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Parametric Study of Mechanically Stabilized Earth Wall

by

Manju Gurung

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ABSTRACT

Conventional embankment construction needs more right of way space and more backfill material or heavy retaining walls to retain the soil. This may lead to foundation problems in areas of weak soil. Reinforced soil can be used for greater heights, vertical slopes, less and uniform deformations. They are easy to work with, takes less time and are cost effective. This paper attempts to make parametric analysis of geosynthetic reinforced wall known as Mechanically Stabilized Earth (MSE) wall. Numerical simulations are done using a Finite Element Program (PLAXIS 2D). Soil is simulated as Mohr-Coulomb material and geosynthetic reinforcement modeled as elastic material. Parametric analysis of spacing of geosynthetics, stiffness values, aspect ratio (L/H), slope of wall, angle of internal friction and height of wall on factor of safety (FOS) and maximum horizontal displacement are studied. The analysis showed that increasing geosynthetics stiffness greatly reduces maximum horizontal displacement. Increasing the aspect ratio has a direct effect on FOS due to increased length of geosynthetics available. The increase of water table decreases the FOS by about 45%.

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ABBREVIATION

γ	Unit weight of soil
γ_w	Unit weight of water
ε	Strain in reinforcement
ϕ	Internal Friction angle of the soil
c	Cohesion of soil
cm	Centimeter
ft	Feet
mm	Millimeter
kN/m^2	Kilonewton per square meter
kN/m^3	Kilonewton per cubic meter
E	Young’s Modulus of Elasticity
EA	Axial stiffness
EI	Bending Stiffness
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
FEM	Finite Element Method
FOS	Factor of Safety
LEM	Limit Equilibrium Method
Max.	Maximum
$\sum M_{sf}$	Factor of Safety using PLAXIS
USCS	Unified Soil Classification System
2D	Two dimensional

1 INTRODUCTION

1.1 Background

The settlement in urban areas is increasing enormously in search for better education, opportunities and a higher standard of living. As a result, urban areas are becoming crowded and more restricted in space as compared to the countryside. Road construction in these areas is limited by the right of way availability demanding for vertical walls. Conventional near vertical walls like masonry retaining wall, concrete retaining wall are in practice, but these walls exert a great pressure on the foundation soil and demands for foreign materials (cement, sand, aggregate, reinforcement etc.). Geosynthetic reinforced earth wall have been in use for many decades in other countries but very limited use can be seen in our country Nepal. This technology can be used for attaining very high walls in limited space.

ASTM (1997) as cited in (Berg et al., 2009) has defined geosynthetics as a planar product manufactured from a polymeric material used with soil, rock, earth, or other geotechnical-related material as an integral part of a civil engineering project, structure, or system. The common type of geosynthetics includes geotextiles, geomembranes, geogrids, geocomposites, geofoams, geocells etc. The basic functions of geosynthetics are drainage, filtration, separation and reinforcement.

There are two approaches for the stability analysis of a wall i.e. Limit Equilibrium Analysis and Finite Element Analysis. Limit Equilibrium Method is a conventional method and also called ‘method of slices’ which uses force and moment equilibrium while Finite Element Method is computer based numerical modeling, is more powerful, accurate, reliable and versatile method to find the slope deformation and stress analysis.

1.2 Need for the Research

Conventional embankment construction needs more right of way space and more backfill material or heavy retaining walls to retain the soil. This may lead to foundation problems in areas of weak soil. Reinforced soil can be used for greater heights, vertical slopes, less and uniform deformations. They are easy to work with, takes less time and cost effective. Roads cannot be imagined without embankments in a country like ours and we know that soil is good in compression but weak in tension.

Whereas the geosynthetics materials are stronger in tension. This thesis attempts to study the use of geosynthetics in a wall with a slope of 1:10 having facing element known as Mechanically Stabilized Earth Wall (MSE wall) by FEM method. It also tries to study certain parametric variation like change in geosynthetics spacing, stiffness, slope of wall etc.

1.3 Objective

1.3.1 Overall Objective

The main objective of this research is to perform the stability analysis MSE wall under different parametric variation for an optimum design.

1.3.2 Specific Objectives:

i. To develop 2D numerical modeling of MSE wall by Finite Element Method and find the factor of safety, deformations.
ii. Parametric study of MSE wall.

1.4 Scope

The arbitrary values of soil parameters after studying the literature will be taken for both foundation soil and reinforced soil. The geosynthetic reinforced soil will be modeled by using Praxis 2D. Parametric variation of geosynthetics spacing, stiffness, aspect ratio will be done to achieve the required factor of safety and deformations. Effect of wall slope, effect of water table and effect of change in angle of internal friction of soil will also be studied. Finally, verification of the results obtained is done from literature.

1.5 Limitations of the Study

i. Arbitrary values of soil are taken from literature.
ii. Soil properties are assumed isotropic and homogeneous.
iii. 2D analysis or plane strain problem is used in modeling.

2 LITERATURE REVIEW

2.1 Historical Development

Inclusions have been used since ancient times to improve soil strength. Earlier examples can be seen in using straw, stick and branches to reinforce mud dwellings. (Elias et al., 2001) During the 17th and 18th centuries, French settlers along the Bay of Fundy in Canada used sticks to reinforce mud dikes. Some other early examples of manmade soil reinforcement include dikes of earth and tree branches that have been used in China for at least 1000 years and along the Mississippi River in the 1880s. Other examples include wooden pegs used for erosion and landslide control in England and bamboo or wire mesh, used universally for revetment erosion control. Soil reinforcing can also be achieved by using plant roots.

The modern methods of soil reinforcement for retaining wall construction were pioneered by the French architect and engineer Henri Vidal in the early 1960s. His research led to the invention and development of Reinforced Earth, a system in which steel strip reinforcement is used. The first wall to use this technology in the United States was built in 1972 on California State Highway 39, northeast of Los Angeles.

Retaining structures are an essential element of highway construction. They are used in slope stabilization, bridge abutments, minimize right of way, dikes etc. Conventional retaining walls is made of reinforced concrete and designed in the form of gravity wall, cantilever wall, buttress wall which are costly and exert great pressure that poses problems in areas with weak soil. If the height of wall has to be increased in such soils, the cost of such structures also becomes very high.

Reinforced soil slopes have been in use for past few decades and its use is growing more attributed to its cost effectiveness, accommodating larger settlements that reinforced concrete walls. The tensile reinforcements used in soil increase the strength of the soil to a degree that the wall face is self supporting with a higher slope. Facing elements in the wall prevent raveling of the soil and to attain vertical slopes.

2.2 Soil Reinforcement Materials

A number of different geosynthetic materials can be used for soil reinforcement. (Nicholson, 2014) Early versions of MSE wall used steel strips as reinforcement. Though having a good serviceability track record, some issues like corrosion of metallic reinforcement was faced. As a result, metallic reinforcing members were replaced by polymeric, geosynthetic material for some applications. Corrosion of metallic inclusions is dependent on a number of factors like saturation, acidity and sulfate content, among others. Corrosion rates may be predicted with some accuracy and some corrosion allowance is made as part of design. On the other hand factors like creep, durability, installation damage needs to be considered while working with geosynthetics As per FHWA-HI-95-038 cited from (Berg et al., 2009), Geosynthetics are generally identified by:-

1. Polymer (descriptive terms, e.g. High density, low density)
2. Type of element (e.g. Filament, yarn, strand, rib, coated rib)
3. Distinctive manufacturing process (e.g. Woven, needlepunched nonwoven, heatbonded nonwoven, stitch bonded etc.)
4. Primary type of geosynthetics (e.g. Geotextile, geogrid, geomembrane etc.)
5. Mass per unit area or thickness if appropriate
6. Any additional information or physical properties necessary to describe the material in relation to specific applications

Apart from reinforcing slopes, geotextiles are also used to distribute loads beneath embankments and roadways over soft subgrade soils to reduce settlements and lateral deformations. Geotextiles also act as a separation layer to separate fine grade subgrade with sub-base in highway construction.

Polymeric geogrids can be used to attain higher reinforcement strength. The open apertures of geogrids allow interconnectivity of the soil above and below, and therefore provides additional passive resistance along the sides of the transverse ribs.

2.3 Soil Reinforcement Fundamentals

Soil is weak in tension and good in compression and shear. When reinforcing elements are placed in soil the shear resistance of the system is a combination of the interface friction between materials, adhesion between material and in some cases like geogrids the passive resistance of reinforcements that is illustrated in details in the later section. The interface friction can be found from direct shear test.

2.4 Slope Stability Analysis

Slope stability analysis is performed to access the safety and economic design of the slopes that may be cut slopes, embankments or the slope in natural existing state. A slope is unstable when the applied shear stress exceeds the resisting shear strength developed in the soil mass.

2.4.1 Limit Equilibrium Method

Limit Equilibrium Approach is the conventional method used to analyze the slope, which is still in use due to its simplicity. The outcome of all types of limit equilibrium analysis is that the results may be represented as a factor of safety. The factor of safety is defined as the ratio of the summation of resisting forces and moments to the summation of driving forces and moments which bring the slope into a state of equilibrium along a given slip surface (Omari, A., and Boddula R.K., 2012).

$$F \quad = \frac{\sum R \;\; s \qquad f \qquad , m}{\sum D \qquad f \qquad , m} \qquad \text{Equation 2.1}$$

These methods consist of cutting the slope into fine slices and applying appropriate equilibrium equations (equilibrium of the forces and/or moments). Ordinary method of slices also known as Swedish Method of Slices or the Fellenius Method assumes a circular slip surface, neglects all interslice forces and fails to satisfy force equilibrium for the slide mass as well as for individual slices. The simplified Bishop method assumes that the vertical interslice shear force does not exist and the resultant interslice force is therefore horizontal (Bishop, 1955). It satisfies the equilibrium of moment but not the equilibrium of forces. Janbu simplified method method uses the horizontal forces equilibrium equation to obtain the factor of safety. It does not include interslice forces in the analysis but account for its effect using a correction factor. The correction factor is related to cohesion, angle of internal friction and the shape of the failure surface (Janbu et al., 1956). Spencer method is a very accurate method which satisfies both equilibrium of forces and moments and it works for any shape of slip surface. The basic assumption used in this method is that the inclinations of the side forces are the same for all the slices. Morgenstern and Price proposed a method that is similar to Spencer's method, except that the inclination of the interslice resultant force is assumed to vary according to a "portion" of an arbitrary function. This method allows one to specify different types of interslice force function (Morgenstern and Price, 1965).

2.4.2 Finite Element Method

This method is more powerful, accurate, reliable and versatile method to find the slope deformation and stress analysis. The soil mass is divided into small noded elements. This method utilizes the stress-strain relationship among the soil elements and helps better visualization of deformation of soil mass and no assumption for location of failure surface is made. This method has been widely accepted for the analysis of slope stability. Material is controlled by the infinitesimal incremental stress and strain relationship. Strength reduction method, also called ϕ-c reduction method is used to obtain the factor of safety of the slope. In this technique, the strength parameters ‘tan ϕ’ and ‘c” of the soil are reduced in steps until the soil mass fails. In this research, we talk about the use of numerical model PLAXIS 2D based on FEM to analyze the slope under static condition.

2.5 Terminology and Components of MSE Wall

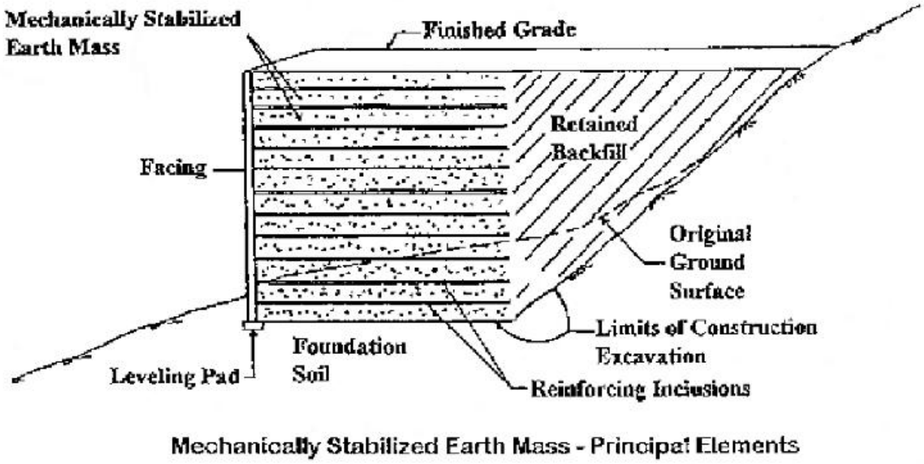


Figure 2.1: Components of MSE Wall (Elias, Christopher & Berg, 2001)

As per (Elias et al., 2001), the terminologies that needs to be understood for MSE wall are as follows.

i. Inclusion is a generic term that encompasses all man-made elements incorporated in the soil to improve its behavior. Examples of inclusions are steel strips, geotextile sheets, steel or polymeric grids, steel nails and steel tendons between anchorage elements. The term reinforcement is used only for those inclusions where soil-inclusion stress transfer occurs continuously along the inclusion.

ii. Mechanically Stabilized Earth Wall (MSEW) is a generic term that includes reinforced soil (a term when multiple layers of inclusion act as reinforcement in soils placed as fill).

iii. Geosynthetics is a generic term that encompasses flexible polymeric materials used in geotechnical engineering such as geotextiles, geomembranes, geonets and grids (also known as geogrids).

iv. Facing is a component of the reinforced soil system used to prevent the soil from raveling out between the rows of reinforcement. Common facings also include precast concrete panels, dry cast modular blocks, metal sheets and plates, gabions, welded wire mesh, shotcrete, wood lagging and panels and wrapped sheets of geosynthetics. The facing also plays a minor structural role in the stability of the structure.

   a) Segmental Precast Concrete Panels:- The precast concrete panels have a minimum thickness of 140 mm abd are of a cruciform, square, rectangular, diamond, or hexagonal geometry. Temperature and tensile reinforcements are required but will vary with the size of the panel. Vertically adjacent units are usually connected with shear pins.

   b) Dry cast modular block wall (MBW) units:- These are relatively small, squat concrete units that have been specially designed and manufactured for retaining wall applications. The mass of these units commonly rabges from 15 to 50 kg, with units of 35 to 50 kg routinely used for highway projects. Unit heights typically range from 100 to 200 mm for the various manufactureres. Exposed face length usually varies from 200 to 450 mm. Nominal width of unkits typically ranges between 200 and 600 mm. Units may be manufactured solid or with cores. Full height cores are filled with aggregate during erection. Units are normally dry-stacked (i.e. without mortar) and in a running bond configuration. Vertically adjacent units may be connected with shear pins, lips, or keys.

   c) Metallic Facings:- The original Reinforced system had facing elements of galvanized steel sheet formed into half cylinders. Although precast concrete panels are now commonly used in Reinforced Earth walls, metallic facings may be appropriate in structures where difficult access or difficult handling requires lighter facing elements.

d) Welded Wire Grids:-Wire grid can be bent up at the front of the wall to form the wall face. This type of facing is used in the Hilfiker, Tensar and Reinforced Earth wire retaining wall systems.

e) Gabion Facing:- Gabions (roak filled wire baskets) can be used as facing with reinforcing elements consisting of welded wire mesh, welded bar-mats, geogrids, geotextiles or the double twisted woven mesh placed between or connected to the gabion baskets.

f) Geosynthetic Facing:- Various types of geotextile reinforcement are looped around at the facing to form the exposed face of the retaining wall. These faces are susceptible to ultraviolet light degradation, vandalism and damaged due to fire. Alternatively, a geosynthetic grid used for soil reinforcement can be looped around to form the face of the completed retaining structure in a similar manner to welded wire mesh and fabric spacing. Vegetation can grow through the grid structure and can provide both ultraviolet light protection for the geogrid and a pleasing appearance.

g) Postconstruction Facing:- For wrapped faced walls, gthe facing whether geotextile, geogrid or wire mesh can be attached after construction of the wall by shotcreting, guniting, cast in place concrete or attaching prefabricated facing panels made of concrete, wood or other materials. This multi staging facing approach adds cost but is advantageous where singninificant settlement is anticipated.

v. Retained backfill is the fill material located between the mechanically stabilized soil mass and the natural soil.

vi. Reinforced backfill is the fill material in which the reinforcements are placed.

MSE walls require high quality backfill for durability, good drainage, constructability and good soil reinforcement interaction which can be obtained from well graded, granular materials. Many MSE systems depend on friction between the reinforcing elements and the soil. In such cases, a material with high friction characteristics is specified and required. Some systems rely on passive pressure on reinforcing elements and in those cases, the quality of backfill is still critical. These performance requirements generally eliminate soils with high clay contents.

From a reinforcement capacity point of view, lower quality backfills could be used for MSEW structures, however a high quality granular backfill has the advantages of being free draining, providing better durability for metallic reinforcement, and requiring less reinforcement. There are also significant handling, placement and compaction advantages in using granular soils. These include an increased rate of wall erection and improved maintenance of wall alignment tolerances.

The backfill material used in the structure shall be free from organic or other deleterious material and shall conform to the gradation limit as follows:-

U.S Sieve Size	Percent Passing
102 mm (4 in)	100
0.425 mm (No.40)	0-60
0.075 mm (No. 200)	0-15

Plasticity Index shall not exceed 6.

Lighter compaction equipment should be used to compact the fill material near the face of the panels to prevent build up of high lateral pressure and bulging of facing panels. The presence of fine materials in granular fill may prevent free draining and hence it should be carefully evaluated to allow for proper drainage.

2.6 Advantages of MSE Walls

MSE walls have many advantages compared with conventional reinforced concrete and concrete gravity retaining walls. (Berg et al., 2009) as cited in FHWA-NHI-10-024, FHWA GEC 011-Vol I summarizes some advantages listed below:

i. Use simple and rapid construction procedures and do not require as large of construction equipment.
ii. Do not require special skills for construction.
iii. Require less site preparation than other alternatives.
iv. Need less space in front of the structure for construction operations.
v. Reduce right of way acquisition.

vi. Do not need rigid, unyielding foundation support because MSE structures are tolerant to deformations.

vii. Are cost effective.

viii. Are technically feasible to heights in excess of 100 ft (30 m).

2.7 Potential Disadvantages

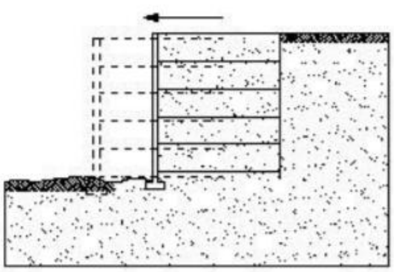
(Berg et al., 2009) as cited in FHWA-NHI-10-024, FHWA GEC 011-Vol I summarizes some disadvantages listed below:

i. Require a relatively large space (e.g., excavation if in a cut) behind the wall or slope face to install required reinforcement.

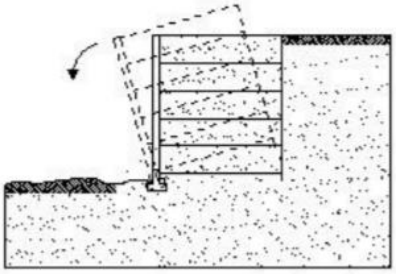
ii. MSE walls require the use of select granular fill. (At some sites, the cost of importing suitable fill material may render the system uneconomical.)

2.8 External Stability

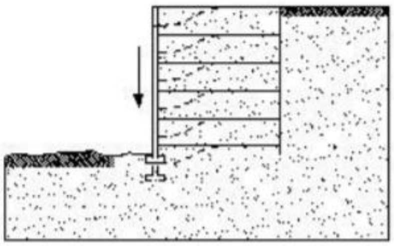
External stability is evaluated by considering the reinforced soil mass as a semi-rigid gravity retaining wall with active pressure applied behind it. Then, conventional limit equilibrium methods are used to check the performance of the wall against sliding, overturning, bearing capacity and deep or overall stability.



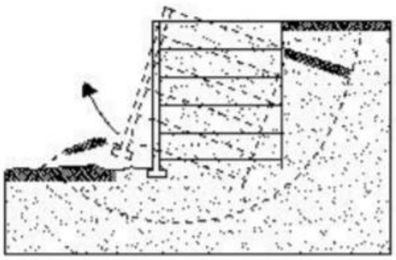
(1) Sliding



(2) Overturning



(3) Bearing Capacity



(4) Slope Stability Failure

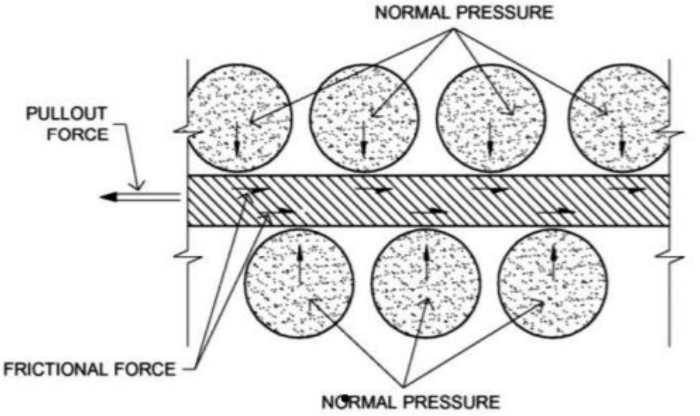
Figure 2.2: Failure Mechanism for External Stability evaluation (after Anderson et al., 1995) as cited from (Abdelmawla, 2017)

2.9 Internal Stability

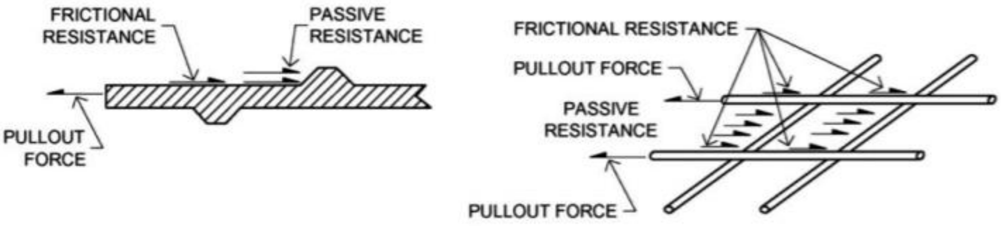
When considering internal stability, it must be understood that the stresses of the

reinforcement are transferred into the soil differently upon the system selected. The soil to-reinforcement relative movement required to mobilize the design tensile force depends mainly upon the load transfer mechanism, the extensibility of the reinforcement material, the soil type, and vertical stress.

(Christopher et al., 1990) Stresses are transferred between soil and reinforcement by friction and/or passive resistance depending on the reinforcement geometry.



A) Frictional Stress Transfer Between Soil and Reinforcement Surfaces.



B) Soil Passive (Bearing) and Frictional Resistance on Reinforcement Surfaces.

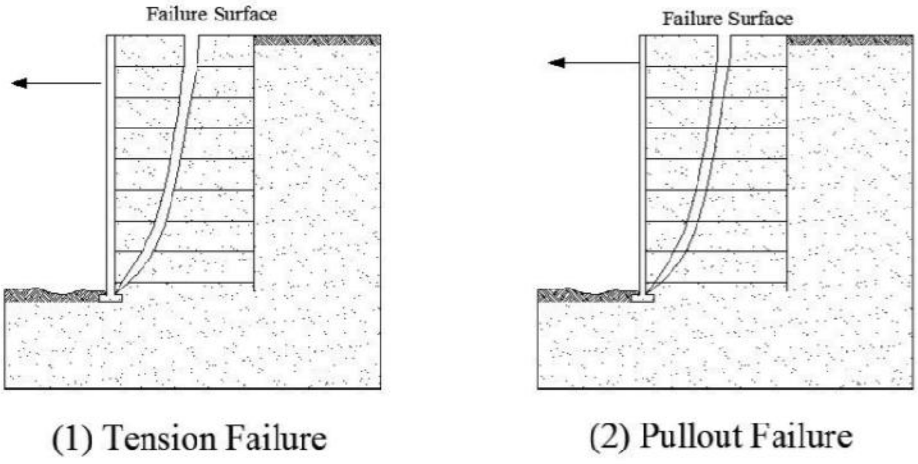
Figure 2.3: Stress Transfer Mechanisms for soil reinforcement (Abdelmawla, 2017)

Friction develops at locations where there is a relative shear displacement and corresponding shear stress between soil and the reinforcement surface. Reinforcing elements dependent on friction should be aligned with the direction of soil reinforcement relative movement. Examples of such reinforcing elements are steel strips, longitudinal bars in grids, geotextile, geosynthetic straps, and some geogrid layers.

Passive resistance occurs through the development of bearing type stresses on "transverse" reinforcement surfaces normal to the direction of soil reinforcement relative movement. Passive resistance is generally considered to be the primary interaction for bar mat, wire mesh reinforcements, and geogrids with relatively stiff cross machine direction ribs, the transverse ridges on "ribbed" strip reinforcement also provide some passive resistance.

Safety against structural failure or internal stability is evaluated with respect to Pullout and rupture of the reinforcement. Both failure modes are critical: tensile

failure can lead to progressive collapse of the reinforced structure as the load is transmitted to the remaining elements; Pullout resistance on the other hand can lead to progressive deformation of the wall due to redistribution of stresses (Budhu, 1999).



(1) Tension Failure

(2) Pullout Failure

Figure 2.4: Internal Failure Modes for MSE Walls (after Anderson et al., 1995)

Table 2.1: Minimum Recommended FOS for MSE Walls (Christopher et. al, 1990)

Failure mode	**Resisting Component**	**Symbol**	**Minimum Recommended FOS**
External Stability	Sliding along the base	FOS_S	1.5
	Overturning	FOS_O	2.0
	Bearing Capacity	FOS_B	2.0

	Global stability	FOS_G	1.3
Internal Stability	Tensile Resistance	FOS_T	1.5
	Pullout resistance	FOS_P	1.5

2.10 Research Review

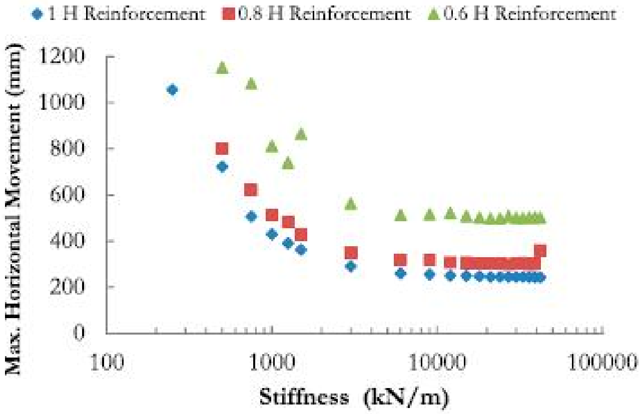
Research in the field of using geosynthetics to improve the strength of soil has been done in the past both in lab as well as by numerical modeling. Various numerical models using finite element/finite difference method like PLAXIS, FLAC, Phase have been used to study different properties associated with reinforced soil. Associated parameters like effect on factor of safety and displacement due to spacing of geosynthetics, length of geosynthetics, axial stiffness of geosynthetics, slope of wall,

angle of internal friction of soil have been studied.

(Vashi et al., 2017) conducted a parametric study of impact of spacing of geogrid and impact of height of wall on displacement using PLAXIS 2D. It was found that the total displacement increased by 10% when spacing increased from 1m to 1.5m and reduced by 24.31% when spacing reduced to 0.5m. Also with the increase in height of wall, the total displacement as well as vertical displacement increased.

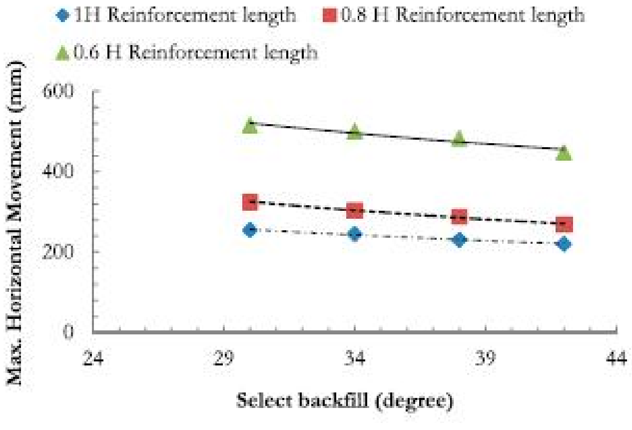
(Mahmood, 2009) studied the failure analysis of a segmental block, MSE retaining wall located in Rockville, Maryland. In 1996 a maximum of 15ft high segmental retaining wall was constructed along the eastern boundary of the Tower Oaks residential develoment in Roakville. Large gaps and separations in the wall facing blocks were observed during late 2002. The greatest leaning and bulging occurred where the wall height was highest. Surveying of the wall indicated that the wall movements were as large as about 12 to 18 inches. Gaps and separations continued to increase until wall collapse occurred in 2003. Scarp like failures were visible at several locations along the slope at the top of the wall prior to failure. The scarps were generally located at a distance of about 16 to 17 feet behind the wall face. Then a 2-D analysis of the model similar to the field condition of Maryland was done using PLAXIS-2D. The model showed the highest displacement of 1.27ft (15 inches). The position of maximum displacement was also exactly at the same position as actual field condition that is at the top of the facing wall. Thereafter, the effect of different parameters like reinforcement length, stiffness, water table, cohesion and friction angle on total displacement of wall for both cohesive and cohesionless soil were studied. It showed that for both cohesive and cohesionless soil, the extreme total displacement decreased with increasing grid strength and the effect was more pronounced for water table at mid height. The results also showed that increasing the grid length decreased extreme total displacement upto certain point after which displacement remained unaffected which can be attributed to the effective length required being reached. For cohesive soil increase in angle of internal friction decreased displacement and value were similar for three different grid length for the case water level at bottom but displacement was more for small grid length in case of water level at mid height. Also sandy soil with some cohesion showed less displacement compared to cohesionless soil.

(Kibria et al., 2014) performed a case study of MSE wall located on State Highway 342 in Lancaster, Texas wherein horizontal movement of the MSE wall was between 300mm and 450mm within five years of construction. Two inclinometers were installed to monitor additional movement of wall and was found that the wall moved at an average rate of 4.5mm/month. The same was modeled using finite element program, which were in good agreement with the inclinometer results. Numerical analysis results indicated that the effect of reinforcement stiffness was not significant at a wall height of 4m compared with 8m and 12m. The wall movement varied from 74mm to 29mm for an increase in reinforcement stiffness from 250 kN/m to 42,000 kN/m at 1.0H reinforcement length.



(c) MSE wall height 12 m

Fig. 7. Effect of stiffness on horizontal displacement of MSE wall



(c) Wall height 12 m

Figure 2.5: Effect of stiffness and angle of internal friction on maximum horizontal displacement (Kibria, Hossain, & Khan, 2014)

(Abdelrahman et al., 2014) studied behaviour of narrow mechanically stabilized earth wall (wall aspect ratio, L/H<0.7). The results indicated that increasing aspect ratio increases the factor of safety, maximum horizontal displacement, maximum tensile force. Increasing elastic stiffness increase factor of safety, maximum tension force of reinforcement element while decreasing the maximum horizontal displacement.

2.11 Numerical Modeling

In geotechnical engineering practices, design and analysis of any problem is done by any of the three types of modeling procedures: Physical/Empirical Modeling, Mathematical/Analytical Modeling and Numerical Modeling.

Physical modeling incorporates laboratory and in situ model tests gives some information to Engineers to achieve some empirical solution of problem. However, these are costlier and time consuming.

Mathematical modeling uses differential or algebraic equation which cannot solve most of the engineering problems analytically. It is because of the complexity in geometry, non-homogeneity of material and non-linear constitutive behavior of the medium.

Numerical models are mathematical models that use some sort of numerical time-stepping procedure to obtain the models behavior over time. Numerical models in combination with mathematical models, calibrating and validating against preexisting data and analytical results, iterative calculation of the results in step with error analysis is done until the required numerical results are obtained. The generated table and/or graph represent the mathematical solution.

Numerical methods are techniques to approximate the governing equations in the mathematical models.

Numerical methods available for problem solving in geotechnical engineering are Finite Element Method (FEM), Spectral Element Method (SEM), Finite Difference Method (FDM), Finite Volume Method (FVM), Discrete Element Method (FEM).

These Finite Element Method (FEM) is a technique which approximates the solution

of governing differential equations in the mathematical model by dividing the domain into meshes or grids and applying simpler equations to individual elements or nodes in the mesh to approximate the solution by minimizing the associated error function (Ismail-Zadeh & Tackley, 2010) (Atkinson, 2007)

2.11.1 PLAXIS 2D as FEM Tool

PLAXIS 2D is a finite element two-dimensional elastoplastic program used in geotechnical applications developed for stress and deformation analysis. It is extensively used in mining and geotechnical activities like excavation design, underground excavation design, consolidation, seepage flow, dynamic analysis, slope stability analysis of unreinforced as well as reinforced soil and rock elements.

It includes static elastoplastic deformation, advanced soil models, consolidation, updated mesh and steady-state groundwater flow. Dynamic module can be used to analyze vibration in soil and excess pore pressure.

PLAXIS 2D has been developed to simulate geosynthetic reinforced embankment with proper boundary condition, geometric and material model, proper mesh, groundwater condition and pseudostatic condition. As a result, stress and deformation analysis and overall stability analysis can be obtained.

The calculation method in PLAXIS 2D yields a value of incremental multiplier $\sum M_{sf}$ as results converge when slope failure is reached. This value of incremental multiplier is treated as factor of safety (FOS) value for unreinforced and reinforced slope.

3 METHODOLOGY

3.1 Methodology

The methodology of the research mainly focuses on the objective of the project. Few input parameters for foundation soil and reinforced fill are taken as follows.

Table 3.1: Typical Mass Densities of basic soil types as cited from Structural Engineering Forum of India, 2003.

Type of Soil	**Mass density (kN/m^3)**◆			
	Poorly Graded Soil		**Well Graded Soil**	
	Range	Typical Value	Range	Typical Value
Loose Sand	16.7-18.6	17.2	17.2-19.6	18.2
Dense Sand	18.6-20.6	20.3	19.6-21.6	20.6
Soft Clay	15.7-18.6	17.2	15.7-18.6	17.2
Stiff Clay	18.6-22.1	19.6	18.6-22.1	20.3
Silty Soils	15.7-19.6	17.2	15.7-19.6	17.2
Gravelly Soils	18.6-22.1	20.3	19.6-22.6	21.1

◆Values are representative of moist sand, gravel, saturated silt, and clay.

Table 3.2: Typical Values of soil friction angle for different soils as per Unified Soil Classification System (USCS) as cited from Geotechdata.info, 2013.

Description	**USCS**	**Soil Friction Angle**	
		Minimum	**Maximum**
Well graded gravel, sandy gravel, with little or no fines	GW	33°	40°
Poorly graded gravel, sandy gravel, with little or no fines	GP	32°	44°
Loose sand	SW, SP	29°	30°
Medium sand	SW, SP	30°	36°
Dense sand	SW, SP	36°	41°
Silty sand - Loose	SM	27°	33°
Silty sand - Dense	SM	30°	34°
Clayey sands	SC	30°	40°

Description	**USCS**	**Soil Friction Angle**	
		Minimum	**Maximum**
Inorganic clays, silty clays, sandy clays of low plasticity	CL	27°	35°
inorganic silts of high plasticity	MH	23°	33°
Inorganic clays of high plasticity	CH	17°	31°
Silty Clay	OL, CL, OH, CH	18°	32°
Clay	CL, CH, OH, OL	18°	28°
Peat and other highly organic soils	Pt	0°	10°

Table 3.3: Elastic Constants of Various Soils Modified after U.S. Department of the Navy (1982) and Bowles (1988) (AASHTO Table 10.6.2.2.3b-1) as cited in AASHTO LRFD Specifications for Serviceability in the Design of Bridge Foundations

Soil Type	**Typical Range of Young's Modulus (kN/m^2)**	**Poisson's Ratio**
Clay:		0.4-0.5 (undrained)
Soft sensitive	2,680-16,080	
Medium stiff to stiff	16,080-53,600	
Very stiff	53,600-1,07,250	
Loess Silt	2,140-21,450	0.3-0.35
	16,080-64,350	0.1-0.3
Fine Sand:		0.25
Loose	8,580-12,870	
Medium Dense	12,870-21,450	
Dense	21,450-32,170	
Sand:		
Loose	10,725-32,175	0.20-0.35
Medium Dense	32,175-53,625	
Dense	53,625-85,800	0.30-0.40
Gravel:		
Loose	32,175-85,800	0.2-0.35
Medium Dense	85,800-1,07,250	
Dense	1,07,250-2,14,500	0.3-0.4

The model is then prepared using PLAXIS 2D. The numerical modeling is carried out to compute deformation and FOS values. The methodology of this research can be visualized from the flowchart shown below:

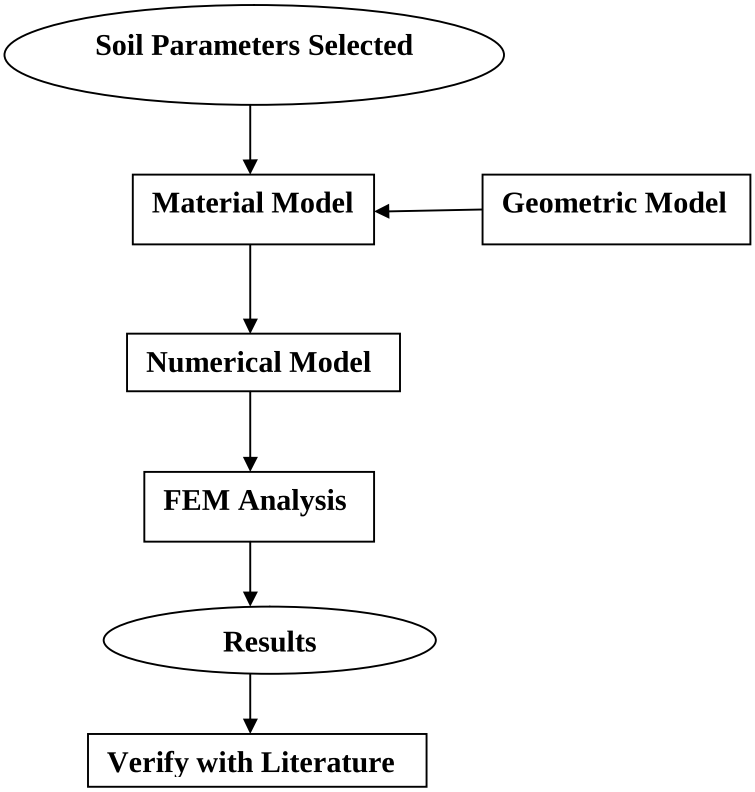


Figure 3.1: Flowchart of the methodology

3.2 Material Model

The material model is prepared using PLAXIS V8.2 for both soil and geosynthetics.

The failure criterion of soil model is assumed as Mohr-Coulomb (elastic-perfectly plastic) (Griffths, 1999).

Table 3.4: Model Parameters for Soil

S.No.	Parameters	Foundation Soil	Reinforced Soil
1	Cohesion, c (kPa)	0.2	0.2
2	Angle of internal friction, ϕ (Degree)	30	32
3	Modulus of Elasticity, E (kPa)	30,000	50,000
4	Poisson's ratio, υ	0.3	0.32
5	Dilation angle, ψ (Degree)	0	0

S.No.	Parameters	Foundation Soil	Reinforced Soil
6	Unit weight (saturated), γ_{sat}(kN/m^3)	19	20
7	Material type	Drained	Drained

3.3 Model Parameter of geosynthetic reinforcement and facing element

The design of reinforcement materials are a function of geometric characteristics, strength, durability and material type. The two most commonly used reinforcements are steel and geosynthetics. Here the geosynthetic reinforcement is discussed. The tensile properties of geosynthetics is affected by a number of environmental factors like creep, installation damage, aging, temperature and confining stress. Thus the design long term reinforcement load T_a is calculated as follows.

$$T_a = \frac{T_u}{R \ * F} = \frac{T_a}{F}$$ Equation 3.1

$$T_a = \frac{T_u}{R_C * R_D * R_{ID}}$$ Equation 3.2

T_a = Long term tensile strength per unit width

T_u = Ultimate (or yield) Tensile Strength

R_C = Creep Reduction Factor is the ratio of the ultimate strength T_u to the creep limit strength obtained from laboratory tests.

R_D=Durability Reduction Factor based on susceptibility of the geosythetic to be attacked by microorganisms, chemical, thermal oxidation, hydrolysis.

R_{I} = Installation Damage Reduction Factor depending on backfill gradation and material handling.

The strain limits based on the type of soil fill materials and for construction over peats are (Holtz et al., 1998) :-

Cohesionless soils: $\varepsilon_{geosynthetics}$ = 5 to 10 %
Cohesive Soil: $\varepsilon_{geosynthetics}$ = 2 %
Peats: $\varepsilon_{geosynthetics}$ = 2 to 10 %

The minimal (initial) axial stiffness of geotextile from a short term experiment (load rate according to EN ISO 10319) for x% strain (as cited from https://www.finesoftware.eu/help/geo5/en/axial-stiffness-of-geosynthetics-01/) is given by :-

$$J_{\varepsilon=x} \approx E \cdot A = \frac{T_{\varepsilon=x}}{\varepsilon}$$ Equation 3.3

$J_{\varepsilon=x}$ ≈ ***E.A*** = Axial Stiffness of Geosynthetics (where ***E***=Modulus of Elasticity, ***A***= cross-sectional area)

$T_{\varepsilon=x}$ = Tensile Strength at x% strain

ε = Strain

Axial Stiffness value of geosynthetic reinforcement is used for modeling in PLAXIS. The values adopted are 1000 kN/m and 800 kN/m.

The facing element of MSE wall is modeled as plate element in PLAXIS. The properties on plate is given in table 3.5

Table 3.5: Model Parameters for Plate (Shrestha, Baral, Bergado, Chai, & Hino, 2014)

S. No.	**Parameter**	**Adopted Value**
1	Axial Stiffness, EA (kN/m)	42 x 10^6
2	Bending Stiffness, EI (kNm^2/m)	78500
3	Weight, w (kN/m/m)	3.6
4	Poisson's ratio, υ	0.15

3.4 Geometric Model

MSE wall of 10 m and 5 m are taken into consideration for parametric studies. A typical section of the wall is shown in Figure 3.2.

3.4.1 Mesh generation

The model is assumed as plane strain case. The model is discretized with fine mesh density on the soil cluster and the meshing is done by 15-noded triangular element.

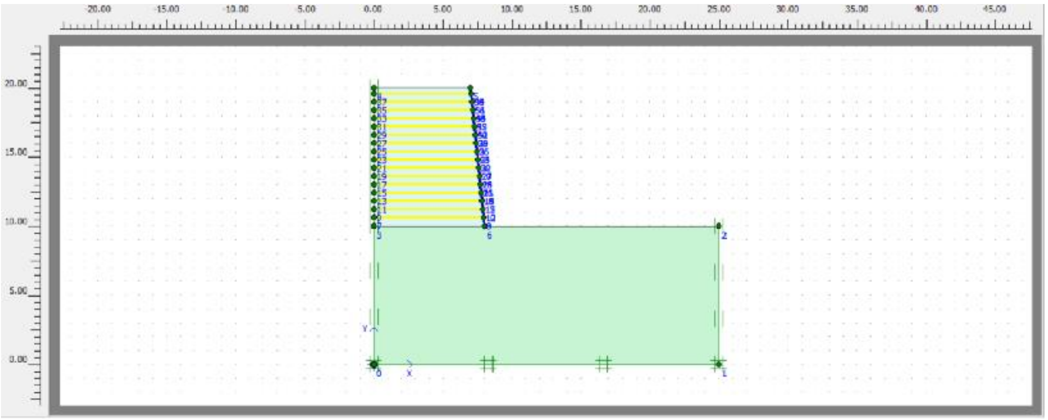


Figure 3.2: Geometric model of MSE Wall

3.4.2 Boundary Condition

The boundary condition of the model is done by restraining the horizontal and vertical displacement on the bottom boundary and the left and right boundaries are restrained horizontally. The upper horizontal and slope portion are set free to analyze the behavior of ground surface as practicable to the actual ground condition.

3.4.3 Numerical Modeling

From the obtained geometric and material model, numerical modeling is done for the reinforced MSE wall. The objective of the study is to assess the behaviour of geosynthetic reinforced MSE wall. The behaviour in relation to the spacing of geosynthetics layers, the effect of geosynthetics stiffness, the slope of wall, aspect ratio, angle of internal friction of reinforced soil and effect of water level is studied.

4 RESULTS AND DISCUSSION

4.1 Analysis and Results

The analysis of the MSE wall is done using PLAXIS V8.2 for a height of 10m and 5m (for spacing of geosynthetics and water table study). Various parametric variations were studied using the above heights of MSE walls. The factor of safety and displacements are studied.

4.2 Effect of various parameters

The effect of various parameters like spacing of geosynthetics, stiffness values, aspect ratio, angle of internal friction, slope of wall, water table level were modeled to understand the effect of these parameters on wall stability. This may further assist in designing of MSE walls keeping the above factors into consideration.

4.2.1 Effect of change in Spacing of Geosynthetics

The spacing of geosynthetic reinforcements is varied between 15cm to 60cm with an axial stiffness value of 1000 kN/m. The height of wall is taken as 5m. The FOS is found to decrease with increase in the spacing of geosynthetic reinforcement. Similarly, the maximum displacements are found to increase with the increase in geosynthetics spacing. This may be attributed to the fact that decreasing spacing increases the length of geosynthetics available for friction resistance to counteract the lateral earth pressure. The soil body collapsed for a spacing of 75mm.

Table 4.1: Effect of Geosynthetics Spacing on FOS and maximum horizontal and vertical displacement of wall

S. No.	Spacing of Geosynthetics (cm)	FOS	Maximum Horizontal Displacement (mm)	Maximum Vertical Displacement (mm)
1	15	2.137	8.07	33.02
2	30	2.116	15.09	41.96
3	45	2.101	23.78	52.13
4	60	2.088	32.98	64.09

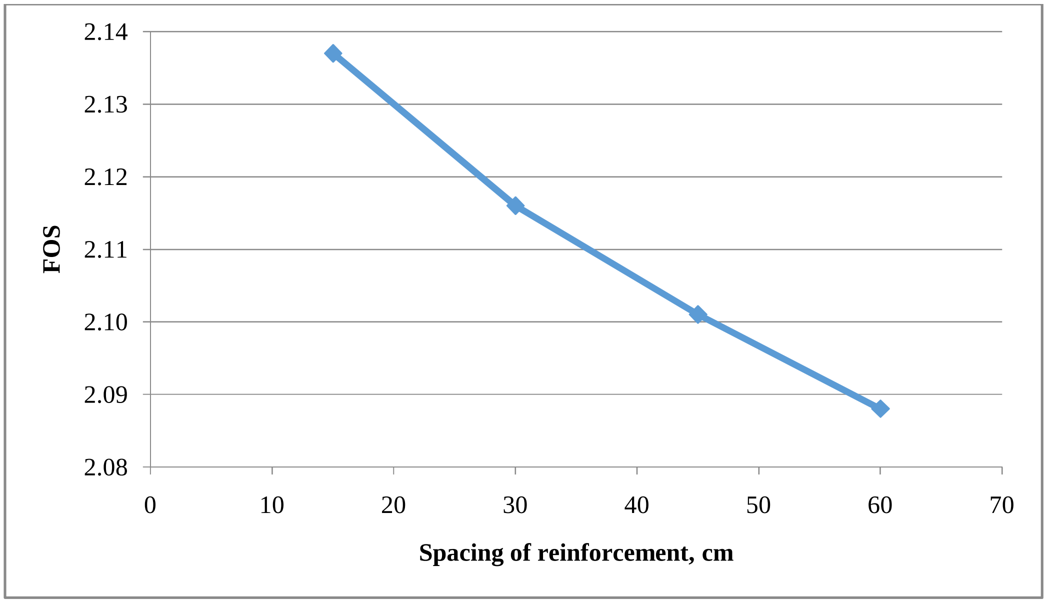


Figure 4.1: Variation of FOS with change in Spacing of reinforcement

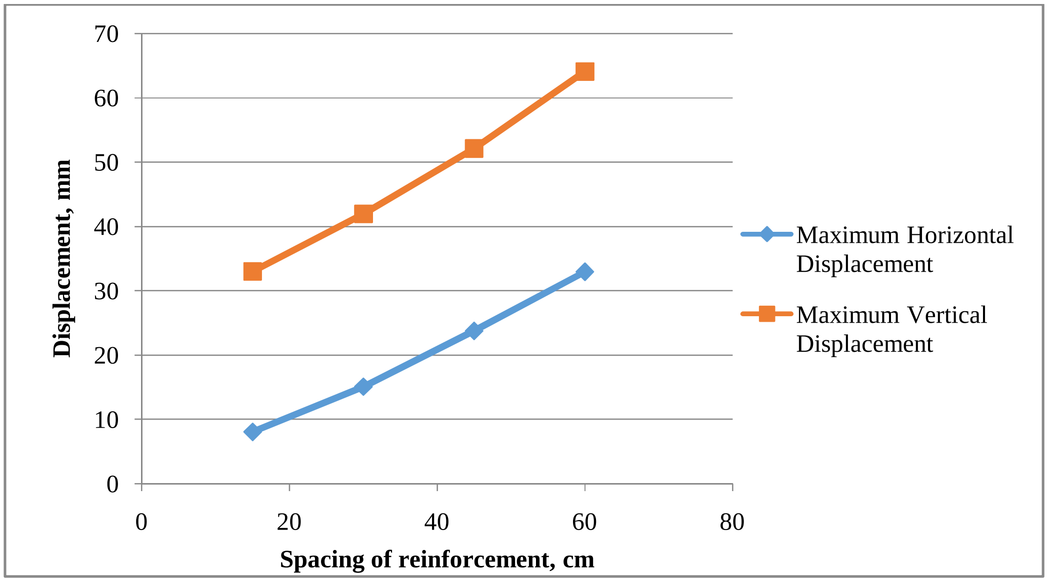


Figure 4.2: Variation of maximum horizontal and maximum vertical displacement with change in Spacing of reinforcement

4.2.2 Effect of Geosynthetics Stiffness

Geosynthetics with axial stiffness values of 500 kN/m to 2500 kN/m is used in 10m height wall for a spacing of 30cm. The FOS initially increased marginally with increase in the stiffness whereas axial stiffness value of 2000 kN/m and 2500 kN/m yielded the same FOS value of 2.091. So, it can be inferred that the FOS remains constant after a certain maximum axial stiffness value is reached for a certain system. However maximum horizontal displacement is found to reduce considerably with increase in stiffness values. Stiffness is the property of material to resist deformation in response to an applied load and as stiffness is increased more resistance to deformation takes place and thus the displacements are decreased. However, FOS being same after 2000 kN/m axial stiffness value may be due to the maximum resisting force being achieved against the activating forces and further increase in stiffness value has no effect on FOS.

Table 4.2: Effect of Axial Stiffness on FOS and maximum horizontal displacement

S.No.	Geosynthetics Axial Stiffness (kN/m)	FOS	Maximum Horizontal Displacement (mm)
1	500	Soil Body Collapsed	
2	800	2.050	67.62
3	1000	2.065	56.14
4	1500	2.084	42.86
5	2000	2.091	36.11
6	2500	2.091	32.06

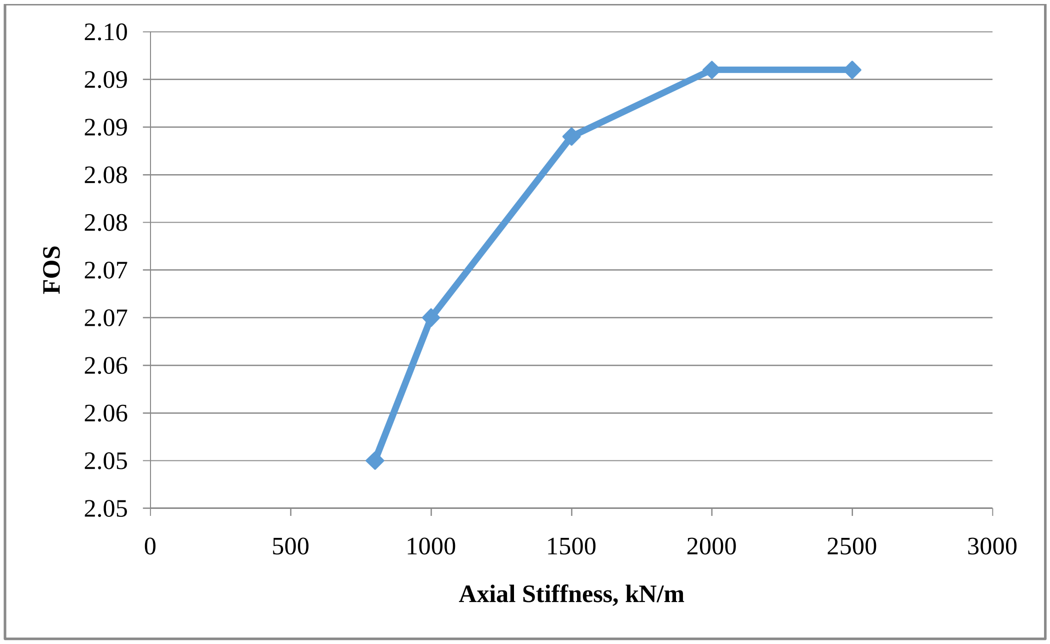


Figure 4.3: Variation of FOS with change in Axial Stiffness

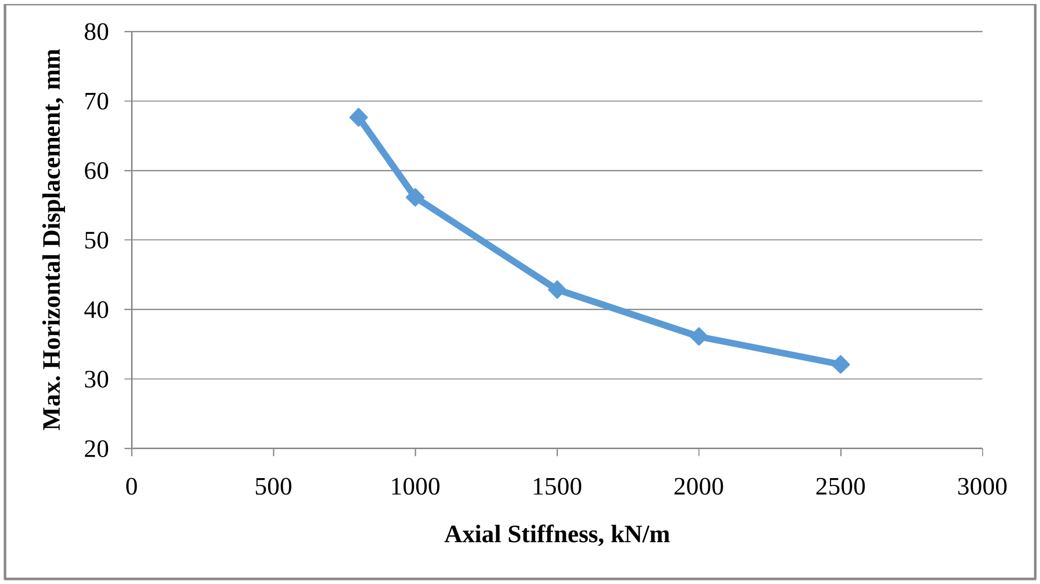


Figure 4.4: Variation of maximum horizontal displacement with change in Axial Stiffness of geosynthetics.

4.2.3 Effect of change in Aspect Ratio

Aspect ratio of MSE wall is the ratio of the length (L) of geosynthetics/reinforcement and the height of wall (H). The height of wall is taken 10m, axial stiffness value of 1000 kN/m and spacing 30cm for the study. Factor of safety (FOS) is found to increase with the increase in aspect ratio of the wall. This may be due to the more length of geosynthetics available for resistance. The maximum horizontal displacement increased slightly with increasing aspect ratio.

Table 4.3: Effect of Axial Ratio on FOS and maximum horizontal displacement

S.No.	Aspect Ratio (L/H)	FOS	Maximum Horizontal Displacement (mm)
1	0.2	1.601	47.91
2	0.3	1.738	48.55
3	0.4	1.832	52.30
4	0.5	1.909	54.33
5	0.6	2.023	53.36
6	0.7	2.065	56.14

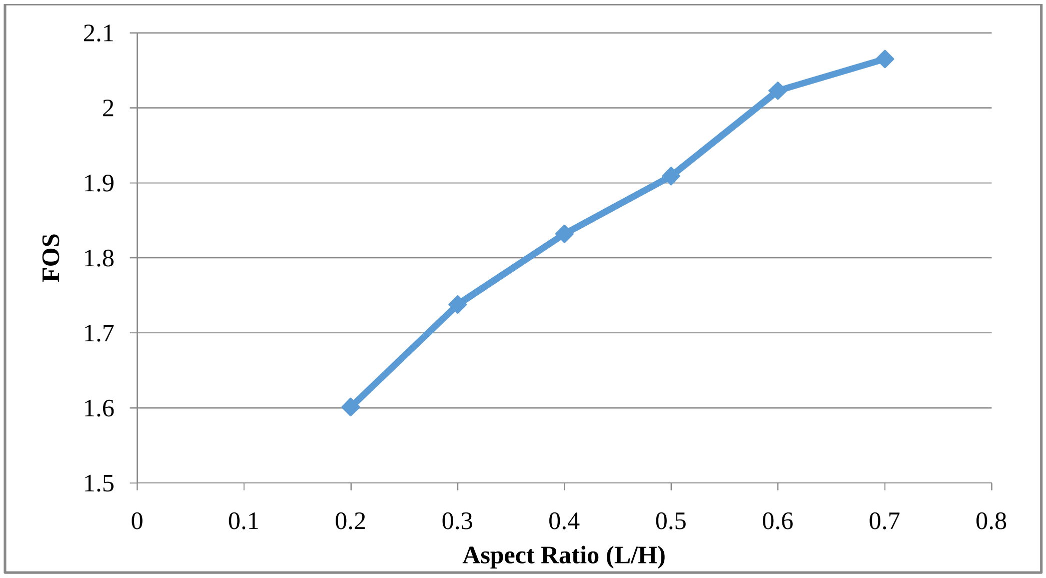


Figure 4.5: Variation of FOS with change in Aspect Ratio, L/H

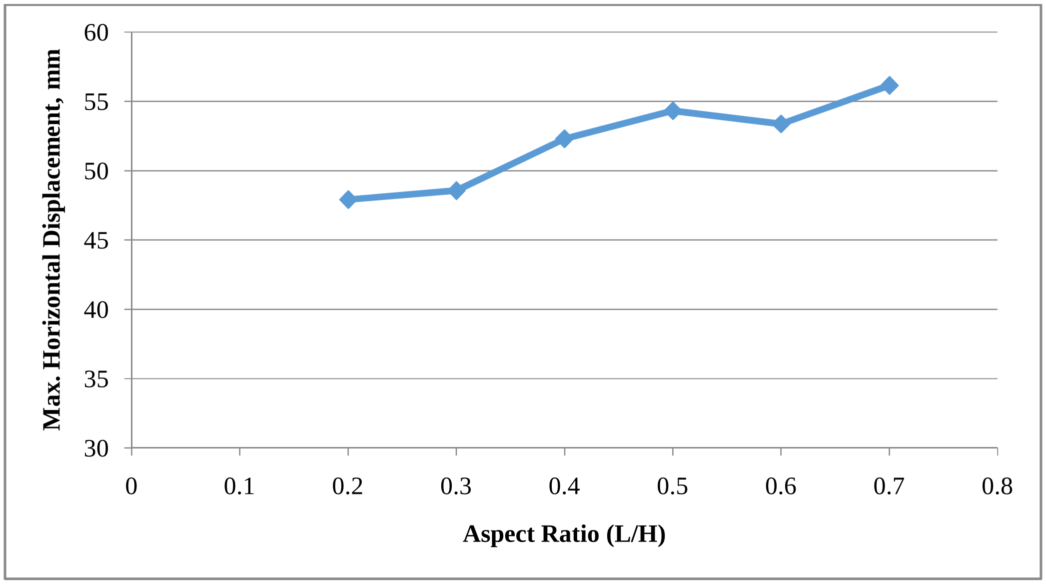


Figure 4.6: Variation of maximum horizontal displacement with change in Aspect Ratio, L/H

4.2.4 Effect of change in slope of MSE Wall

As the slope of the wall decreases the FOS increases from a value of 1.886 with vertical wall face to 2.299 for 1:4 slope. The horizontal displacement is found to decrease marginally. It can also be attributed to the increase in frictional resistance on both the faces of geosynthetics which increases with the decrease in slope of wall.

Table 4.4: Effect of Wall Slope on FOS and maximum horizontal displacement

S.No.	**Slope**	**FOS**	**Maximum Horizontal Displacement (mm)**
1	Vertical Face (90˚)	1.886	56.79
2	1:10 (84.29˚)	2.065	56.14
3	1:8 (82.88˚)	2.098	58.00
4	1:6 (80.54˚)	2.148	49.99
5	1:4 (75.96˚)	2.299	47.84

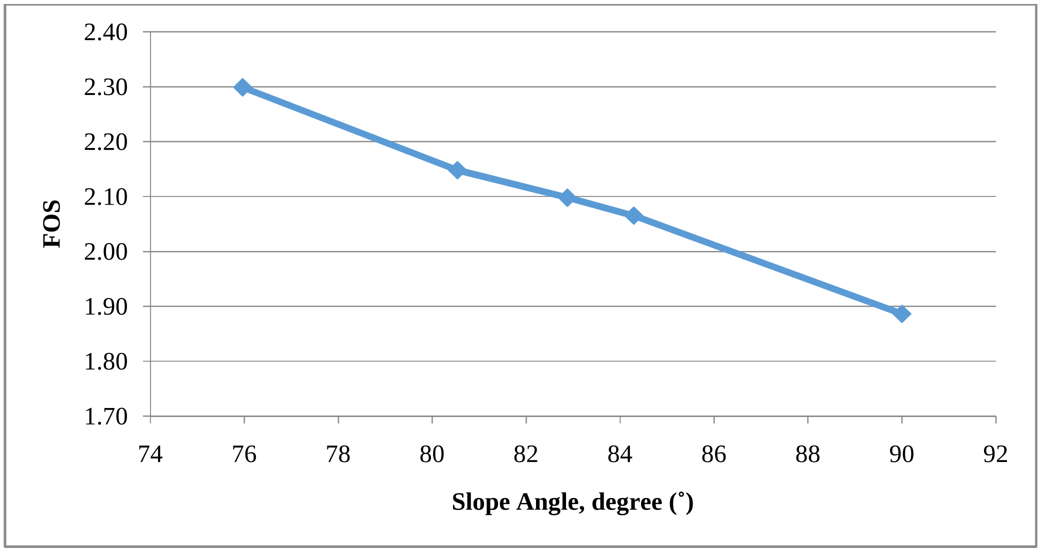


Figure 4.7: Effect of wall Slope on FOS

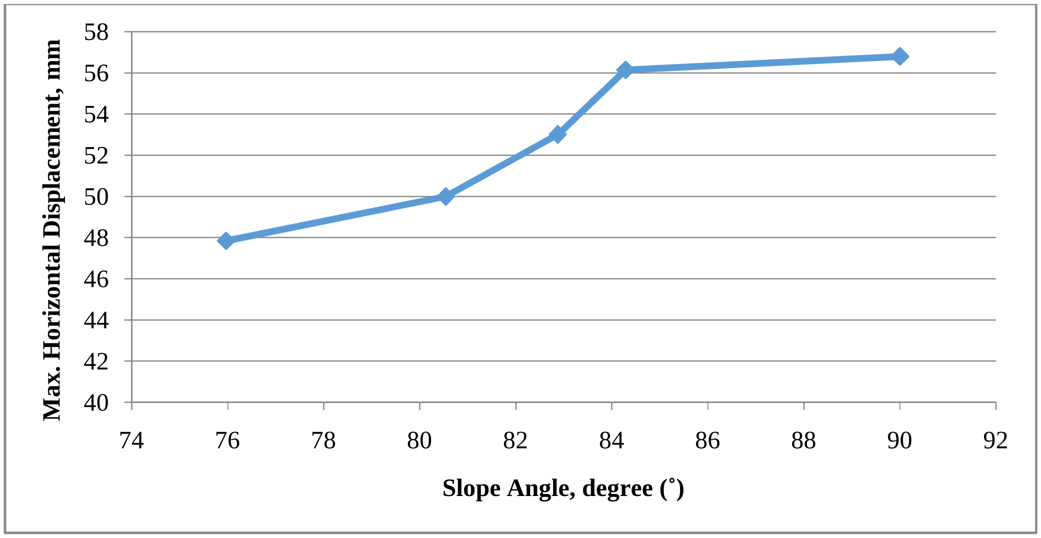


Figure 4.8: Effect of wall Slope on maximum horizontal displacement

4.2.5 Effect of change in Angle of internal friction of Reinforced soil

The FOS of wall increased with increase in angle of internal friction of reinforced soil by 11.3% and horizontal displacement decreased by 41.68mm when angle of internal friction increased from 24° to 36°. Angle of internal friction of soil is directly related to its shear strength, so the factor of safety increases with increase in angle of internal friction when other parameters remains constant. Axial stiffness value of 800 kN/m is used for analysis.

Table 4.5: Effect of Angle of internal friction on FOS and maximum horizontal displacement

S.No.	Angle of Internal Friction (°)	FOS	Maximum Horizontal Displacement, (mm)
1	24	1.902	99.65
2	26	1.942	87.29
3	28	1.980	78.44
4	30	2.016	72.52
5	32	2.050	67.62
6	34	2.086	62.70
7	36	2.117	57.97

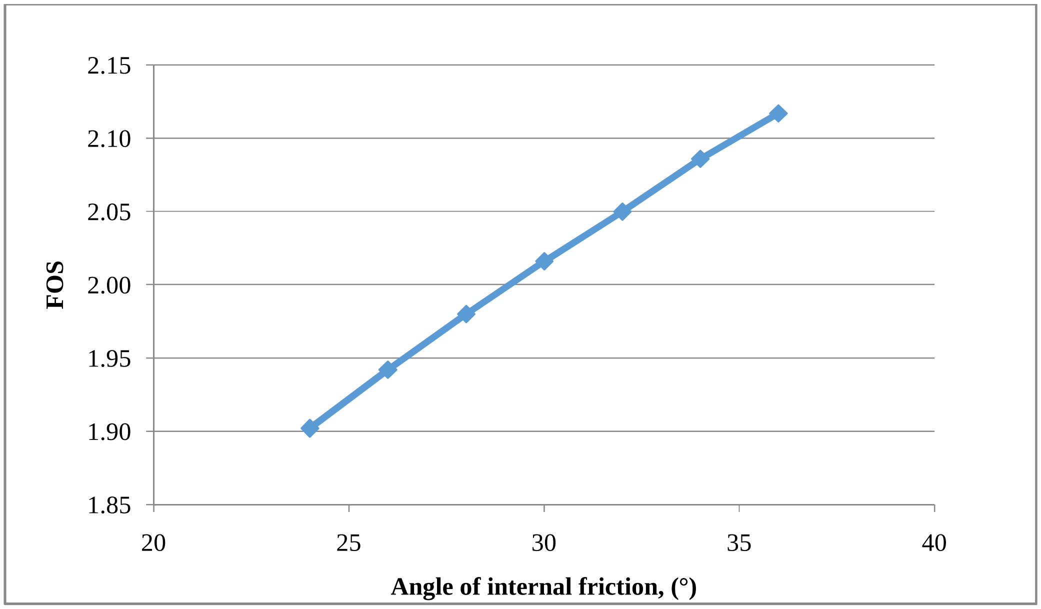


Figure 4.9: Variation in FOS with change in Angle of internal friction of reinforced soil

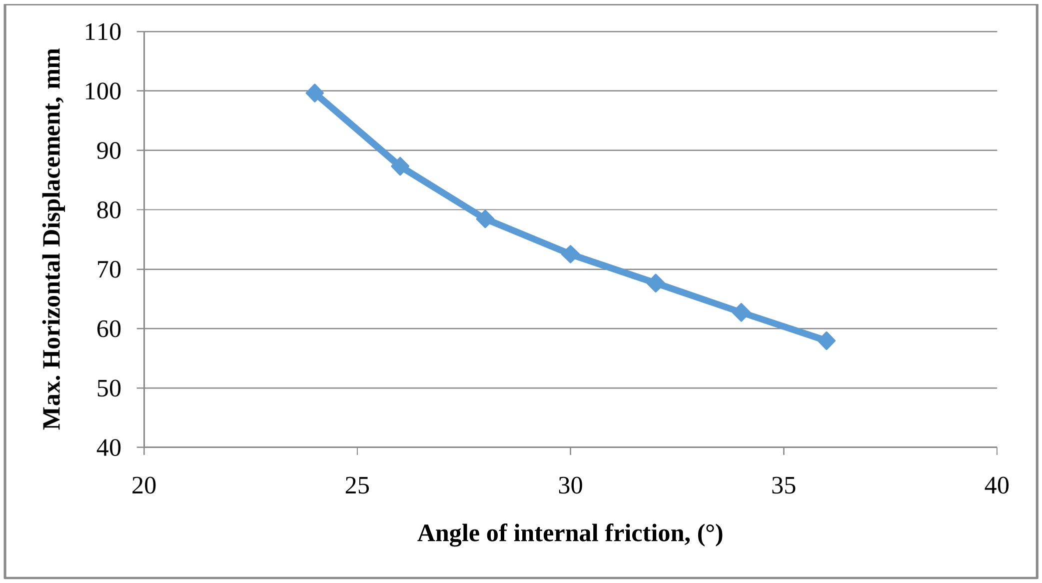


Figure 4.10: Variation in maximum horizontal displacement with change in Angle of internal friction of reinforced soil

4.2.6 Effect of change in Angle of internal friction of Foundation soil

The FOS of wall increased with increase in angle of internal friction of foundation soil by 7.78% and horizontal displacement decreased by 73.26 mm when angle of internal friction increased from 24° to 32°. Axial stiffness value of 800 kN/m is used for analysis.

Table 4.6: Effect of Angle of internal friction on FOS and maximum horizontal displacement

S.No.	**Angle of internal friction (°)**	**FOS**	**Maximum Horizontal Displacement (mm)**
1	24	1.67	132.00
2	26	1.81	102.93
3	28	1.94	82.42
4	30	2.05	67.62
5	32	2.19	58.74

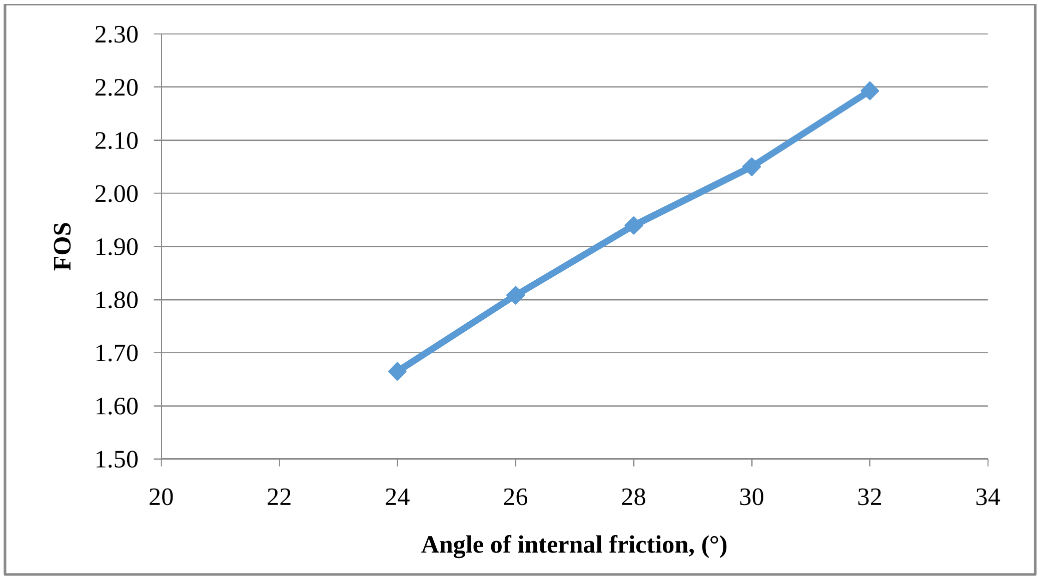


Figure 4.11: Variation in FOS with change in Angle of internal friction of foundation soil

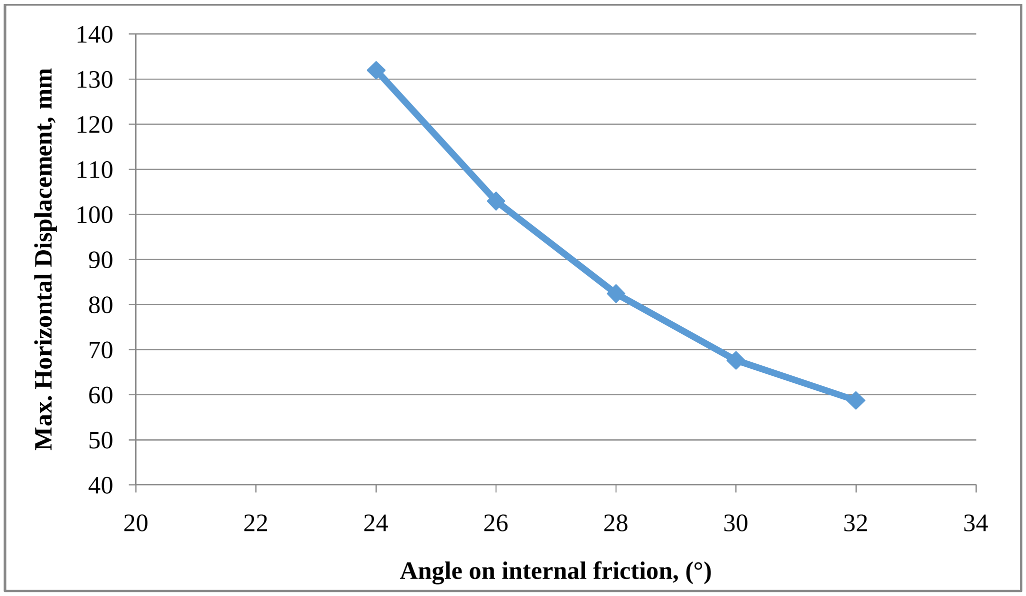


Figure 4.12: Variation in maximum horizontal displacement with change in Angle of internal friction of foundation soil

4.2.7 Effect of increase in Height of wall

A study is done to see the effect of increase in height of wall on factor of safety (FOS) and horizontal displacement of wall. For this top width of wall is taken as 7m for all cases and height 10m, 12m, 15m and 20m taken into account with a slope of 1:10. As the wall height increases FOS decreases and maximum horizontal displacement increases significantly from 56.14mm to 167.98mm. This may be due to the increase in lateral earth pressure with increase in height of wall. The graph obtained is more or less linear for both FOS and displacement.

Table 4.7: Effect of increase in Height of wall on FOS and maximum horizontal displacement

S.No.	Height of Wall (m)	FOS	Maximum Horizontal Displacement (mm)
1	10	2.065	56.14
2	12	2.001	75.46
3	15	1.879	113.23
4	20	1.725	167.98

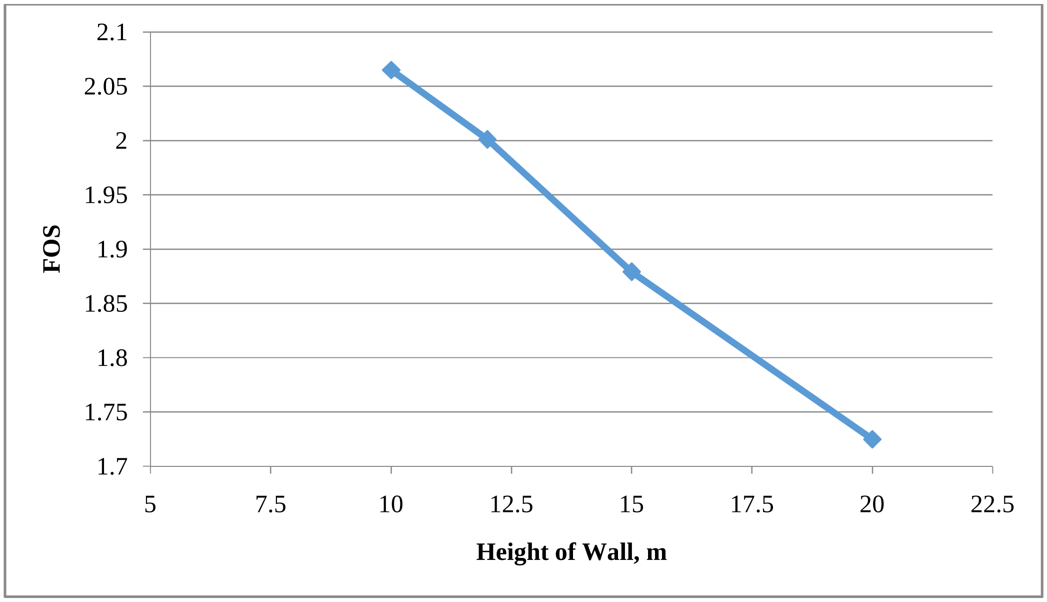


Figure 4.13: Variation in FOS with increase in height of wall

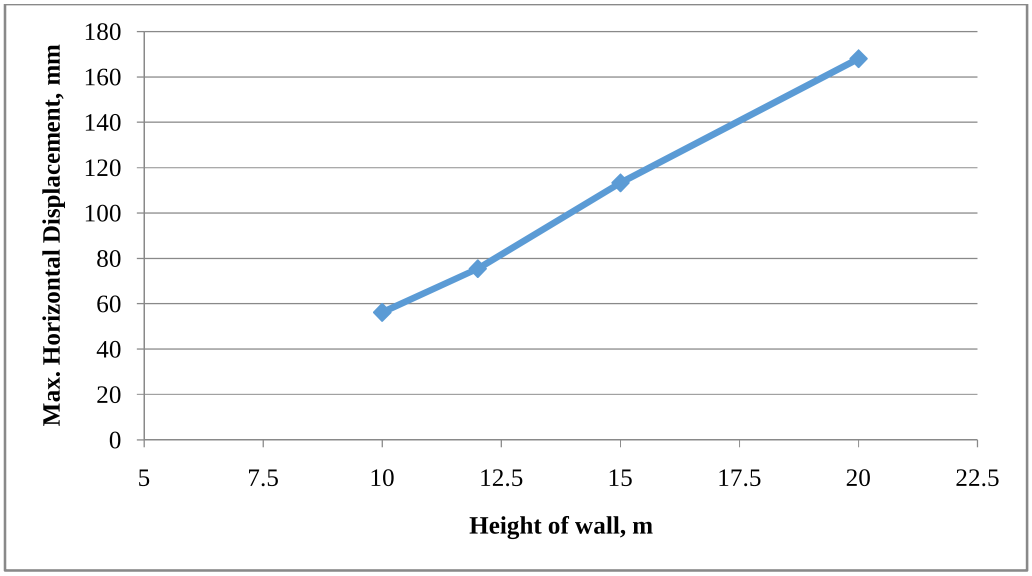


Figure 4.14: Variation in maximum horizontal displacement with increase in Height of wall

4.2.8 Effect of Water Level

The effect of water on the stability and horizontal displacement is studied for 5m height wall. Water level is placed at 2m height of the reinforced soil. Three spacing values of 30cm, 45cm and 60cm walls are modeled. The wall collapsed at a spacing of 60cm. The FOS reduced by around 45% for other two cases. The maximum horizontal displacement increased to 28.53mm from 15.09mm (water at bottom) for 30cm spacing of geosynthetics.

Table 4.8: Effect of Water Level on FOS and maximum horizontal displacement

S.No.	Spacing of Reinforcement, cm	FOS	Maximum Horizontal Displacement (mm)
1	30	1.451	28.53
2	45	1.425	40.78
3	60	Soil Body Collapsed	

4.3 Validation

Verification of the result obtained from the analysis done in this thesis is compared with the paper published on Parametric Study for Narrow Mechanically Stabilized

Earth Walls by (Abdelrahman et al., 2014). In this paper the effect of wall height, H is studied on the maximum horizontal displacement of wall. The height of the wall used are 2m, 6m, 8m, 10m and 12m for L/H ratio of 0.6 and 0.8 and spacing between the reinforcement is 0.5m. In this thesis the same effect study is done for a height of 10m, 12m, 15m and 20m for L/H ratio of 0.7 and spacing of reinforcement 0.3m. The numerical data from the curve on effect of wall height is extracted using WebPlotDigitizer and these values are presented in the same figure of graph between maximum horizontal displacement and height of wall of the model studied in this thesis. The slope thus obtained is found to match with the slope obtained in this thesis work.

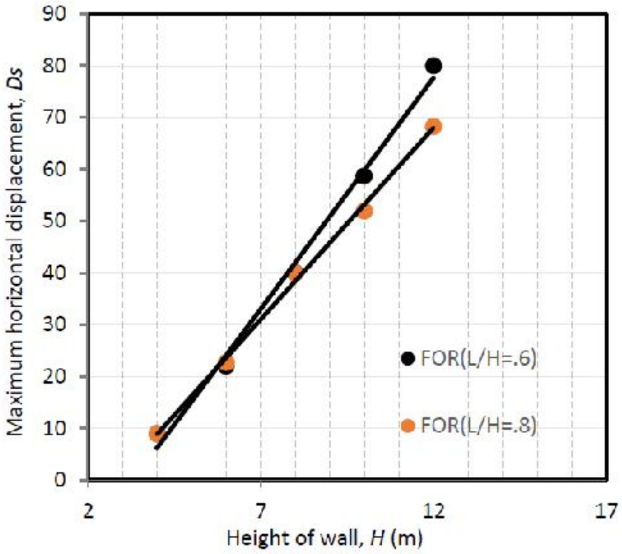


Figure 11: Relationship between Height of wall, *H*, and maximum horizontal displacement, for aspect ratio, *L/H*= 0.6 and spacing between reinforcing elements, *S*=0.5m.

Figure 4.15: Relation between height of wall and maximum horizontal displacement from (Abdelrahman et al., 2014)

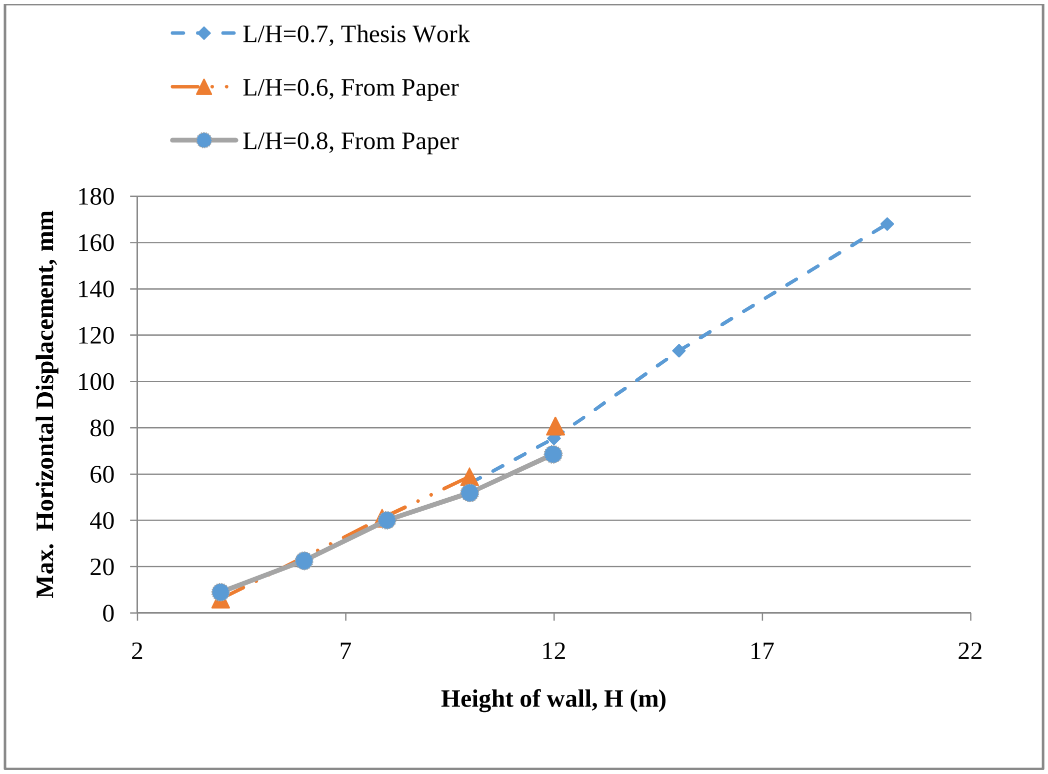


Figure 4.16: Relation between height of wall and maximum horizontal displacement

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The MSE wall is modeled using Finite Element Program to study parametric variation of geosynthetics on stability and deformation characteristics of the wall. The different parameters used are spacing of geosynthetics, aspect ratio, geosynthetics stiffness, slope of wall, angle of internal friction, height of wall and effect of water table. The conclusions drawn from the numerical modeling of geosynthetics reinforced Mechanically Stabilized Earth (MSE) wall are as follows:

- Increase in spacing of geosynthetics, increase in slope of wall and increase in height of wall decreases the FOS and increases maximum horizontal displacement.
- Higher geosynthetics stiffness values greatly reduce the maximum horizontal displacement.
- Increase in aspect ratio increases FOS due to more length of geosynthetics available for resistance.
- Increase in angle of internal friction increases FOS and decreases maximum horizontal displacement as the shear strength of soil increases.
- Increase in water table greatly reduces FOS (45 %) and increases displacement as effective stress decreases and so does the shear strength. Hence, free draining condition and/or drainage measures should be adopted to increase stability.

5.2 Recommendations

- A three dimensional study can be done for MSE wall for better visualization and representation of actual environment.
- Axial forces in reinforcement and internal stability of MSE wall can be studied.
- Variation of FOS and deformation in seismic condition can be studied.
- Geosynthetics stiffness needs to be further studied in future research.

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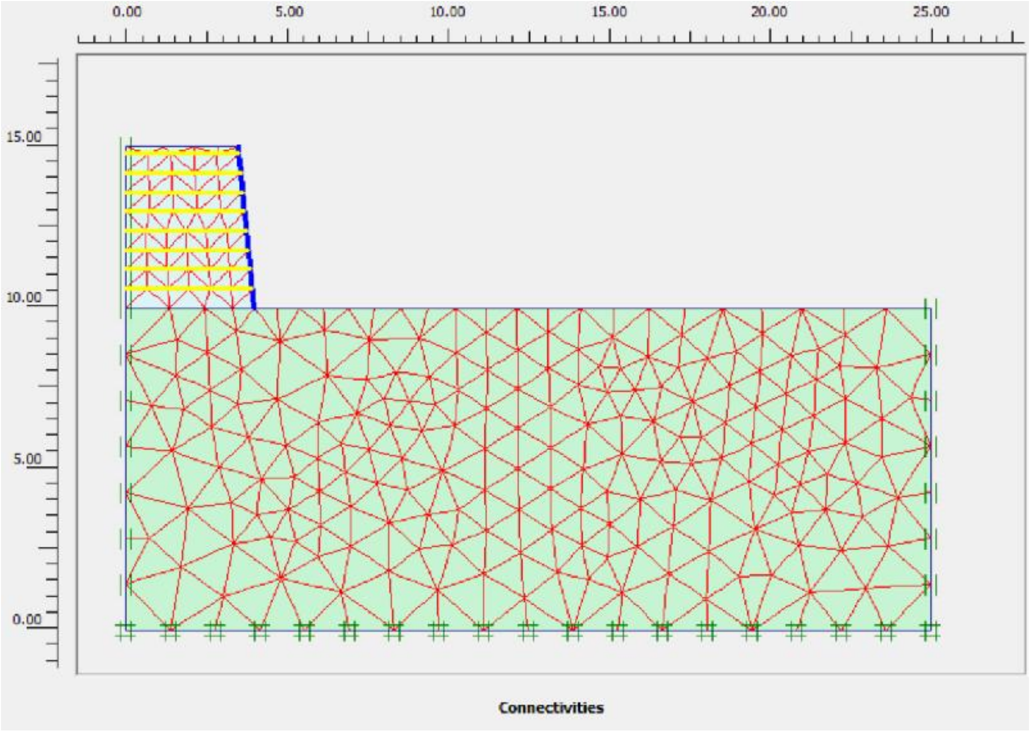
ANNEX



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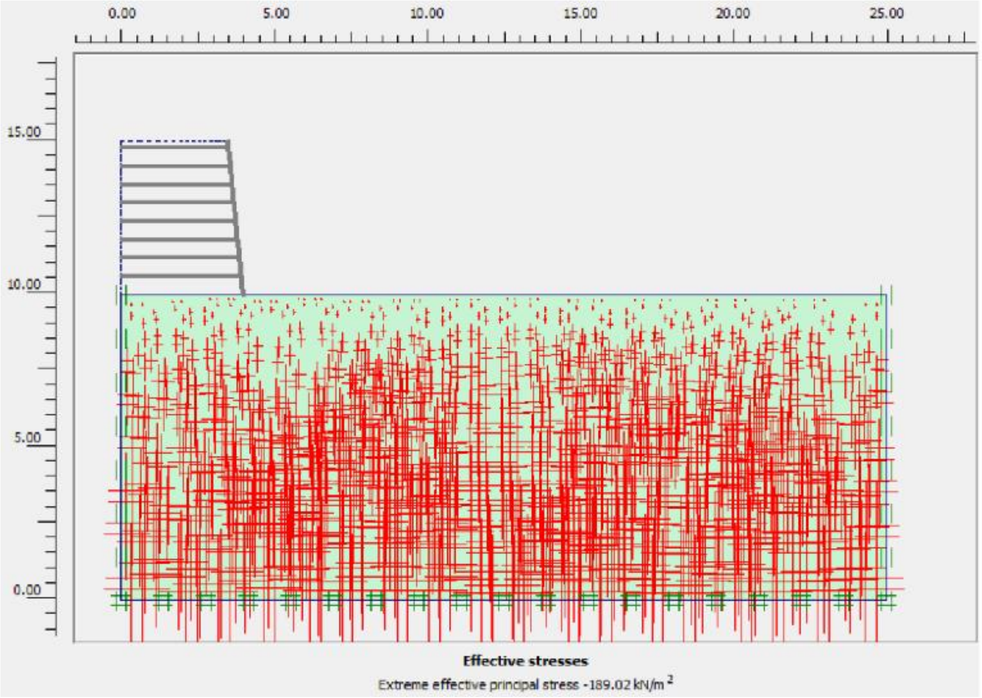

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Figure A.1: (a) Geometric model with connectivities; (b) Effective Stress

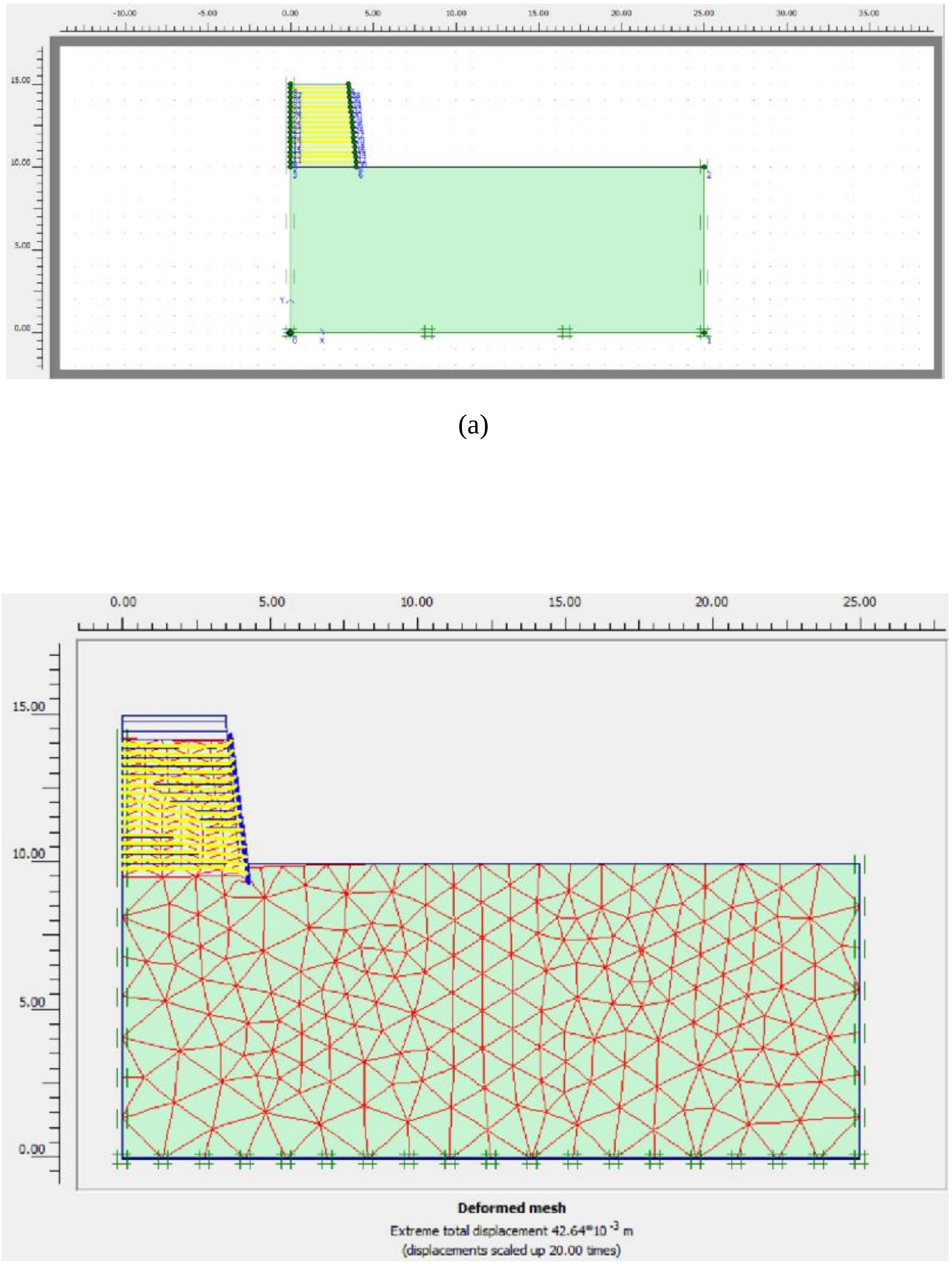

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Figure A.2: (a) Geometry Model (Spacing of reinforcement=30cm); (b) Deformed Mesh

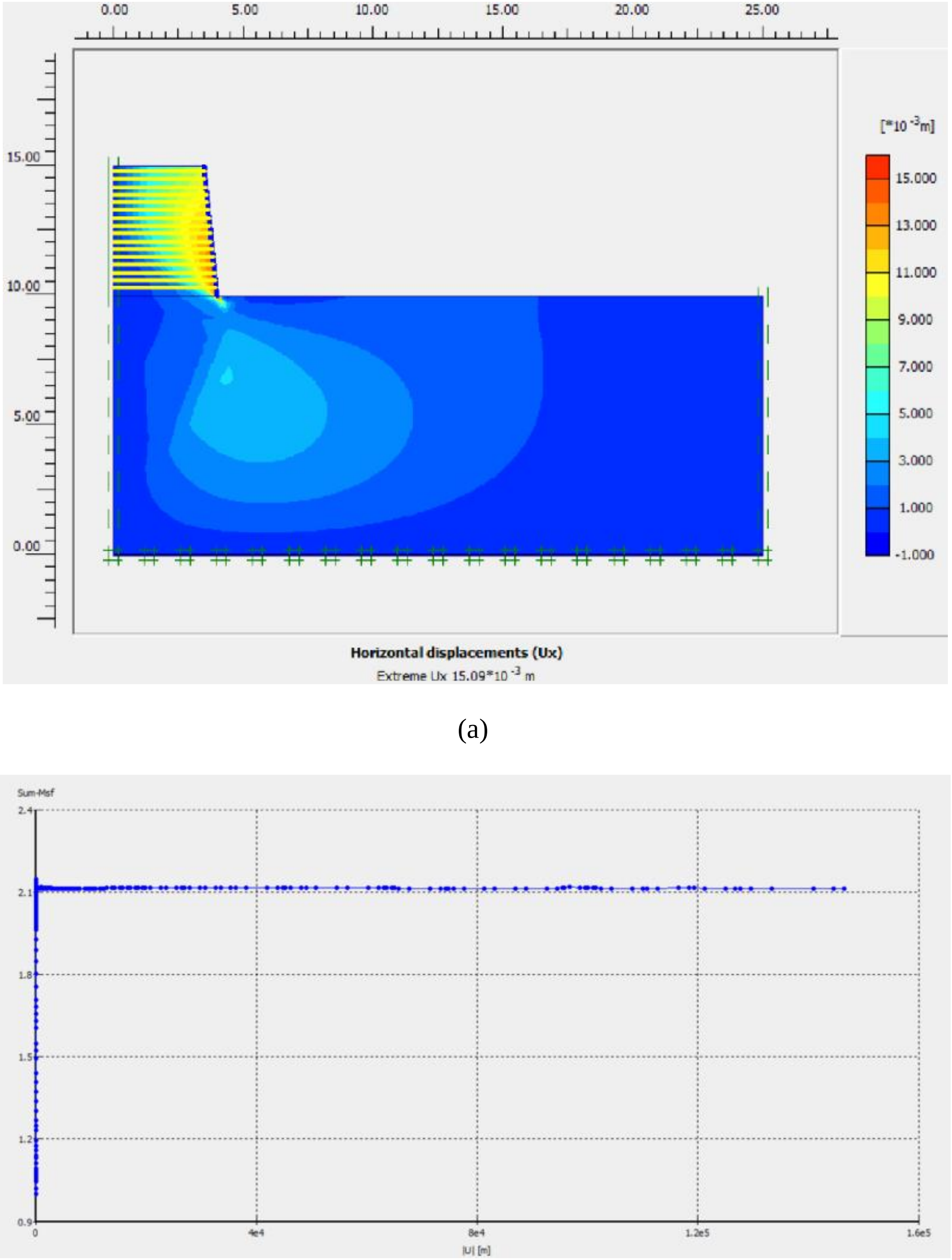

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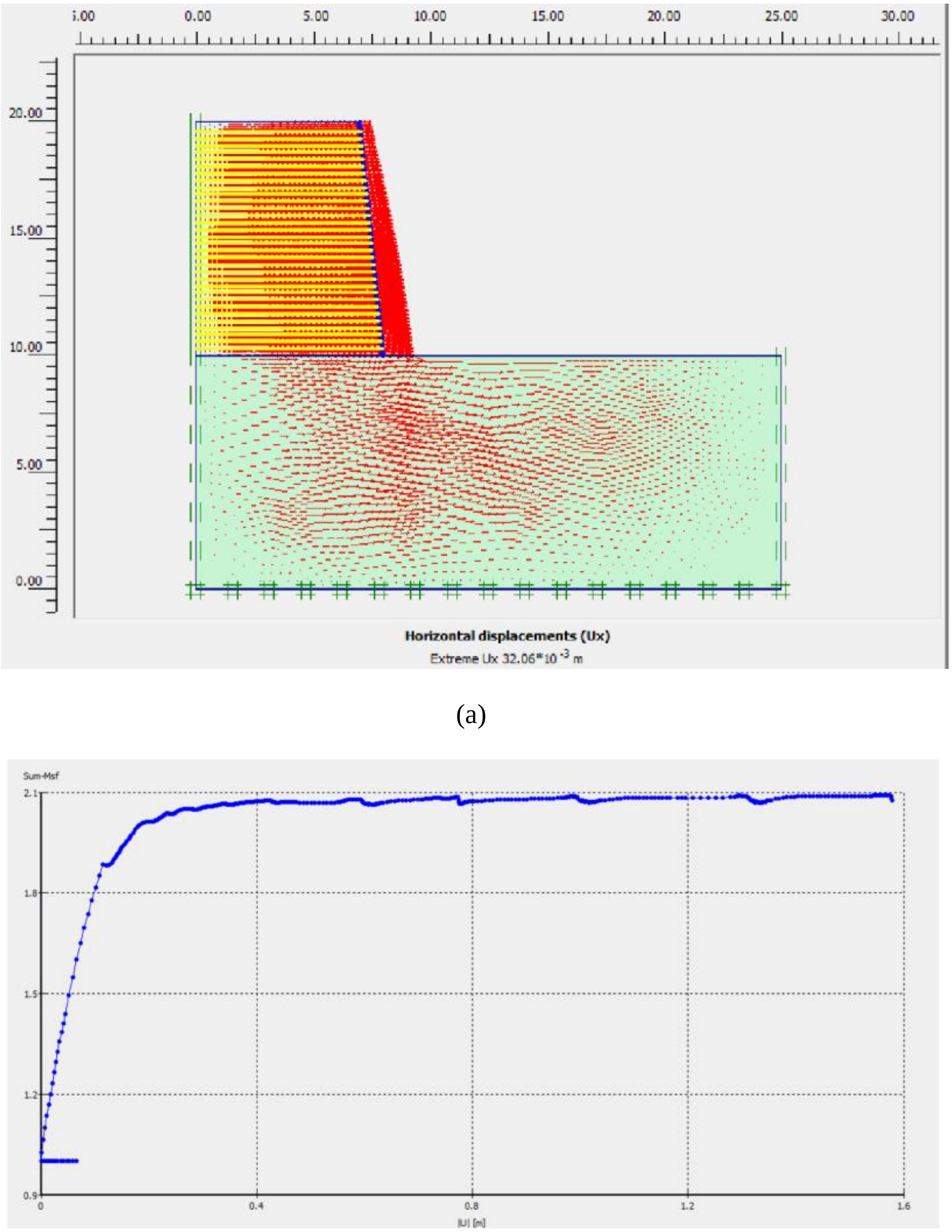
Figure A.3: (a) Horizontal Displacement (spacing=30cm); (b) $\sum M_{sf}$ versus total displacement plot (spacing=30cm)



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(b)

Figure A.4: (a) Horizontal Displacement (EA=2500 kN/m); (b) $\sum M_{sf}$ versus total displacement plot (EA=2500 kN/m)

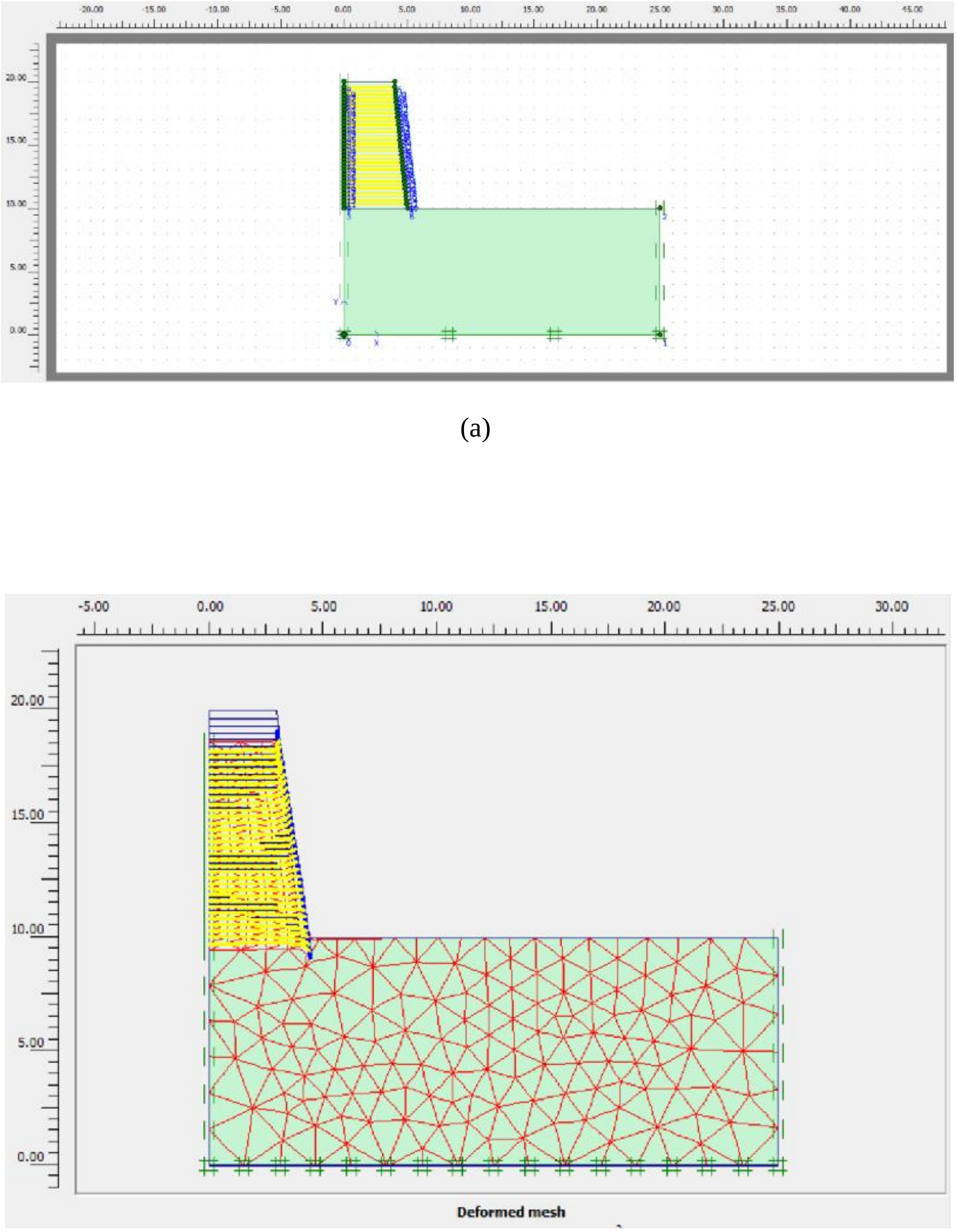

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Figure A.5: (a) Geometric model (L/H=0.3); (b) Deformed Mesh

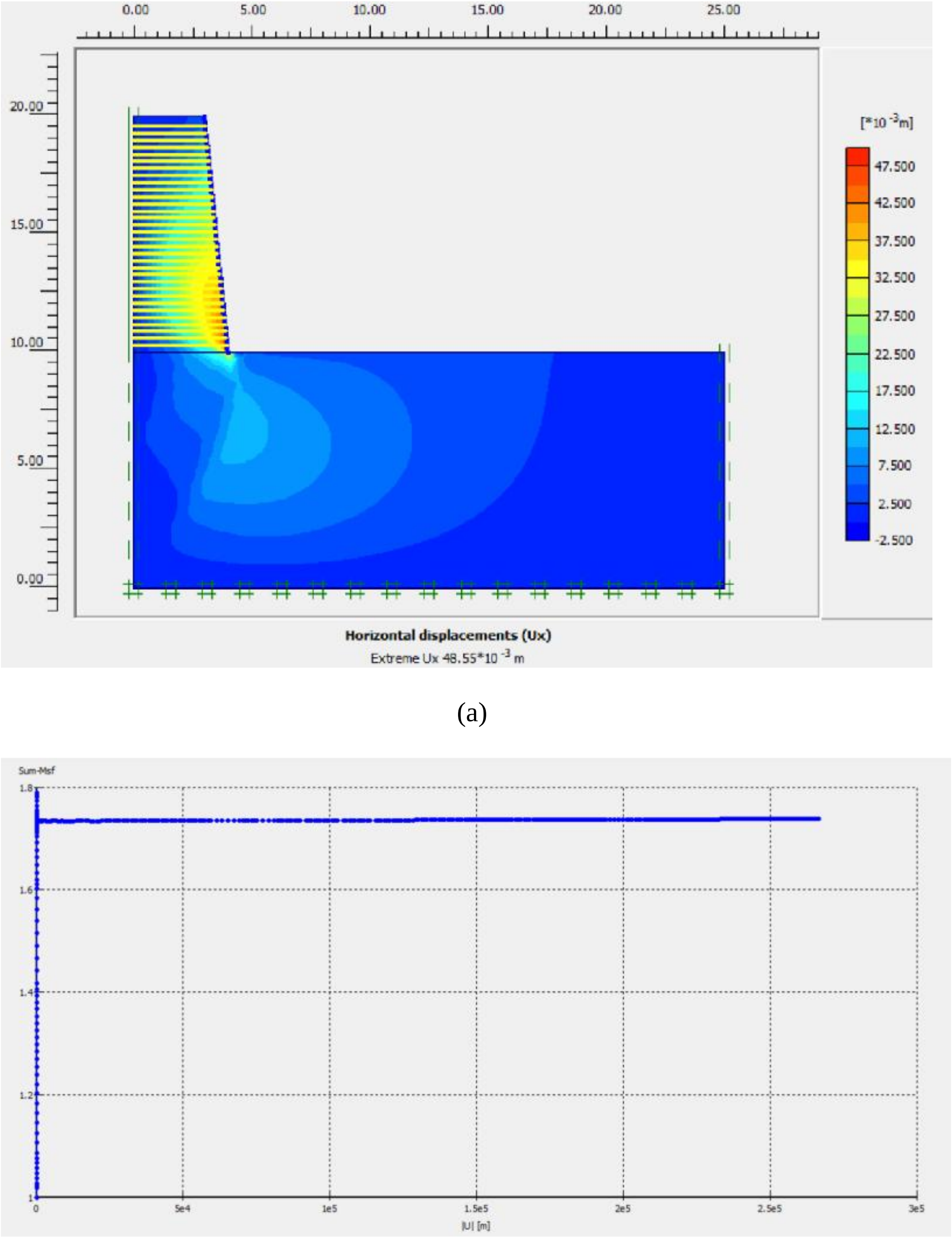

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Figure A.6: (a) Horizontal Displacement (L/H=0.3); (b) $\sum M_{sf}$ versus total displacement plot (L/H=0.3)

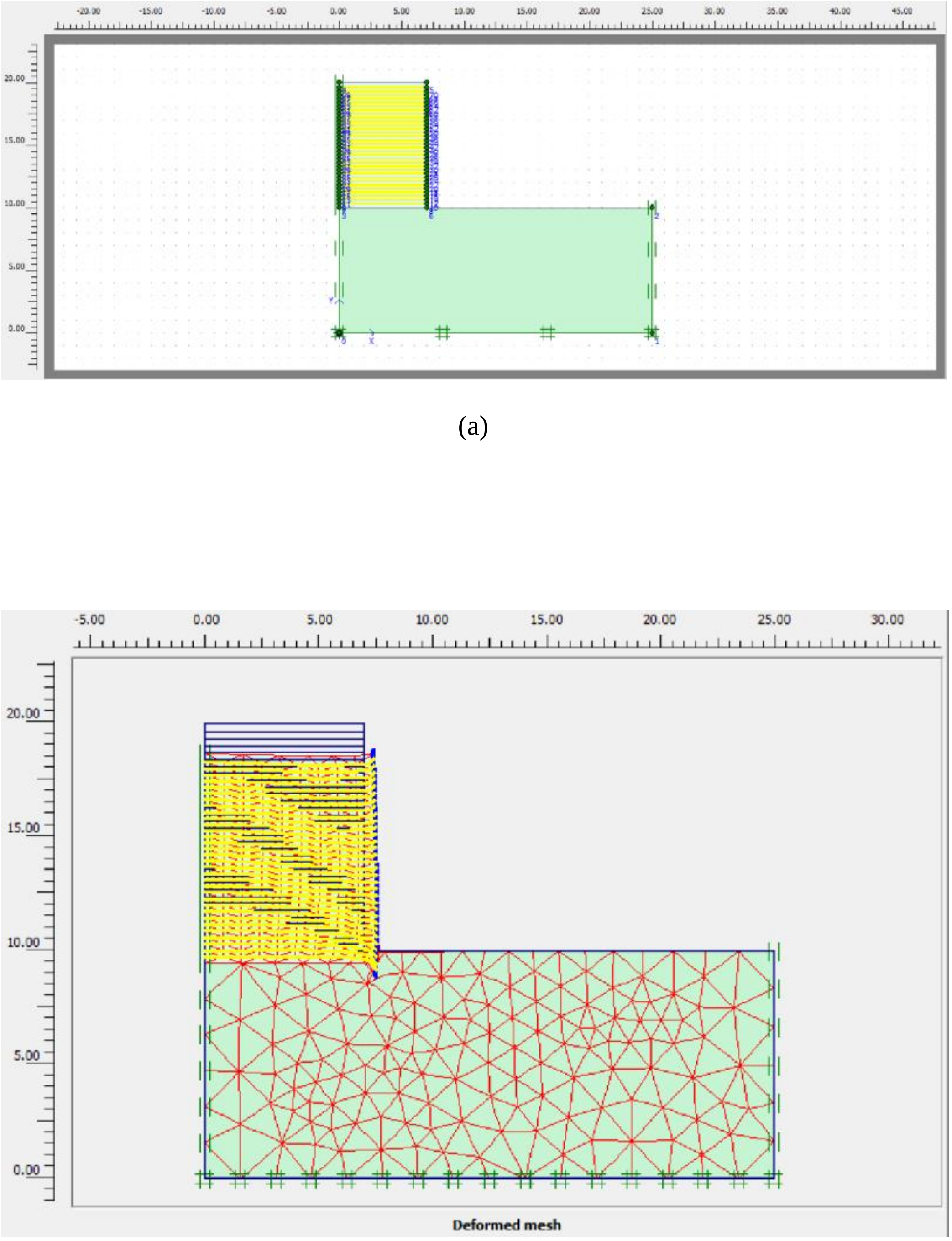

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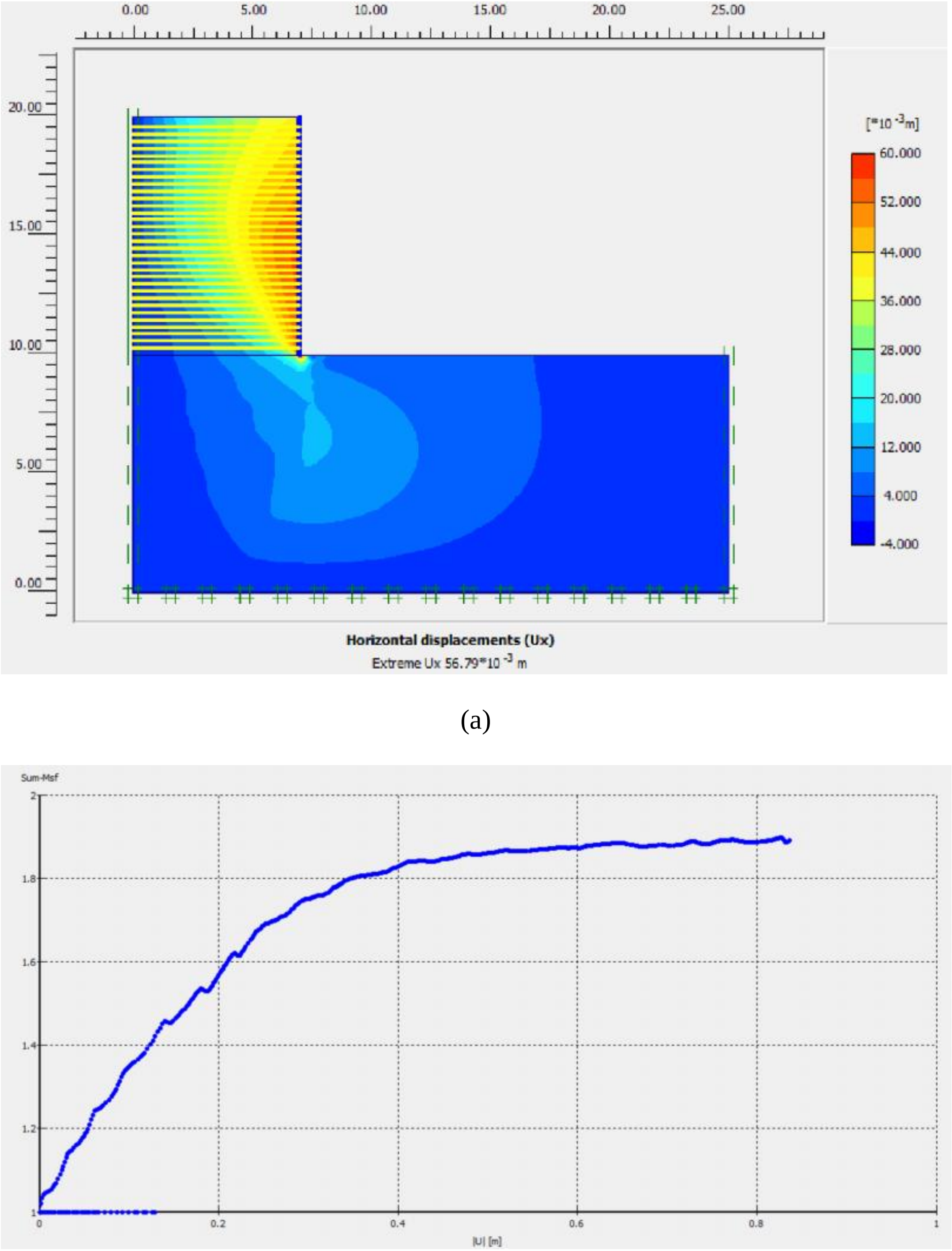
Figure A.7: (a) Geometry Model (Slope=90°); (b) Deformed Mesh (Slope=90°)



(a)

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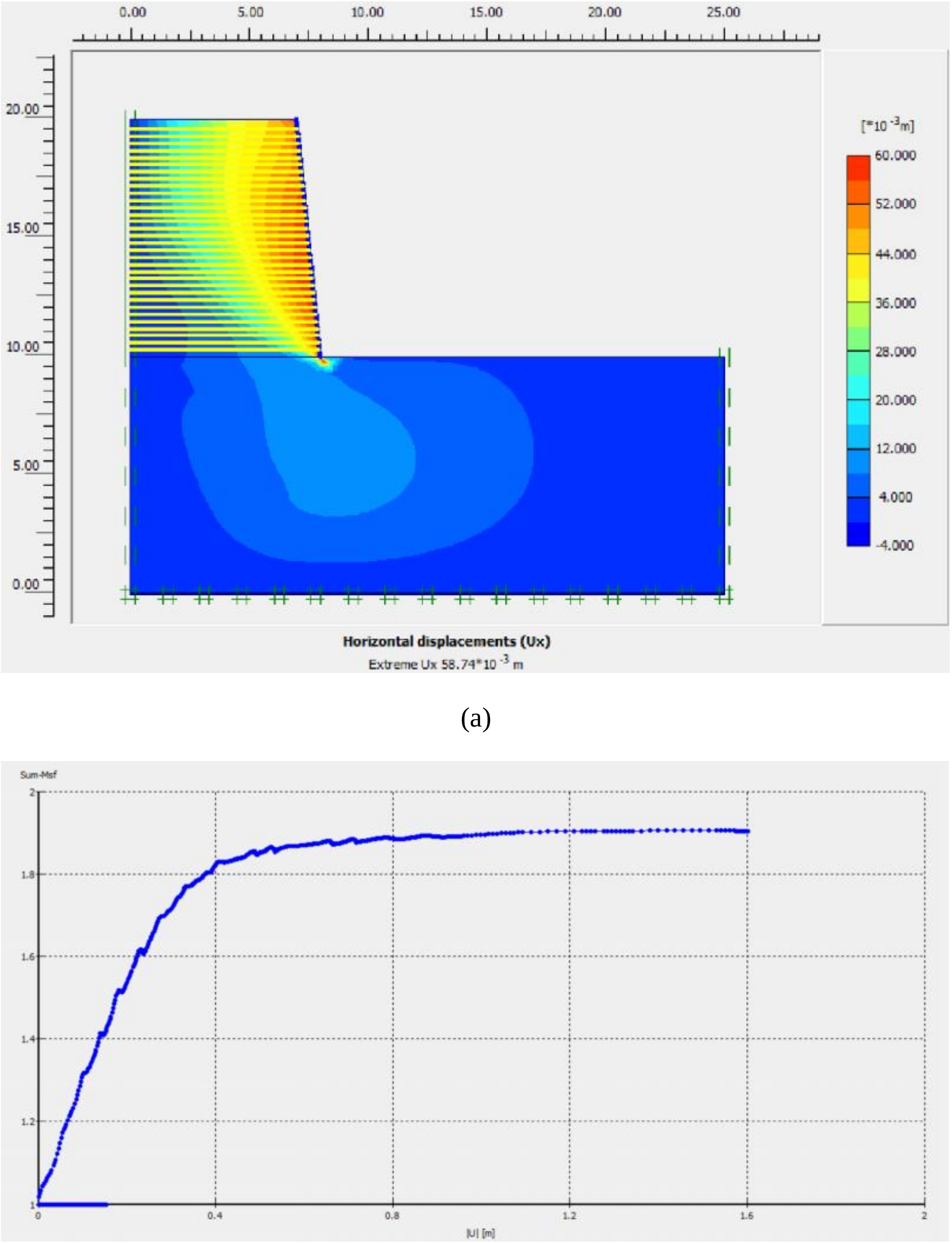
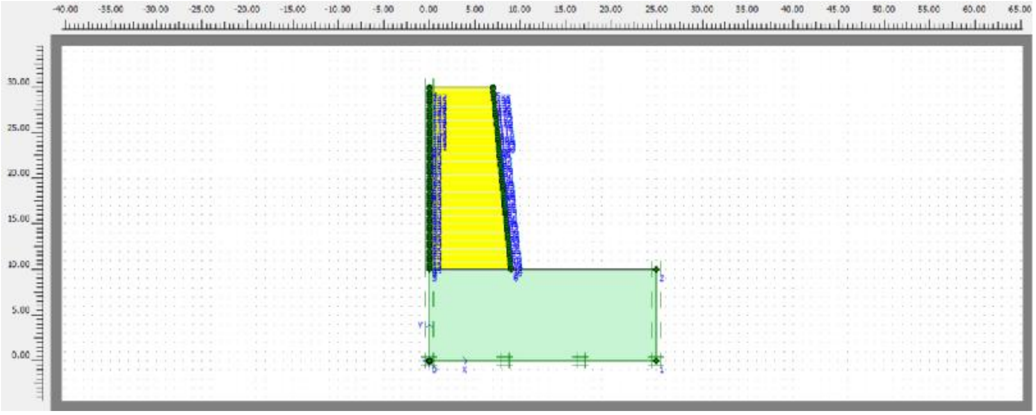
Figure A.8: (a) Horizontal Displacement (Slope=90°); (b) $\sum M_{sf}$ versus total displacement plot (Slope=90°)



(a)

(b)

Figure A.9: (a) Horizontal Displacement (Angle of internal friction of foundation soil=32°) (b) $\sum M_{sf}$ versus total displacement plot (Angle of internal friction of foundation soil=32°)



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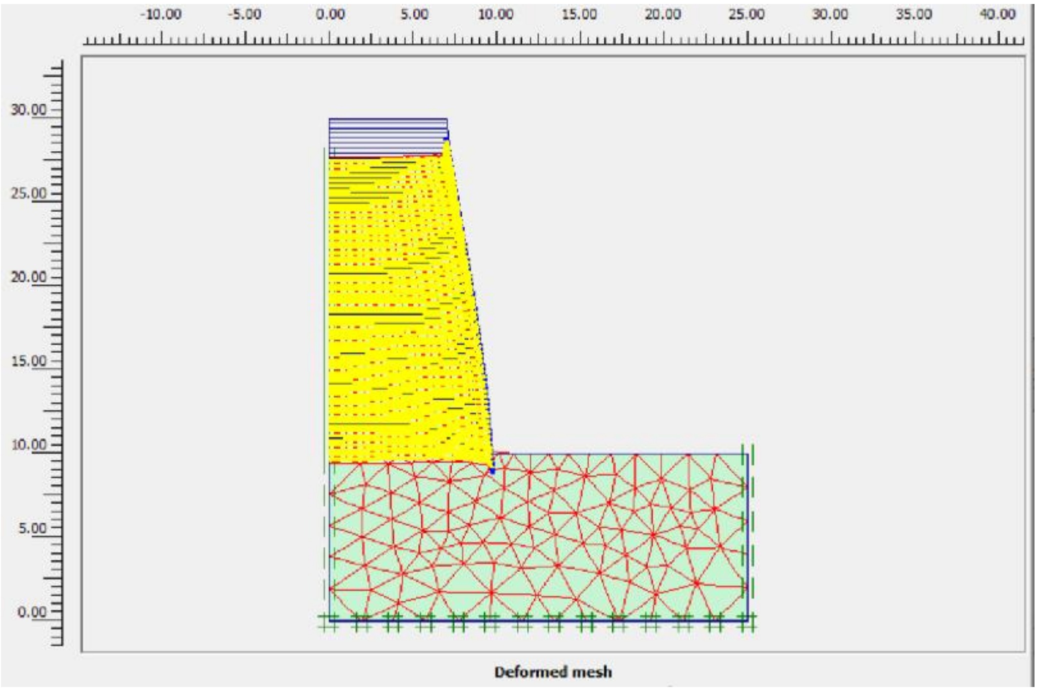
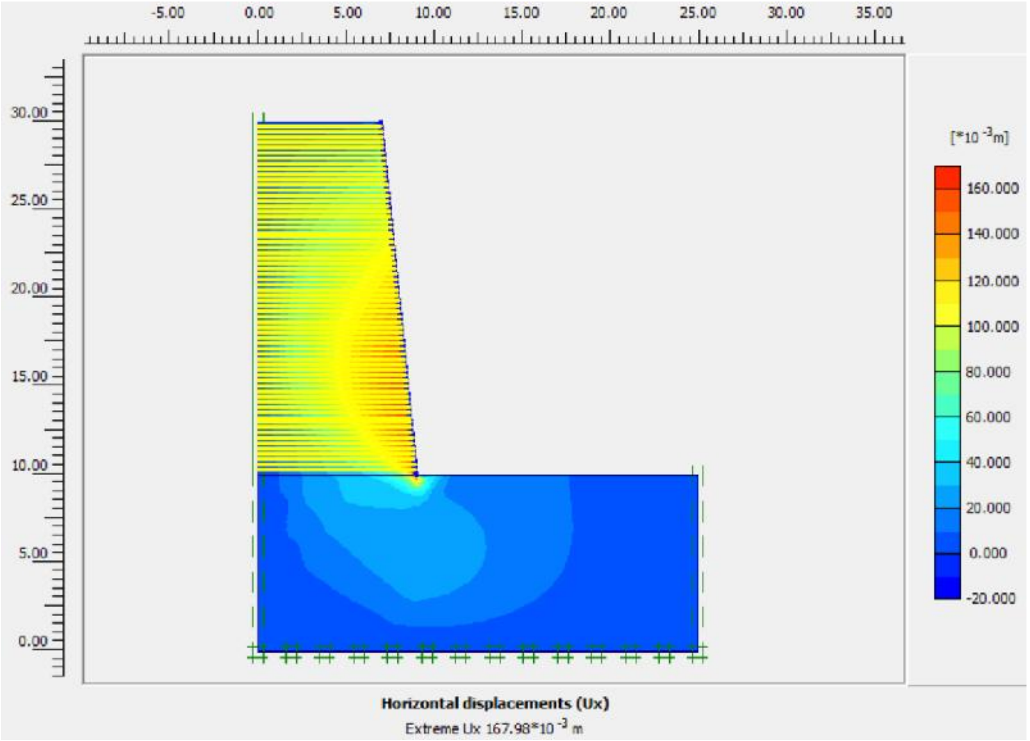


(b)

Figure A.10: (a) Geometry Model (20m height wall, spacing=30cm) (b) Deformed Mesh (20m height wall, spacing=30cm)



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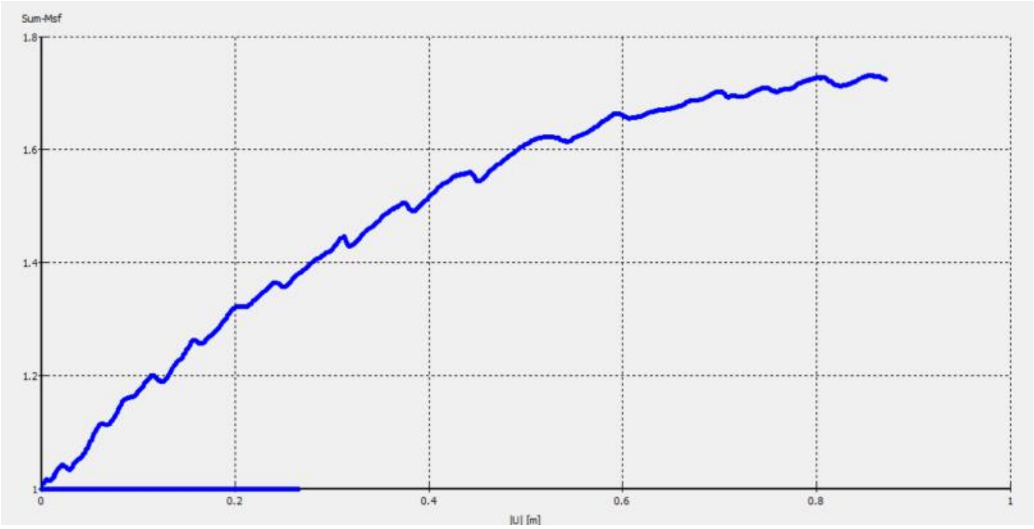
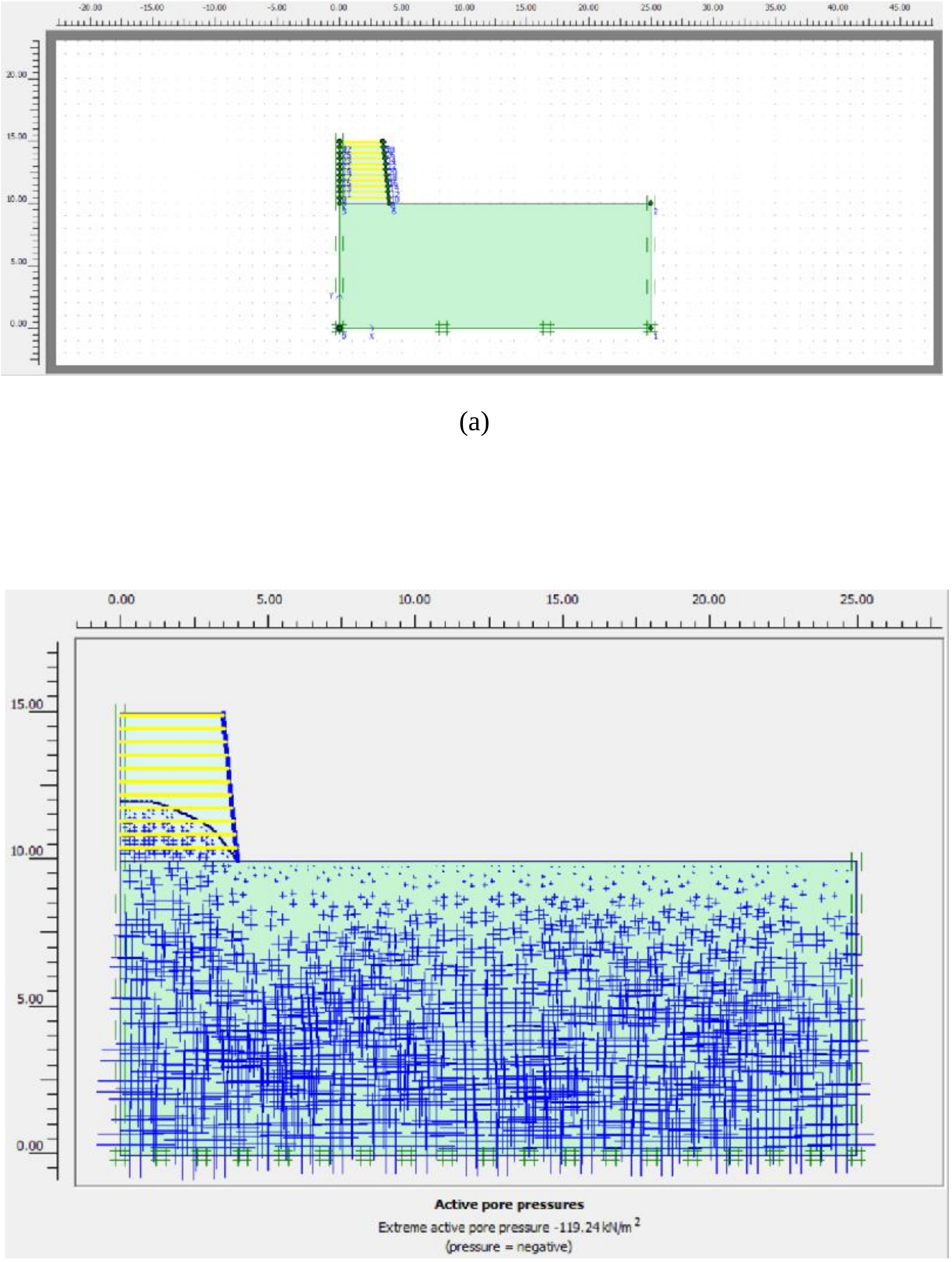


(b)

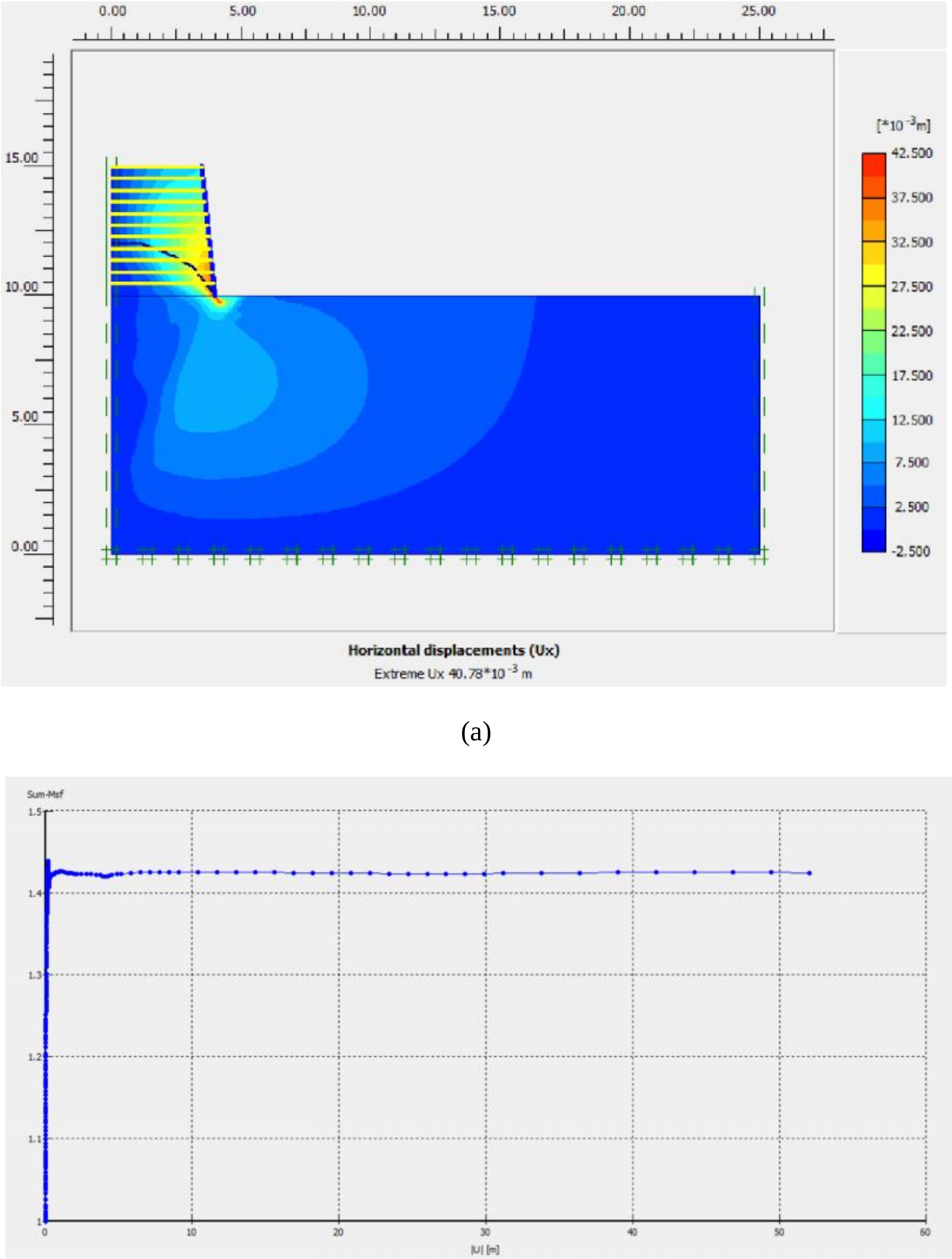
Figure A.11: (a) Horizontal Displacement (20m height wall, spacing=30cm) (b) $\sum M_{sf}$ versus total displacement plot (20m height wall, spacing=30cm)



(a)

(b)

Figure A.12: (a) Model Geometry (b) Active pore water pressure (Height of water level= 2m from base of MSE wall, spacing=45cm)



(a)

(b)

Figure A.13: (a) Horizontal Displacement (Height of water level= 2m from base of MSE wall, spacing=45cm) (b) $\sum M_{sf}$ versus total displacement plot (Height of water level= 2m from base of MSE wall, spacing=45cm)