decreases from 1:1.5 to 1:2 and gradually from 1:2 to 1:3.
- Horizontal displacement and vertical displacement decrease when axial stiffness of geogrid increases. Based on these findings increasing axial stiffness results reduced lateral strain and vertical displacement(settlment). But in increased heights the effect of axial stifness decreases since reduction factor decreases when compared to lower heights.
- Based on the parametric study the geogrid reinforced road embankment with side slope of 1:3, TEMA-Xgrid-300(EA-1600kN/m) for 1m selected and recommended as the most efficient combination of the rest all. The settlment of the reinforced embankment was reduced by 33% and lateral displacement reduced by 15% of unreinforced one.
- The performance of geogrid reinforced road embankment for 2m and 3m , height with respect to settlment efficient combination is side slope of 1.5H:1V and TEMA-Xgrid-300(EA-1600kN/m) in which settlment of the reinforced embankment was reduced by 30%and 25% respectively of unreinforced one.
- Generally, since embankments on weak soils goverened by settlment criteria due to high compressibility of soil geogrid materials are used in reducing settlment and lateral deformation.

5.2.Recommendation

- This work presents a study toward understanding the behavior of reinforced road embankment. However, the performance of reinforced embankment is influenced by numerous factors. Due to limited time, this study cannot address all these factors. The future research is recommended to address other parameters like reinforcement vertical spacing, number of reinforcement layers, width ratio, weight of fill material, angle of internal friction and other parameters which have influence on performance of geogrid reinforced embankment.
- Future study should focus on Using the finite element model for the reinforced road embankment to simulate a full-scale geogrid reinforced approach slab embankment and compare the finite element results with field measurements from monitoring instrumental embankments.

REFERENCES

- Abdul Aziz A. Kamal, Pauleen A. Lane and Ali A.R. Heshmati 2005. "Parametric Study of Reinforced and Unreinforced Embankment on Soft Soil1" *Research Gate* :238659082 https://www.researchgate.net/publication/238659082
- Abramson, L. W., Lee, T. S., Sharma, S., & Boyce, G. M. (2001). *Slope stability and stabilization methods*. John Wiley & Sons.
- Alamshahi, S., Hataf, N., 2009. Bearing capacity of strip footings on sand slopes reinforced with geogrid and grid anchors. *Geotextextiles and Geomembr*.27, 217–226
- Alemineh Sorsa Sanjaya Senadheera and Yoseph Birru Engineering(2020) Characterization of Subgrade Soils of Jimma Town, Ethiopia, for Roadway Design. *Geosciences, 10,* 94; doi:10.3390/geosciences10030094
- Berg, R. R., Christopher, B. R., & Perkins, S. W. (2000). Geosynthetic reinforcement of the aggregate base course of flexible pavement structures. *GMA White Paper II, Geosynthetic Materials Association, Roseville, MN, USA, 130p*.
- British Standards Institute. BS 8006-1, (2010.) "Code of Practice for Strengthened/Reinforced Soils and other Fills", London: British Standards.
- Brocklehurst, J.C., (1993). "Finite element studies of reinforced and unreinforced two-layer soil system." *A Thesis submitted for the Degree of Doctor of Philosophy at the University of Oxford.*
- Che Mamat R. (2013) Engineering properties of Batu Pahat soft clay stabilized with lime, cement and bentonite for subgrade in road construction. MS Thesis, Faculty of Civil and Environmental Engineering, Universiti Tun Hussien Onn Malaysia.
- Che Mamat, Anuar Kasa, Sitifatin Mohad Razali 2019 A Review Of Embankment Stability On Soft Ground: Problems and Future Perspective. IIUM Engineering Journal, Vol. 20, No. 2.
- Chen, Q., et al., Laboratory investigation of behavior of foundations on geosynthetic reinforced clayey soil. Transportation research record, 2007. **2004**(1): p. 28-38
- Christopher, B.R. and Holtz, R.D. (1985). Geotextile Engineering Manual, Federal Highway Administration, FHWA-TS-86/203, March, 1044 p.
- Davis EH, Booker JR. (1973) The effect of increasing strength with depth on the bearing capacity of clays. Géotechnique, 23(4):551-563.
- Dafalla MA. (2009) Improvement of coastal silty sand of Saudi Arabia using preloading technique. In: GeoHunan Int. Conf. American Society of Civil Engineers, Changsha, Hunan, China, pp 100-105.
- Das, B. (2010). Use of Geogrid in Subgrade-Ballast System of Railroads Subjected to Cyclic Loading for Reducing Maintenance. *California State University, Sacramento, USA.*

- Dong, Y., Han, J., & Bai, X. (2010). A numerical study on the stress-strain responses of biaxial geogrids under rension at different directions. *ASCE G-I GeoFlorida Conference.*
- Dong, Y.-L., Han, J., & Bai, X.-H. (2011). Numerical analysis of tensile behavior of geogrids with rectangular and triangular apertures. *Geotextiles and Geomembranes, 29*(2), 83-91
- Duncan JM. (1996) State of the Art: Limit Equilibrium and Finite-Element Analysis of Slopes. Journal of Geotechnical Engineering, 122(7):577-596.
- Ehrlich, M.&Becker, L.D.B. (2010) *Reinforced Soil Walls and Slopes: Design and Construction*, CRC Press, Balkema
- ERA. Geotechnical Design Manual-2013; ERA: Addis Ababa, Ethiopia, 2013.
- Haliburton, T.A., Lawmaster, J.D. and McGuffey, V.C. (1981). Use of Engineering Fabricsin Transportation Related Applications, Federal Highway Administration, FHWA
- DTFH61-80-C-00094.
- Howard, I., and Warren, K., (2006). "Finite element approach for flexible pavements with geosynthetics." *GeoCongress 2006-ASCE*. 187-192
- Idrus, M.; Singh, M.; Musbah, A.; Wijeyesekera, C. (2016) Investigation of Stabilised Batu Pahat Soft Soil Pertaining on its CBR and Permeability Properties for Road Construction. In Soft Soil Engineering International Conference; IOP Publishing: Bristol, UK, 2016; pp. 1–7.
- Javad Safadoust Shahin Nayyeri Amiri and Asad Esmaeily (2013) Numerical Analysis of Reinforced Embankment Over Soft Foundation Journal of Engineering Science and Technology Review 6 (3) 153- 159
- Kempfert, H.; Gebreselassie, B. (2006) Excavations, and Foundations in Soft Soils; Springer: Berlin, Germany,;pp. 11–55.
- Killeen, M. (2012). Numerical modelling of small groups of stone columns. Phd Thesis, National University of Ireland, Galway
- Kong X. (2016) Prediction of Subgrade Settlement Based Fuzzy Self Adaptable Method of Artificial Intelligence. 9th International Symposium on Computational Intelligence and
- Design, (7):144-147.
- Kong X. (2016) Prediction of Subgrade Settlement Based Fuzzy Self Adaptable Method of Artificial Intelligence. 9th International Symposium on Computational Intelligence and Design, (7):144-147.
- *Koerner, R. M. (2005). Designing with Geosynthetics, 2nd Ed., Englewood Cliffs, N.J. Prentice Hall.*

- Latha, G. M and Somwanshi, A., 2009. “Bearing capacity of square footings on geosynthetic reinforced sand” Geotextiles and Geomembranes 27, pp. 281–294.
- Le TM, Fatahi B, Khabbaz H. (2012) Viscous Behaviour of Soft Clay and Inducing Factors. Geotechnical and Geological Engineering.
- Liu SY, Shao LT, Li HJ. (2015) Slope stability analysis using the limit equilibrium method and two finite element methods. Computers and Geotechnics, 63:291-298.
- Marradi a, Pinori U, Betti G. (2012) The Use of Lightweight Materials in Road Embankment Construction. Procedia - Social and Behavioral Sciences, 53(0):1000-1009.
- Michalowski RL. (1992) Bearing Capacity of Nonhomogeneous Cohesive Soils Under Embankments. Journal of Geotechnical Engineering, 118(7):1098-1118.
- Nazzal, M. D., Tao, M., Mohammad, L. N., Zhang, Z., & Wu, Z. (2010). Application of shakedown theory in characterizing traditional and recycled pavement base materials. *Journal of Transportation Engineering*, *136*(3), 214-222
- Oser C, Cinicioglu SF. (2017) Embankment Design Method Combining Limit-State Approach with Stress-Path Application. International Journal of Geomechanics ASCE, 17(4):1-16.
- Perkins, S., Christopher, B., Cuelho, E., Eiksund, G., Hoff, I., Schwartz, C.,Watn, A. (2004). *Development of Design Methods for Geosynthetic Reinforced Flexible Pavements*. Report No. DTFH61-01-X-00068, U.S. Department of Transportation, Federal Highway Administration, Washington D.C., USA.
- Rabie M. (2014) Comparison study between traditional and finite element methods for slopes under heavy rainfall. HBRC Journal, 10(2):160–168.
- Saad, B., Mitri, H., and Poorooshasb, H., (2006). "3D FE analysis of flexible pavement with geosynthetic reinforcement." *J. Transportation Engineering 132*, 402-415.
- Salahudeen, A. B. and Sadeeq, J. A.2016 NUMERICAL MODELLING OF SOIL REINFORCEMENT USING GEOGRIDS Fourth International Conference on Engineering and Technology Research ISBN: 978-2902-58-6 Volume 4
- Suman Hazari1, Sima Ghosh2, Richi Prasad Sharma(2018)Experimental and Numerical Study on Reinforced Soil Slope Conference on GEO-HAZARDS AND FUTURE DEVELOPMENTS OF CIVIL ENGINEERING
- The International Geosynthetics Society (IGS), (April,2019). www.geosyntheticssociety.org
- US DOT FHWA (2001). *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines*. Department of Transportation, Federal Highway Authority Publication No. NHI-00-043. Washington D.C., USA.
- Yu Z, Jianhui Z, Xu Z, Xiaodong P, Hongwei L, Hao C. (2017) Finite Element Analysis of Embankment with Soft Foundation Reinforced by Geogrids. Modern Civil and Structural Engineering, 1(1):78-83.

- Zornberg, J.G. (2007). “New Concepts in Geosynthetic-Reinforced Soil.” Keynote lecture, Proceedings of the Fifth Brazilian Symposium on Geosynthetics, Geossinteticos 2007, and of the Sixth Brazilian Congress on Environmental Geotechnics, REGEO `2007, pp. 1-26 (CD-ROM
- Zornberg, J. G., & LaRocque, C. J. (2008). Technical Report Documentation Page 1. Report No.
- Zornberg, J.G. (2011). “Advances in the use of geosynthetics in pavement design." *Geosynthetics India*, 11, 3-21.
- Zou C, Wang Y, Lin J, Chen Y. (2016) Creep behaviors and constitutive model for high density polyethylene geogrid and its application to reinforced soil retaining wall on soft soil foundation. Construction and Building Materials, 114:763-771.

APPENDICES

Appendix A: laboratory test results

A-1-summarry of laboratory results

A-1-summarry of laboratory results (Alemineh et.al(2020)

Laboratory Tests		sample	
		Site 1	Site 2
Moisture content(%)		40.77	54.50
Specific gravity(GS)		2.7	2.77
Atterberg limits(%)	LL	81	67
	PL	41	31
	PI	40	35
OMC(%)		33.5	32
MDD (gm/cm^3)		1.41	1.48
Density at 95% MDD (gm/cm^3)		1.34	1.41
CBR at 95%MDD(%)		1.8	2.4
Triaxial Compression	C(KPa)	93	38
	$\phi(^0)$	16	5
	$\gamma_{bulk(KN/m3)}$	16.8	16.6
Unconfined compressive strength	q_u(KPa)	50	41
	C_u(KPa)	25	20.5
Grain size analysis		Fine-grained soil	
Soil classification(AASHTO)		A-7-5	

Appendix B: PLAXIS 2D Input parameters

B-1. Subgrade and Embankment material input parameters

Table B-1 Summary of subgrade and embankment materials

Soil parameter	Subgrade soil	Embankment	unit
Material model	Mohr-coulomb	Mohr-coulomb	-
Type of material behaviour	Undrained	Drained	-
Saturated unit weight(γunsat)	16.6	20	KN/m^3
Unsaturated unit weight (γunsat)	14.1	17	kN/m^3
Young's modulus (E)	1000	30000	kN/m^2
Poisson‟s ratio (ν)	0.35	0.3	-
Cohesion (Cref)	38	1	kN/m^2
Friction angle (ϕ‟)	5	34	-
Dilatancy angle (ψ)	0	4	-
Over-consolidation ratio	1	1	-
Depth	0-3.0	1	M

B-2. AC Pavement material input parameters

Table B-2: Pavement material properties

Pavement properties	Asphalt concrete	Unit
EA	1.580 E+07	kN/m
EI	1.179 E+05	kNsq.m/m
W	1.8	kN
ν	0.15	-

B-3. Geogrid input parameters

Table B-3: : Geogrid material properties

Geogrid type	Nominal Tensile strength(kN/m)	Axial stiffness(EA) (kN/m)
TEMA Xgrid 300 **	300	1600
TEMA Xgrid 200**	200	1100
TEMA Xgrid 150**	150	800

Appendix C: PLAXIS 2D Output

C-1. the results of FEA of a road embankment of 1m height

Table C-1:The results of FEA of a road embankment of 1m height

Slope height	Slope V:H	Reinforcement	Parametric results		
			Horizontal displacement [mm]	Vertical displacement [mm]	Effective mean stress [kN/sq.m]
1m	1.5:1	Unreinforced	64.2	45.76	78.70
		Reinforced with TX-150	58.2	35.9	76.16
		TX-200	57.03	33.7	75.02
		TX-300	55.45	31.8	74.84
	2:1	Unreinforced	63.67	45.76	77.27
		Reinforced with TX-150	56.66	33.52	75.38
		TX-200	55.63	32.27	75.34
		TX-300	54.06	30.48	74.41
	3:1	Unreinforced	61.18	45.32	77.36
		Reinforced with TX-150	55.03	34.08	67.89
		TX-200	53.93	32.43	63.98
		TX-300	52.4	30.23	63.48

C-2. The results of FEA of a road embankment of 2m height

Table C-2: the results of FEA of a road embankment of 2m height

Slope height	Slope V:H	Reinforcement	Parametric results		
			Horizontal displacement [mm]	Vertical displacement [mm]	Effective mean stress [kN/sq.m]
2m	1.5:1	Unreinforced	93.35	61.04	73.20
		Reinforced with TX-150	77.44	48.49	62.07
		TX-200	75.21	46.28	60.39
		TX-300	72.09	43.15	59.17
	2:1	Unreinforced	87.16	58.93	72.02
		Reinforced with TX-150	81.47	50.07	63.64
		TX-200	72.14	44.9	58.69
		TX-300	68.99	41.79	57.53
	3:1	Unreinforced	69.17	51.07	68.4
		Reinforced with TX-150	61.33	47.2	59.96
		TX-200	59.85	39.72	57.64
		TX-300	57.73	37.14	55.11

C-3. The results of FEA of a road embankment of 3m height

Table C-3: The results of FEA of a road embankment of 3m height

Slope height	Slope V:H	Reinforcement	Parametric results		
			Horizontal displacement [mm]	Vertical displacement [mm]	Effective mean stress [kN/sq.m]
3m	1.5:1	Unreinforced	120.35	80.32	72.28
		Reinforced with TX-150	103.53	67.64	70.27
		TX-200	99.13	64.95	69.79
		TX-300	91.94	60.08	68.79
	2:1	Unreinforced	114.17	70.57	70.17
		Reinforced with TX-150	104.65	68.96	66.59
		TX-200	102.09	61.31	65.29
		TX-300	97.73	58.32	64.44
	3:1	Unreinforced	99.74	68.96	68.81
		Reinforced with TX-150	84.32	60.34	64.32
		TX-200	79.15	58.23	63.54
		TX-300	77.16	54.83	62.91