ANALYSIS OF SOIL BEHAVIOUR DURING BOX JACKING

A

PROJECT REPORT

Submitted in fulfillment of the requirements for the award of the degree of

BACHELOR OF TECHNOLOGY

IN

CIVIL ENGINEERING

Under the supervision

of

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HIMACHAL PRADESH, INDIA

June, 2020

STUDENT'S DECLARATION

We hereby declare that work presented in the Project report entitled **" Analysis of soil behavior during box jacking"** submitted for partial fulfillment of the requirements of the degree of Bachelor of Technology in Civil Engineering at **Jaypee University of Information Technology, Waknaghat** is an authentic record of my work carried out under the supervision of **Dr. Saurabh Rawat.** This work has not been submitted elsewhere for the reward of any other degree/diploma. I am fully responsible for the contents of project report.

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CERTIFICATE

This is to certify that the work which is being presented in the project report titled **"Analysis of soil behavior during box jacking"** in partial fulfillment of the requirements for the award of the degree of Bachelor of Technology in Civil Engineering submitted to the Department of Civil Engineering, **Jaypee University of Information Technology, Waknaghat** is an authentic record of work carried out by **Sushant Gupta (161646)** and **Yashwant Singh Rana (161634)** during a period from August, 2019 to November, 2019 under the supervision of **Dr. Saurabh Rawat**, Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

The above statement made is correct to the best of our knowledge.

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ABSTRACT

The building of shallow box tunnel beneath an existing railway track or a highway using jack driving has become a completely familiar approach now-a-days to make an undisturbed flow of vehicles in metropolitan cities. In the course of pushing of box tunnel, the OB cohesion-less soil encounters excessive stresses and extravagant lateral displacements at the tunnel face, which usually causes a mishap leading to loss of lives. In order to surpass this difficulty, a laboratory model study has been carried out. A model tank of size 300mm × 300 mm × 450 mm, loaded with cohesion-less soil was used, in which a square stain-less steel box tunnel of inner dimension 40 mm × 40 mm with 1 mm thick wall will be used as the tunnel. This tunnel will slowly drive into the model tank filled with soil with the help of scissors jack. To reduce the extravagant lateral displacement, the OB soil over the box tunnel will be reinforced with GFRP bars before the driving of box tunnel into the soil takes place.

Keywords: Shallow tunnel; Jack pushing; Underpass; Lateral displacement; Cohesion-less; FRP bars, Load Intensity.

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CFRF	Carbon fiber reinforced polymer
DST	Direct Shear Test
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
LVDT	Linear Variable Differential Transformer
OD	Overburden
PMMA	Plymethylmethacrylate

LIST OF SYMBOLS

γ_d	Dry Unit weight
I_D	Relative density
c	Cohesion of soil
ϕ	Angle of internal friction
δ	Angle of interface friction
C_u	Uniformity coefficient
C_c	Curvature coefficient
D_{10}	Effective size of soil
D_{50}	Mean diameter of soil
k	Coefficient of lateral earth pressure
γ	Unit weight
H	Height of overburden soil
D	Depth of box tunnel
d	Diameter of GFRP bars
$\gamma_{d(max)}$	Maximum dry unit weight of soil
$\gamma_{d(min)}$	Minimum dry unit weight of soil

CHAPTER 1

INTRODUCTION

1.1. General

Box jacking also called tunnel jacking involves the pushing of pre-cast rectangular or circular shape section using high capacity hydraulic jacks. Box tunnelling is a non-interrupting technique for developing underground passage at shallow depths, especially beneath the existing infrastructure such as a highway or a railway track. This technique of tunnelling is achieving boost because of non-availability of sufficient space on the roadways in big metropolitan cities across the world. The non-disruptive nature of the process together with its inherent safety, simplicity and economy makes box jacking a useful tool in civil engineering.

1.2. Need for study

The rapid development of urban road system has brought up new engineering challenges such as construction of underpasses under existing highway and railway tracks. Box jacking is one of the solutions to such problem which is fast and affordable construction technique. It is a well established means of engineering tunnels or culverts below railway embankments or waterways to allow smooth flow of traffic. It is a way of circumventing geo-physical hindrances in order to build a road or rail network. It is used for large tunnelling projects, which can be performed quite quickly once the concrete section has been constructed on site. Hence box jacking requires minimum number of operatives and is therefore cost effective from labour point-of-view.

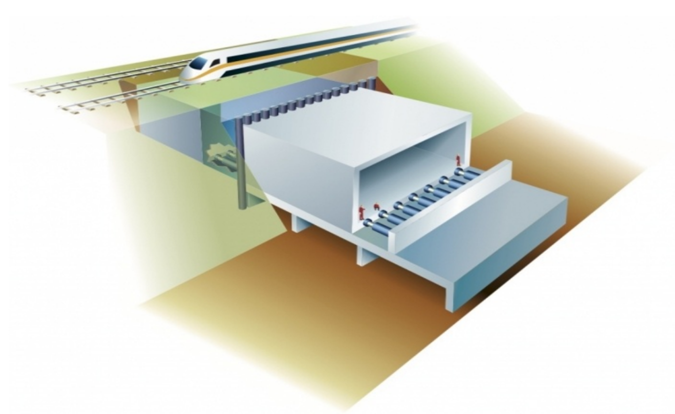


Figure 1.1 Box jacking beneath existing railway track (Ropkins, John W. T., 1999)

1.3. Comparison between box jacking and conventional method

1.3.1. Cut and cover

Cut and cover is the simplest technique of fabrication of tunnels at shallow depths in which a trench is excavated and roofed above with an overhead support system strong enough to carry the load of what is to build above the tunnel. Two basic techniques of cut and cover method are:

- **Bottom-up method:** In this method a trench is first excavated with a necessary ground support system followed by tunnel construction. The tunnel may be of in-situ concrete a pre-cast concrete. The trench is then back filled and the surface is restored in its former condition.

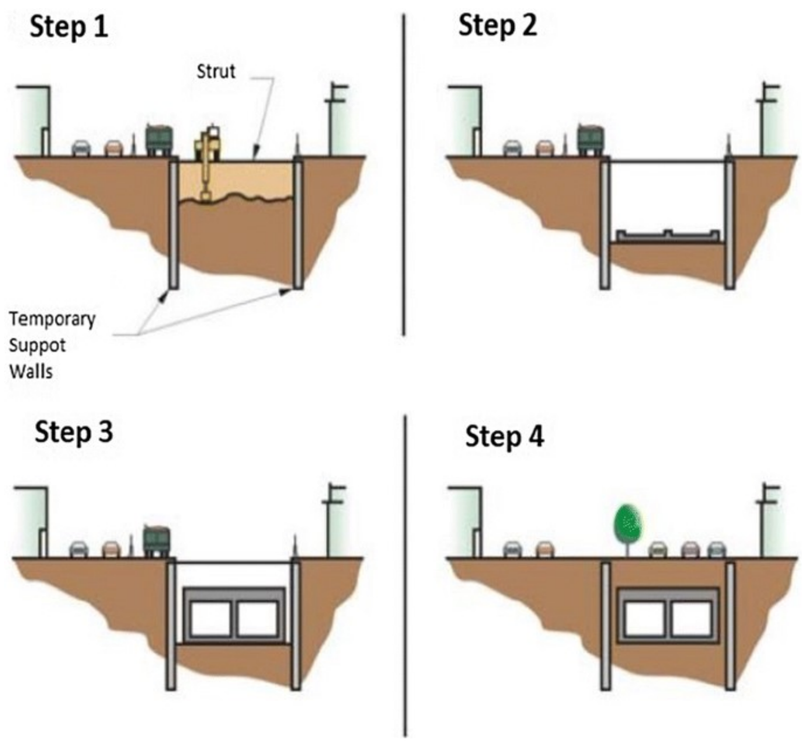
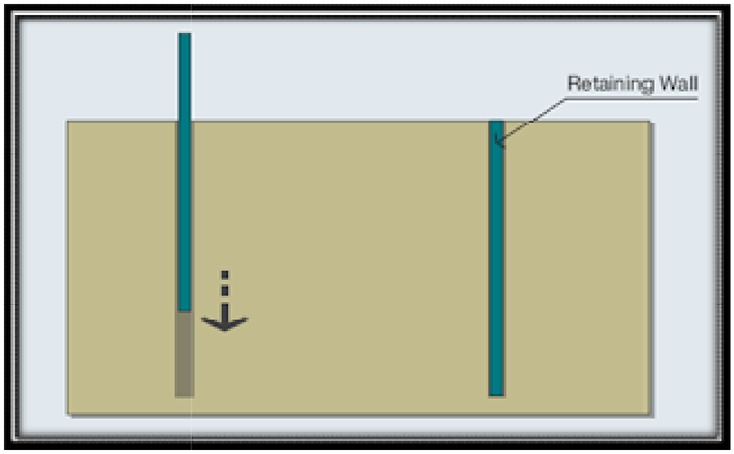


Figure 1.2 Conventional bottom-up method (Abdullah, R.A., 2016)

- **Top-down method**: Side support walls and capping beams are constructed starting from ground level by method such as contagious bored piling or slurry walling. In this process a shallow excavation is required to fabricate the tunnel roof using pre-cast beams or in-situ concrete sitting on walls. The surface is then restored except for access to openings, allowing the early restoration of roads, services and other surface features. Further excavation then take place under the permanent tunnel roof and base slab is constructed.

The major drawback of cut and cover method is the widespread disruption generated at surface level during construction.



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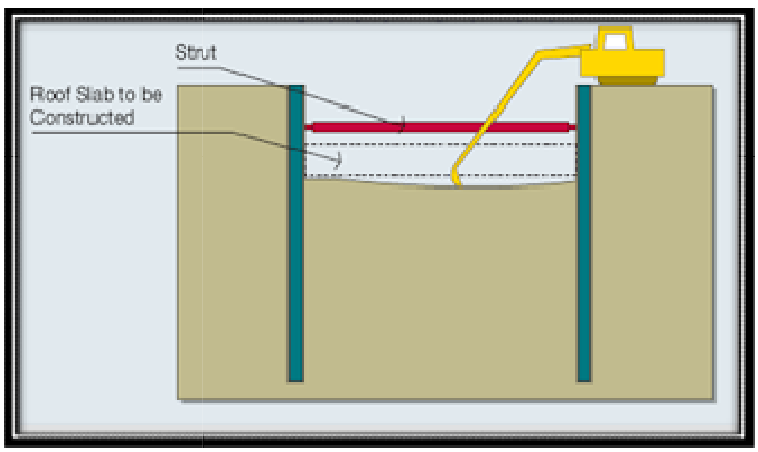

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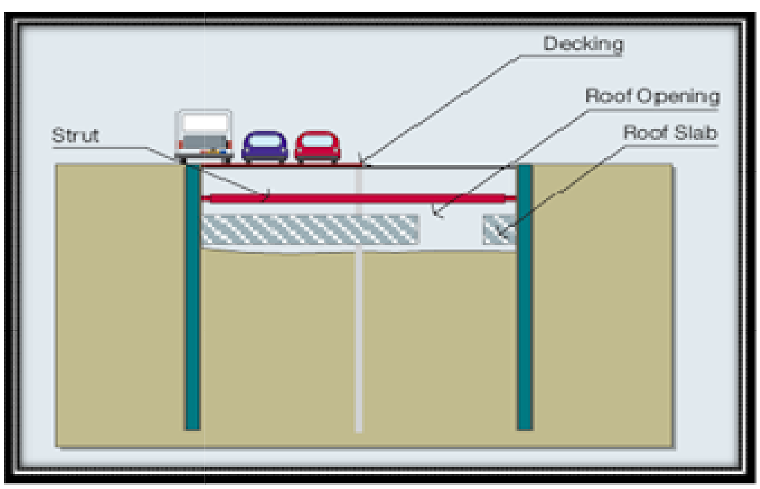

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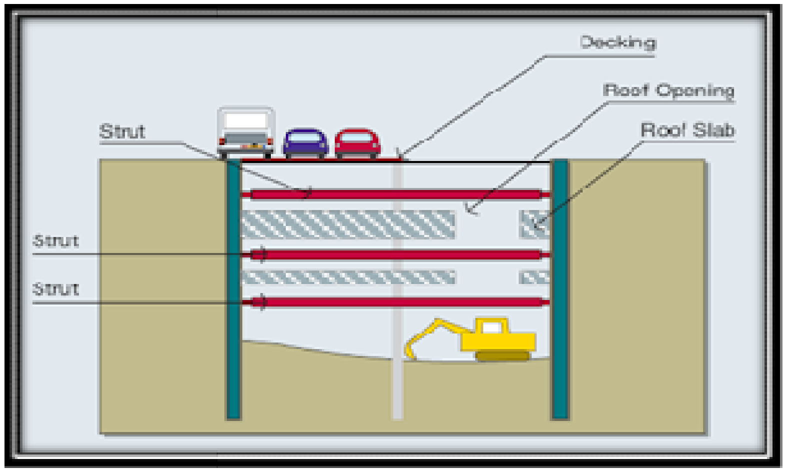

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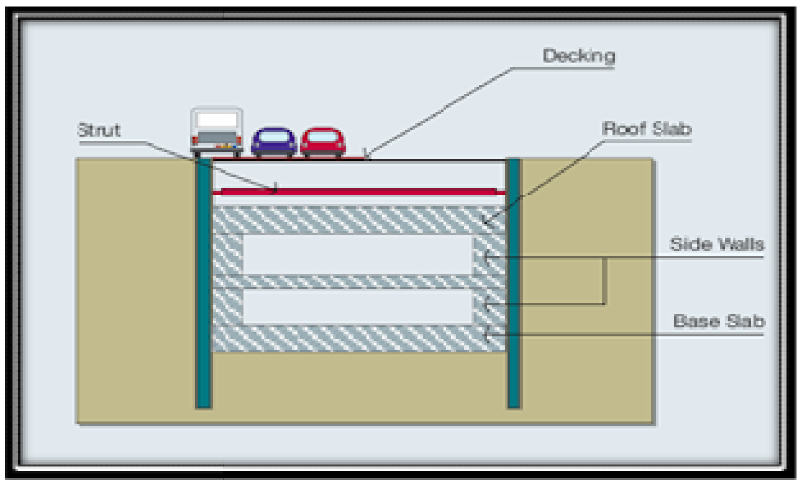

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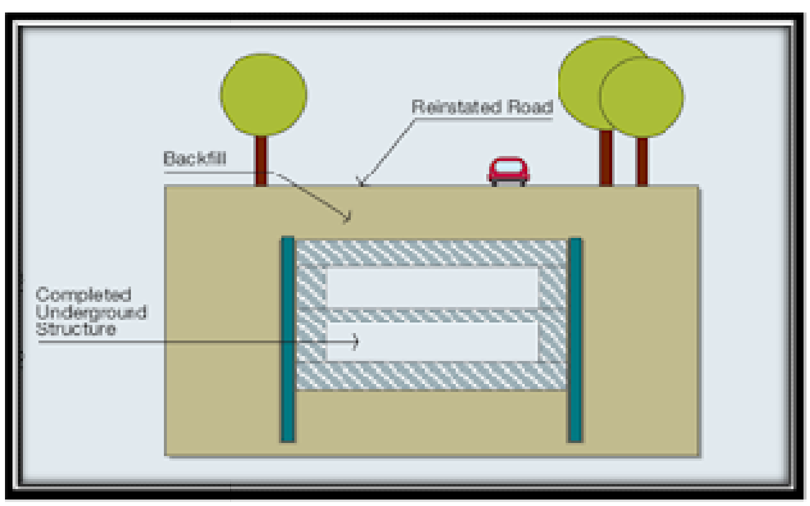

(f) Step - 6

Fig 1.3 Conventional top-down method (RailSystem, 2015)

1.3.2. Box jacking

The box jacking process initiates with excavation of a jacking area or a jacking pit where a stable backdrop can be installed to accommodate the hydraulic jacking rams that provides the necessary push to the precast concrete box sections into soil. Once the section is jacked into the position, an excavator digs the spoil at the face and removes it for disposal. As the excavation continues, section is pushed slowly and steadily into location to form the roof, floor and side walls of the tunnel.

The major advantage of box jacking over conventional method is its less inconvenience caused to the general public.

Figure 1.4 Jacking pit and jacked box section (Gordon, E. K., 2015)

Table 1.1 Comparison between trenchless construction and conventional method

PLANNING ELEMENT	TRENCHLESS CONSTRUCTION	CONVENTIONAL METHOD
Schedule	Hours/Day	Days/Weeks
Excavation	Minimal or Not required	Entire length of installation must be exposed
Traffic Control	Minimal - if any	Usually required
Utility Support	Typically not required	Often required
Site Restoration	Minimal or not required	Major resurfacing or restoration required
Worker Experience	New Technology – limited pool of skilled workers	Proven Method – many skilled workers
Safety	Only pits required	Trenchless required

1.4 Parameters affecting box jacking

1.4.1. Crew and operator experience

An experienced team can highly affect the productivity rate for box jacking operations. Crew's experience can impact the initiation and correction time involved in box installation.

1.4.2. Restrictions to working hours

Restrictions to working hours are the main cause of productivity loss. This technique of tunneling is advised to be done in continuous operations and also does not allow for the soil above the box section to settle. Productivity variations can easily be spotted due to restriction to working hours.

1.4.3. Technical support

Hand mining and mechanical excavation methods are the two different excavation methods that can be performed during box jacking. During hand mining it is advisable to have an experienced superintendent or project engineer to guide the crew when obstructed by unknown soil condition or sudden change in water or to make correction in grade and line alignment of the line. During mechanical excavation it is advisable to have representatives from machine manufacturer present onsite to train and observe the operator's performance.

1.4.4. Design and size of the drive shaft

Construction site should have enough space for storing and handling of box, spoil & shaft. The length, width, height and jacking shield and system dimensions, thrust wall design, pressure rings and guide rail system determines the size of jacking shaft.

1.4.5. Soil type

Type of soil available at site plays a major role in entire jacking operation. The soil types are classified as:

- Non-cohesive soil (soil having very high sand content)
- Cohesive soil (soil having very high clay content)
- Mixed soil
- Solid rock

- Fill material
- Boulders and cobbles

The type of soil and their relative parameters are important parameters in calculating productivity of jacking process.

1.4.6. Drive length

Drive length is the length a box segment can be jacked or pushed in one pass during jacking operation. It depends upon number of factors such as stability and the friction characteristics of the soil to jacked through, self-weight and size of the box, method of excavation and available jacking reaction. Nature of ground and ground water characteristics will play as major constraints. However, methods like use of intermediate jacking stations and use of lubrication during jacking process can be employed to increase drive length.

1.4.7. Geotechnical investigations

It is necessary to identify what type of soil lies along the intended alignment before starting the jacking operation as it will help contractor to select suitable equipment for the task to maximize productivity.

1.4.8. Use of lubrication

Lubrication is used to reduce friction between the box and the soil and doing so will also help in increasing productivity. Following are the benefits of using lubrication:

- Improves stability of tunnel face
- Reduces the needed jacking force
- Reduces permeability of soil around the machine

1.4.9. Groundwater conditions

The construction, spoil removal system, type of excavation method and depth of installation is adversely affected by presence of ground water. Addition grouting of the shaft can reduce the groundwater effect. Generally, it is advised to jack with totally wet or totally dry soil face because mixed soil will disturb the machine performance.

1.4.10. Obstruction or unusual soil conditions

Obstructions like trees, old foundations, structures, sudden change in soil condition along the jacking path are taken as unforeseen ground conditions. Proper and intensive soil investigation can reduce the probability of facing such conditions.

1.4.11. Use of intermediate jacking stations

When the frictional forces or resistances between soils are expected to exceed the capacity of main jack or rating of jacking box, the intermediate jacks between the box segments are installed at periodic intervals. Intermediate jacking stations also overcomes the issue of excessive jacking force requirement.

1.5. Soil Mechanics Aspects of Box Jacking

Tunnels are fabricated in varying soil conditions ranging from soft clays to hard rock. In order to identify the technique of trenching to be used, a thorough study on ground properties, in-situ stresses and various other soil parameters are necessary. In box jacking similar conditions are encountered further incorporating the response of ground movement and its resistance against the forward movement of the box section, along with the level of ground pressure applied on the box section.

1.5.1. Ground pressures on tunnels

In most cases the force acting on a tunnel is usually with the vertical stress acting on the top surface of tunnel, however in few scenarios lateral stress is of greater importance than the roof stress. The in-situ stresses are usually determined from earth pressure theory.

Before evaluating ground pressure it is of most importance to recognize the mechanism of soil surrounding the tunnel, as soil arching phenomena have a bit of role to play in case of vertical pressure on the tunnel. The action between yielding sand and adjacent sand is restrained by the frictional resistance through the contact line between them. This indicates that the decrement in vertical pressure on the yielding strip is connected to the increase in vertical pressure on the adjoining parts.

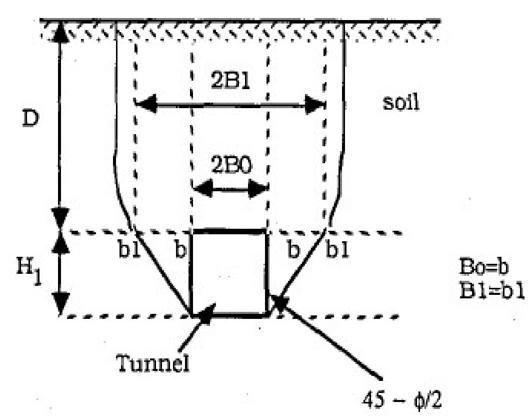

Figure 1.5 Soil arching mechanism (Mamaqnai, B., 2014)

The width of the yielding strip, at the top of a box tunnel, is given by eq. (1.1)

$$2B_1 = 2\left[B_\circ + H_1 \tan\left(45^\circ - \frac{\phi}{2}\right)\right] \quad (1.1)$$

Where,

B_1 = Width of tunnel,

B_0 = Half the width of tunnel

H_1 = Height of the box tunnel

The vertical pressure (σ_v) on the horizontal section b_1b_1 of width $2B_1$ is given by eq. (1.2)

$$\sigma_v = \gamma B\left(1 - e^{-ktan\phi.\frac{D}{B}}\right).\left(\frac{1}{ktan\phi}\right) \quad (1.2)$$

Where, D = depth of box tunnel

1.6. Box jacking forces

The resistance generated during tunnel driving is usually due to forces on the shield and due to sliding resistance betwixt the soil and the outside surface of the box along its length. The applied jacking forces should be able to overcome these resistances. The two basic factors affecting the jacking force are:

1.6.1. Frictional Resistance due to ground pressure

These properties are used in theoretical approach to calculate the required force:

a. Box shape

b. Box self weight

c. Box dimensions

d. Surface surcharge

e. Unit weight of the soil

f. Type of soil

g. Rigidity of box structure

h. Coefficient of friction of the box soil interface

1.6.2. Construction factors

The factors that influence the magnitude of calculated force during the installation of the box:

a. Face resistance

b. Overcut

c. Variation of ground conditions

d. Rate of installation and magnitude of delays

e. Joint deformation, both angular and laeral

f. Lubrication

g. Use of intermediate jacking stations

h. Jacking around curves

1.7. Soil nailing

Soil nailing is construction technique to stabilize unstable soil slopes. The technique involves insertion of reinforcing bars (rebar) using different methods. In most cases pre-drilled holes are installed with solid bars and then grouted into the place. Soil nailing might be used to stabilize fill slopes, retaining walls or as in our case – we used this technique to stabilize overburden soil.

1.7.1. Types of soil nailing techniques

a. Drilled and grouted soil nailing method

- In this method, hole are drilled on the face of walls or slopes
- Then, nails are inserted into those pre drilled holes
- After placing nails, holes are filled with grouting material

b. Driven soil nailing method

- This method is employed where temporary stabilization of soil slopes is required.
- This method is considerably fast when compared to other methods
- The nails are driven into the slopes during excavation process.

c. Self drilling soil nailing method

- This technique involves the use of hollow bars

- Bars are drilled into the slopes while simultaneously being injected with grouting material
- It is faster than drilled and grouted soil nailing method

d. Jet grouted soil nailing method

- Jets are employed for eroding soil to form holes in the surface
- After that, reinforcement bars are installed in the holes and are grouted.
- This method provides good corrosion protection to the nails.

e. Launched soil nail method

- Here, nails are forced into soil with a single shot using compressed air
- Installation is fast but it is difficult to control the length of nail penetration
- No corrosion protection is provided.

1.7.2. Construction procedure for Soil nailing

Step1 – Excavation: The procedure of soil nailing starts with excavation of the slope. Excavation is done by following top down approach. Excavation depth depends on the in-situ ground conditions.

Figure 1.6 Excavation (Prashant, A., 2010)

Step 2 – Drill holes: the excavation is then followed by drilling of holes. Except for launched soil nailing method and driven soil nailing method, the diameter of holes are greater than the diameter of nail in order to accommodate grouting. The drilling is done using drilling equipments such as auger, rotary or percussion drilling. Cohesion-less soils, collapsible soils, grained soils or granular soils with high water table are considered to be unfavorable for soil nailing; if such in-situ condition is encountered drilling is performed with casing to prevent bore hole from collapsing.

Figure 1.7 Drilling (Prashant, A., 2010)

Step 3 – Nail installation and Grouting: After drilling holes the nails are placed in the holes using tendons to ensure that the nail is placed at the centre of the grout column. Tremie grout pipe is used for grouting of drill hole. The tendons also facilitate the proper flow of grouting material by providing desired space between drill hole walls and nails.

Figure 1.8 Nail installation (Prashant, A., 2010)

Figure 1.9 Grouting (Prashant, A., 2010)

1.7.3. Advantage and disadvantages of soil nailing

- **Advantages**
  - ✓ Causes less disruption to the environment and nearby structures.
  - ✓ Even useful in remote locations as equipments requires small space.
  - ✓ Whole procedure is very fast and requires very less construction equipments.
  - ✓ Causes very minimum congestion whine excavating at the bottom as compared to braced excavation.
  - ✓ Soil nails tends to perform well during seismic events resulting from overall flexibility of the system.
  - ✓ Soil nailing is much more economical than concrete gravity walls.
- **Disadvantages**
  - ✓ Not suitable for projects which requires strict deformation control as system requires some soil deformation to bring resistance into action.
  - ✓ Not recommended for grounds with high ground-water table as water seepage may produce hindrance while drilling.
  - ✓ This technique is very difficult to use in cohesionless soil.
  - ✓ Whole procedure requires to be carried out under the guidance and supervision of specialized and experienced contractors.

1.7.4. Factors affecting soil nailed slopes

There are various factors that affect the stability and feasibility of soil nailing. Soil nailing is subjected to ground conditions along with internal and external stability factors.

- **Favorable ground condition-** Stiff to hard fine-grained soils including clays, silty clays, clayey silts, sandy clays, sandy silts etc. are well suited for soil nailing operation. Soil nailing is not recommended for poorly graded cohesion-less soils, dry soils, highly corrosive soils, organic soils or soils with very high water table.
- **External stability-** it includes stability of overturning and sliding of soil nail system, stability of nailed slope, seeping water, poorly drained system etc.
- **Internal stability-** it includes different failure modes of nailed structure such as nail tensile failure, punching shear or facing flexural failure.

Such issues may be resolved by:

- Conducting ground investigation to identify soil parameters and ground characteristics.
- Performing test for nail strength and in-situ tests for soil-nail interaction.
- Effective design of nailed slope system.

1.8 Organization of Project report

The first chapter of the project report gives a brief introduction on concept of box jacking and soil nailing and there advancement over time. It elaborates the various construction method adopted for box tunnel followed by type of soil and various advantages and disadvantages of the box tunnel. The chapter also provides a brief idea about soil nailing techniques and there advantages in daily construction projects.

The second chapter presents the literature review available on small scale model studies in laboratories and large scale field testing. It gives a brief idea about past experimental, analytical and theoretical studies conducted to understand the relationship between depth of box tunnel with height of overburden soil and the methods to reduce ground movements during jacking operation. The chapter provides a summary to the literature review with evaluated research gaps.

The third chapter deals with the material testing i.e. soil and model testing of unreinforced and reinforced overburden soil when the bars were placed at different depths from the top (i) H/4 (ii) 3H/4. The chapter provides a detailed test procedure of box jacking at different tunnel depths of (i) 0.75D (ii) 1.5D and (iii) 2.0D.

The fourth chapter includes the results generated from model testing and provides a detailed comparison of un-reinforced and reinforced overburden soil during jacking operation.

The fifth chapter presents the conclusion derived from model testing on reinforced overburden soil prior to tunnel pushing.

CHAPTER 2

LITERATURE REVIEW

2.1. General

The construction of shallow box tunnel under existing highway and railway track The use of jack pushing has emerge as a pretty common approach nowadays to create an uninterrupted drift of visitors in metropolitan cities. The jacking operation sometimes causes the overburden cohesion-less soil to undergo large stresses and excessive lateral displacement at the box tunnel face which sometimes lead to accidents and loss of lives. The scope behind making a small test box is developing a system by which the jacked box section is to penetrate. The test box is designed to hold the cohesion less soil. On top of it, the box supports a loading arrangement in a manner that vertical effective stress can be applied to the soil so as to create live traffic conditions during jacking operation.

2.2. Literature review

Zhiochao [22]

The main objectives of the study were to introduce box jacking and to check the settlement characteristics of the existing highway. A numerical analysis was used to establish a 3D numerical model, validated by field measurements. The results showed that:

(1) The box jacking method is safe, economical, and successful.

(2) The highway settlement gradually decreases along jacking direction.

(3) While jacking, the settlement behavior of the overlaying highway underwent three stages, namely slow growth, rapid growth, and a steady stage.

Singh and Mittal [18]

The overburden soil faces large stresses and extravagant lateral displacements at the box tunnel face during the jacking of shallow box tunnel underpass. In the sight to solve this difficulty, a laboratory model study has been conducted. In this study- “to eliminate the large lateral displacement, of the OB soil above the shallow box tunnel was reinforced with 8 mm diameter tor steel nails prior to pushing of box tunnel". The results showed that- when the overburden soil is reinforced with nails prior to the jacking of box tunnel, the chances of collapse or lateral displacement at shallow box tunnel face soil can be reduced for construction practices of shallow underpass.

Dindarloo and Saeid [17]

In this study, a shallow tunnel classification system (STCS) based on maximum settlement is introduced. The STCS holds on the results of several tunneling projects around the globe. STCS categorizes a tunnel based on geometry, ground, and performance characteristics. The categorization led to formation of four classes of tunnels which were defined as follow:

(i) Class A (maximum settlement < 9.9 mm)

(ii) Class ''B'' (10 ≤ maximum settlement < 19.9 mm)

(iii) Class ''C'' (20 ≤ maximum settlement < 29.9 mm)

(iv) Class ''D'' (maximum settlement > 30 mm).

Singh and Kanwar [19]

In this study, "an innovative technique of 'Soil Nailing' has been invented for stepwise vertical de-stabilization and stabilisation of compacted collapsible sandy soil for the construction of railway underpasses in live railway loading conditions. This Soil Nailing Technique controlled de-stabilisation of soil and again stabilisation in steps proved a superficial method of stabilisation with other methods for such kind of dynamic loading situations".

Singh and Kanwar [19]

This paper is about use of soil nailing technique in jacked box tunneling by destabilization and stabilization of compacted sandy soil for construction of rail underpass.

Prashant and Amit [11]

This study talks about soil nailing as a soil stabilization technique, different types of soil nailing techniques and their application.

Ropkins [13]

This paper highlights- "engineering principles relating to the design of jacked box tunnels as developed by the author on a series of projects carried out in the UK".

Yonan [8]

In this research work, a detailed review of investigate work into pipe jacking operations, and in the forces generated during the process of jacking operation is presented. The factors affecting these forces were studied and their influence was examined in order to give a clear cut out on their magnitude and behavior.

Hu Zhu et al. [14]

From the research paper it was evident that it is technically feasible to use GFRP bars as soil nails to stabilize slopes for excavation. GFRP materials have the superiority of high corrosion resistance, high strength-to weight ratio, low thermal stress, and high adaptability to fiber optic sensors. GFRP materials gives feasible methods to corrosion and site-maneuvering complications for civil infrastructures using conventional steel bars as reinforcements. However, the reduced stiffness, creep effect, and fatigue potential of GFRP soil nails should also be noted.

Cheng et al. [15]

For steep slopes with strenuous access or slopes in a corrosive environment, there are varied difficulties associated with the use of conventional steelt bars as soil nails. For loose fill slopes or clay slopes, the development of sufficient nail bond strength is another practical issue which should be reviewed. CFRP and GFRP in several forms and installation techniques have been studied as the alternatives to the conventional steel bar.

2.3 Summary of literature review

From the literature review it was analyzed that small scale model tests have always been used to analyze the movement of overlying soil caused during box jacking. The laboratory experiments based on model tests involved examination of soil properties, surcharge effect, vertical and horizontal offset of tunnel.

- Vertical ground movements accompany conventional tunneling techniques. Hence a method can be found for easy and quick tunnel installation.
- Variation of Interface friction during jacking should be investigated for evaluating jacking force or developing correlation of jacking force with other parameters.
- Lateral displacements are not recorded by past researchers during box jacking.
- Strains developed along the box tunnel are not comprehensively studied. Similarly, in – situ stress development during box tunnelling requires in depth investigation

- New rectification method with durability characteristics apart from geosynthetics and nailing technique can be employed for minimizing face losses and ground movements.

2.4 Objectives

From the summary of literature review, following objectives are derived:

- To analyze vertical ground settlement (soil arching) during jacking of box tunnel at different vertical offsets by model testing
- To remediate soil movements during jacking by using FRP micro-piles at different depths in overburden soil in model testing.
- To analyze the increase in load carrying capacity of overburden soil by reinforcing it with GFRP bars.

2.5 Scope of the Research Work

The following research works is carried out by studying the basic material properties of soil used and bars material. GFRP bars are used for model testing of overburden soil at increasing load intensity until its failure into the tunnel face. The bars are placed at different depths of H/4 and 3H/4 from the top, at 10d horizontal spacing. 3 bars are placed in each layer that occur in the dispersion zone due to above live load. For comparative results the depth of tunnel is also varied throughout the test.

CHAPTER 3

METHODOLOGY

3.1. General

The chapter represents the experimental study of material carried out, used for fabrication of model tank. A detailed procedure depicting the construction of model tank and its installation is also shown. The chapter deals with complete model testing of un-reinforced and reinforced soil with GFRP bars at different depths of H/4 and 3H/4 and varying depth of box tunnel i.e. 0.75D, 1.5D and 2.0D from the top.

3.2. Material testing

3.2.1. Sand

The sand used as a filling material in the model tank is collected from Tehsil Ghanari, District Una (Himachal Pradesh). Preliminary tests on soil were performed in the lab to determine various soil parameters. To evaluate particle size distribution of soil, sieve analysis was performed as per IS: 2720 (Part IV).

The whole sieve analysis was performed by using a series of sieve arranged as 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.15mm, 0.075mm and pan. A soil mass of 1kg oven dried sample was fed through the sieves. The shaking was done manually for 4-5minutes and mass retained on each sieve was noted. From particle size distribution curve, the sand is classified as well graded sand (SW) with a uniformity coefficient (C_u) = 8.286 and curvature coefficient (C_c) = 1.086. The effective size (D_{10}) so obtained is 0.21mm.

The pycnometer test is performed to obtain specific gravity of sand using eq. 3.1:

$$G = \frac{M_2 - M_1}{(M_2 - M_1) - (M_3 - M_4)} \tag{3.1}$$

Where, M1 = Mass of pycnometer,

M2 = Mass of Pycnometer + Mass of Soil,

M3 = Mass of Pycnometer + soil + water

M4 = Mass of pycnometer + water

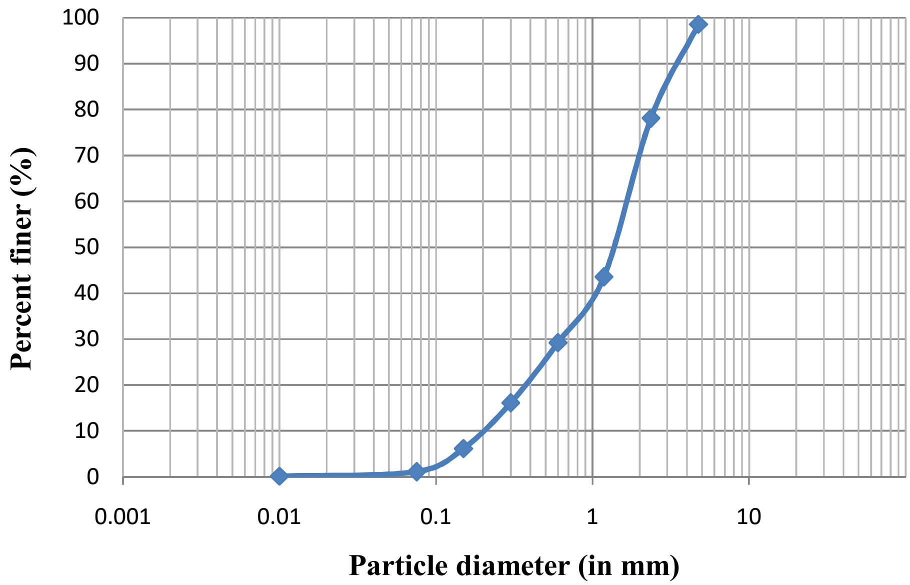

Figure 3.1 Grain Size Distribution Curve

The maximum dry density $(\gamma_d)_{max}$ and minimum dry density $(\gamma_d)_{min}$ of sand is determined through vibratory table test.

The density of sand at 90% relative density was calculated using eq. 3.2:

$$Relative\ Density, \quad I_D = \frac{\frac{1}{(\gamma_d)_{min}} - \frac{1}{(\gamma_d)}}{\left(\frac{1}{(\gamma_d)_{min}} - \frac{1}{(\gamma_d)_{max}}\right)} \tag{3.2}$$

The shear strength parameters (c and ϕ) of soil were calculated following Indian Standards Codes using DST at 5% moisture content. The DST was conducted at an I_D of 90% under normal stresses of 50, 100and 150kPa with a strain rate of 0.625mm/min.

In order to understand the effect of reinforcement and generation of shear strength by GFRP bar, DST was conducted with and without GFRP bar. It was noticed that the GFRP bar position was slightly deviated from its initial position as shown in fig. 3.4. The shear strength of the reinforced soil slightly enhanced by (25-30%) of the unreinforced soil under similar normal stress. The shear strength parameters of the soil are summarized in table 3.1.

Table 3.1 Soil-GFRP Bar interface properties obtained from DST

Interface	Apparent Cohesion (c) (kN/m^2)	Angle of internal/ interface friction	Interface friction coefficient	Types of test (direct Shear Test)
Sand - Sand	5.35	$\phi = 32$	tan (ϕ°) = 0.624	Without GFRP
Sand – GFRP Bar	17.53	$\delta = 38.46$	tan (δ°) = 0.792	With GFRP bar

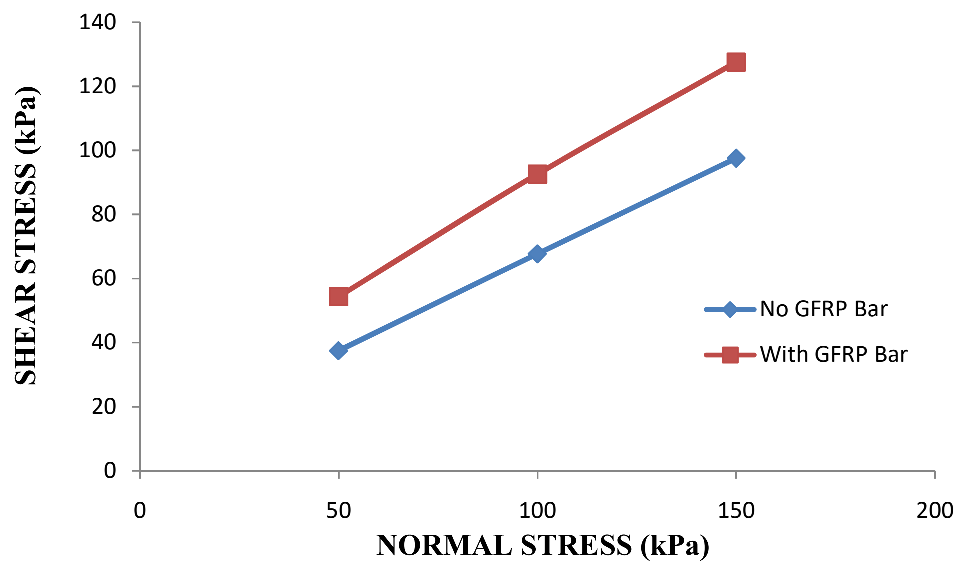

Figure 3.2 Shear stress vs Normal stress for soil sample

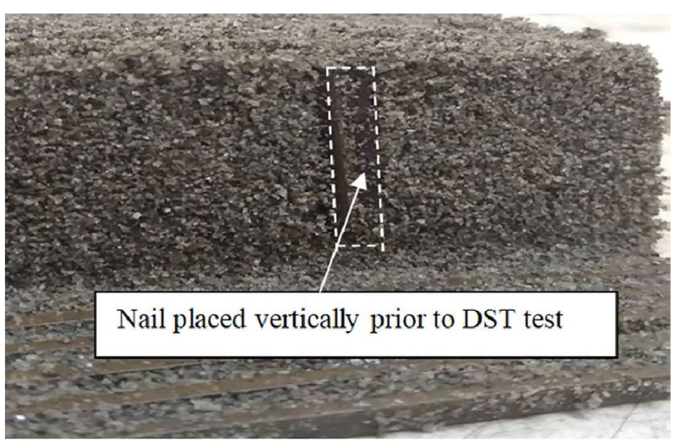

Figure 3.3 Nail position before DST

Figure 3.4 Nail position after DST

The basic properties of the soil are summarized in table 3.2:

Table 3.2 Soil properties

SOIL PROPERTIES	RESULTS	STANDARDS CODES
Specific Gravity of cohesion-less soil	2.67	IS: 2720 (Part IV)
Percentage fines (<75μ sieve)	0.941	ASTM D6913-04 (2009)
D_{10} (mm)	0.21	
D_{30} (mm)	0.63	
D_{50} (mm)	1.40	
D_{60} (mm)	1.74	
C_u	8.286	
C_c	1.086	
$\gamma_{d\max}$ (g/cc)	1.701	ASTM D 4253: 2016
$\gamma_{d\min}$ (g/cc)	1.092	
Density at 90% I_D, γ_d (g/cc)	1.611	
Poisson's Ratio, (ϑ)	0.3	
Indian Standard Soil Classification System	SW	IS: 1498 (2014)

The sand was poured into the model tank using raining method to get a desired relative density of 90%. The sand was poured in layers of 100mm each and compacted.

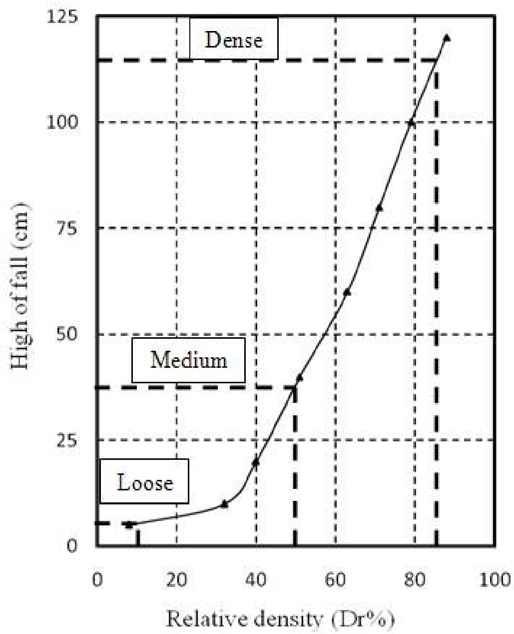

Figure 3.5 Relation between height of fall and relative density

Figure 3.6 Sand pouring in to the model tank

3.2.2. GFRP BARS

Glass fiber reinforced polymer (GFRP) is a common type of fiber-reinforced plastic using glass fiber. The fibers are usually randomly arranged, flattened into sheets or woven into fabric.

Figure 3.7 GFRP Bars (Safety Tonny Trade, 1997)

The conventional steel used in daily construction is both labour intensive and expensive. As these nail are buried into ground in case of soil stabilization techniques, they cannot be maintained on a routinely basis, hence corrosion protection is of topmost importance for the longevity of steel nail installed in ground.

Due to above mentioned drawbacks of conventional steel the construction industry is slowly shifting towards GFRP. This major shift in construction practice attributed to GFRP's flexibility of having high strength to weight ratio, corrosion resistance, durable and better stiffness than a conventional steel bar.GFRP bars are manufactured using Pultrusion method that enables production of high fibre content (60-80%) GFRP bar. The fibres that are generally used to manufacture GFRP bar have a diameter ranging from $10\mu m$ to $4.5\mu m$ depending upon the type of glass fiber.

Table 3.3 Typical mechanical properties of GFRP composite (P.R., 1996)

MATERIAL	FIBER CONTENT % BY WEIGHT	DENSITY (kg/m^3)	LONGITUDINAL TENSILE MODULUS (GPa)	TENSILE STRENGTH (MPa)
Glass fiber/polyster GFRP laminate	50-80	1600-2000	20-55	400-1800

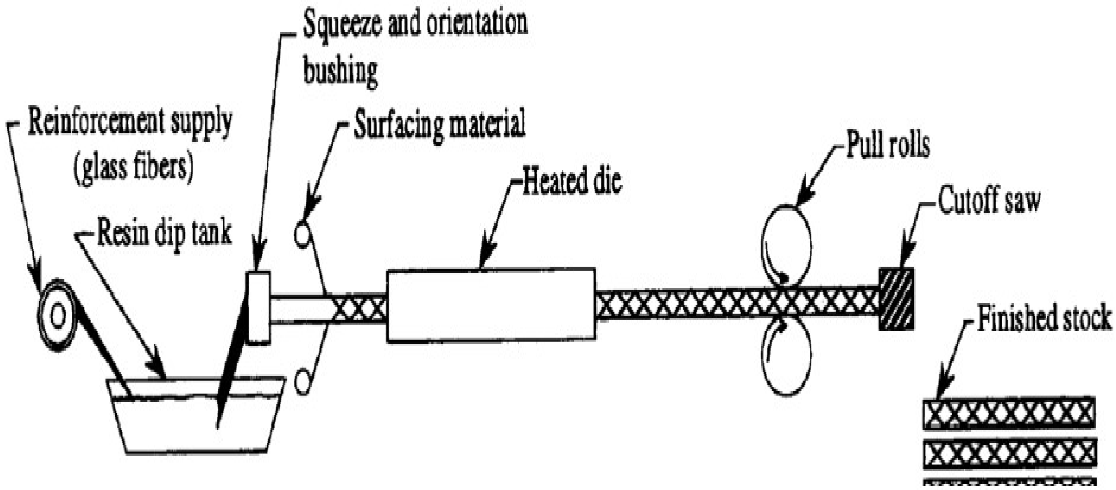

Figure 3.8 Pultrasion of GFRP bars (Benmokrane B., 1995)

GFRP bars have a higher tensile strength (500-1200 MPa) compared to steel bars (250-550 MPa). The diameter of the GFRP bar and its strength has an inverse relation. This is due to the phenomenon "shear-lag". Shear lag is the variation in stress from centre of the bar to its surface. The compressive strength of GFRP bars is 40-60% than that of its tensile strength**.**

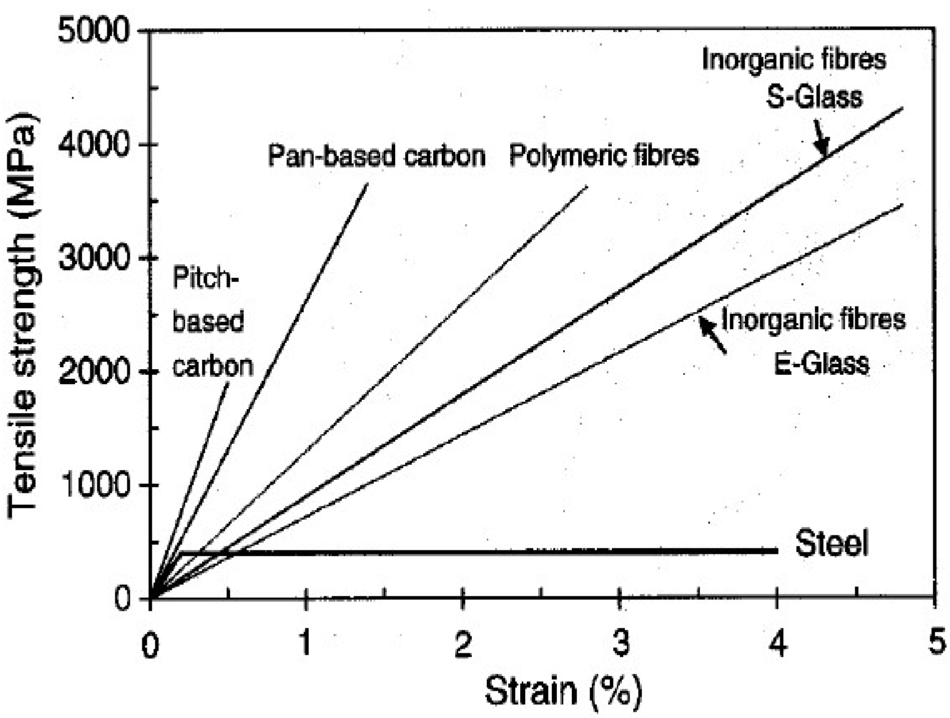

Figure 3.9 Stress strain relationship of FRP materials (Husain, S. F., 2018)

3.3. Model box

The main objective of performing the lab model tank study is to understand the lateral displacement characteristics of cohesion-less OB soil towards the box tunnel face during tunnel jacking operation, subjected to live loads and to introduce a solution to minimize it. A model tank of size 300 mm × 300 mm × 450 mm (length × width × height) was fabricated for the model test. The model fabricated has been shown in the Fig. 3.8 and Fig. 3.9.

The arrangement of driving the box tunnel have been made with the scissors jack of 2 ton capacity installed at one face (450 mm × 300 mm) of the tank during the fabrication process. In the model study, vertical load will be applied on the OB soil using an hydraulic jack of 3 ton capacity to simulate the traffic loads in actual site conditions.

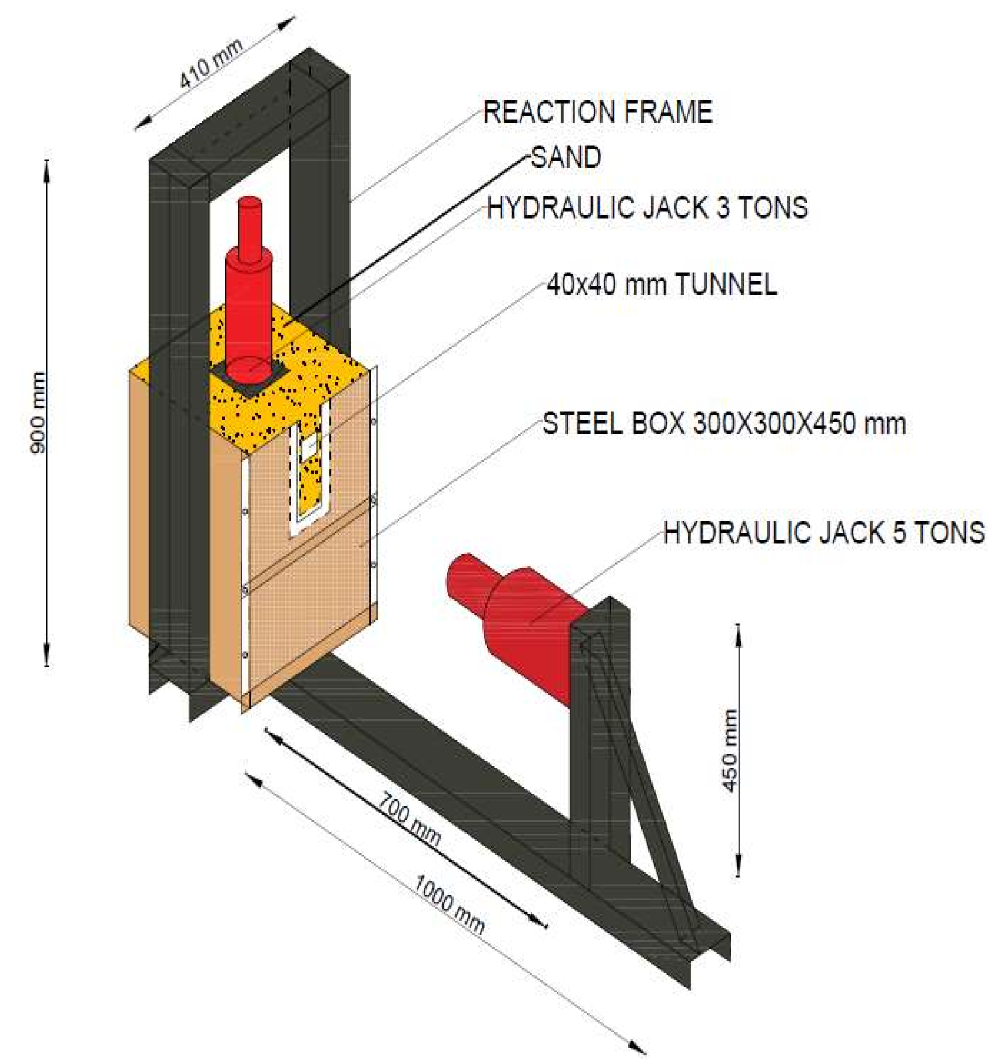

Figure 3.10 AutoCAD drawing of model

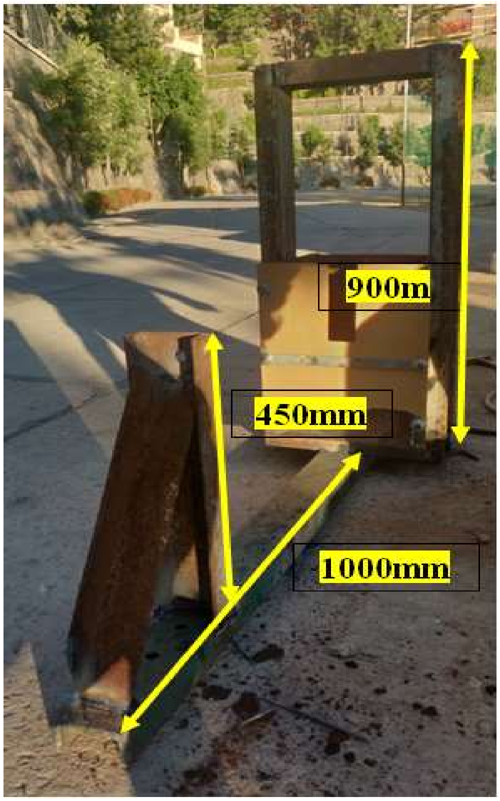

Figure 3.11 Reaction Frame

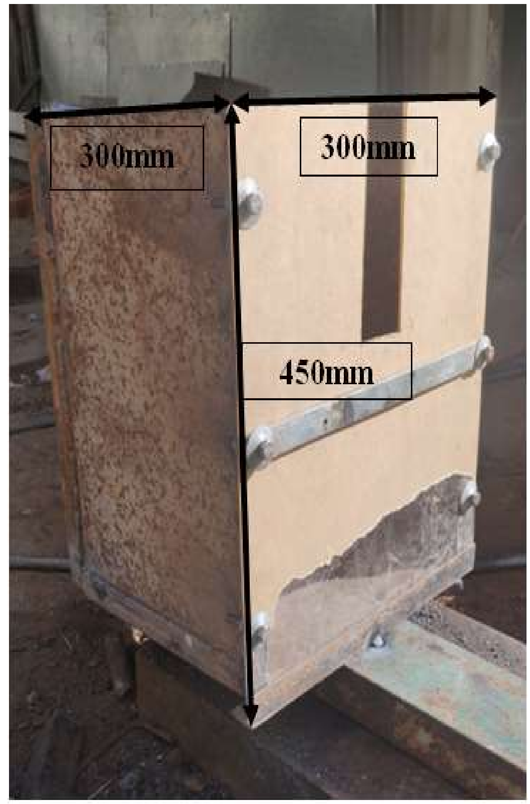

Figure 3.12 Steel box

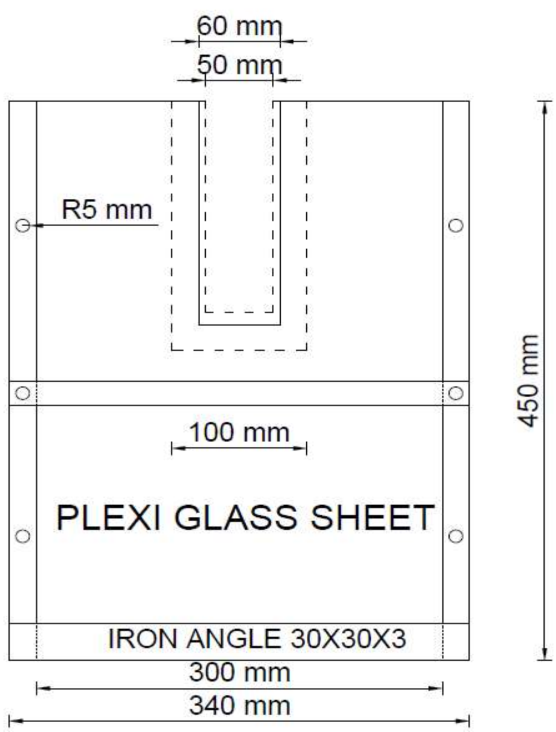

Figure 3.13 AutoCAD drawing steel box

Materials used for fabrication of the model box were as follows:

3.3.1. Plexiglas sheet

Plymethylmethacrylate (PMMA) aka acrylic, acrylic glass, or Plexiglas and some times also called Crylux, Acrylite, Plexiglas, Lucite, Perspex and Perclax is transparent plastic often used in sheet form as a lightweight or shatter-proof alternative to glass.

PMMA is a strong, lightweight and tough material. The density of the material is 1.17 to 1.2 g/cm^3 which is less than that of glass (2.47 g/cm^3). It also has ability to withstand impacts that would shatter the glass easily.

Plexiglas sheet used in the model fabrication has dimensions as 450x300 (height x width) and was 3mm thick. The main reason we used Plexiglas sheet was to make it possible for us to observe soil deformation during jacking and after the completion of jacking process. It was installed onto the face where tunnel is to be jacked. PMMA transmits up to 92% of visible light through a 3mm thick sheet which makes it ideal for the purpose.

3.3.2. Steel sections

Structural steel is a category of steel used for making construction materials in a variety of shapes. Many structural steel shapes take the form of an elongated beam having a profile of a specific cross section. Structural steel shapes, sizes, chemical composition, mechanical properties such as strengths, storage practices, etc., are regulated by standards in most industrialized countries.

We used angle section of dimensions 30x30x3, MC100 channel section and steel plates of thickness 3-5mm.

3.3.3. Hydraulic jack :

A hydraulic jack uses a liquid, which is incompressible, which is forced into a cylinder by a pump plunger. Since oil is self lubricating and stable it is used at the liquid medium in the jack. When the plunger pulls back, it sucks oil out of the reservoir through a suction check valve into the pump chamber. When the plunger moves forward, it pushes the oil through a discharge check valve into the cylinder. The suction valve ball is within the chamber and opens with each draw of the plunger. The discharge valve ball is outside the chamber and opens when the oil is pushed into the cylinder. At this point the suction ball within the chamber is forced shut and oil pressure builds in the cylinder.

A jack of 3 ton capacity will be installed vertically above overburden soil to replicate live load conditions generated by moving traffic in an actual site.

Figure 3.14 Hydraulic jack (3 ton)

3.3.4 Scissors Jack

A scissors jack is a type of jack which is operated by rotating a liver arm. It is generally used to lift moderately heavy weights. The scissor jack of capacity 2tons will be used to push the tunnel into the soil.

Fig 3.15 Scissors Jack (2 ton)

Figure 3.16 Trial test to check the pushing of tunnel

3.4. Equipments

3.4.1. Load cell

A load cell is a type of transducer, specifically a *force* transducer. It converts a force such as tension, compression, pressure, or torque into an electrical signal that can be measured and standardized. As the force applied to the load cell increases, the electrical signal changes proportionally. The most common types of load cell used are hydraulic, pneumatic, and strain gauge.

Figure 3.17 Load cell (Finetec, 2017)

3.4.2 LVDT

A linear variable differential transformer (LVDT) is an outright measuring instrument that converts linear displacement into an electrical signal through the principle of mutual induction. Its design and operation are relatively simple, providing very precise high resolution in a device suitable for a wide range of applications and environments.

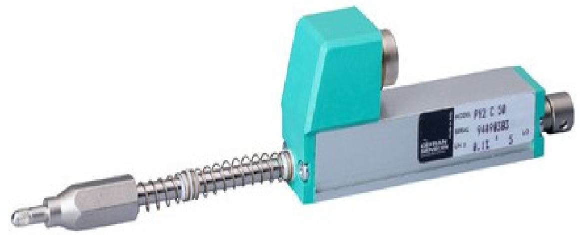

Figure 3.18 LVDT (Sensotronic system, 2018)

3.5. Test procedure

The main objective of the lab model tank test was to analyze the lateral displacement of cohesion-less OB soil towards the box tunnel face during jacking operation subjected to live loads and to instigate a solution to eliminate it.

- During the experiment, the overburden soil of box tunnel was subjected to external load using a hydraulic jack of capacity 3tons to replicate the traffic loads in real life situation.
- The provision of pushing the box tunnel into the model tank was made using a screw jack which was installed at one face of the model setup during fabrication. The location of jack was changed as the (H/D) varied during testing, as per table 3.4.

Table 3.4 Experimental test plan of model tank with and without GFRP bars in OB soil

Height to Depth Ratio From Top of Tank (H/D)	GFRP Bar Position From Top	Horizontal Displacement
0.75	No GFRP bar in OB soil	Measured for each test
1.5	1 Layer OF GFRP bar in OB soil @H/4	
2	2 Layer of GFRP bar in OB soil @ (i)H/4 (ii)3H/4	

- A schematic diagram showing the position of tunnel and bars in the OB soil is shown in fig 3.19 and fig. 3.21

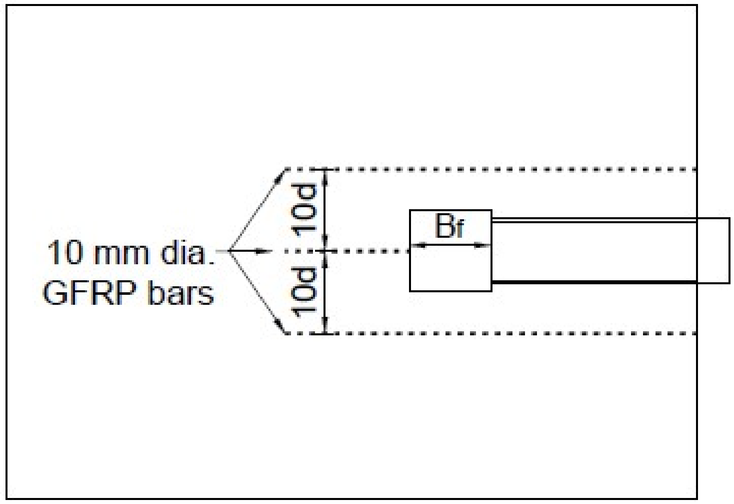

Figure 3.19 Position of GFRP bars w.r.t. tunnel (top view)

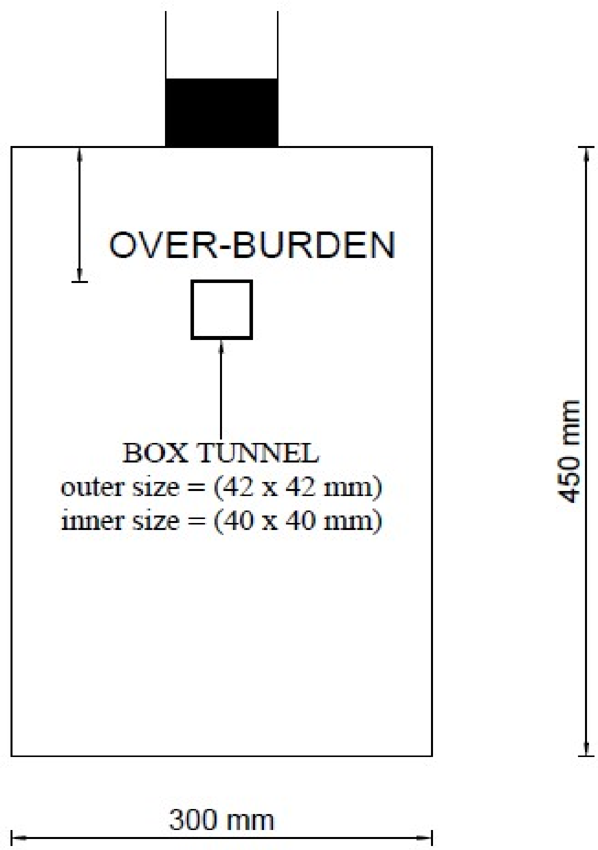

Figure 3.20 Front view drawing of setup

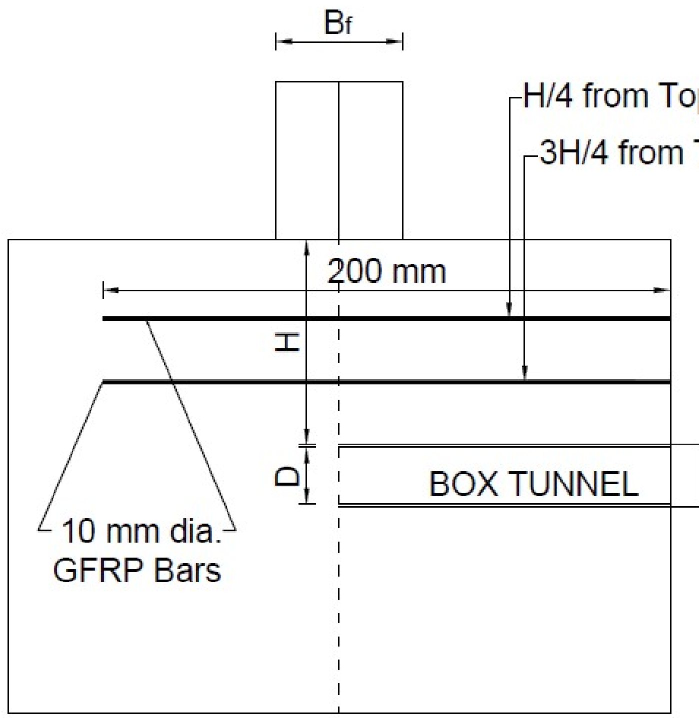

Figure 3.21 Position of nails w.r.t. depth of tunnel (side view)

- On front face of the model tank a slit face of size slightly greater than the tunnel dimension of (40x40mm) so as to insert the tunnel through it. The slit face could be closed and opened as per requirement for refilling the sand after each test.
- The tests were conducted at 5% moisture content. In order to protect the setup from moisture loss, the inside faces of the model tank were covered with polythene sheets and thereafter the sand was poured by raining method from a height of 1200mm to 1250 mm so as to achieve a relative density of 80 -90%. After compacting the soil the model tank was closed from above using a cast iron sheet which could be removed as desired for refilling the sand.
- The hydraulic jack was placed at centre over a channel section that was placed on the iron sheet, to replicate the real life traffic situation. After the setup was complete the box tunnel of (40x40mm) made of stain less steel with 1mm thick walls, was placed at desireable height to depth ratio, H/D = 0.75, 1.5 and 2.0 where, D is the depth of box tunnel. The tunnel was drived manually using a screw jack to a desirable position. During jacking operation the soil that entered into the tunnel was removed using a spoon.

- In case of reinforced OB, the bars length was kept 200mm, 10mm dia., at 10d horizontal spacing. The length and spacing of bars was based on previous studies. After the tunnel was derived into the soil up to desired length load was applied using hydraulic jack till the failure of OB soil occurred. The soil movement of the OB soil was measured using LVDT.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. General

The following chapter includes data obtained after tests were performed on the soil in the model tank and also includes the graphical representation of the data obtained.

4.2. Results from model testing

The results from model testing includes measurement of lateral displacement of soil under varying load intensities until failure in case of no GFRP bars in the OB soil, with 1layer of GFRP bars in the OB soil and with 2 layers of GFRP bars in the OB soil at three different depths of the tunnel.

Table 4.1, Table 4.2 and Table 4.3 represents the results of lateral displacement (in mm) of soil at varying load intensity (in kN/m^2) at different height to depth ratio (H/D) of box tunnel (i) 0.75 (ii) 1.5 (iii) 2.0.

The GFRP bars were actually placed within the zone of dispersion due to live load. The length of each bar was kept about 200mm. To understand the behaviour of OB soil different layers of bars were provided for each test (i) no GFRP bar, (ii) 1 layer of GFRP bar at H/4 depth from top, (iii) 2 layer of GFRP bar at H/4 and 3H/4 from the top.

The first layer of GFRP bar in the OB soil increased the soil-bar interface friction, resulting in increase in shear strength of soil which ultimately minimized the lateral displacement of soil. To further increase the shear strength of soil and reduction in lateral displacement of soil a second layer of GFRP bars was introduced in the model tank.

The load intensity vs lateral displacement at box tunnel face were analysed from the data gathered using LVDT and load cell. The results were recorded after every 5s interval till the failure of OB soil occurred. The test results are as shown in Table 4.1, Table 4.2 and Table 4.3 for different tunnel depths.

The minimum ultimate yield load obtained from test results was 400 kN/m^2 when there was no nail in the OB soil. The test results are summarised in table 4.10.

4.2.1 Results for height to depth ratio (H/D) = 0.75

The given data was recorded from digital analogue using LVDT at every 5 sec interval.

Table 4.1 Lateral displacement at H/D=0.75 with no bars in the OB soil

LATERAL DISPLACEMENT (mm)	**LOAD INTENSITY (kN/m^2)**
0	0
0.053	48.673
0.133	97.452
0.241	155.365
0.371	201.458
0.512	245.783
0.686	296.658
0.851	340.253
1.049	375.256
1.392	405.373
1.867	434.278
2.465	446.734
2.934	458.153
3.697	471.648
4.545	485.594
5.113	494.374
5.941	506.542
6.678	514.912
7.432	523.275
8.236	530.567

The above data representing lateral displacement w.r.t. load intensity in case of no bars in overburden soil when the tunnel depth is H/D = 0.75 from top, shows us that there is a sudden failure of OB soil as the load intensity reaches 400 kN/m^2.

Table 4.2 Lateral displacement at H/D=0.75 with 1 layer of bars in the OB soil

LATERAL DISPLACEMENT (mm)	LOAD INTENSITY (kN/m^2)
0	0
0.067	71.432
0.093	126.561
0.136	167.539
0.158	223.504
0.247	294.631
0.295	349.095
0.361	407.458
0.452	513.376
0.669	592.371
0.891	663.264
1.473	778.192
1.942	843.581
2.759	901.357
3.864	953.862
4.925	991.107
6.046	1008.503
6.932	1018.872
7.541	1021.765
8.197	1023.527

The above data in case of 1 layer of GFRP bars in overburden soil when the tunnel depth is H/D = 0.75 from top, shows us that there was an increase in load carrying capacity of overburden soil from $400kN/m^2$ to $900\ kN/m^2$.

Table 4.3 Lateral displacement at H/D=0.75 with 2 layers of bars in the OB soil

LATERAL DISPLACEMENT (mm)	LOAD INTENSITY (kN/m^2)
0	0
0.023	73.542
0.075	142.546
0.112	197.786
0.133	236.434
0.165	302.565
0.197	339.782
0.277	407.752
0.314	473.543
0.484	579.987
0.648	641.921
1.273	791.622
1.883	883.872
2.693	973.342
3.751	1037.982
4.939	1083.842
5.974	1107.274
6.891	1124.122
7.545	1132.921
8.217	1135.175

The above data in case of 2 layer of GFRP bars in overburden soil when the tunnel depth is H/D = 0.75 from top, shows us that there was not a significant increase in load carrying capacity of OB soil as was in case of 1 layer.

4.2.2 Results for height to depth ratio (H/D) = 1.5

The given data was recorded from digital analogue using LVDT at every 5 sec interval.

Table 4.4 Lateral displacement at H/D=1.5 with no bars in the OB soil

LATERAL DISPLACEMENT (mm)	LOAD INTENSITY (kN/m^2)
0	0
0.034	20.342
0.079	75.578
0.122	106.536
0.197	175.557
0.284	235.243
0.354	263.976
0.437	296.234
0.596	339.156
0.845	374.578
1.579	411.264
2.183	433.675
2.942	447.342
3.753	457.897
4.731	461.763

The above data represents the lateral displacement of OB soil with increase in load intensity when the tunnel was a depth of H/D = 1.5 from top. The soil is not reinforced with bars and hence the test is performed on a virgin soil.

Table 4.5 Lateral displacement at H/D=1.5 with 1 layer nails in the OB soil

LATERAL DISPLACEMENT (mm)	**LOAD INTENSITY (kN/m^2)**
0	0
0.025	34.724
0.064	81.347
0.097	168.671
0.138	272.973
0.182	363.781
0.243	439.679
0.449	521.478
0.743	591.932
1.136	634.926
1.974	672.125
2.852	707.789
3.671	733.107
4.606	740.063

The above data represents the lateral displacement of OB soil with increase in load intensity when the tunnel was a depth of H/D = 1.5 from top. The soil is reinforced with 1 layer of bar at a horizontal spacing of 10d and at a depth of H/4 from top.

Table 4.6 Lateral displacement at H/D=1.5 with 2 layers nails in the OB soil

LATERAL DISPLACEMENT (mm)	**LOAD INTENSITY (kN/m^2)**
0	0
0.017	55.261
0.032	93.584
0.056	174.109
0.094	287.239
0.125	371.291
0.179	463.913
0.323	559.543
0.457	602.298
0.806	685.579
1.057	728.493
1.849	783.343
2.833	824.312
3.725	842.339

The above data represents the lateral displacement of OB soil with increase in load intensity when the tunnel was a depth of H/D = 1.5 from top. The soil is reinforced with 2 layer of bar at a horizontal spacing of 10d and at a depth of H/4 and 3H/4 from top.

4.2.3 Results for height to depth ratio (H/D) = 2.0

The given data was recorded from digital analogue using LVDT at every 5 sec interval.

Table 4.7 Lateral displacement at H/D=2 with no bars in the OB soil

LATERAL DISPLACEMENT (mm)	LOAD INTENSITY (kN/m^2)
0	0
0.012	21.259
0.038	89.261
0.095	187.012
0.157	251.182
0.241	307.107
0.326	353.459
0.391	385.239
0.473	403.328
0.521	410.983

The data represents the lateral displacement of OB soil with increase in load intensity when the tunnel was a depth of H/D = 2.0 from top. The soil is not reinforced with bars and hence the test is performed on virgin soil. It was noted that the soil didn't go large displacement as in previous cases

Table 4.8 Lateral displacement at H/D=2 with 1 layer of bars in the OB soil

LATERAL DISPLACEMENT (mm)	LOAD INTENSITY (kN/m^2)
0	0
0.009	27.862
0.032	98.671
0.077	192.682
0.107	261.129
0.162	349.232
0.235	457.313
0.313	543.019
0.432	602.109
0.513	617.521

The above data represents the lateral displacement of OB soil with increase in load intensity when the tunnel was a depth of H/D = 2.0 from top. The soil is reinforced with 1 layer of GFRP bars at 10d horizontal spacing and at a depth of H/4 from top. It was noted that the soil didn't go large displacements as in previous cases.

Table 4.9 Lateral displacement at H/D=2 with 2 layer of bars in the OB soil

LATERAL DISPLACEMENT (mm)	LOAD INTENSITY (kN/m^2)
0	0
0.007	56.978
0.024	126.102
0.072	248.792
0.098	313.873
0.127	373.029
0.183	465.973
0.268	567.393
0.347	615.083
0.421	648.041

The above data represents the lateral displacement of OB soil with increase in load intensity when the tunnel was a depth of H/D = 2.0 from top. The soil is reinforced with 2 layer of GFRP bars at 10d horizontal spacing and at a depth of H/4 and 3H/4 from top. It was noted that the soil didn’t go large displacements as in previous cases.

4.3 Graphical Representation of results

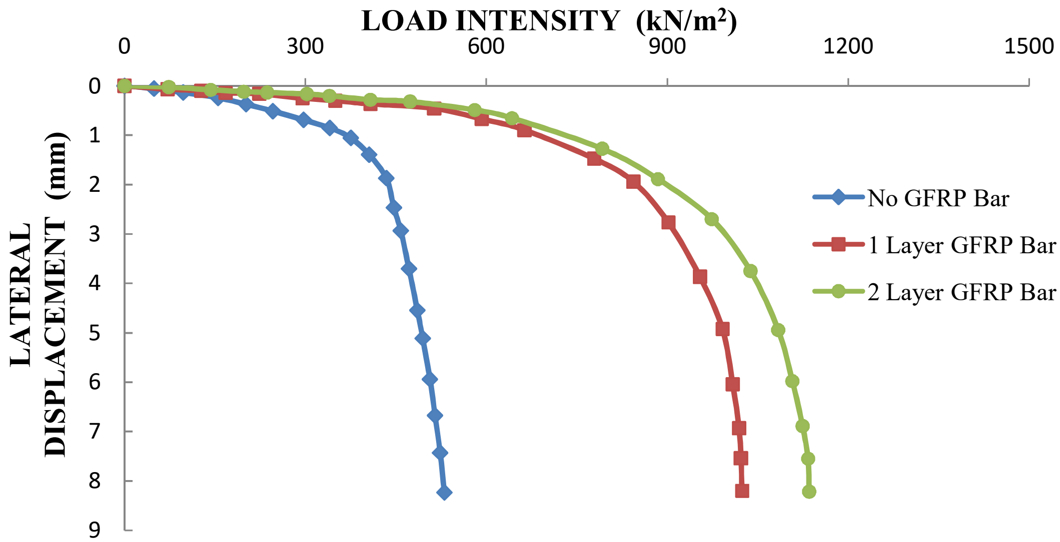

Figure 4.1 Lateral displacement v/s load intensity for H/D=0.75

The above graph is a representation of lateral displacement vs load intensity, showing the increase in load carrying capacity of OB soil in 3 different cases at H/D = 0.75. It can be noted that as 1st layer of GFRP bar was introduced in the OB soil the load carrying capacity of the above soil for same settlement of 1.33mm increased by almost 87.53% whereas the increase was just 6.7% when the second layer was inserted.

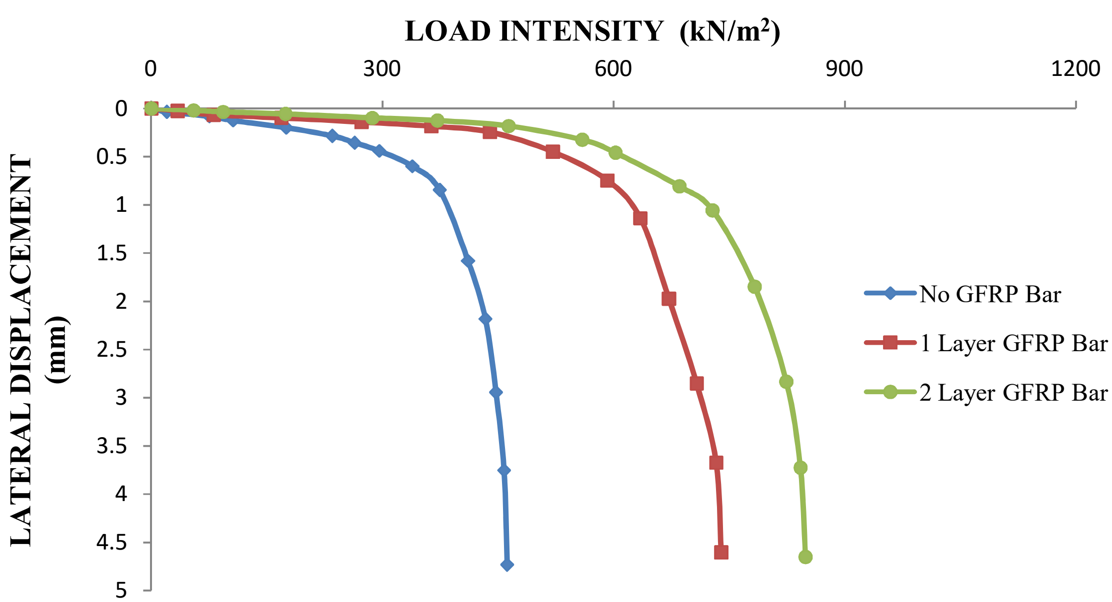

Figure 4.2 Lateral displacement v/s load intensity for H/D=1.5

The above graph is a representation of lateral displacement vs load intensity, showing the increase in load carrying capacity of OB soil in 3 different cases at H/D = 1.5. It can be noted that as 1st layer of GFRP bar was introduced in the OB soil the load carrying capacity of the above soil, for same settlement of 1.234mm increased by almost 62.24% whereas the increase was just 15.87% when the second layer was inserted. Also it was noted that the settlement at load intensity of 400 kN/m^2 decreased from 1.331mm to 1.234mm when depth of tunnel was changed.

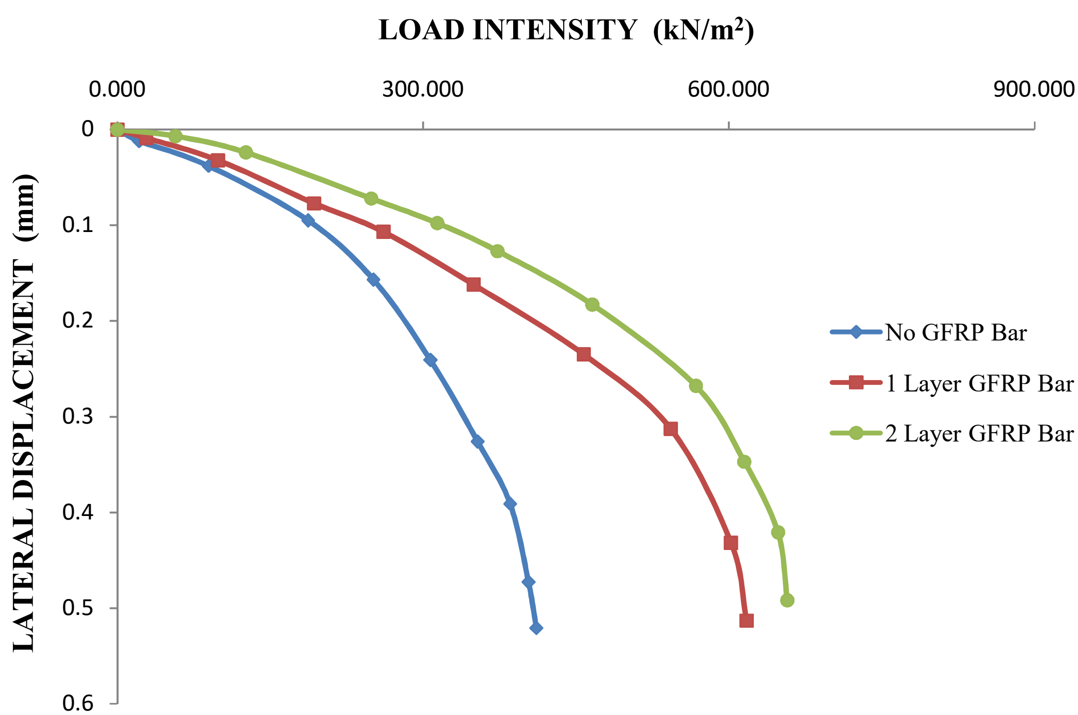

Figure 4.3 Lateral displacement v/s load intensity for H/D=2

The above graph is a representation of lateral displacement vs load intensity, showing the increase in load carrying capacity of OB soil in 3 different cases at H/D = 2.0. It can be noted that as 1st layer of GFRP bar was introduced in the OB soil the load carrying capacity of the above soil, for same settlement of 1.234mm increased by almost 51.75% whereas the increase was just 7.04% when the second layer was inserted. Also it was noted that the settlement at load intensity of 400 kN/m^2 decreased from 1.331mm to 1.234mm when depth of tunnel was changed from H/D = 0.75 to H/D = 1.5 and it further decreased from 1.234mm to 0.458mm at tunnel depth of H/D = 2.0.

4.4 Summarized Results of Model Testing

The summarized results of lateral displacement vs height to depth ratio of box tunnel at load intensity 400kN/m^2 are show in table 4.10-

Table 4.10 Lateral Displacement Results at Permissable Stress of 400kN/m^2

HEIGHT TO DEPTH RATIO (H/D)	No GFRP Bar in Over Burden soil	1 Layer of GFRP Bar in Over Burden soil	2 Layer of GFRP Bar in Over Burden soil
0.75	1.331	0.353	0.268
1.5	1.234	0.211	0.142
2	0.458	0.196	0.143

Percentage decrease in lateral displacement at load intensity of 400kN/m^2, is represented in table 4.11-

Table 4.11 Percentage decrease in lateral displacement at load intensity of 400kN/m^2

HEIGHT TO DEPTH RATIO (H/D)	1 Layer of GFRP Bar in Over Burden soil	2 Layer of GFRP Bar in Over Burden soil
0.75	73.48%	79.86%
1.5	82.90%	88.49%
2	57.21%	68.78%

Table 4.11 represents a percentage decrease in lateral displacement of OB soil at load intensity of 400kN/m2 when the tunnel is placed at H/D = 0.75, 1.5 and 2.0 from top. It is seen that the there was a significant decrease in soil movement when 1st layer of bar was introduced in OB soil but the 2nd layer didn't show that much decrease in soil movement.

CHAPTER 5

CONCLUSION

5.1 GENERAL

The following chapter describe the conclusion obtained from test results on model testing of box tunnel at three different depth of box tunnel. The chapter also includes the scope for future work that can be carried out for further research in the same field.

5.2 CONCLUSIONS

To minimize the ground settlement, soil nailing technique using GFRP bars instead of conventional steel has been adopted. Model testing of reinforced overburden soil with GFRP bars was carried out in the model test at 3 different depths of box tunnel and different layers of bars at different depths.

- With the data obtained from tests in can be successfully concluded that the nailing of overburden soil decreases the ground settlement of overburden soil significantly.
- It was also noted that as the height to depth ratio of tunnel increased the soil movement of overburden soil declined, this was due to soil arching phenomenon starts dominating as the depth increased.
- The lateral displacement of soil substantially decreased from 1.331mm to 0.353mm when the overburden soil was reinforced with only one layer of GFRP bar, where as there wasn't a significant difference when a second layer of GFRP bar was introduced in the overburden soil i.e. 0.353mm to 0.268mm.
- It was also noted that the minimum settlement of ground took place at H/D = 2 where it was only 0.458mm and dropped to 0.143mm after soil nailing.
- The graph plotted between lateral displacement and load intensity also indicate that there was an increase in load carrying capacity of soil from 400 kN/m^2 to over 900 kN/m^2 with and without bars respectively.
- Hence it can be finally concluded that the chances of collapse of overburden soil at the tunnel face can me reduced significantly by the application of GFRP bars, even at higher loading conditions, prior to the pushing of box tunnel into the ground.

5.3 SCOPE OF FUTURE WORK

- The present study was limited to analyse the lateral displacement of soil by introducing GFRP bars into overburden soil.
- During the experiment the in-situ variation of stresses in the ground was not taken into consideration during box jacking and hence a research can be carried out on the same.
- Also the development of stresses on box tunnel edges was not accounted for and hence can be researched further.
- Furthermore the research work can be used for large scale filed studies using similar nailing techniques.

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